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Age and correlation of Silurian rocks in Sheboygan, Wisconsin, using integrated stable carbon isotope stratigraphy and facies analysis

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ABSTRACT

The exact age of Silurian rocks in eastern Wisconsin is uncertain; biostratigraphic precision here approximates +/- 2 million years. Much of this ambiguity stems from limited surface exposure, poor biostratigraphic control, and prominent facies changes north of the well-studied sections in southeastern Wisconsin. The primary objective of this study is to evaluate the efficacy of high-resolution carbon isotope stratigraphy in resolving this chronostratigraphic uncertainty. Development of a carbon isotope global standard has revolutionized chronostratigraphy in the Silurian and is applicable to Wisconsin rocks.

Recent bedrock mapping in Sheboygan County led to the acquisition of 15 new bedrock cores, four of which were analyzed for carbon and oxygen isotopes. A core drilled in Quarry Park in the city of Sheboygan's north side was sampled at less than 2-foot (0.6 m) intervals through more than 600 feet (180 m) of Silurian rock. Three additional cores, drilled nearby along the Lake Michigan shoreline (about 1,500 feet, 460 m, northeast of North Shore Park), were sampled at a similar interval. Correlation of these cores around the city of Sheboygan allows for construction of a composite section. Carbon isotope results from this composite section exhibit many of the patterns present in the global composite. As a result, the uncertainty on age assignment of strata within this interval may be reduced to approximately a 100,000-year scale. The Sheboygan-area chemostratigraphy provides a preliminary revision to the age of these Silurian rocks and provides a starting point for the future revision of Silurian chronostratigraphy throughout eastern Wisconsin and the Great Lakes region for improved prediction and assessment of natural resources.

INTRODUCTION

Accurate correlation of Silurian stratigraphic units in Wisconsin and the surrounding region is increasingly important for a number of reasons. Approximately half of the citizens of Wisconsin live atop Silurian bedrock along the eastern margin of the state and many in this area depend on drinking water sourced from Silurian bedrock aquifers. These rocks are also pivotal to the infrastructure development of Wisconsin because they are the main source of crushed stone in the state and one of the primary sources of building stone in the region (USGS, 2009). Wisconsin's construction and transportation industries are dependent upon these materials for foundations of buildings and roads, facing stone, and retaining walls, among other uses. Despite their penetration by quarries and by thousands of drinking water wells, the Silurian rocks in eastern Wisconsin are still poorly understood; in large part due to a paucity of stratigraphically complete sections provided by deep cores and a cost-efficient quantitative method of fine-scale stratigraphic correlation. Yet, this area sustains the highest population densities of the state (U.S. Census Bureau, 2010), and is projected to experience some

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of the state's most rapid population growth (Eagan-Roberts and others, 2004). Thus, it is becoming essential to understand the stratigraphic architecture of the Silurian bedrock to better predict and assess the natural resources of eastern Wisconsin.

This study had three objectives: (1) to determine whether high-resolution carbon isotope chemostratigraphy would be able to resolve the age and improve correlation of Silurian rocks in eastern Wisconsin, (2) to establish the relationship of sedimentary facies and sequence stratigraphic surfaces to C-isotope signatures, and (3) to assess the relationship of C-isotope patterns in Sheboygan County to the global composite record to understand temporal completeness.

Geologic setting

Silurian rocks in eastern Wisconsin form the western margin of the Michigan Basin (fig. 1). These rocks consist of a dolostone-dominated succession as much as 600 feet (200 m) thick that is mostly buried beneath a thick glacial sediment cover that can exceed 250 feet (80 m) in thickness. Bedrock in this area typically dips to the east and southeast approximately 10 to 60 feet per mile (less than 0.01 degrees) (calculated, for example, by Luczaj, 2013; McLaughlin, 2013; and others). This succession is well studied in southeastern Wisconsin (fig. 2), especially the Milwaukee metropolitan area, in large part because of extensive quarry exposures and bedrock cores. Similarly, the Silurian rocks of Door County, about 150 miles (240 km) to the north in northeastern Wisconsin, have been well studied because of numerous natural exposures as well as a

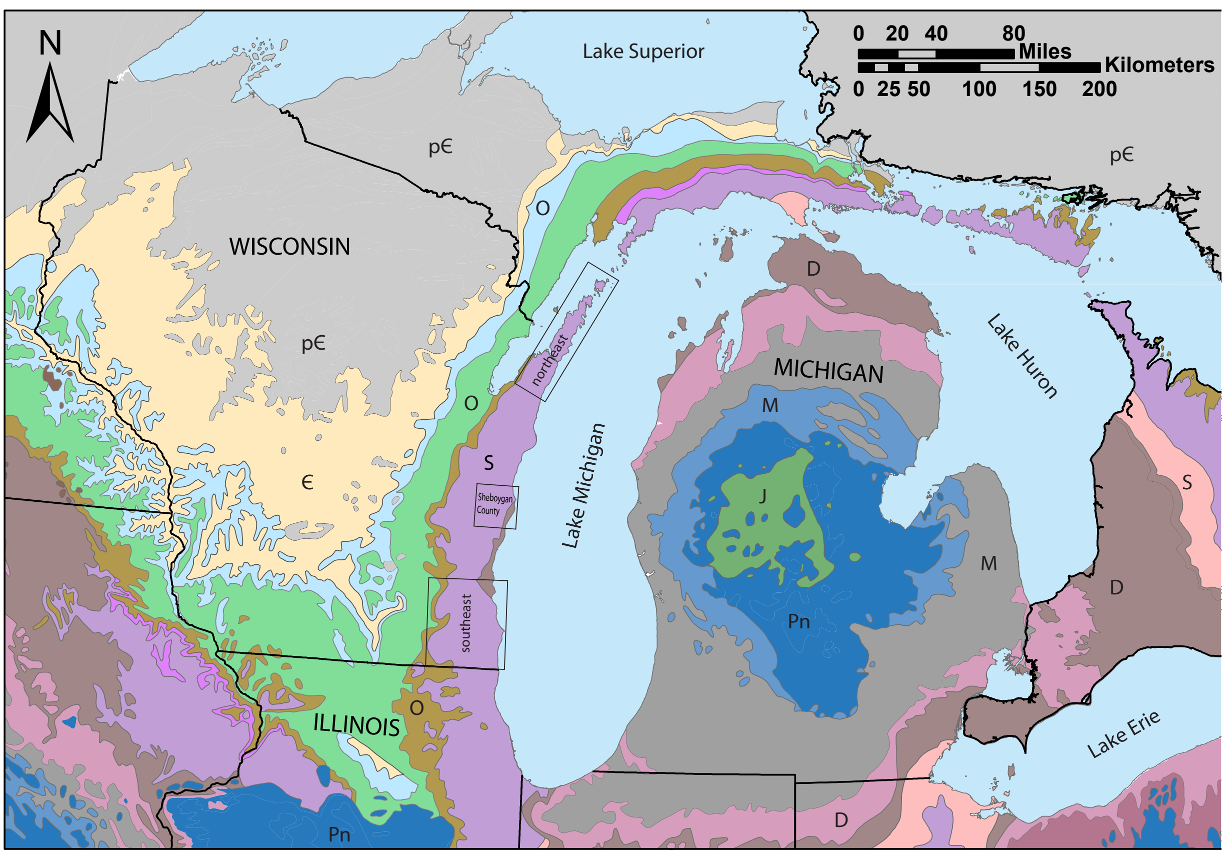


Figure 1. *Regional geologic map showing the position of classic areas of Silurian (S) bedrock studies in southeastern and northeastern Wisconsin relative to the position of Sheboygan County. Modified from Luczaj (2013).*

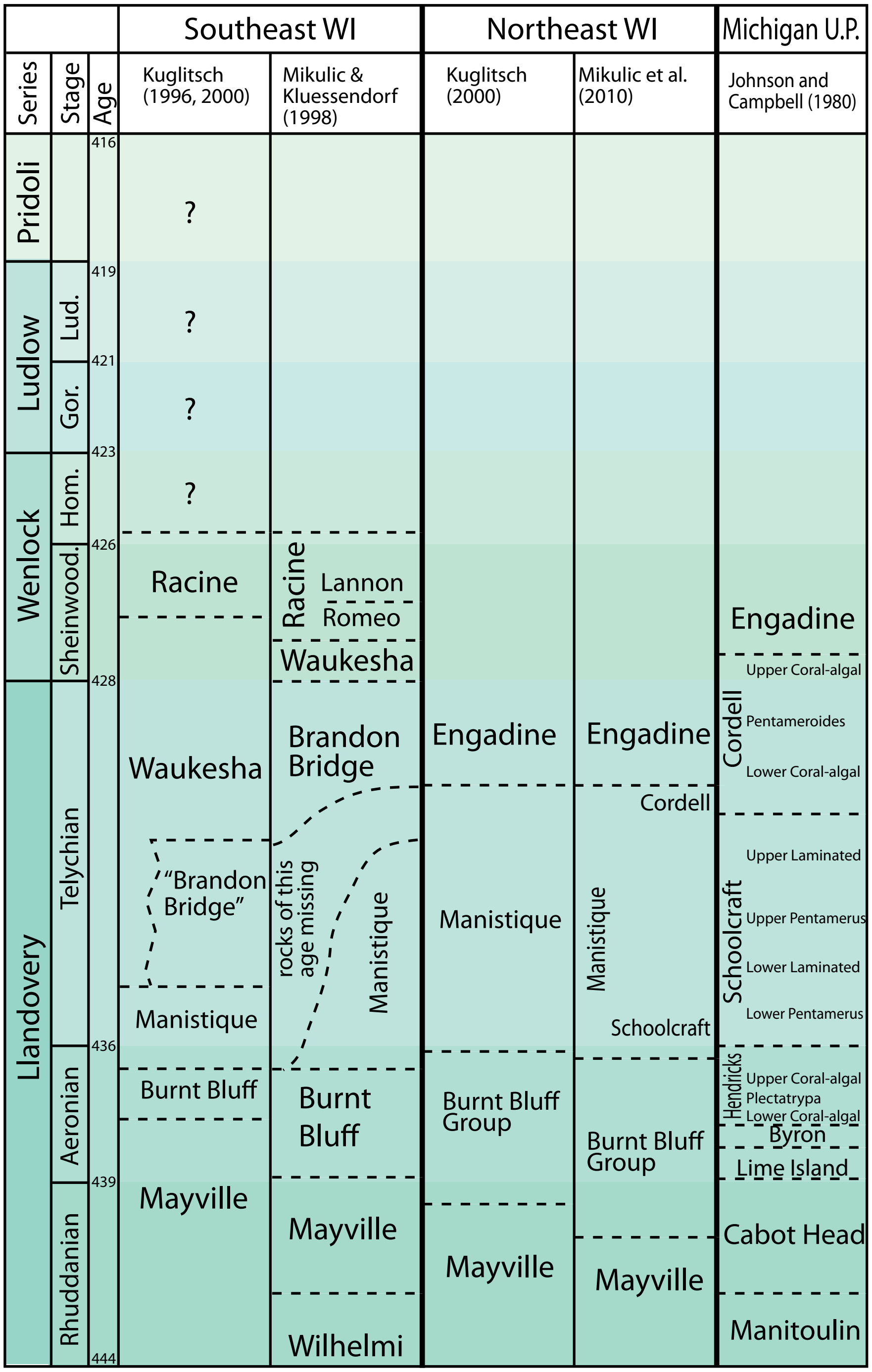


Figure 2. *Recent examples of lithostratigraphic classification and biostratigraphic assignment of Wisconsin Silurian rocks compared with that of the Upper Peninsula of Michigan. Question marks in the left column indicate the uncertain age assignment of the Waubakee Formation—while it locally contains brachiopods that indicate Silurian age, no biostratigraphically diagnostic taxa are known from this unit to provide further refinement.*

handful of quarries and a single core. The intervening area of east-central Wisconsin has received comparatively limited study due to sparse bedrock exposures that only contain isolated parts of the Silurian succession and a general lack of drill cores.

Lithostratigraphy

Division of the Silurian strata into consistently definable and mappable units is a critical objective in advancing understanding of this rock succession. However, consistent assignment of rock packages based on their lithic characteristics in east-central Wisconsin has been difficult, chiefly because of the significant lack of exposures and the radically different appearance and age of the Silurian rocks between this area and the southeastern part of the state (fig. 2). These differences result primarily from broad facies and thickness changes in Llandovery rocks extending from central Illinois into Michigan (Mikulic and Kluessendorf, 1998). In addition, a poor understanding of Wenlock reef development in the east-central region further complicates correlation of the youngest part of the Silurian succession (Kluessendorf and Mikulic, 1996; Mikulic and Kluessendorf, 1998). In a map of seven counties in southeastern Wisconsin (Kenosha, Milwaukee, Ozaukee, Racine, Walworth, Washington, and Waukesha), Evans and others (2004) divided the Silurian strata into six map units (from bottom to top): Kankakee equivalent, Brandon Bridge, Manistique, Waukesha, Racine, and Waubakee. Studies in Door County in the northeast tend to follow stratigraphic nomenclature developed in the Upper Peninsula of Michigan, which include from bottom to top: Mayville Formation, Burnt Bluff Group (Byron and Hendricks Formations), Manistique Formation (Schoolcraft and Cordell Members), and Engadine Formation (Johnson and Campbell, 1980; Kluessendorf and Mikulic, 1989; Harris and others, 1996; Mikulic and others, 2010; Luczaj, 2011). It is important to note that lithocorrelation has no implicit chronostratigraphic meaning other than that of general stratigraphic position and so additional techniques are required to establish age relations.

Biostratigraphy

Attempts to establish the age relationships between Silurian rocks across eastern Wisconsin have primarily relied upon biostratigraphy. The relative age of some intervals in the Silurian rocks of Wisconsin are well defined using biostratigraphy of both microfossils and macrofossils. Unfortunately, some geographic areas and/or stratigraphic intervals reveal little or no useful biostratigraphic information for a variety of reasons. In east-central Wisconsin, where significant surface exposures are lacking, virtually no biostratigraphic work has been done because of the difficulty in collecting suitable samples to process. In contrast, diverse and abundant conodonts have been recovered from some parts of the Silurian section in southeastern Wisconsin, although some intervals exhibit only low yields of generally long-ranging taxa. Most noteworthy, the late Llandovery and early Wenlock age rocks of southeastern Wisconsin produce biostratigraphically precise conodont biotas (Kluessendorf and Mikulic, 1994, 1996, 1997; Norby and others, 1996; Mikulic and Kluessendorf, 1998). As in most of the Midwest, late Wenlock, and possibly younger, rocks in southeastern Wisconsin lack biostratigraphically useful conodonts in the reef and carbonate bank facies of much of the Racine and Waubakee formations. Some stratigraphic intervals, such as the early to mid-Llandovery rocks of southeastern Wisconsin, contain few conodonts that are biostratigraphically useful, except in limited horizons. This is mainly due to a general lack of robust conodont biotas in rocks of this age; across much of the central United States, rocks of the same age exhibit a similar limited biota, regardless of rock type.

One of the most recent and extensive biostratigraphic studies in eastern Wisconsin was performed by Kuglitsch (1996, 2000) (fig. 2). His study sampled partial Silurian sections throughout eastern Wisconsin All formations yielded conodonts except for the Racine and Waubakee Formations. The oldest conodonts, indicative of the *D. kentuckyensis* Zone, were recovered from the Mayville and Burnt Bluff Group in southern Wisconsin. Samples from the Brandon Bridge Formation yielded *Pt. celloni* Zone conodonts (confirming the findings reported in Kluessendorf and Mikulic, 1996). Kuglitsch (1996) found conodonts indicative of the *K. walliseri* Zone in the basal Racine and conodonts from the *O. s. sagitta* Zone in upper Racine indicating a Sheinwoodian through early Homerian age. In northeastern Wisconsin, conodont yields were dominated (more than 50%) by the very long-ranging genus Panderodus and yielded zonally diagnostic conodonts in only two stratigraphic units—Burnt Bluff and Engadine, which yielded taxa indicative of Aeronian and Telychian ages, respectively (fig. 2).

Macrofossils have helped refine the biostratigraphy of intervals lacking zonally diagnostic conodonts. For example, monograptid graptolites have been recovered from the late Telychian (Llandovery) of southeastern Wisconsin (Mikulic, 1979; Kluessendorf and Mikulic, 1994). Mikulic (1979) and Mikulic and Kluessendorf (1999) demonstrated that major changes in trilobite associations coinciding with the Ireviken and Mulde Events, two extinction events that occurred between the late Llandovery and late Wenlock, helped define these time intervals. Throughout most of the Llandovery in eastern Wisconsin, pentamerid brachiopods have been useful for biostratigraphic zonation, especially as conodonts and graptolites have not been found in most of the section (Mikulic and Kluessendorf, 1998, 2009; Kluessendorf and Mikulic, 2004; Mikulic and others, 2010) and seem to correlate well with areas throughout the Great Lakes region (Johnson and Campbell, 1980; Johnson, 1981; Colville and Johnson, 1982).

Sequence stratigraphy

Sequence stratigraphic methods provide some further refinement to the chronostratigraphy of Wisconsin Silurian rocks. These methods rely heavily on the identification and mapping of major regional unconformities (Mikulic, 1979; Kluessendorf and Mikulic, 1994, 1996; Mikulic and Kluessendorf, 1996, 1998). The lateral continuity of *Thalassinoides* hardground unconformities at discrete horizons across this area is documented by Mikulic and Kluessendorf (1996, 1998) and by Kluessendorf and Mikulic (1996). These sequence boundaries are correlated with the greatest degree of confidence in late Llandovery through early Wenlock units, where they are bracketed by biostratigraphic information. In the rest of the Silurian section, sequence boundaries are recognizable; however, the lack of precise biostratigraphic data makes their correlation over large distances more speculative. In northeastern Wisconsin, the general lack of biostratigraphic information and the repetitive nature of facies in the predominantly Llandovery age section make the precise correlation of sequence boundaries with those mapped in the south more problematic (see also, Mikulic and Kluessendorf, 1996; Harris and others, 1998).

Chemostratigraphy

Recently, Cramer and others (2011b) provided a plot of published and new Silurian strontium-isotope data ($^{87}Sr/^{86}Sr$) against a recent, and significantly updated, time scale (Melchin and others, 2012). This provides a refined means for assessing previously generated strontium-isotope data for Wisconsin rocks (fig. 3). Kuglitsch (2000) conducted strontium-isotope analysis on conodonts from some partial sections of Silurian formations in eastern Wisconsin. The primary exceptions were the Waubakee and most of the Racine, which did not yield any conodonts. In total, he analyzed 18 samples (each sample consisting of several *Panderodus* conodont elements) from 10 localities. The lightest Sr-isotope values came from the base of the Mayville at Neda in Dodge County, which indicate a middle Rhuddanian age. Samples from the type section for the Hendricks in the Upper Peninsula of Michigan yielded Sr-isotope values suggestive of latest Aeronian to basal Telychian age. Cordell and Engadine samples from Door County yielded nearly identical values indicative of mid-Telychian age. Brandon Bridge samples from the Voree Quarry in Walworth County yielded values suggesting a slightly younger, middle Telychian age. Conodonts from the Waukesha–Racine boundary interval (as designated in Watkins and others, 1999) in Waukesha County yielded Sr-isotope values reinforcing an early to mid-Sheinwoodian age. All of these results are consistent with and provide slight refinement to the age of these rocks based on their biostratigraphy.

Recent development of a carbon isotope global standard provides exceptional opportunity to greatly refine the chronostratigraphy of Wisconsin Silurian rocks. The global composite standard was developed through the integration of regional carbon isotope data sets in the Baltic region that had been rigorously studied biostratigraphically (Cramer and others, 2011a). The correlations of these well-preserved fossiliferous limestones were further refined through tracing of regionally extensive potassium-bentonite (K-bentonite) beds and sequence stratigraphic surfaces (for example, Calner and others, 2006). The Baltic region Silurian succession is relatively thick by comparison with others around the world and is

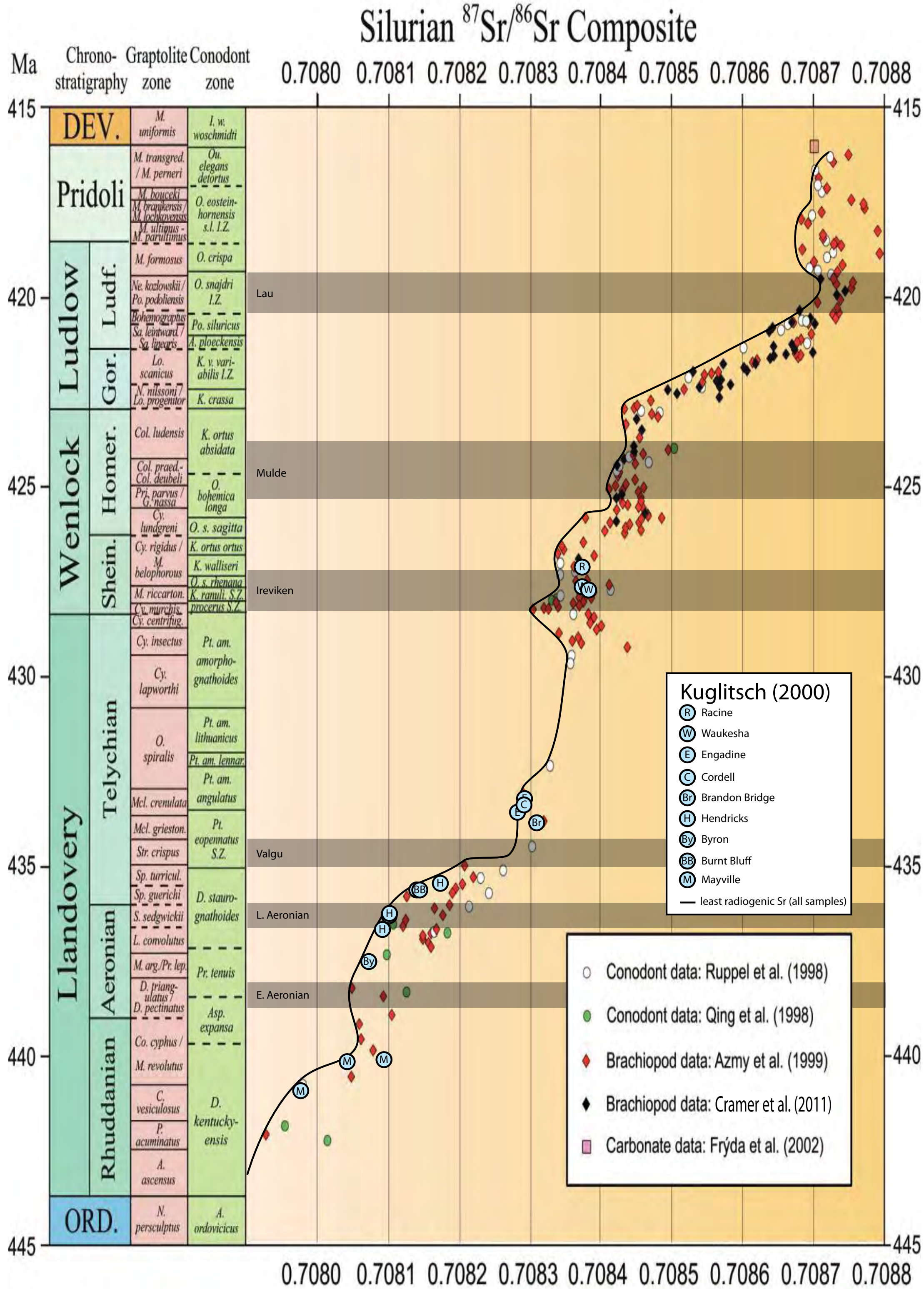


Figure 3. *Silurian strontium-isotope curve plotted against the most recent Silurian time scale (modified from Cramer and others, 2011). Least radiogenic line added. Data from Kuglitsch (2000) plotted by assigned conodont zone for reference.*

considered to be one of the most temporally continuous. Further integration with data from other parts of the world provided additional refinement. Recent uranium-lead (U-Pb) laser ablation thermal ionization mass spectrometry (LA-TIMS) analysis of zircons from several K-bentonites throughout the Silurian has yielded a highly refined time scale (Melchin and others, 2012). Thus, the Silurian now has a framework for unparalleled temporal resolution of the evolution of life as well as changes in sea-water chemistry, sea-level fluctuation, and climate change (Munnecke and others, 2010).

METHODS

Fifteen new Silurian cores, ranging in length from 20 to 950 feet (6 to 290 m) (figs. 1, 4) were acquired by the WGNHS to support bedrock mapping in Sheboygan County between 2008 and 2011. The deepest of these cores was drilled in 2010 at the (Roth) Quarry Park on the northwest side of the city of Sheboygan using wire line coring (SB-3). The objective of this 950-foot (290 m) core hole was to recover rocks from the exposed Silurian down to the top of the Galena Group as part of a STATEMAP project to map the entire county. Quarry Park is one of the few

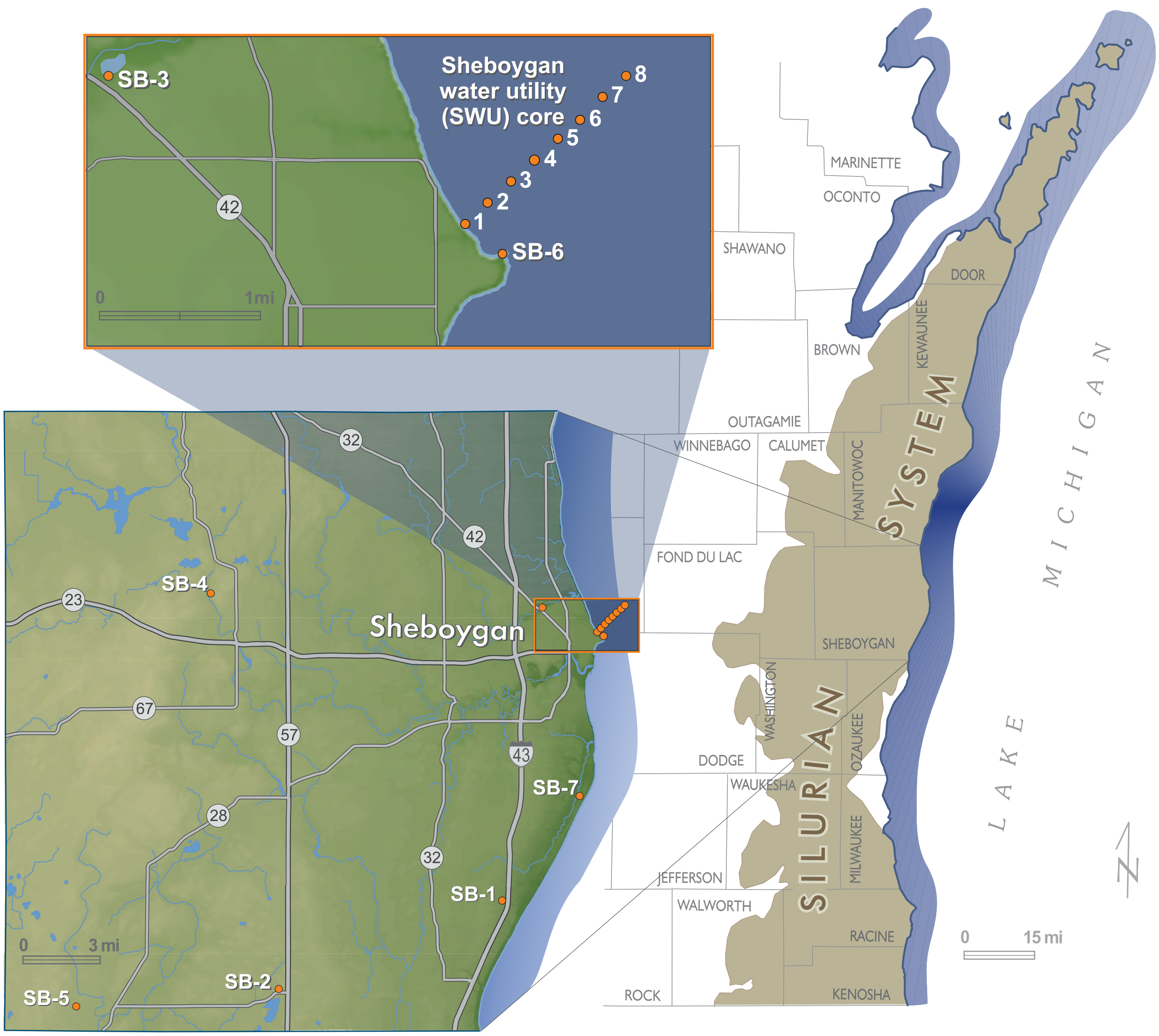


Figure 4. *Map showing the distribution of Silurian rock in eastern Wisconsin. Core locations discussed in this article are shown on the map of Sheboygan County. Cores SB-3, SB-6, SWU-1, SWU-5 (locations shown in the inset box) were analyzed for carbon and oxygen isotopes in this study.*

places in Sheboygan County where bedrock is exposed at the surface (fig. 5). Casing was set 2 feet (0.6 m) into the bedrock, recovery was excellent (more than 98%), and the core hole was logged for geophysical properties. An additional 75-foot (23 m) core was drilled about 2.4 miles (4 km) away at North Shore Park, on a rocky outcropping along the Lake Michigan shoreline (SB-6). The Sheboygan Water Utility donated eight cores (SWU 1–8) that were drilled using a barge-mounted drill rig along a 7,000-foot (2,133 m) northeast–southwest transect (fig. 4). The transect began about 1,500 feet (457 m) northwest of SB-6. The other five cores drilled in Sheboygan County provided additional information about regional trends, but were not directly used to create the composite section.

All 15 cores were photographed at high resolution under daylight spectrum lights enclosed in soft boxes with diffusion cloth to lessen glare. The photos were processed in Photoshop to increase clarity (figs. 6 and 7). The distribution of distinctive lithofacies compositions, macrofossils, sedimentary structures and lithofacies contacts were documented in the file. The position and distribution of these features were used to correlate the cores, and geophysical logs provided additional insights. The cores, geophysical data, and photographs are archived by the WGNHS and are available upon request.

Once the SB-3, SB-6, SWU-1, and SWU-5 cores were logged, they were sampled for stable carbon- and oxygen-isotope chemostratigraphy (fig. 8). Lithologically, the Silurian rocks in the cores are dolostone, containing admixtures of the minerals calcite and dolomite. Minor amounts of clay minerals, pyrite, chert, and phosphate also have been visually identified. Texturally, many features have survived dolomitization. For example, pelmatozoan skeletal grains are still largely discernible from other skeletal grains. Brachiopods and corals are abundant in some intervals, but are largely dominated by external molds, with the original low and high magnesium calcite skeletal grains having been dissolved away, replaced or cast by chert. These taxa, regardless of preservation, were always avoided during sampling to avoid spurious results related to vital effects. Vugs, sparry features, stylolites, and other secondary diagenetic features were also avoided during sampling. Samples were collected by powdering micrite and pelmatozoan skeletal grains using a drill press fit with a tungsten carbide masonry bit. Powdered samples were analyzed at the University of Kansas Keck Paleoenvironmental Stable Isotope Laboratory. Results are presented in standard $\delta^{13}C$ and $\delta^{18}O$ notation.

RESULTS

The high-resolution carbon isotope profiles through the SB-3, SB-6, SWU-1, and SWU-5 cores display a complex structure with abrupt changes in trend and several sharp offsets in values (fig. 8). Values range from –4 to nearly +5‰ (parts per thousand) and intervals with consistent values that span more than a few tens of feet thick are rare. Importantly, the largest offsets are coincident with abrupt facies changes. For example, the approximately 2‰ increase at 126 feet (38 m) coincides with an abrupt disappearance of cherty dolomudstone facies and the appearance of coarse-grained biohermal facies.

Oxygen isotopes are typically not reported for dolomite-bearing intervals because they are fractionated during the process of dolomitization, overprinting the original environmental signal. However, the composite Sheboygan succession shows varying admixtures of calcite and dolomite and thus the data are reported here for consideration (table 1, at end of article). Oxygen isotopes results range from –3.5 to –7.5‰, but unlike the carbon isotopes, show only a few abrupt changes in values and are largely out of phase with changes in facies. For example, the interval in SB-3, from approximately 0 to 200 feet (0 to 61 m), displays some of the largest changes in carbon isotope values while the oxygen isotope trend remains nearly flat. Conversely, the interval from 625 to 650 feet (191 to 198 m) shows very similar patterns.

Facies analysis of the Sheboygan cores and outcrops identified many distinctive litho- and biofacies packages (figs. 5, 6, and 7). Lithostratigraphic/lithofacies differentiation of this dolostone-dominated succession is based on changes in grain size, sedimentary structures, fossil content, bioturbation, and color (fig. 8). Facies packages are typically bound by planar or undulating surfaces across which there are sharp offsets in facies. These surfaces are sometimes marked by mudcracks (fig. 5C) or hardgrounds (fig. 6F), but more commonly the original characteristics of these contacts are obscured by pressure solution (for example, fig. 6B). Multiple hardgrounds are also found internally within some packages (fig. 7B). The presence of facies offsets coincident with abrupt changes in $\delta^{13}C$ present in the Engadine and Waubakee prompted the

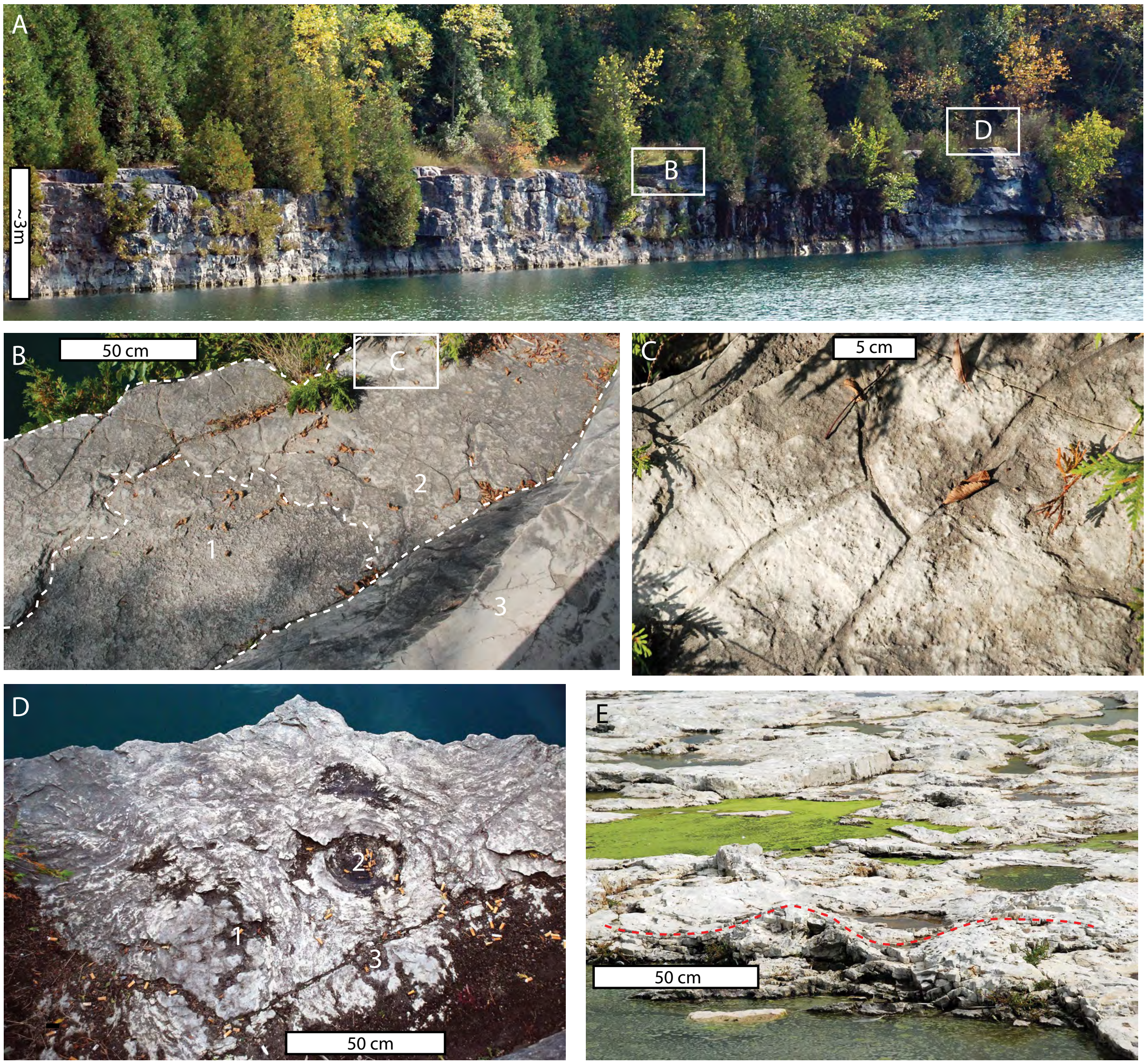
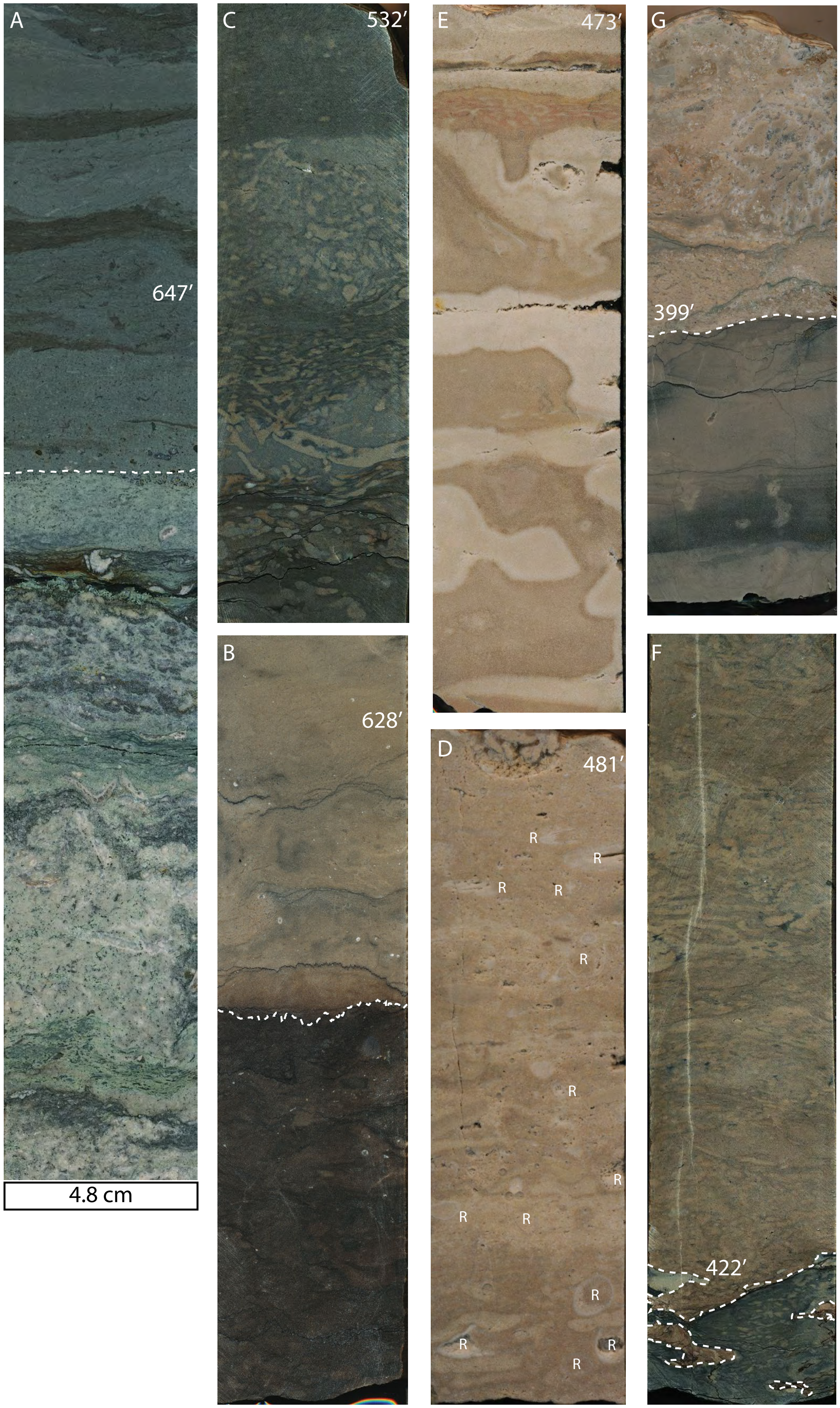


Figure 5. *Outcrop exposures at Quarry Park (A–D) and North Shore Park (E) in the city of Sheboygan.* **A.** *Southeastern exposed quarry face, about 10 feet (3 m) high, showing the location of close-ups B and D.* **B.** *Contact between fossiliferous dolowackestones to packstones (1), mudcracked surface (2), and stromatolitic dolomudstone (3).* **C.** *Close-up of mudcracks (shown in upper unit of B).* **D.** *Bedding plane of upper unit showing cluster of three stromatolites.* **E.** *Oblique view of undulating bedding plane (red dashed line) associated with stromatolitic structures in fine-grained dolomudstone, similar to that viewed at Quarry Park.*


A
647′
4.8 cm
C
532′
B
628′
E
473′
D
481′
R
R
R
R
R
R
R
R
R
R
R
R
G
399′
F
422′

informal designation of "A" and "B" units to facilitate discussion (fig. 8).

A composite section was created by correlating the SB-3 core into the SB-6 core and SWU-1–8 cores through comparative analysis of isotope profiles and facies. The varying dip of the Silurian rocks eastward along the margin of the Michigan Basin requires that fine-scale correlation, even over the distance of a few miles, must be approached with caution. Therefore, correlation of sections in the Sheboygan area was approached through a hierarchical method that integrated carbon isotope patterns, facies offsets, marker beds, and hardgrounds, with the least weight given to similarity of oxygen-isotope patterns. Following this methodology, the upper part of the thick SB-3 core was correlated eastward across 2.4 miles (3.9 km) to the sections near the Lake Michigan shoreline (SB-6, SWU-1, SWU-5; fig. 9) to create a composite section for the Sheboygan area. The correlation between the 0- to 52-foot (0 to 16 m) interval in the SB-3 core and the 23- to 75-foot (7 to 23 m) interval in SB-6 (stratigraphic offset of 23 feet, or 7 m, down to the east; a vertical change of 9.6 feet per mile) was supported by a nearly perfect overlap in their $\delta^{13}C$ profiles. Moreover, the slope of the rapid drop from about +2.5 to –0.2‰ in this correlated interval is not reproduced anywhere else in the entire SB-3 Silurian profile. The SB-6 core was correlated to the SWU-1 core through a similar close overlap in $\delta^{13}C$ values—notably a rapid drop from +0.8‰ to a virtually flat trend in values around +0.2‰. Interestingly, this correlation is reinforced by a rapid 2‰ rise in $\delta^{18}O$ values near the top of both these sections from –6‰ to –4‰. Surprisingly, this strong correlation indicates that SWU-1 is stratigraphically offset downward 45 feet (14 m) relative to SB-6. Considering that this relationship is the reverse of the expected values, given the eastward position of SB-6 relative to SWU-1 (fig. 9B) and the regional dip of the Silurian to the east, a fault is inferred (fig. 9A red arrows). Correlation of SWU-1 northeastward into SWU-2 suggests a tentative 10-foot (3 m) downward displacement through correlation of argillaceous marker beds. None of the facies or isotope trends present in SWU-2 and the onshore Sheboygan area cores are present in SWU-3–8. These cores contain two distinctive facies packages (Waubakee A and B) separated by a sharp facies offset that provides a high degree of confidence in correlation of these closely

◀ **Figure 6.** *Scanned images of drill core slabs showing diagnostic facies features and facies offsets for the lower part of the SB-3 core. Position in core marked on images; all images are 1⅞ inches (4.8 cm) in diameter.*

A. Contact between green argillaceous wackestone-packstone with robust calcareous bioclasts and beneath dark gray argillaceous fine-grained dolomudstone: Brainard-"Wilhelmi" contact.

B. Sharp stylolite contact between dark brown to gray burrow-mottled fine grained dolomudstone to dolowackestone and below yellowish gray, burrow-mottled dolowackestones: "Wilhelmi"-Mayville Formation contact and approximate position of the Ordovician-Silurian boundary.

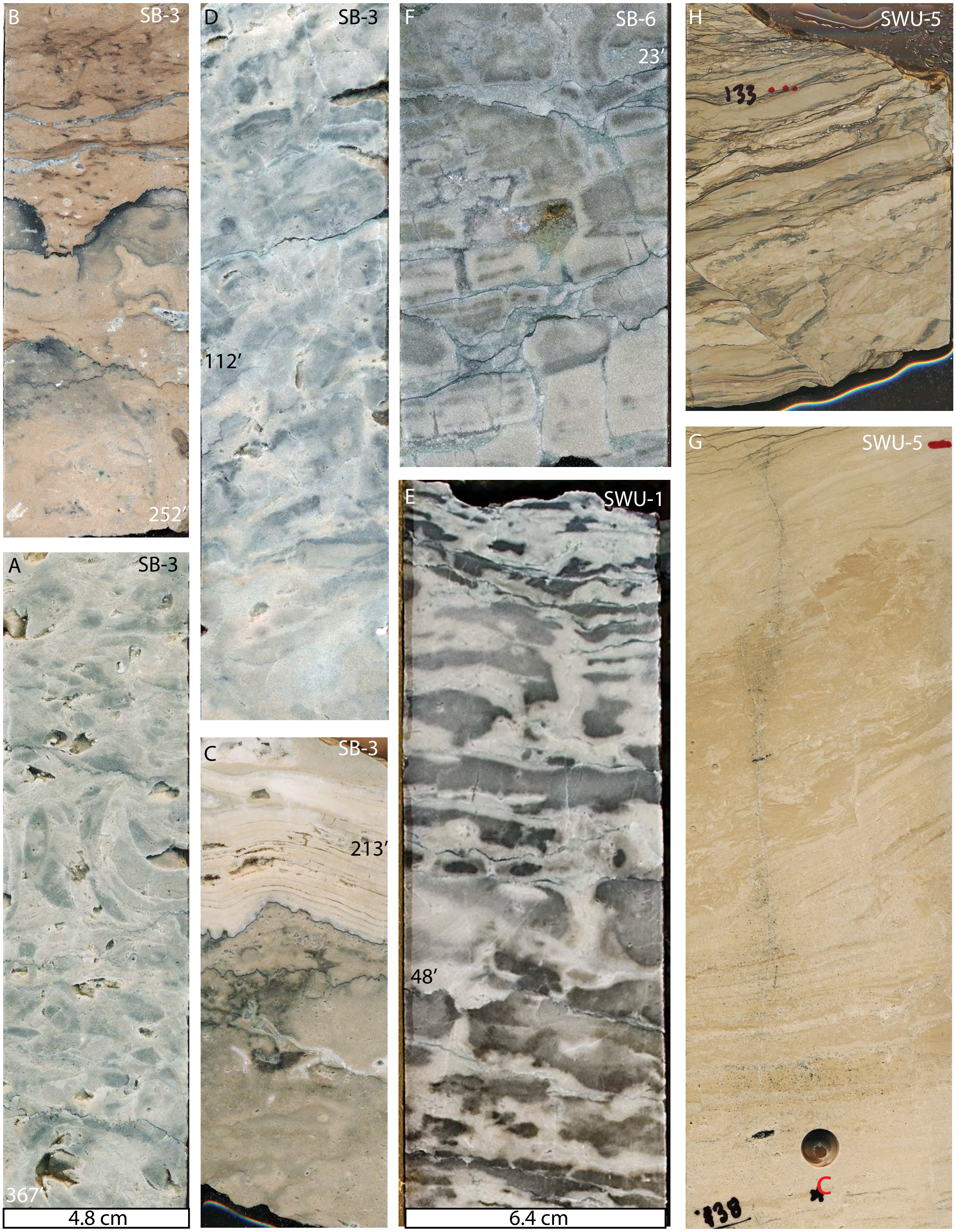
C. Dark gray fine-grained dolomudstone containing robust Chondrites *burrows, some compacted in more argillaceous zones: Lower Mayville Formation.*

D. Abundant small rugose corals (R) in fine- to medium-grained yellowish gray dolopackstone to dolograinstone: Mayville Formation.

E. Mottled yellowish gray dolomudstone mottled with Thalassinoides *burrows, some fillings show* Chondrites *burrows: Upper Mayville Formation.*

F. Thalassinoides *hardground contact between* Chondrites-*burrowed, dark gray, fine-grained dolomudstone and beneath medium gray, fine-grained dolomudstone, mottled by* Chondrites *and other burrows: Lower Hendricks Formation.*

*G. Dark gray, locally laminated dolomudstone overlain sharply by coral-rich (*Halysites*) yellowish gray dolopackstone: Hendricks Formation.*


B
SB-3
252′
D
SB-3
112′
F
SB-6
23′
H
SWU-5
133
A
SB-3
367′
C
SB-3
213′
E
SWU-1
48′
G
SWU-5
138
4.8 cm
6.4 cm

spaced cores. Correlation of this surface indicates more than 30 feet (9 m) undulating relief across this transect. The $\delta^{13}C$ profile for SWU-5 shows values and trends that do not correlate with those collected in any other Sheboygan core. However, the uppermost parts of SB-6 and SWU-1 show an upward positive shift in $\delta^{18}O$ values that terminate in short nearly flat trends near –4‰, SWU-5 shows a similar nearly flat trend near –4‰ throughout. Facies with characteristics of the Waubakee A unit of the SWU-3–8 cores are present at the top of the Quarry Park and North Shore Park exposures.

DISCUSSION

The combination of high-resolution $\delta^{13}C$ and sequence stratigraphic analysis permits precise age assessment and stratigraphic correlation. Striking similarity between the Sheboygan composite $\delta^{13}C$ profile and the global composite curve, particularly from the base of the Silurian to the mid-Sheinwoodian, indicates that eastern Wisconsin contains one of the most complete Llandovery successions in the world (fig. 10). Above this level the Sheboygan composite appears to be incomplete with no apparent record for the upper Sheinwoodian to mid-Ludfordian or Pridoli. Moving from the bottom of the $\delta^{13}C$ profile upward, values within the upper Maquoketa Group (Clermont, Ft. Atkinson, and Brainard) show an abrupt positive shift at the contact with overlying dark gray fine-grained dolostone (647 feet, 197 m) (fig. 6A). The facies and carbon isotope trend of this dolostone unit are similar to that of the well-characterized Wilhelmi Formation of Illinois, assigned to the latest part of the Hirnantian Stage of the Ordovician (Bergstrom and others, 2011). Upward, a facies offset into yellowish gray to reddish gray fine-grained dolostones of the Mayville Formation (628 feet, 191 m) (fig. 6B), is marked by an abrupt drop in C-isotope values of nearly 1‰ that is characteristic of the unconformity at the Ordovician-Silurian boundary. The Mayville values rise upward and oscillate around 0‰, suggesting an early Rhuddanian age. A drop in values to near –1‰ in the overlying cherty dolostones (about 585 feet, 178 m) is interpreted as the mid-Rhuddanian age negative excursion. A rapid rise to, and brief plateau in, C-isotopes indicates a late Rhuddanian age at about 545 to 560 feet (166 to 171 m). A rapid rise in values of nearly 1‰ occurs through a narrow coral and stromatoporoid interval indicates the onset of the first of two Aeronian-age C-isotope excursions (533 feet, 162 m). The lower Aeronian C-isotope excursion ends with an abrupt 1‰ fall in values

◀ **Figure 7.** *Drill core slabs from the upper part of the SB-3 core (A–D), SWU-1 core (E), SB-6 core (F), and SWU-5 core (G–H). Cores A–D are 4.8 cm (1⅞ inches) in diameter; cores E–H are 6.4 cm (2½ inches) in diameter.*

A. Pale bluish-gray pentamerid brachiopod-rich dolowackestone to dolopackstone: Schoolcraft Member.

B. Mineralized, undulating to stylolitic hardgrounds in yellowish-gray dolowackestone, containing mineralized Thalassinoides *and smaller* Chondrites *burrows: Cordell Member.*

C. Stromatoporoid overlying coral-bearing, medium gray, dolowackestone to dolopackstone with stylolites and burrows: Cordell Member.

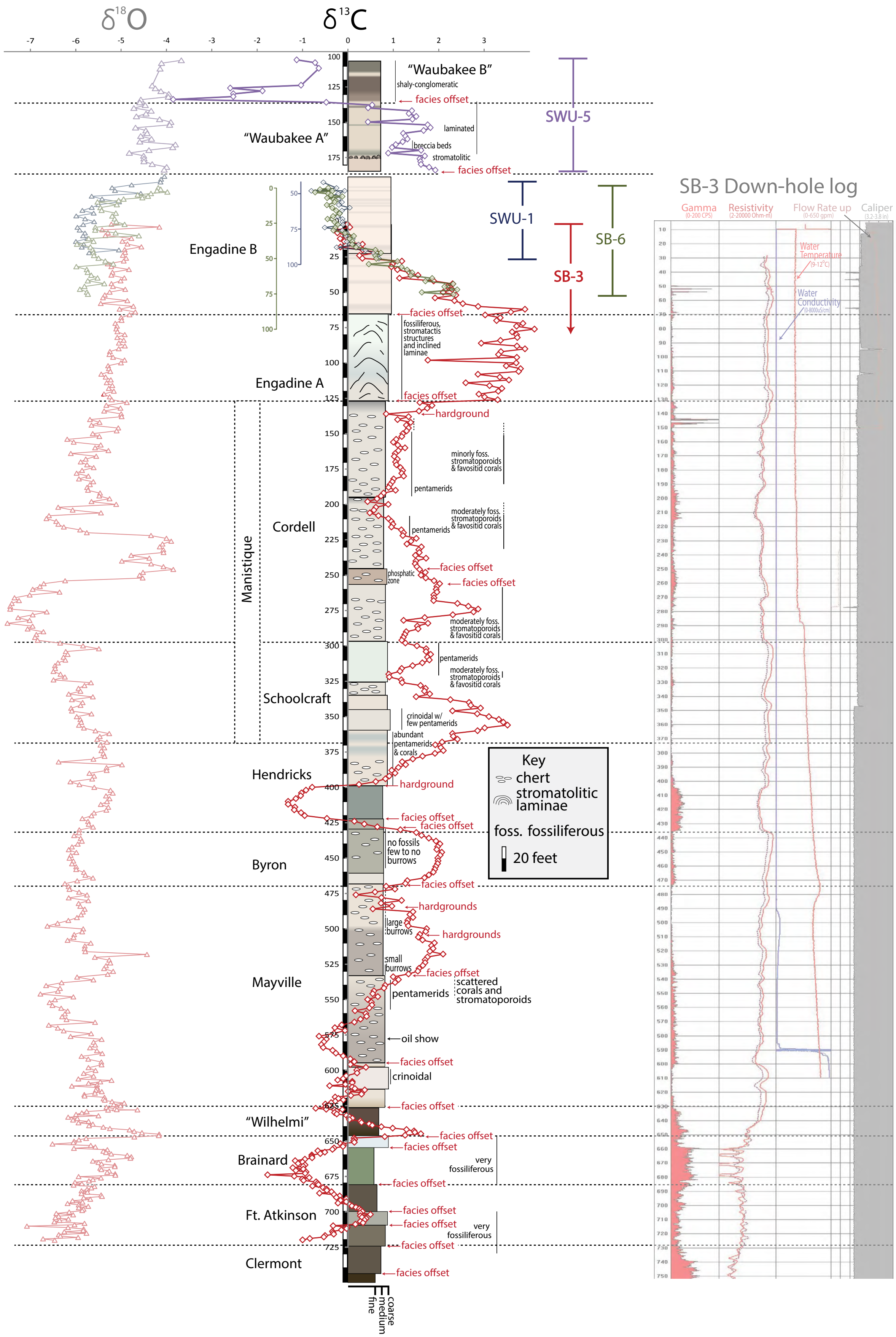
D. Inclined fabric of yellow to pink elongate sparry masses (incipient stromatactis structure?) interspersed in bluish-gray dolowackestone to dolopackstone with minor green clay stringers: Engadine Formation.

E. Light gray and dark gray dolomudstone to dolowackestone with disrupted banding and burrow-mottling: Engadine Formation.

F. Solution-enlarged cavities containing bluish gray to greenish gray silt in brecciated pinkish-gray dolomudstone: Engadine Formation.

G. Stromatolitic and horizontal planar laminae in fine-grained yellowish gray dolomudstone, exhibiting soft-sediment deformation: Waubakee A.

H. Argillaceous, weakly laminated, yellowish-gray dolomudstone with brecciation and synsedimentary deformation structures: Waubakee B.

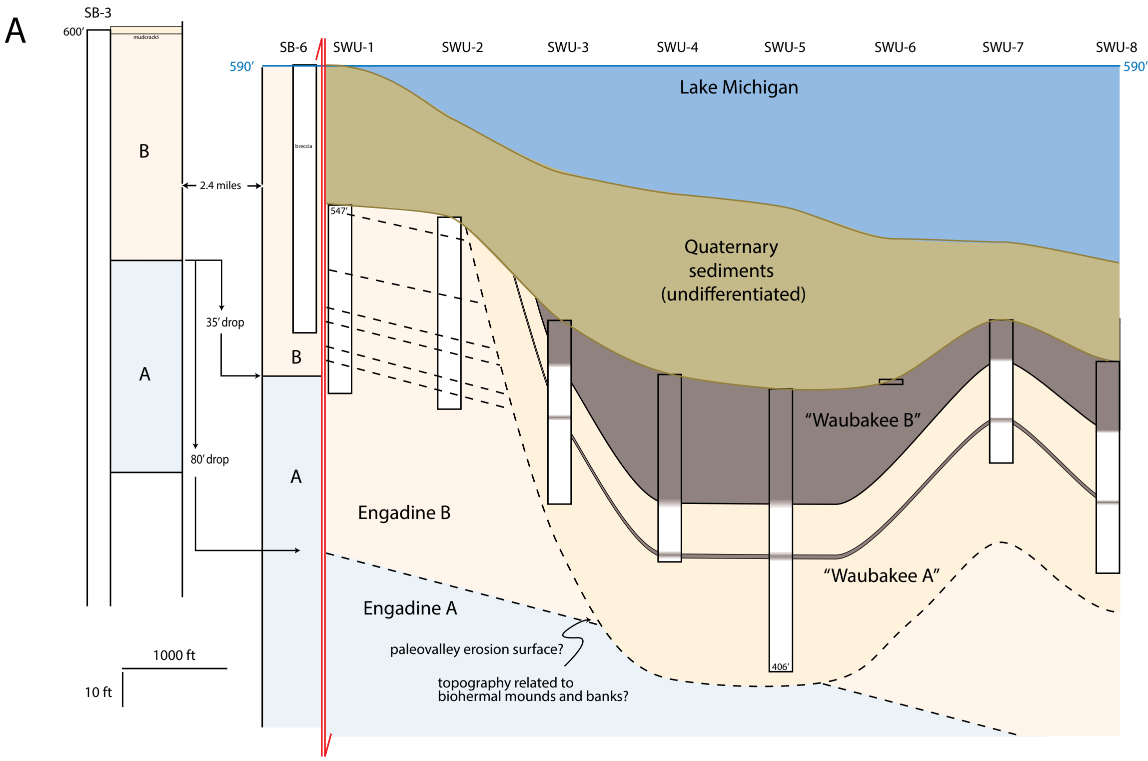

δ18O
δ13C
"Waubakee B"
shaly-conglomeratic
facies offset
laminated
"Waubakee A"
breccia beds
stromatolitic
SWU-5
SB-3 Down-hole log
Gamma
Resistivity
Flow Rate up
Caliper
Water Temperature
Water Conductivity
SWU-1
SB-6
SB-3
Engadine B
fossiliferous, stromatactis structures and inclined laminae
Engadine A
hardground
minorly foss. stromatoporoids & favositid corals
pentamerids
moderately foss. stromatoporoids & favositid corals
Cordell
Manistique
phosphatic zone
Schoolcraft
crinoidal w/ few pentamerids
abundant pentamerids & corals
Hendricks
Key
chert
stromatolitic laminae
foss. fossiliferous
20 feet
Byron
no fossils few to no burrows
hardgrounds
large burrows
small burrows
Mayville
scattered corals and stromatoporoids
oil show
crinoidal
"Wilhelmi"
Brainard
very fossiliferous
Ft. Atkinson
Clermont
coarse
medium
fine

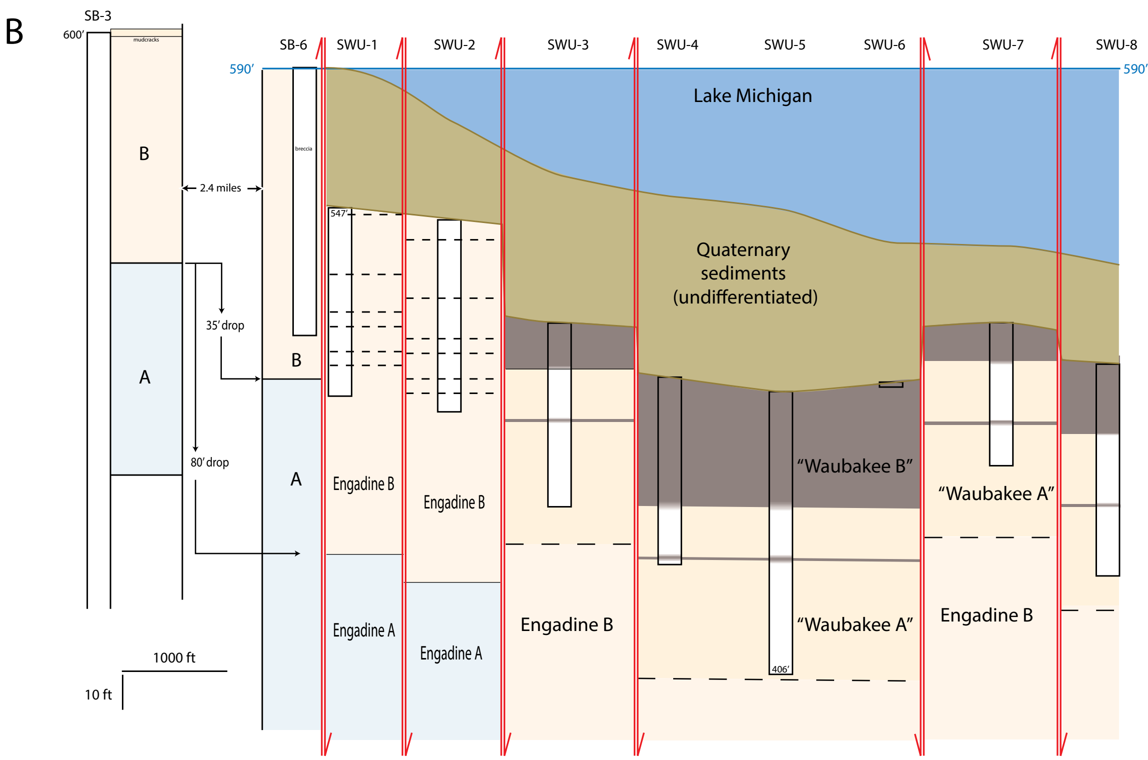
(487 feet, 148 m). An abrupt increase in C-isotopes of greater than 1‰ across an abrupt offset in facies is interpreted as an unconformity marking the base of the upper Aeronian C-isotope excursion (470 feet, 143 m). The upper excursion plateaus within very nodular fine-grained cherty dolostone, which shows evidence of mud cracks near the top. Two phosphatic *Thalassinoides* hardgrounds separate this unit from the overlying very fine-grained bluish-gray dolostones (431 and 422 feet, 131 and 129 m) (fig. 6F). C-isotope values show two abrupt drops across these surfaces totaling greater than a –3‰ shift. Values abruptly rise at 400 feet (122 m)—this large negative excursion clearly indicates the Aeronian-Telychian boundary. The sharp facies offset at 399 feet (121.6 m) is marked below by a *Thalassinoides* hardground (fig. 5G). The succession above the hardground shifts from cherty, coral-bearing, fine-grained dolostone to a grayish-blue pentamerid brachiopod coquina upward (378 feet, 115 m) (fig. 7A) as carbon isotopes also shift to a positive excursion with values exceeding +2‰. Isotope values abruptly jump to nearly +3.5‰ with the appearance of crinoidal dolostone containing a few small scattered pentamerids (359 feet, 109 m). This carbon isotope excursion is indicative of the early Telychian Valgu Event. Upward, isotope values drop rapidly in a stepwise manner to +1‰ coincident with the appearance of chert, stromatoporoids, and corals (320 feet, 97 m). A small positive excursion of +1‰ spans the interval from about 320 to 300 feet (97 to 91 m) and is accompanied again by slightly bluish dolostone with pentamerid brachiopods. A shift into cherty dolostone is accompanied by a short positive excursion with values near +3‰, followed by a short plateau at about +2‰. To our knowledge, this is a previously unrecognized carbon isotope excursion. A thin phosphatic zone, bound by sharp facies offsets, accompanies an abrupt fall of about 1‰. In the overlying interval isotope values gradually fall to about +0.5‰ and then rise again to plateau near 1‰, accompanied by the appearance of cherty fossiliferous facies containing pentamerids, corals, and stromatoporoids (135 to 245 feet, 41 to 75 m). An abrupt disappearance of chert is accompanied by a hardground and shift to more argillaceous facies and about a +1‰ shift in values (135 feet, 41 m). This succession is sharply overlain by an interval of fine-grained, mottled and highly fossiliferous dolowackestone to dolopackstone with inclined (5 to 40 degrees from horizontal) faint yellow to pink cemented intervals (incipient stromatactis?),

◀ **Figure 8.** *Carbon and oxygen isotope data and graphic logs for SB-3, SB-6, SWU-1, and SWU-5 cores. Graphic log shows approximate color for the dolostone-dominated succession. Width of graphic log represents general variations in texture from fine to coarse grained. Lithostratigraphic designations follow those of Door County provided in Harris and others (1996). Carbon- and oxygen-isotope values are plotted in per mil notation.*

Alignment of SB-3, SB-6, and SWU-1 cores is based on carbon isotope trend and similarity of facies. Alignment of SWU-5 is based on similarity of stromatolitic dolomudstone facies at the base of that core and at the top of the SB-6 and SB-3 outcrop sections (see fig. 5) and similarity in oxygen-isotope values between those intervals.

The down-hole log for SB-3 (at right in figure) shows total gamma, resistivity, fluid conductivity, fluid temperature, fluid flow rate, and caliper. Stratigraphic depths are given in feet below land surface.


A
SB-3
600′
mudcracks
B
A
2.4 miles
35′ drop
80′ drop
1000 ft
10 ft
SB-6
SWU-1
SWU-2
SWU-3
SWU-4
SWU-5
SWU-6
SWU-7
SWU-8
590′
breccia
547′
Lake Michigan
Quaternary
sediments
(undifferentiated)
"Waubakee B"
"Waubakee A"
Engadine B
Engadine A
paleovalley erosion surface?
topography related to
biohermal mounds and banks?
406′


B
SB-3
600′
mudcracks
B
A
2.4 miles
35′ drop
80′ drop
1000 ft
10 ft
SB-6
SWU-1
SWU-2
SWU-3
SWU-4
SWU-5
SWU-6
SWU-7
SWU-8
590′
breccia
547′
Lake Michigan
Quaternary
sediments
(undifferentiated)
"Waubakee B"
"Waubakee A"
Engadine B
Engadine A
406′

skeletal stringers, large bioclasts, laminae, pressure solution surfaces and bedding throughout the 70- to 125-foot (21 to 28 m) interval suggests the presence of a bioherm. The base of this interval shows a jump in carbon isotope values from about +2‰ to +4‰ indicative of the Sheinwoodian Ireviken Event. The flat-line, stepped offset of the $\delta^{13}C$ values, together with the abrupt offset of facies, indicates an unconformity where latest Telychian to earliest Sheinwoodian time is not recorded. Throughout the 70- to 125-foot (21 to 28 m) interval, the carbon isotope values oscillate rapidly between +3 and +4‰. Values abruptly drop from near +4 to +2‰ coincident with an abrupt facies offset from biohermal to fine-grained, locally bioturbated, pinkish-gray dolowackestones to dolopackstones (66 feet, 20 m) (fig. 7E). Values within this facies package fall gradually then begin to hold steady near –0.2‰ (recorded in the SB-3, SB-6, and SWU-1 cores). This fall indicates the end of the Ireviken Event and a late Sheinwoodian age. An abrupt positive shift to near +2‰ occurs with the appearance of stromatolitic laminae (fig. 7G) and the disappearance of bioturbation (SWU-5, Waubakee A). It is possible that this C-isotope excursion represents the mid-Homerian age Mulde Event, however its magnitude and facies are more similar to the Lau Event as seen in other sections around the Great Lakes region (McLaughlin and others, 2012). This interpretation is reinforced by the presence of a sharp negative excursion to –4‰, coincident with the appearance of organic-rich, argillaceous and brecciated facies (Waubakee B; fig. 7H). This facies succession and drop in $\delta^{13}C$ values of over 6‰ is only otherwise known from the Silurian of the Midwest immediately above the Lau Excursion (for example, the Kokomo core IGS-251 held by the Indiana Geological Survey where the Ireviken, Mulde, and Lau excursions are clearly differentiated) (McLaughlin and others, 2012). Exposure of the lower laminated Waubakee A unit at Quarry Park in the city of Sheboygan shows that it rests sharply on fine-grained light-pinkish gray dolostone within thin medium gray argillaceous bands, burrow mottled zones (fig. 7E), and horizons with scattered pelmatozoans and small corals at a mudcracked and scalloped surface. This surface of subaerial exposure (also present in the top of the SB-3, SWU-1, and SWU-3 cores; fig. 9) may indicate the presence of an undulating sequence boundary with local relief exceeding 130 feet (40 m). These mid-Ludfordian dolostones appear to be the youngest Silurian rocks in Sheboygan County and there is no evidence for Devonian age rocks, though they occur just 15 miles (24 km) to the south in northern Ozaukee County.

◀ **Figure 9.** *Cross-section of Sheboygan Water Utility (SWU) cores and relationship to SB-3 and SB-6, providing two scenarios for their interpretation (A and B). Note that even though SB-6 and SWU-1 are only about 1,500 feet (457 m) apart, the carbon isotope correlation (fig. 8) suggests that SWU-1 is stratigraphically offset downward by 45 feet (14 m), thus a fault (red vertical arrows) is inferred.*

A. Hypothesis A—"Waubakee A-B" sits at the same or lower elevation than "Engadine B" due to the presence of paleovalley incision at its base or non-erosional topography related to the development of biohermal mounds and carbonate bank features associated with the basin margin, exceeding 130 feet (40 m). Orientation of Engadine A-B contact inferred from correlation of marker beds between SWU-1 and SWU-2.

B. Hypothesis B—"Waubakee A-B" sits at the same or lower elevation than "Engadine B" due to the presence of multiple closely spaced near vertical faults with displacement on most faults down to the east. Cross-section orientation is northeast–southwest. Elevations are given for the top of bedrock for SB-3 (600 feet, 183 m), SB-6 (590 feet, 180 m), and SWU-1 (547 feet, 167 m). Correlation of SB-3 to SB-6 and SWU-1 was made by aligning their carbon isotope values (see fig. 7).

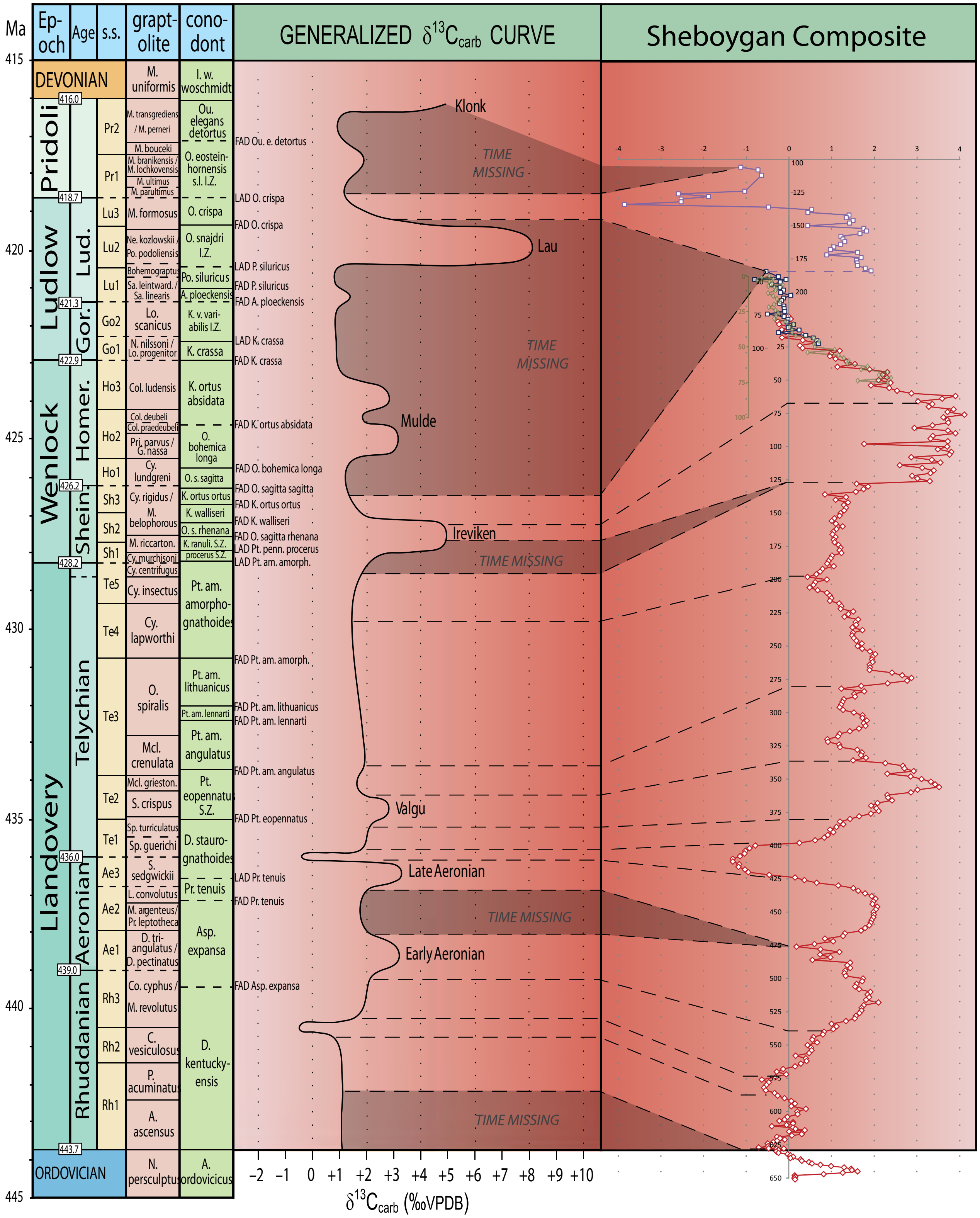


Figure 10. *Composite Sheboygan area carbon isotope curve (vertical axis in feet) against the global composite standard (vertical axis in millions of years; modified from Cramer and others, 2011a). Correlation of the carbon isotope curve to the composite curve is marked by dashed lines. Dark shaded areas represent time preliminarily interpreted to be missing in Sheboygan County.*

CONCLUSIONS

This study demonstrates that high-resolution carbon isotope stratigraphy combined with facies analysis is a powerful method for fine-scale stratigraphic correlation and age assessment of the Silurian bedrock in east-central Wisconsin. The Sheboygan composite profile provides a framework to integrate previously established biostratigraphic and sequence stratigraphic studies. The striking correlation between our new C-isotope profile and the global composite standard constrains the age of the Silurian rocks in east-central Wisconsin.

An important finding of this study is that the Llandovery age-strata represent one of the most temporally complete early Silurian records in the world. Coincidence of facies and carbon isotope changes suggest a common genetic cause that may help unravel the interrelationship between global climate change, sea-level oscillation, and local stratigraphy. Future work will expand use of the techniques demonstrated here throughout the Silurian of Wisconsin to provide a detailed temporal and depositional regional framework. Our goal is to develop an understanding of the compositional heterogeneity of this interval for improved assessment of natural resources in eastern Wisconsin.

ACKNOWLEDGEMENTS

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REFERENCES CITED

Bergstrom, S.M., Kleffner, M.A., and Schmitz, B., 2011, Late Ordovician–Early Silurian $\delta^{13}C$ chemostratigraphy in the Upper Mississippi Valley: Implications for chronostratigraphy and depositional interpretations: *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, v. 102, p. 159–178.

Calner, M., Kozlowska, 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.

Colville, V.R., and Johnson, M.E., 1982, Correlation of sea-level curves for the Lower Silurian of the Bruce Peninsula and Lake Timiskaming District (Ontario): *Canadian Journal of Earth Sciences*, v. 19, p. 962–974.

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., 2011a, Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and $\partial^{13}C_{carb}$ chemostratigraphy: *Lethia*, v. 44, p. 185–202, DOI 10.1111/j.1502-3931.2010.00234.x.

Cramer, B.D., Munnecke, A., Schofield, D.I., Haase, K.M., and Haase-Schramm, A., 2011b, A revised $^{87}Sr/^{86}Sr$ curve for the Silurian: Implications for global ocean chemistry and the Silurian timescale: *Journal of Geology*, v. 119, p. 335–349.

Eagan-Roberts, D., Harrier, D., and Kale, B., 2004, Wisconsin population 2030: A report on projected state, county and municipal populations and households for the period 2000–2030: Division of Intergovernmental Relations, Wisconsin Department of Administration, 24 p.

Evans, T.J., Massie-Ferch, K.M., and Peters, R.M., 2004, Preliminary bedrock geologic map of Walworth, Racine, Kenosha, Milwaukee, Waukesha, Ozaukee, and Washington Counties: Wisconsin Geological and Natural History Survey Open-File Report 2004-19, 1 plate.

Harris, M.T., Kuglitsch, J.J., Watkins, R., Hegrenes, D.P., and Waldhuetter, K.R., 1998, Early Silurian stratigraphic sequences of eastern Wisconsin: *New York State Museum Bulletin*, v. 491, p. 39–49.

Harris, M.T., Hegrenes, D.P., and Muldoon, M.A., 1996, Jarmen Road core study, in Harris, M.T., Muldoon, M.A., and Stieglitz, R.D., eds., The Silurian dolomite aquifer of the Door Peninsula: Facies, sequence stratigraphy, porosity, and hydrogeology: Field Trip Guidebook, 1996 Fall Field Conference of the Great Lakes Section of the SEPM and Pre-meeting field trip for the 1997 Meeting of the North-Central Section of the GSA, p. 39–51.

Jeppsson, L., 1997, A new latest Telychian, Sheinwoodian and early Homerian (Early Silurian) standard conodont zonation: Transactions of the Royal Society of Edinburgh: *Earth Sciences*, v. 88, p. 91–114.

Johnson, M.E., 1981, Correlation of Lower Silurian strata from the Michigan Upper Peninsula to Manitoulin Island: *Canadian Journal of Earth Sciences*, v. 18, p. 869–883.

Johnson, M.E., and Campbell, G.T., 1980, Recurrent carbonate environments in the Lower Silurian of northern Michigan and their inter-regional correlation: *Journal of Paleontology*, v. 54, p. 1041–1057.

Kleffner, M.A., 1987, Conodonts of the Estill Shale and Bischer Formation (Silurian, Southern Ohio): Biostratigraphy and Distribution: *Ohio Journal of Science*, v. 87, p. 78–89.

Kluessendorf, J., and Mikulic, D.G., 1989, Bedrock geology of the Door Peninsula of Wisconsin, *in* Palmquist, J.C., ed., Wisconsin's Door Peninsula: A natural history: Appleton, Wis., Perin Press, p. 12–31.

Kluessendorf, J., and Mikulic, D.G., 1994, Waukesha Lime and Stone Company quarries, Waukesha, Wisconsin, *in* Travis J., ed., Guidebook to the problems associated with artesian systems and land-usage in southeastern Wisconsin, Wisconsin Section: American Institute of Professional Geologists, Annual Fall Geology Field Conference guidebook, p. 34–58.

Kluessendorf, J., and Mikulic, D.G., 1996, An early Silurian sequence boundary in Illinois and Wisconsin, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic sequence stratigraphy: Views from the North American Craton: Boulder, Colo., Geological Society of America Special Paper 306, p. 177–185.

Kluessendorf, J., and Mikulic, D.G., 1997, Sequence stratigraphy and depositional environments of Silurian strata in southeastern Wisconsin: Guide to field trips in Wisconsin and adjacent areas of Minnesota, 31st Annual Meeting of Geological Society of America-North Central Guide to Field Trips, p. 85–93.

Kluessendorf, J., and Mikulic, D.G., 2004, The lake and the ledge: Geological links between the Niagara Escarpment and Lake Winnebago: 65th Annual Tri-State Geological Field Conference Guidebook, 64 p.

Kuglitsch, J.J., 1996, Conodont biostratigraphy of the Racine and Waukesha formations of northeastern Waukesha County, Wisconsin: Milwaukee, University of Wisconsin, M.S. thesis, 230 p.

Kuglitsch, J.J., 2000, Correlation of the Silurian rocks of southeastern and northeastern Wisconsin using conodonts and conodont strontium isotope ratios and proposed conodont and ostracode biofacies models for the environs of the middle Aeronian Michigan Basin: Madison, University of Wisconsin, Ph.D. dissertation, 349 p.

Luczaj, J.A., 2011, Preliminary geologic map of the buried bedrock surface, Brown County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2011-02, 1 plate.

Luczaj, J.A., 2013, Geology of the Niagara Escarpment in Wisconsin: *Geoscience Wisconsin*., v. 22, no. 1, p. 1–34.

McLaughlin, P.I., 2013, Preliminary bedrock geologic map of Sheboygan County: Wisconsin Geological and Natural History Survey Open-File Report 2013-03, 1 plate.

McLaughlin, P.I., Emsbo, P., Brett, C.E., and Mikulic, D., 2012, Detection of the Lau Excursion across the eastern US—key to regional chronostratigraphy: Cincinnati, Ohio, Field Meeting for the International Geoscience Program Project 591: Early to Middle Paleozoic Revolution IGCP 2012 field meeting.

Melchin, M.J., Sadler, P.M., and Cramer, B.D., 2012, Chapter 21: The Silurian Period, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G., eds., The Geologic Time Scale 2012: New York, Elsevier, p. 525–558.

Mikulic, D.G., 1979, The paleoecology of Silurian trilobites with a section on the Silurian stratigraphy of southeastern Wisconsin: Oregon State University, Ph.D. dissertation, 864 p.

Mikulic, D.G., and Kluessendorf, J., 1988, Subsurface stratigraphic relationships of the Upper Silurian and Devonian rock of Milwaukee County, Wisconsin: *Geoscience Wisconsin*, v. 12, p. 1–23.

Mikulic, D.G., and Kluessendorf, J., 1998, Sequence stratigraphy and depositional environments of the Silurian and Devonian rocks of southeastern Wisconsin: Guidebook for the 1998 Fall Field Conference for the Joint Meeting of SEPM Great Lakes Section and the Michigan Basin Geological Society, p. 1–84.

Mikulic, D.G., and Kluessendorf, J., 1999, Stasis and extinction of Silurian (Llandovery-Wenlock) trilobite associations related to oceanic cyclicity: *Journal of Paleontology*, v. 73, no. 2, p. 320–325.

Mikulic, D.J., and Kluessendorf, J., 2009, Pentamerid brachiopod intervals and their relationship to depositional sequences in the Silurian (Llandovery) of eastern Wisconsin and northeastern Illinois: Geological Society of America, Abstracts with Programs, North-Central Section, 42nd annual meeting, v. 41, no. 4, p. 61.

Mikulic, D.G., Kluessendorf, J., McLaughlin, P., and Luczaj, J., 2010, Bedrock geology of the Niagara Escarpment on the Door Peninsula of Wisconsin: Sturgeon Bay, Wis., Field Guidebook for the Joint Meeting of the Great Lakes Section SEPM Fall Field Conference and 65th Annual Tri-State Geological Field Conference, September 24–26, 2010, 79 p.

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.

Norby, R.D., Mikulic, D.G., Kluessendorf, J., and Kleffner, M.A., 1996, Silurian conodont biostratigraphy of the Lake Michigan area: Rochester, N.Y., the James Hall Symposium, Second International Symposium on the Silurian System, Program and Abstracts, p. 78.

U.S. Census Bureau, 2010, 2010 Census, www.census.gov/2010census.

U.S. Geological Survey, 2013, 2009 minerals yearbook (advance release): The mineral industry of Wisconsin: U.S. Geological Survey, 5 p.

Table 1. *Sheboygan core names and corresponding WGNHS Geobase identification numbers.*

Core name	Geobase ID
SWU-1	60000531
SWU-2	60000532
SWU-3	60000533
SWU-4	60000534
SWU-5	60000535
SWU-6	60000536
SWU-7	60000537
SWU-8	60000538
SB-1	60000539
SB-2	60000540
SB-3	60000541
SB-4	60000542
SB-5	60000543
SB-6	60000544

Table 2. *Carbon and oxygen isotope data from Sheboygan County cores (SB-1, SB-6, SWU-1, and SWU-6).*

Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)
SB-1											
2	0.00	-5.22	96	3.72	-5.18	190	1.05	-5.73	284	1.77	-7.51
4	0.05	-4.16	98	1.77	-4.93	192	0.79	-5.47	286	1.53	-6.95
6	-0.25	-5.42	100	3.71	-5.00	194	0.73	-5.48	288	1.55	-7.06
8	-0.23	-5.29	102	3.49	-5.29	196	0.65	-5.26	290	1.29	-6.71
10	0.01	-5.35	104	3.81	-5.27	198	0.44	-5.66	292	1.26	-6.87
12	-0.17	-4.78	106	3.76	-5.24	200	0.89	-5.11	294	1.22	-6.90
14	-0.07	-4.98	108	2.87	-5.44	202	0.62	-6.39	296	1.19	-6.84
16	0.33	-4.86	110	3.35	-5.34	204	0.58	-6.07	298	1.27	-6.34
18	-0.16	-4.56	112	3.55	-5.23	206	0.49	-5.45	300	1.52	-5.84
20	0.33	-4.92	114	2.60	-5.32	208	0.68	-6.59	302	1.73	-5.49
22	0.64	-4.91	116	3.12	-5.19	210	0.89	-6.65	304	1.73	-6.22
24	0.26	-4.96	118	3.39	-5.27	212	0.96	-6.43	306	1.83	-6.18
26	0.32	-4.89	120	3.32	-5.16	214	1.00	-6.39	308	1.76	-6.27
28	1.19	-4.94	122	2.89	-5.38	216	0.96	-6.26	310	1.80	-6.23
30	0.99	-5.30	124	3.01	-5.25	218	1.18	-5.91	312	1.64	-6.40
32	0.97	-5.22	126	3.30	-5.21	220	1.23	-5.76	314	1.43	-6.46
34	1.10	-4.83	128	1.59	-4.88	222	1.22	-4.34	316	1.19	-6.46
36	1.36	-5.19	130	1.86	-5.33	224	1.51	-4.00	318	1.15	-6.49
38	1.55	-5.22	132	1.75	-5.01	226	1.39	-3.90	320	0.91	-6.34
40	1.14	-4.93	134	1.57	-5.38	228	1.30	-4.09	322	0.92	-6.24
42	1.89	-5.01	136	0.85	-5.00	230	1.62	-4.15	324	1.18	-6.49
44	2.31	-5.21	138	1.34	-4.99	232	1.57	-4.07	326	1.20	-5.67
46	2.20	-5.18	140	1.10	-5.69	234	1.58	-4.07	328	1.60	-5.81
48	2.30	-4.91	142	1.39	-5.48	236	1.49	-4.78	330	1.71	-5.94
50	2.10	-5.25	144	1.29	-5.65	238	1.73	-4.38	332	1.69	-5.90
52	2.38	-5.36	146	1.34	-5.07	240	1.50	-4.98	334	1.81	-6.16
54	1.92	-5.40	148	1.30	-5.10	242	1.49	-4.34	336	1.51	-5.63
56	2.35	-4.87	150	1.21	-5.63	244	1.52	-4.07	338	2.26	-6.09
58	2.54	-5.45	152	1.19	-5.48	246	1.58	-3.85	340	2.67	-5.85
60	2.87	-4.73	154	1.07	-6.19	248	1.71	-4.52	342	2.71	-5.90
62	3.90	-5.04	156	1.01	-6.05	250	1.61	-4.59	344	2.92	-6.11
64	3.59	-4.69	158	1.10	-5.45	252	1.72	-4.53	346	2.31	-6.09
66	3.03	-4.82	160	1.26	-5.58	254	1.90	-6.24	348	2.85	-5.66
68	3.36	-5.00	162	1.12	-5.28	256	2.03	-6.71	350	3.11	-5.98
70	3.28	-4.99	164	1.05	-6.11	258	1.96	-6.79	352	3.33	-5.90
72	3.86	-5.13	166	1.03	-5.55	260	1.95	-6.95	354	3.43	-5.88
74	3.72	-5.09	168	1.09	-5.78	262	1.97	-6.36	356	3.52	-5.93
76	4.11	-5.11	170	1.05	-5.89	264	1.90	-7.02	358	3.02	-5.82
78	3.62	-5.09	172	1.07	-5.75	266	1.90	-7.35	360	2.86	-5.57
80	3.72	-4.92	174	1.16	-5.61	268	1.89	-7.25	362	2.31	-5.26
82	3.74	-5.09	176	1.21	-5.86	270	2.42	-7.41	364	2.33	-5.47
84	3.36	-4.94	178	1.19	-5.98	272	2.66	-7.44	366	2.42	-5.53
86	2.94	-5.05	180	1.23	-5.72	274	2.87	-7.45	368	2.08	-5.31
88	3.73	-4.92	182	1.01	-5.93	276	2.77	-6.64	370	1.93	-5.46
90	3.90	-5.05	184	0.98	-5.61	278	2.31	-6.95	372	2.05	-5.37
92	3.37	-5.25	186	0.93	-5.69	280	1.70	-7.27	374	2.11	-5.44
94	3.32	-5.26	188	0.90	-5.75	282	1.23	-7.02	376	1.92	-5.39

Table 2. *Carbon and oxygen isotope data from Sheboygan County cores—continued.*

Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)
SB-1—*continued*											
378	1.65	-5.37	472	1.04	-6.14	566	0.15	-5.58	631	-0.24	-5.99
380	1.43	-5.61	474	0.60	-5.93	568	-0.13	-6.60	632	-0.03	-5.50
382	1.20	-6.38	476	0.18	-5.75	570	-0.28	-6.40	633	0.04	-6.17
384	1.28	-4.98	478	0.74	-6.16	572	-0.06	-6.27	634	0.10	-5.97
386	1.12	-5.32	480	1.19	-5.72	574	-0.30	-5.66	635	0.04	-6.06
388	0.97	-5.32	482	0.74	-5.94	576	-0.63	-6.12	636	0.28	-5.72
390	1.04	-5.70	484	0.98	-5.90	578	-0.47	-5.43	637	0.31	-5.94
392	0.92	-5.60	486	0.55	-5.80	580	-0.52	-5.61	638	0.47	-5.62
394	0.83	-5.64	488	1.44	-5.84	582	-0.58	-5.57	639	0.54	-5.71
396	0.62	-6.12	490	1.37	-5.89	584	-0.54	-5.69	640	0.74	-5.39
398	0.25	-5.92	492	1.44	-5.98	586	-0.33	-5.53	641	0.99	-5.25
400	-0.78	-5.59	494	1.32	-6.16	588	-0.26	-5.42	642	1.30	-4.82
402	-0.92	-5.24	496	1.31	-6.40	590	-0.10	-5.88	643	1.46	-4.71
404	-1.02	-5.19	498	1.33	-6.63	592	0.06	-5.73	644	1.48	-4.54
406	-1.03	-5.34	500	1.74	-5.84	594	0.15	-5.44	645	1.61	-4.16
408	-1.14	-5.26	502	1.72	-5.86	596	0.06	-5.43	646	1.26	-4.17
410	-1.31	-5.31	504	1.59	-6.04	598	0.40	-5.72	647	0.82	-4.71
412	-1.31	-5.45	506	1.55	-6.05	600	0.20	-5.57	648	0.14	-5.77
414	-1.16	-5.28	508	1.65	-6.18	602	0.21	-5.83	649	0.16	-5.93
416	-1.18	-5.33	510	1.91	-5.67	604	-0.03	-5.61	650	0.13	-6.04
418	-1.03	-5.60	512	1.85	-5.80	606	-0.10	-5.94	651	0.15	-6.05
420	-0.95	-5.66	514	1.88	-5.81	607	-0.22	-5.21	652	-0.16	-6.51
422	-0.46	-5.86	516	1.81	-5.79	608	0.10	-5.46	653	-0.09	-5.67
424	0.15	-5.73	518	2.10	-4.43	609	0.10	-5.72	654	-0.10	-5.57
426	0.37	-5.72	520	1.76	-5.58	610	-0.05	-5.53	655	-0.30	-6.04
428	0.65	-5.62	522	1.71	-5.26	611	-0.40	-6.09	656	-0.34	-5.30
430	1.16	-5.92	524	1.70	-5.24	612	0.10	-5.53	657	-0.66	-5.39
432	1.51	-5.93	526	1.65	-5.34	613	0.16	-5.54	658	-0.50	-5.34
434	1.63	-6.04	528	1.57	-5.38	614	0.37	-5.56	659	-0.60	-5.22
436	1.79	-5.89	530	1.55	-5.18	615	0.01	-5.43	660	-0.79	-4.87
438	1.94	-5.86	532	1.34	-5.30	616	0.31	-5.58	661	-0.79	-4.78
440	2.03	-5.96	534	1.00	-5.97	617	0.31	-5.81	662	-0.78	-4.80
442	1.98	-6.08	536	1.12	-5.61	618	0.07	-5.81	663	-0.94	-5.28
444	1.96	-6.16	538	1.04	-6.31	619	-0.28	-5.37	664	-1.16	-5.62
446	2.07	-5.99	540	0.82	-6.65	620	-0.20	-5.39	665	-0.99	-5.50
448	2.04	-6.11	542	0.80	-6.35	621	-0.09	-5.36	666	-1.09	-5.43
450	1.98	-6.14	544	0.58	-6.39	622	-0.27	-5.20	667	-0.94	-5.14
452	1.99	-6.05	546	0.55	-6.78	623	-0.36	-4.93	668	-0.98	-5.14
454	1.98	-6.08	548	0.66	-6.05	624	-0.49	-5.16	669	-1.21	-5.46
456	1.94	-5.99	550	0.44	-6.46	625	-0.41	-5.02	670	-0.98	-5.44
458	1.92	-5.99	552	0.52	-6.58	626	-0.48	-5.32	671	-1.14	-5.26
460	1.89	-5.82	554	0.54	-6.52	627	-0.70	-5.14	672	-0.92	-5.31
462	1.79	-5.79	556	0.48	-6.32	627.7	-0.47	-5.10	673	-0.94	-5.13
464	1.69	-5.62	558	0.16	-6.18	627.85	-0.12	-4.64	674	-1.76	-5.13
466	1.31	-5.97	560	0.40	-6.24	628	-0.29	-5.29	675	-1.18	-5.94
468	1.27	-6.24	562	0.42	-6.30	629	-0.24	-5.76	676	-0.84	-5.44
470	0.85	-6.16	564	0.28	-6.20	630	-0.29	-5.87	677	-1.00	-5.62

Table 2. *Carbon and oxygen isotope data from Sheboygan County cores—continued.*

Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)	Depth (ft.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)
SB-1—*continued*											
678	-0.97	-5.71	689	-0.18	-5.42	700	0.32	-6.15	711	-0.01	-6.17
679	-0.70	-6.02	690	-0.25	-5.83	701	0.28	-6.43	712	-0.02	-5.83
680	-0.66	-5.87	691	-0.03	-5.68	702	0.50	-6.06	713	-0.14	-5.84
681	-0.64	-6.05	692	-0.16	-6.07	703	0.28	-6.38	714	-0.34	-6.25
682	-0.77	-5.59	693	-0.03	-5.85	704	0.32	-6.45	715	-0.32	-5.76
683	-0.54	-5.66	694	-0.21	-6.18	705	0.41	-6.16	716	-0.31	-6.38
684	-0.47	-5.75	695	0.04	-5.94	706	0.37	-6.36	717	-0.50	-6.34
685	-0.46	-5.87	696	0.09	-5.73	707	0.28	-6.47	718	-0.52	-5.95
686	-0.35	-5.75	697	0.18	-5.93	708	0.34	-5.81	719	-0.83	-6.72
687	-0.62	-5.88	698	0.26	-5.83	709	0.17	-6.03	720	-0.99	-6.47
688	-0.30	-5.44	699	0.29	-5.86	710	-0.32	-7.08			
SB-6											
0	-0.45	-4.18	12	-0.48	-5.09	34	0.11	-4.61	56	1.16	-5.99
1	-0.63	-4.13	14	-0.36	-5.46	36	0.02	-5.71	58	1.28	-5.76
2	-0.36	-4.21	16	-0.27	-5.43	38	0.08	-5.61	60	1.39	-5.74
3	-0.74	-3.98	18	-0.20	-5.11	40	0.08	-5.98	62	1.36	-5.66
4	-0.45	-4.34	20	-0.34	-5.20	42	0.16	-5.68	64	1.83	-5.52
5	-0.38	-4.63	22	-0.46	-5.14	44	0.59	-5.63	66	1.69	-5.73
6	-0.14	-4.40	24	-0.31	-5.11	46	0.71	-5.61	68	2.30	-5.37
7	-0.47	-4.53	26	-0.24	-4.92	48	0.59	-5.60	70	2.11	-5.81
8	-0.33	-4.94	28	-0.29	-5.57	50	0.61	-5.50	72	2.38	-5.91
9	-0.29	-5.05	30	-0.34	-5.57	52	1.07	-5.35	74	1.61	-5.76
10	-0.31	-5.52	32	-0.09	-5.12	54	0.44	-5.17	75.5	2.30	-5.73
SWU-1											
42	-0.53	-4.05	56	-0.13	-5.65	70	-0.11	-5.99	84	-0.01	-5.84
46	-0.24	-4.13	58	-0.19	-5.42	72	-0.09	-5.79	86	0.24	-5.75
48	-0.80	-4.14	60	0.05	-5.05	74	-0.50	-5.59	88	-0.24	-6.00
48	-0.06	-4.77	62	-0.12	-5.50	76	-0.11	-5.84	90	0.40	-5.82
50	-0.20	-5.20	64	-0.17	-5.65	78	-0.02	-5.96	92	0.57	-5.87
52	-0.41	-5.14	66	-0.21	-5.85	80	-0.04	-5.91	94	0.66	-5.05
54	-0.20	-4.57	68	-0.11	-5.61	82	0.11	-5.80	96	0.69	-5.71
SWU-5											
106	-1.13	-3.66	136	-0.48	-4.58	154	1.82	-4.67	172	0.89	-4.81
108	-0.72	-4.10	138	0.53	-4.46	156	1.66	-4.44	174	1.69	-4.49
112	-0.64	-4.13	140	0.44	-4.71	158	1.22	-4.41	176	1.58	-4.49
124	-1.03	-4.30	142	1.41	-4.33	160	1.26	-4.56	178	1.60	-4.48
126	-2.59	-4.24	144	1.34	-4.44	162	1.31	-4.32	180	1.61	-4.30
128	-1.88	-4.11	146	1.50	-4.65	164	1.20	-4.58	182	1.79	-3.99
130	-2.53	-3.94	148	1.42	-4.14	166	1.05	-3.79	184	1.92	-4.04
132	-2.53	-3.95	150	0.44	-3.89	168	0.97	-3.85			
134	-3.85	-4.55	152	1.75	-3.92	170	1.61	-4.37			