WISCONSIN'S SPRING RESOURCES: AN OVERVIEW

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ABSTRACT

Wisconsin's extensive spring resources make ecological, cultural, and economic contributions to the state's livelihood. Formal documentation of the variety and distribution of springs began as early as the mid-1800s; however, their abundance challenges resource managers to adequately characterize the full range and significance of spring resources in the state. With these challenges in mind, this case study of Wisconsin's springs aims to summarize their geologic and geomorphic context, the habitats that they create and support, their influence on Wisconsin culture over time, and the policies that affect their management and use.

INTRODUCTION

Wisconsin is home to thousands of springs, found across the state and in every major geologic setting. They support the state's vast wetlands, lakes, and world-class trout streams and sustain critical habitat for endangered and threatened species. Wisconsin's springs are part of a rich cultural history and contribute to agriculture and tourism, two of the largest economic enterprises in the state. Springs supplied water to the earliest homesteads and continue to support livestock and major fish hatcheries. Wisconsin spring water was also widely marketed as restorative water in the late 1800s and continues to appeal to the bottled water industry today. But regardless of their ecological, cultural, and economic contributions, Wisconsin's environmental laws failed to explicitly protect springs until 2003 when the Groundwater Protection Act (2003 WI Act 310) was passed. This act aims to prevent harm to trout streams and springs; however, challenges in crafting a legislative definition of a spring and balancing economic development with resource protection continue to test managers of Wisconsin's springs.

SPRING INVENTORIES

Except for a few recent studies, most of the information on the distribution of springs in Wisconsin stems from two statewide inventories. The first, the Wisconsin Land Economic Inventory (WLEI) (1927–1947), documented land use in nearly every county in the state, so that abandoned farms, cutover forests, and other "idle" land could be resettled, reforested, or otherwise put to wise use (Koch, 2006). Field workers would, in a single day, walk 3 miles along a section line, across ½ mile to the quarter section line, back 3 miles along that line, and then ½ mile back to their starting point. This allowed the surveyors to touch at least one side of every "forty" (40-acre quarter-quarter section) in the surveyed area. A forty was the area of land that was typically considered necessary for a small farm, preferably with another forty of pasture and another of woodland. Hand-drawn field maps were produced for sections or groups of sections in a township and included information on land use, land cover, wildlife, buildings, streams, lakes, and springs. These detailed maps, along with information from the original Federal General Land Office Survey of Wisconsin (1833–1866) and aerial photography, provided the raw material for the published WLEI maps (Koch, 2006).

The second statewide inventory was prepared by the Wisconsin Conservation Department (WCD), a precursor to the Wisconsin Department of Natural Resources (WDNR). The WCD conducted spring surveys for roughly 60 percent of the counties in the state from 1956 to 1962. These county-by-county spring surveys were designed to assess spring resources for fish management purposes. Springs were plotted on plat maps and the WCD recorded information on location, flow rate, substrate material, fish species

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present, and land use. Although the surveys are very detailed, there are inconsistencies among the county surveys, and the quality of some of the information is unknown. For example, spring locations are only accurate to about a quarter-section. In addition, spring flow was sometimes measured using the "floating stick" method or a V-notched weir, but other times it was probably visually estimated. Even so, the surveys represent the most detailed information on the distribution of springs in the state for this time period.

Aside from initiatives primarily aimed at documenting surface water features in Wisconsin (for example, WDNR Surface Water Inventories, 1961–1985), very little has been done since the WCD surveys to characterize springs on a statewide basis. However, following the highly publicized case involving a proposed Perrier bottling plant near Mecan Springs and Big Spring in Waushara and Adams Counties (Glennon, 2002) and the subsequent enactment of groundwater legislation in Wisconsin (2003 WI Act 310), there was renewed interest in the distribution and character of spring resources. In response, Macholl (2007) compiled a statewide springs database (fig. 1). It contains all springs that have been mapped by the WLEI, WCD, or WDNR; recorded in the U.S. Geological Survey Geographic Names Information System; or documented in another local source. In addition to the location of each spring, the database includes the historical information collected during the WCD surveys and, for a few springs, some more recent physicochemical data. Macholl's (2007) statewide springs database will serve as a critical tool in tracking and monitoring changes to Wisconsin's spring resources over time. It provides an estimate of the potential number and position of springs in the state and the range of expected flow rates. Nearly 11,000 individual springs are currently identified in the database, and most of these springs are fifth- or sixth-order springs, according to Meinzer's (1927) discharge classification. The mean flow of the springs in the database is approximately 90 gallons per minute (gpm), or 0.2 cubic feet per second (cfs), and the median flow is 15 gpm, or 0.03 cfs. However, because very few of the springs could be field-checked as part of the effort (less than 2 percent), the database may, for some regions, overestimate or underestimate the current distribution of spring resources.

Studies specific to Brown, Calumet, Iowa, St. Croix, and Waukesha Counties were able to more thoroughly assess the accuracy of the historical sources of springs information and characterize the current state of spring resources in these areas (fig. 2) (Fermanich and others, 2006; Grote, 2007; Swanson and others, 2009). Results of work in Iowa and Waukesha Counties suggest that the positional

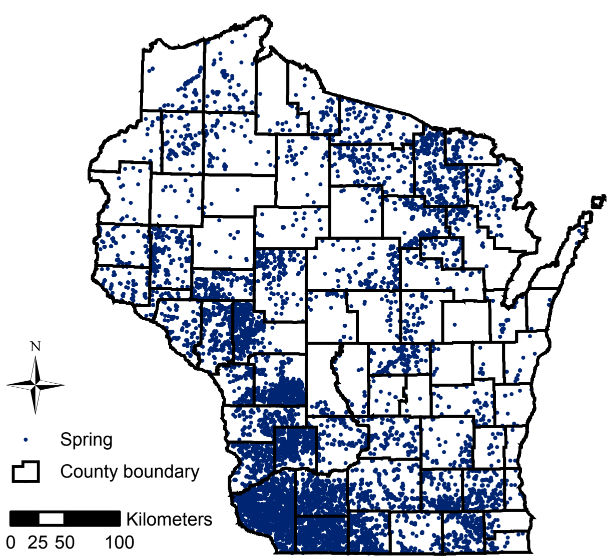

Figure 1. *Distribution of springs in Wisconsin. From Macholl (2007) and Swanson and others (2009).*

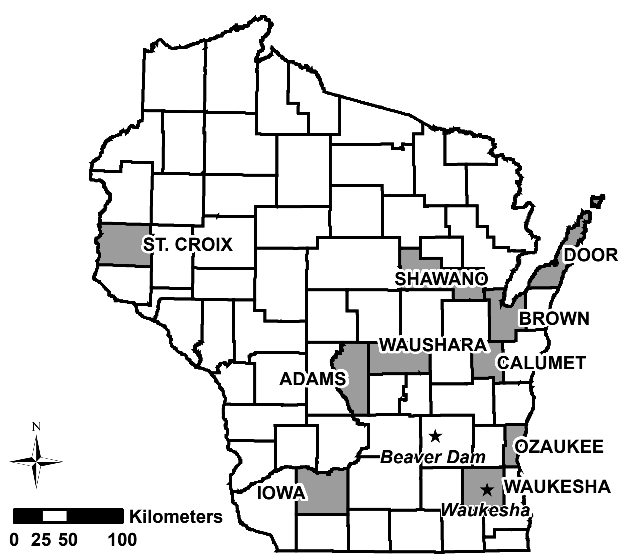

Figure 2. *Locations of cities and counties referred to in this report.*

accuracy of the springs in the WCD surveys is relatively high (at least to one quarter-section), but that the historical spring flow measurements can only be used as qualitative indicators of the size of a spring (first-order, second-order, etc., according to Meinzer, 1927). Because the positions of the springs are reliable, they can be used in association with regional data sets of geochemistry, topography, and geology to reveal important controls on groundwater flow or make initial assessments of the vulnerability of spring flow to groundwater withdrawals (Swanson and others, 2009). Furthermore, they serve as an important data set to which temporal changes in the distribution of springs can be compared. For example, very few of the springs documented in the 1958 survey of Waukesha County remain (WCD, 1958a; Swanson and others, 2009). The apparent loss of spring resources is attributed to urban development and groundwater withdrawals, which are known to have lowered groundwater levels and affected other surface water features in southeast Wisconsin (Feinstein and others, 2005; Swanson and others, 2009).

GEOLOGIC AND GEOMORPHIC CONTEXT

Wisconsin has a complex geologic past. Ancient Proterozoic and Archean sandstones, lava flows, and crystalline rocks underlie most of the state. Above that, mostly undeformed Paleozoic sedimentary rocks gently dip away from the Precambrian high (the Wisconsin Dome) in north-central Wisconsin. Pleistocene glacial deposits cover the bedrock over approximately three-quarters of the state (Mudrey and others, 2007).

The principal aquifers in Wisconsin are composed of Cambrian and Ordovician sandstones and dolomites, Silurian dolomite, and Quaternary sand and gravel deposits. Precambrian sandstone and lava flows are aquifers in northwestern Wisconsin, and the older crystalline rocks are also utilized for water supplies in limited areas (Kammerer and others, 1998).

Kammerer and others (1998) divide the state into four groundwater provinces on the basis of similarity of hydrogeologic regimes (fig. 3). These provinces (described below), along with local studies of spring systems, provide a useful framework for characterizing influences on groundwater flow to springs across the state.

Groundwater Province I

The largest of the four provinces, Groundwater Province I encompasses western and southwestern Wisconsin. Here, the Cambrian and Ordovician age strata generally thicken to the west and south and are overlain by glacial deposits only in the far north and east (Kammerer and others, 1998). Approximately half of the documented springs in the state occur in areas where the depth to bedrock is less than 5 feet, and

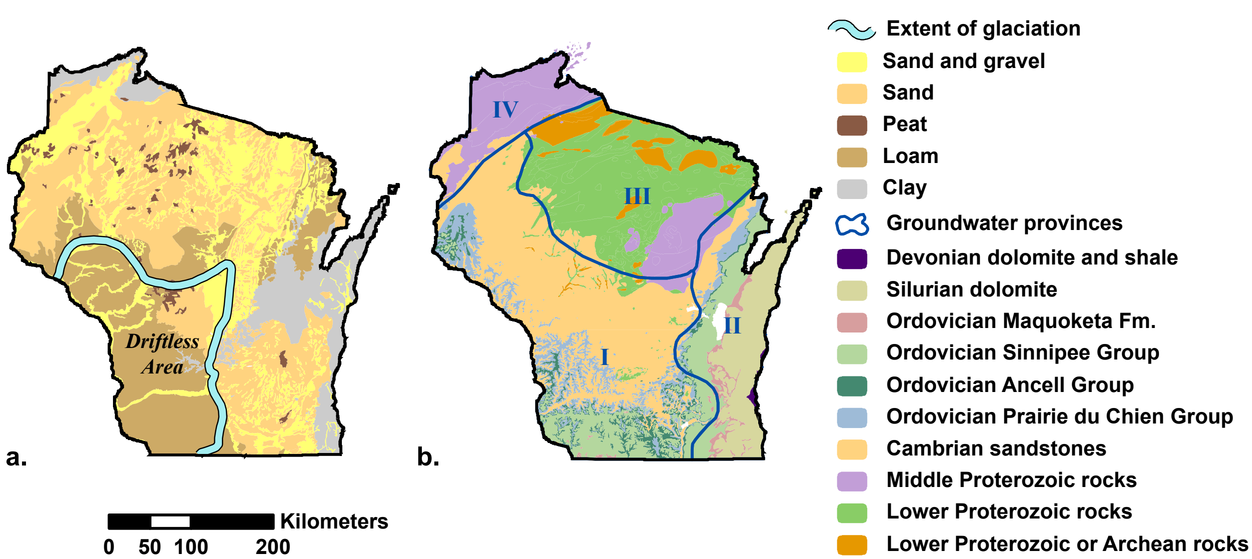

Figure 3. *General geology of Wisconsin.* **A.** *Distribution of surficial materials and extent of glaciation.* **B.** *Bedrock geology and major groundwater provinces. From WGNHS, 1989; Kammerer and others, 1998; Mudrey and others, 2007.*

nearly all of these springs are located in the Driftless Area (figs. 1 and 3). Glacial deposits are absent in the Driftless Area except for thin layers of loess and hillslope sediment on valley sides and stream sediment in valley bottoms, and Paleozoic rocks are deeply dissected and exposed in narrow valleys (Clayton and Attig, 1997).

In the Driftless Area, recharge primarily takes place along ridge tops and hillslopes, and local systems with short flow paths are common in the shallow bedrock aquifers. Perched water tables and local aquitards also occur throughout the region. In this complex setting, the relationship of springs to the groundwater flow system is often poorly understood (Krohelski and others, 2000; Hunt and others, 2003; Juckem and others, 2006; Carter and others, 2010). Groundwater is generally thought to flow preferentially along bedding plane fractures or along lithologic contacts with differences in hydraulic conductivity. The water emerges as contact springs where these features are intersected by stream valleys. Swanson and others (2009) found that springs are associated with every major stratigraphic unit in Iowa County; although most are associated with the heavily fractured Sinnipee Group (Platteville, Decorah, and Galena Formations), near the upper contact of the St. Peter Formation, or near the upper contact of the Cambrian sandstones. De Geoffroy and others (1967, 1970) similarly note that many of the springs in the historic lead-zinc mining district of southwest Wisconsin emanate from fractures and along zones of contrasting permeability in the Platteville, Decorah, and Galena Formations.

Several spring complexes in the eastern glaciated portion of Groundwater Province I have been studied in greater detail (for example, Domber, 2000; Hunt and Steuer, 2000; Anderson, 2002; Swanson and others, 2006). The bedrock surface is also deeply dissected in this area, but the valleys are filled with unlithified glacial deposits. Lakes formed in the low-lying areas during glacial retreat, and springs, composed of clusters of boiling sands, often emerge near the margins of wetlands that now occupy these low-lying areas. The springs are thought to form where high-permeability zones in the shallow sandstone aquifer are truncated by the buried bedrock valleys and where the hydraulic head exceeds the elevation of the land surface. These zones are attributed to erosional disconformities, limited cementation along bedding plane partings, and horizontal fractures in the sandstone aquifer (Swanson and others, 2006; Swanson, 2007).

Other notable patterns in the distribution of springs in Groundwater Province I include the concentrations of springs in the Baraboo Hills and those that coincide with the Johnstown moraine, which marks the farthest extent of late Wisconsin Glaciation in the state. Springs in the Baraboo Hills often emerge at the contact between the Precambrian Baraboo quartzite and the overlying Cambrian sandstones. Most of the springs in the vicinity of the Johnstown moraine are near streams, lakes, and wetlands that drain the hummocky glacial landscape. Groundwater flow paths to many of these springs are thought to be restricted to the sand and gravel aquifer and are not thought to intersect the underlying Cambrian or Ordovician bedrock (Conlon, 1996).

Groundwater Province II

Groundwater Province II covers the eastern part of the state. Here Paleozoic rocks gently dip towards Lake Michigan and are overlain by glacial deposits. Cambrian and Ordovician sandstones and dolomites are the uppermost rocks in the western half of the province. Silurian dolomite and Devonian dolomite and shale are the uppermost rocks elsewhere. The shaley Maquoketa Formation restricts vertical movement of groundwater between the Ordovician Sinnipee Group and the Silurian dolomite and confines the Cambrian-Ordovician sandstone aquifer throughout much of the province (Kammerer and others, 1998).

The spatial distribution of springs in this province is influenced by glacial features like drumlins and the Kettle Moraine, an irregular ridge of glaciofluvial material in southeastern Wisconsin that was formed during the retreat of the Green Bay and Lake Michigan Lobes (Clayton, 2001). In some areas, there is geochemical evidence that suggests that although flow paths originate in the sand and gravel aquifer, groundwater discharging to springs may also flow through shallow bedrock before discharging as depression springs in low-lying wetlands or near streams (Conlon, 1995; Gittings, 2005; Swanson and others, 2009). Elsewhere, flow is entirely within the sand and gravel aquifer (Newport, 1962; Swanson and others, 2009).

The Silurian dolomite aquifer occurs near the land surface throughout much of the central and northeastern part of the province, especially in the Door

County peninsula. The permeability of the dolomite is due primarily to secondary fractures and solution channels, so precipitation enters the groundwater system quickly. Once in the aquifer, groundwater flows laterally, through horizontal fractures, until it discharges to lakes, springs, or streams (Bradbury, 2003). Many small contact springs occur along the Niagara Escarpment near the contact of the dolomite with the underlying Maquoketa shale. These springs are often ephemeral, flowing only during the spring snowmelt (Newport, 1962; Johnson and Stieglitz, 1990).

Groundwater Provinces III and IV

Groundwater Province III extends across the Wisconsin Dome in north-central Wisconsin. Precambrian metasedimentary and metavolcanic rocks, granite, and gneiss are the uppermost rocks. Glacial deposits cover the area and range in thickness from 50 feet (15 m) to 200 feet (60 m).

Groundwater Province IV is located in northwesternmost Wisconsin. Here the uppermost bedrock is Middle Proterozoic volcanic and sedimentary rocks of the Keweenawan Supergroup. These rocks are overlain by glacial deposits that range in thickness from 50 feet (15 m) to over 400 feet (120 m) (Kammerer and others, 1998).

Like other areas of the state, the distribution of springs in both of these provinces is heavily influenced by the position of prominent glacial landforms, such as end moraines associated with the Green Bay, Langlade, Wisconsin Valley, Chippewa, and Lake Superior Lobes. Because the Precambrian rocks are dense and yield water only where fractures are present, most of the springs in these provinces are depression springs resulting from flow through the sand and gravel aquifer. Because some stream courses are influenced by faults in the Precambrian rocks (for example, the White River near Ashland in northern Wisconsin), the distribution of springs may be similarly influenced. However, more detailed research is needed to verify such relationships.

BIOLOGICAL CONTEXT

Springs in Wisconsin create unique habitat for rare and native species of plants and animals. They also support significant assemblages of coldwater organisms and diverse wetland communities, because springs often provide a stable physical and chemical environment (Webb and others, 1998; Epstein and others, 1999a, 1999b; Anderson and others, 2006). Springs can maintain stream flow during dry periods and provide refuge to organisms from heat in summer and cold in winter. Additional benefits may include increasing concentrations of dissolved oxygen and adding small amounts of nutrients that are essential to the health of organisms (Becker, 1983; Grannemann and others, 2000). A few examples of how springs contribute to important plant, insect, and fish habitat in Wisconsin follow.

Temperate zone fens, which are rare wetland plant communities, are frequently associated with springs. In Wisconsin, they most commonly occur in glaciated areas south of the vegetative tension zone between two distinct plant communities: the northern forest and the prairie-forest (Eggers and Reed, 1997; Amon and others, 2002). Amon and others (2002) conclude that Midwestern temperate zone fens are primarily differentiated from other wetlands not by fen indicator species, but instead by the source of the water and hydroperiod. Fens are dependent on continuous, and often focused, groundwater discharge, which allows for stable water levels and saturation of the root zone. Fens are supported by groundwater containing high levels of dissolved minerals, often rich in calcium and magnesium bicarbonates, and with a pH that ranges between 5.5 and 7.4.

Fen plant communities are known for their high botanical diversity. They host a disproportionately high number of rare, threatened, and endangered plant species compared to other plant communities in the Great Lakes Region (Eggers and Reed, 1997; Amon and others, 2002).

A few Wisconsin fens also provide habitat for the Hine's emerald dragonfly (*Somatochlora hineana*), which was listed as endangered by the U.S. Fish and Wildlife Service in 1995 and continues to remain on this list. Current populations are found only in isolated areas of Wisconsin, Illinois, Michigan, and Missouri. While adult Hine's emerald dragonflies are able to forage widely over open wetlands and meadows, their larvae require fen-type wetlands in association with dolomitic bedrock, groundwater seeps, marginal flow, shallow stream channels, and seasonal drying. A number of breeding sites have been identified and studied in Ozaukee and Door Counties, Wisconsin (fig. 2), several of which are spring fed (Soluk and others, 1999; Soluk and others, 2003; Bradbury and Cobb, 2008).

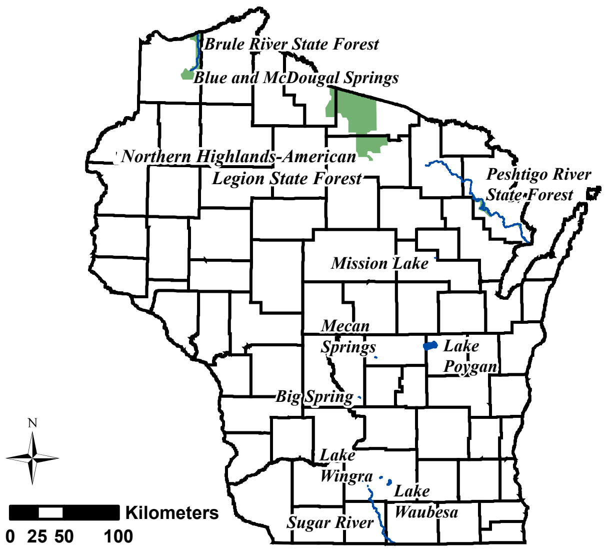

Figure 4. *Locations hydrologic features and state forests referred to in this report.*

Recent biotic inventories of Wisconsin's state forests also highlight the ecological significance of springs, particularly in northern Wisconsin (for example, Epstein and others, 1999a, 1999b; Anderson and others, 2006). The Brule River State Forest is known for its exceptionally rich biota and coldwater fishery (fig. 4). The upper Bois Brule River contains concentrations of soft water springs (for example, the Blue and McDougal Springs) and spring-fed streams, some of which support invertebrates that are very rare in Wisconsin, including two diamesin midges (*Pseudodiamesa pertinax* and *Protanypus* sp.), a bizarre caddisfly (*Lepidostoma libum*), a caenid mayfly (*Caenis youngi*), and a predaceous diving beetle (*Hydroporus pseudovilis*). A number of vascular plants that are listed at the state level as endangered, threatened, or of special concern also rely on the springs and spring-supported habitat in the Brule River State Forest. These include, but are not limited to, mountain cranberry (*Vaccinium vitis-idaea*), listed as endangered; and the fairy slipper (*Calypso bulbosa*) and large water-starwort (*Callitriche heterophylla*), both listed as threatened (Epstein and others, 1999a). The Peshtigo River and Northern Highlands–American Legion State Forests, both in northern Wisconsin, similarly contain ecologically significant spring-supported habitat (fig. 4) (Epstein and others, 1999b; Anderson and others, 2006).

Wisconsin is home to nearly 3,000 trout streams, which are highly valued for their recreational fishing opportunities. Forty percent of these streams are classified as Class 1, which means that they require no stocking because they have sufficient natural reproduction to sustain populations of wild trout at or near their carrying capacity (Becker, 1983; WDNR, 2002). Brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) both thrive in these waters, but brook trout are the only stream trout species native to Wisconsin. Brook trout require cold (≤ 68°F/20ºC), well-oxygenated water and typically inhabit spring ponds and spring-fed streams (Becker, 1983). Although diffuse groundwater discharge can moderate stream temperatures over longer stream reaches, lower water temperatures are most consistent near springs. Therefore, springs are particularly effective at providing thermal refuge for fish, especially in extreme weather conditions (Gaffield and others, 2005). Brown trout often live in waters that are uninhabitable for brook trout, but both species spawn near springs. In addition to lowering stream water temperature, upwelling of groundwater at springs provides oxygen and prevents the deposition of silt on eggs (Carline, 1980; Becker, 1983; WDNR, 2002).

CULTURAL AND HISTORICAL CONTEXT

Generations of Wisconsin's residents have used, revered, and even fiercely protected the state's abundant spring resources. American Indian trails and evidence of villages or camping sites have been found near many springs, and some springs were considered sacred. In southern Wisconsin, the Grand Spring[2] was located along a trail leading from early Ho-Chunk villages along the Sugar River to Lake Waubesa (fig. 4) (Brown, 1943). The Blue Springs are located in northern Wisconsin near the Bois Brule River (fig. 4), and historic American Indian trails are on both sides of the river near these springs (Lucius, 1941). Legends surrounding sacred springs often refer to animal spirits, such as a spirit bear, that inhabit the waters and are worthy of offerings (Overton, 1928; Brown, 1928; Brown, 1938). Artifacts including flint spears, arrowheads, pipes, bone awls, shells, and pieces of deer

[2] The Grand Spring was not identified in a 1958 survey of springs in Dane County (WCD, 1958b), so its precise location is unknown.

horn were recovered from several sacred springs in the Lake Poygan region of east-central Wisconsin. The Menominee tribe has occupied this region since about 1730, but many of these materials may also be associated with much earlier settlements (Overton, 1928). Other legends associated with springs involve spirits who were angered. A powerful spirit living in Mission Lake and Red Springs, in Shawano County (fig. 2, fig. 4), was offended and colored the spring water so that it was of no use to the Stockbridge–Munsee tribe who live in the region. A spirit who lived in a spring in the Menomonee River Valley was offended by the trampling of feet as children walked and sang in the spring. Without warning, the youngest child sank, but the others were able to pull the child out (Brown, 1938). Some American Indians also believed in the medicinal powers of spring water. For example, a spring on the south side of Lake Wingra in Madison was thought to possess medicinal values, and the Vita Spring[3] in Beaver Dam was known to the Ho-Chunk and Potawatomi tribes as a healing spring (fig. 2) (Brown, 1928).

European settlers also believed in the healthful benefits of mineral springs. Wisconsin spring water was widely marketed as restorative water in the late 1800s, and travelers from across the country came to the state's most famous springs in Waukesha (fig. 2). It was the Bethesda Spring that was first promoted for its healing properties by Colonel Richard Dunbar. Colonel Dunbar had apparently been cured by the spring water and began advertising and selling the water in 1869. Announcements of many other mineral springs soon followed, and bottled water became available from a variety of Waukesha springs including the Arcadian, Bethesda, Clysmic, Fox Head, Hygeia, Royal, and Silurian Springs. Waukesha was quickly transformed into a popular resort town with ornate structures built around the springs. By the 1880s elegant hotels were built, and Waukesha, also known as Spring City, became the summer destination of some of the nation's wealthiest families. A plan was even proposed by a Chicago entrepreneur, James McElroy, to pipe water from the Hygeia Spring to the World's Columbian Exposition in Chicago. However, Waukesha residents were vehemently opposed to the plan. They were concerned about the loss of World's Fair visitors to their own city if a pipeline were built and were sure that the pipeline would allow Chicago to demand their spring water in large volumes. Although the Village Board rejected the pipeline proposal, McElroy was persistent in his quest to bring Waukesha's famous spring water to the World's Fair. In May of 1892, he organized a group of over 200 workmen to travel to Waukesha by train in the middle of the night and construct the pipeline before Waukesha residents awoke the next day. However, when they arrived, the men were confronted by over 600 angry residents, many of whom were armed. By morning the workmen were on a return train to Chicago. Although water from the Hygeia Spring was not diverted, McElroy did finally manage to construct a pipeline from Big Bend, approximately 12 miles south of Waukesha, to Chicago (Schoenknecht, 2003; McDaniel, 2005).

Waukesha's springs continued to draw visitors until about 1905, but the advent of car travel coupled with skepticism regarding the benefits of spring water eventually took its toll on Spring City's popularity (McDaniel, 2005). Many of Waukesha's springs are now covered and forgotten, filled-in as development proceeded, or capped with metal covers and locked. Bethesda is one of the few springs that remains in a Waukesha City park, although the building that now houses the spring in no way resembles the ornate structure that stood in the 1890s (fig. 5) (Schoenknecht, 2003).

Wisconsin's spring water continues to appeal to the public and is bottled under labels like Chippewa Spring Water (Premium Waters, Inc.). However, like James McElroy, other bottlers have been met with great resistance from Wisconsin's residents. In 1999, the Perrier Group of America (Perrier) proposed bottling plants, first near Mecan Springs in Waushara County and later near Big Spring in Adams County (fig. 4). Perrier's initial plan was to install a well adjacent to Mecan Springs, which are located on state-owned land, and obtain an easement for access to the well. The proposed bottling plant would be located on privately held property (Seely, 2000, January 2). Although the Mecan Springs plant could eventually employ up to 250 people in this rural area of Wisconsin, residents and their state senator immediately expressed concern over the impacts of groundwater pumping on the state-owned springs and the trout stream fed by the springs (Associated Press, 1999, December 20; State Journal staff, 1999,

[3] A spring house surrounding the Vita Spring still exists today in the Swan City Park, Beaver Dam.

December 24). Vocal opposition only intensified when Perrier began to consider installing the well on adjacent, privately held land. This would eliminate regulatory oversight by the WDNR, and although Perrier would still need approval for a high-capacity well, in other words, a well that pumps more than 100,000 gallons per day (gpd), the only way approval could be denied was if the well was not properly built or if it affected a municipal water supply (Seely, 2000, February 8).

Perrier eventually yielded to the opposition and announced that it would instead pursue a site near Big Spring in Adams County. The thought was that Big Spring would be a more palatable option because, in Perrier's view, the trout streams fed by Big Spring were degraded (Seely, 2000, February 26). They proposed to pump up to 150 gallons per minute (gpm), or just over 200,000 gpd, and voiced willingness to participate in environmental assessments prior to well approval (Seely, 2000, March 2; Seely, 2000, March 9). However, the Big Spring plan was met with similar resistance. Despite vocal opposition at town meetings, rejection of two referendums that asked residents to consider the idea of allowing Perrier to use the spring water or to build a plant to bottle that water, and backing of Perrier opponents by then-presidential candidates Ralph Nader and Al Gore, Perrier continued its pursuit for the high-capacity well approval (Seely, 2000, June 16; Milfred, 2000, September 22; Seely, 2000, October 17).

Because the pumping would not threaten nearby municipal wells (the only mechanism for denial), the WDNR granted approval. However, the WDNR did not set pumping rates. Instead, they negotiated an agreement with Perrier that allowed the agency to modify the company's well approval if environmental problems were to arise (Seely, 2000, September 22). The action sparked lawsuits filed against both Perrier and the WDNR by a group called Concerned Citizens of Newport and by the Ho-Chunk Nation, but plans to install a test well to help determine pumping levels continued. While awaiting the outcomes of the lawsuits and groundwater studies, Perrier announced that it would put their plans for the Adams County bottling plant on hold for up to 5 years and, in the interim, pursue opportunities in Michigan (Seely, 2001, May 11). Six months later, a judge ruled in favor of the Concerned Citizens of Newport, who argued that the WDNR violated the Wisconsin Environmental Protection Act when they issued the high-capacity well approval before the completion of environmental studies near the Big Spring site. The judge did not

Waukesha County Historical Society & Museum

Figure 5. *The Bethesda Spring House, c. 1898.*

revoke the well approval, but he did order the WDNR to conduct a complete environmental review and to hold public hearings prior to setting pumping rates for the wells (Seely, 2002, February 8). In late 2002, Perrier announced that they would let their high-capacity approval expire and that they had no plans to reapply (Gibson, 2002, September 18).

ADMINISTRATIVE CONTEXT, CHALLENGES, AND CONSERVATION

In 2005, Wisconsin's residents used approximately 983 million gallons of groundwater per day (mgd) for domestic, agricultural, and industrial uses (Buchwald, 2009). This is up from 804 mgd in 2000 (Ellefson and others, 2002). At these rates, even a water-rich state like Wisconsin starts to see the impacts of groundwater use on its lakes, rivers, wetlands, and springs. For example, in Madison where pumping has lowered groundwater levels in confined aquifers by approximately 60 feet, lakes that were once regional discharge areas now recharge aquifers near some municipal wells (Bradbury and others, 1999; Krohelski and others, 2000). In southeastern Wisconsin near Milwaukee, expanding communities pump at least 25 percent more groundwater than in 1979. This contributes not only to hundreds of feet of drawdown in the Cambrian-Ordovician aquifer, but also to increased groundwater withdrawals from aquifers with high levels of naturally occurring radium (Gaumnitz and others, 2004). Near Green Bay, municipal pumping has at times resulted in over 300 feet (90 m) of drawdown. In addition, the introduction of oxygen to deep oxygen-depleted aquifers through domestic well boreholes causes sulfide oxidation within a mineralized zone of the St. Peter sandstone, resulting in the release of arsenic to groundwater (Schreiber and others, 2000; Gaumnitz and others, 2004). However, it was the Perrier case concerning springs (discussed earlier) that highlighted the lack of legal protection for groundwater resources, including mechanisms to prevent companies from privatizing public waters. It prompted legislation (2003 Wisconsin Act 310, enacted in March 2004) that addresses groundwater quantity issues by controlling well location and pumping rates to protect sensitive surface water resources, including springs (Gaumnitz and others, 2004; Kwaterski Scanlan and others, 2006).

Wisconsin's groundwater protection law, 2003 WI Act 310, is limited to two primary functions. It created Groundwater Management Areas (GMAs) in southeast and northeast Wisconsin, where groundwater withdrawals have resulted in more than 150 feet (45 m) of drawdown since predevelopment. The drawdown raises concerns over impacts to surface water features and water quality, so the law mandated that plans to manage groundwater resources in a sustainable manner be written for these regions (WGAC, 2006). The second function is to expand the state's authority over new, privately owned high-capacity wells. Specifically, the law requires the WDNR to consider impacts to trout streams, outstanding and exceptional resource waters, and springs in the well-approval process (WGAC, 2007). However, the law does not protect all springs in the state; it defines a spring as "an area of concentrated discharge occurring at the surface of the land that results in a flow of at least one cubic foot per second at least 80 percent of the time (2003 WI Act 310, Wis. Stat. § 281.34(1)(f))." The number and location of springs that meet these criteria are unknown, but the historical records discussed previously suggest that it includes only a small fraction of the springs in the state. Furthermore, the definition as written fails to acknowledge the potential ecological significance of smaller springs.

The Wisconsin Groundwater Advisory Committee (WGAC) was established when the law was enacted to assess the effectiveness of its main elements. With respect to springs, the WGAC was directed to include recommendations regarding the definition as written in the law. In their 2007 report to the Legislature, the WGAC raised concerns with nearly every aspect of the springs definition including the flow rate criterion, the flow frequency criterion, and the language regarding "an area of concentrated discharge occurring at the surface of the land." They also noted the lack of a buffer zone, or distance criterion, although this type of protection measure was applied to surface water bodies, like trout streams, elsewhere in the legislation. The committee reached near-consensus over the need for an updated, statewide springs inventory, which would include all springs with a flow rate of 0.25 cfs or greater, but did not reach consensus on a revised definition of "springs." Instead, they developed two alternatives for the legislature to consider: maintain the existing definition or reduce the threshold flow requirement (WGAC, 2007; WGCC, 2009).

The groundwater protection law, which is now part of the Wisconsin Statutes (Wis. Stat. § 281.34), earned broad, bipartisan support, passing 99-0 in the Wisconsin Assembly and 31-1 in the Senate. Water professionals generally agree that it and the associated rule in the Wisconsin Administrative Code (Chapter NR 820) are significant steps in the protection of groundwater resources in Wisconsin (Gaumnitz and others, 2004; WGAC, 2007). Although disagreement over which springs are most deserving of protection persists, the fact that they are explicitly included in the law illustrates that Wisconsin residents agree that at least some springs are worthy of special recognition.

Subsequently, a decision issued by the Wisconsin Supreme Court in July 2011 also influenced when examination of impacts to springs may be warranted. The decision in the case of Lake Beulah Management District v. State Department of Natural Resources (2011) states that the WDNR's broad obligation to protect waters of the state may be triggered by a proposed high-capacity well permit application. "'Waters of the state' includes those portions of Lake Michigan and Lake Superior within the boundaries of this state, and all lakes, bays, rivers, streams, springs, ponds, wells, impounding reservoirs, marshes, watercourses, drainage systems and other surface water or groundwater, natural or artificial, public or private, within this state or its jurisdiction (Wis. Stat. § 281.01(18))." Although the decision was issued with respect to a lake, it may influence whether a broader range of springs, in other words, beyond those recognized by Wis. Stat. § 281.34(1)(f), receive attention in Wisconsin. Whether ecological and cultural contributions of springs, as well as hydrologic characteristics, are recognized, remains to be seen.

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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

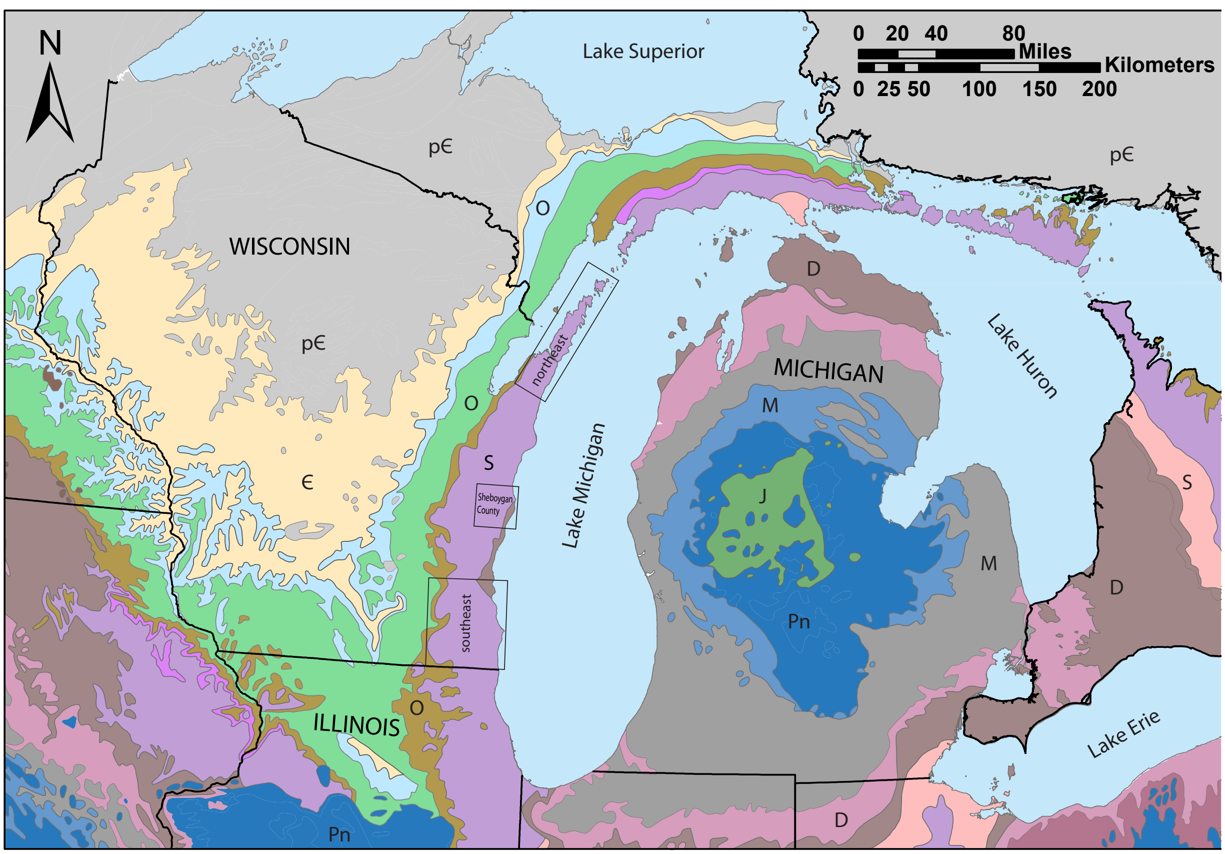


Figure 1. *Regional geologic map showing the position of classic areas of Silurian (S) bedrock studies in southeastern and northeastern Wisconsin relative to the position of Sheboygan County. Modified from Luczaj (2013).*

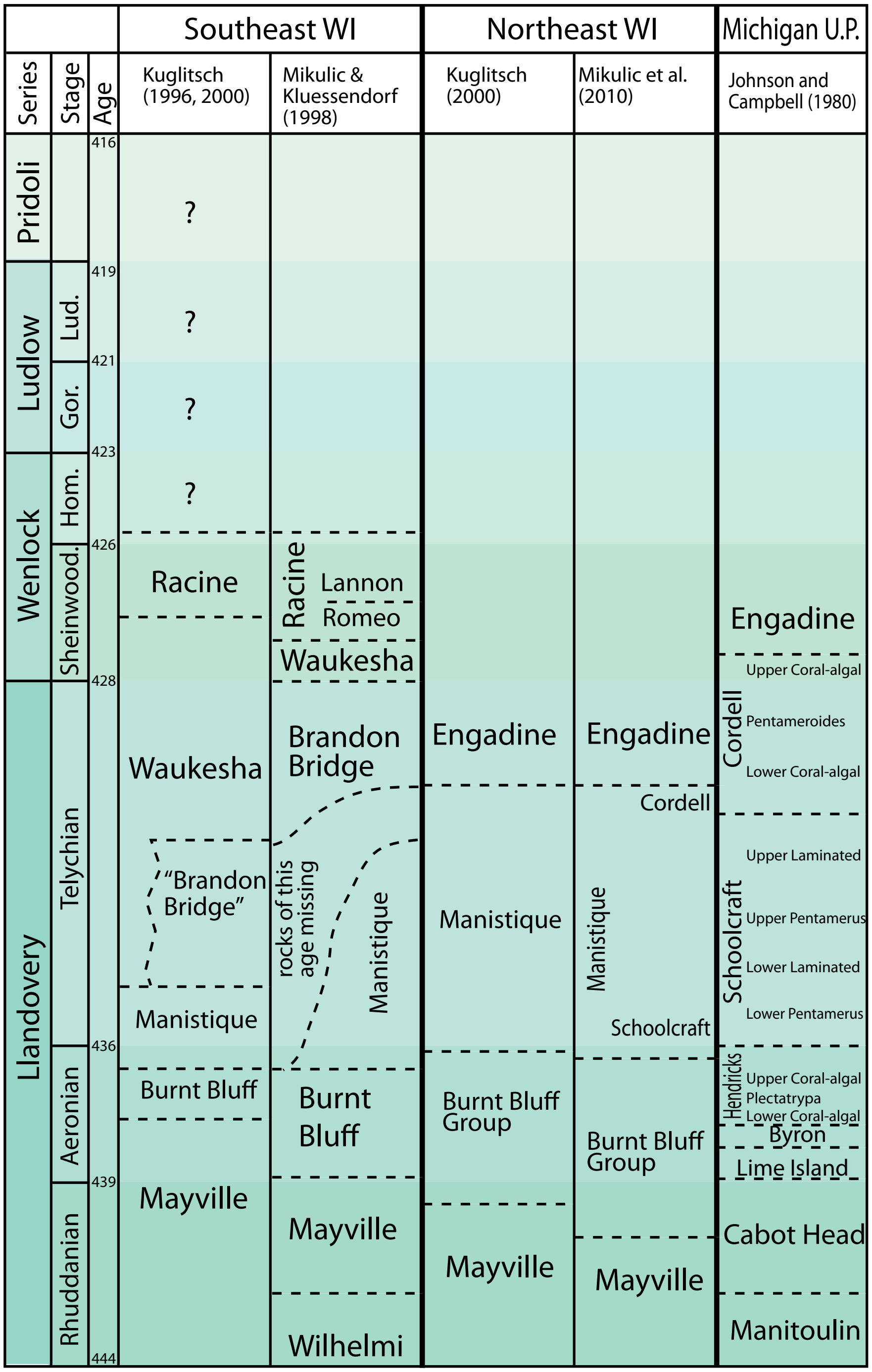


Figure 2. *Recent examples of lithostratigraphic classification and biostratigraphic assignment of Wisconsin Silurian rocks compared with that of the Upper Peninsula of Michigan. Question marks in the left column indicate the uncertain age assignment of the Waubakee Formation—while it locally contains 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

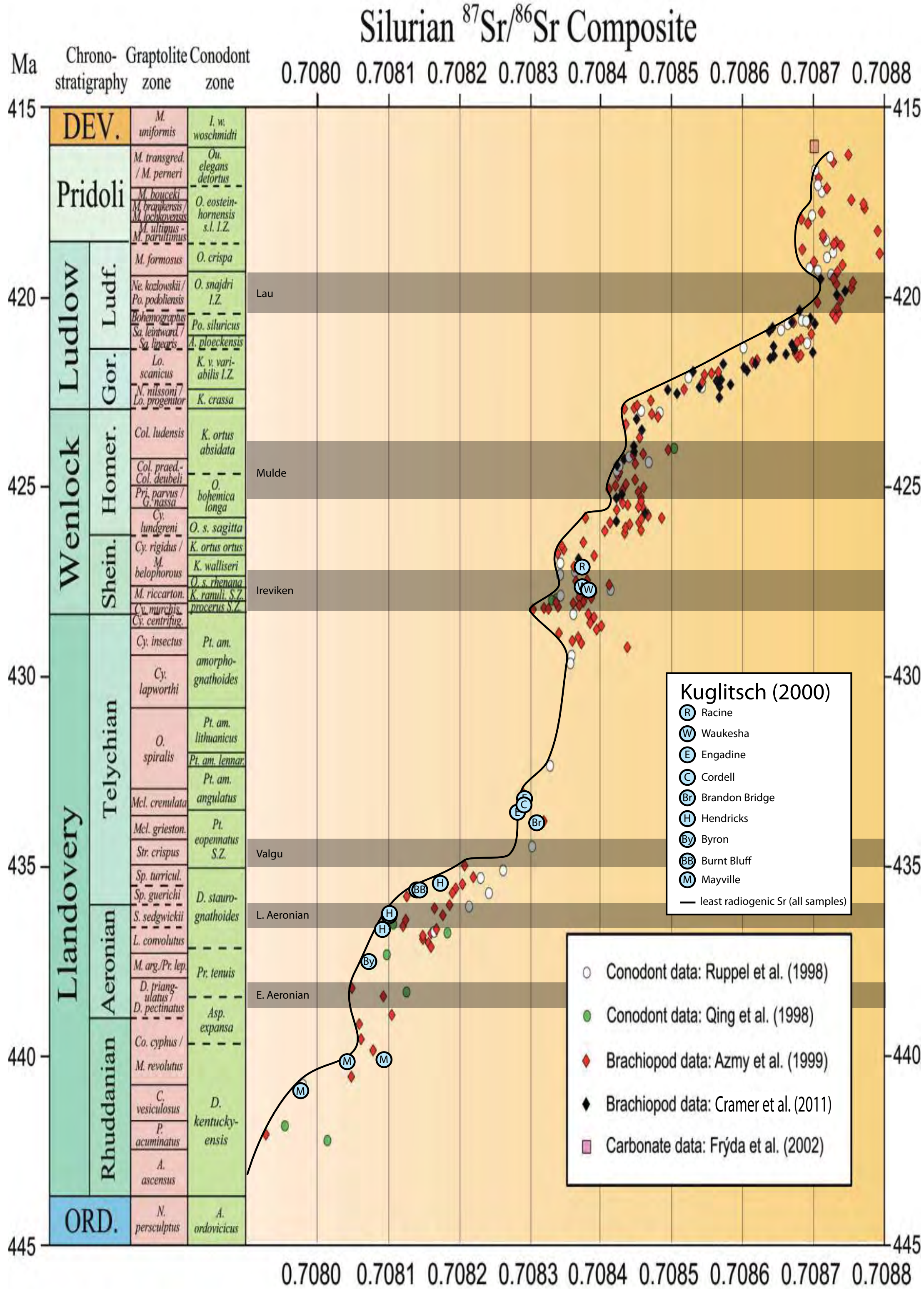


Figure 3. *Silurian strontium-isotope curve plotted against the most recent Silurian time scale (modified from Cramer and others, 2011). Least radiogenic line added. Data from Kuglitsch (2000) plotted by assigned conodont zone for reference.*

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

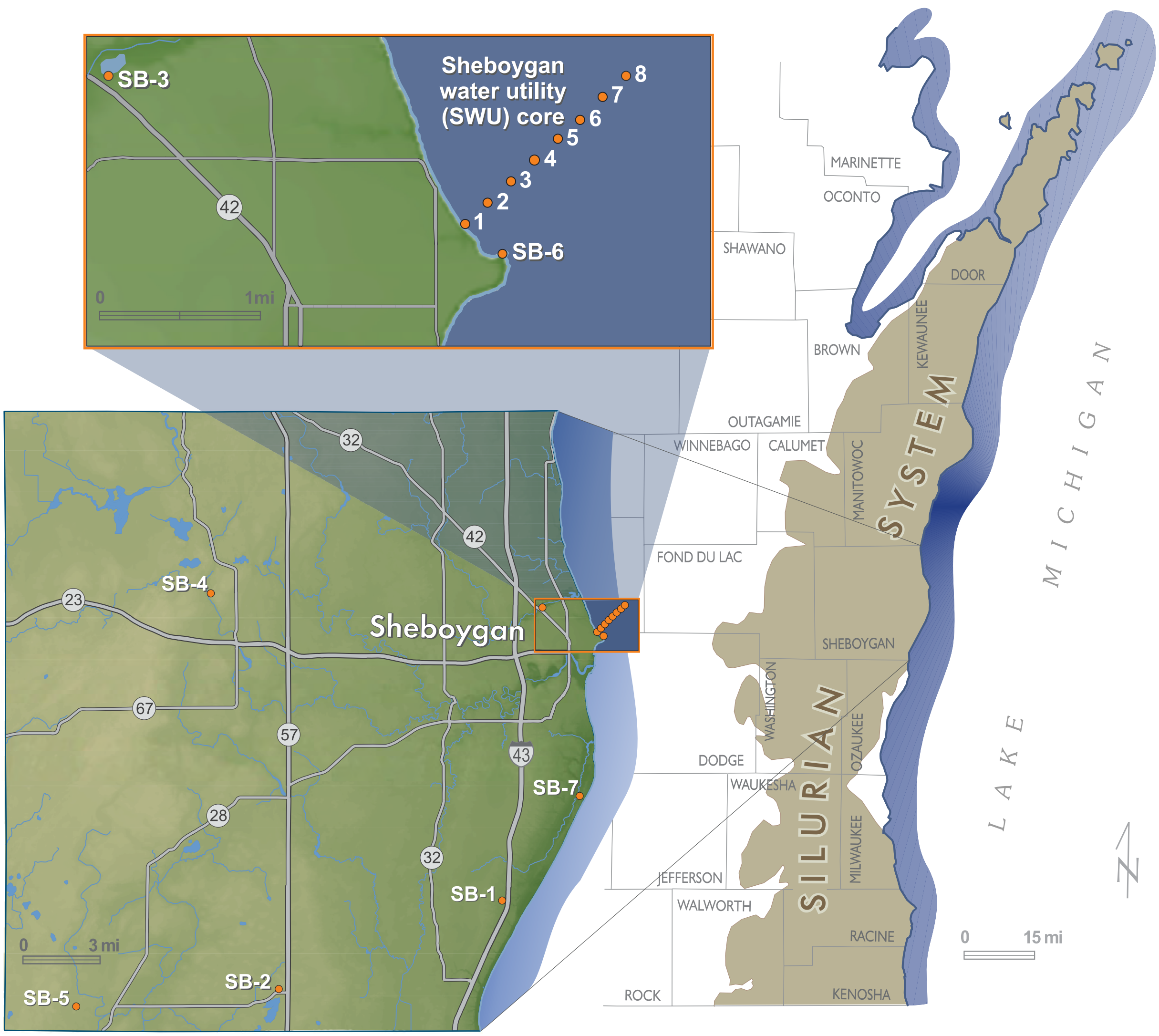


Figure 4. *Map showing the distribution of Silurian rock in eastern Wisconsin. Core locations discussed in this article are shown on the map of Sheboygan County. Cores SB-3, SB-6, SWU-1, SWU-5 (locations shown in the inset box) were analyzed for carbon and oxygen isotopes in this study.*

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

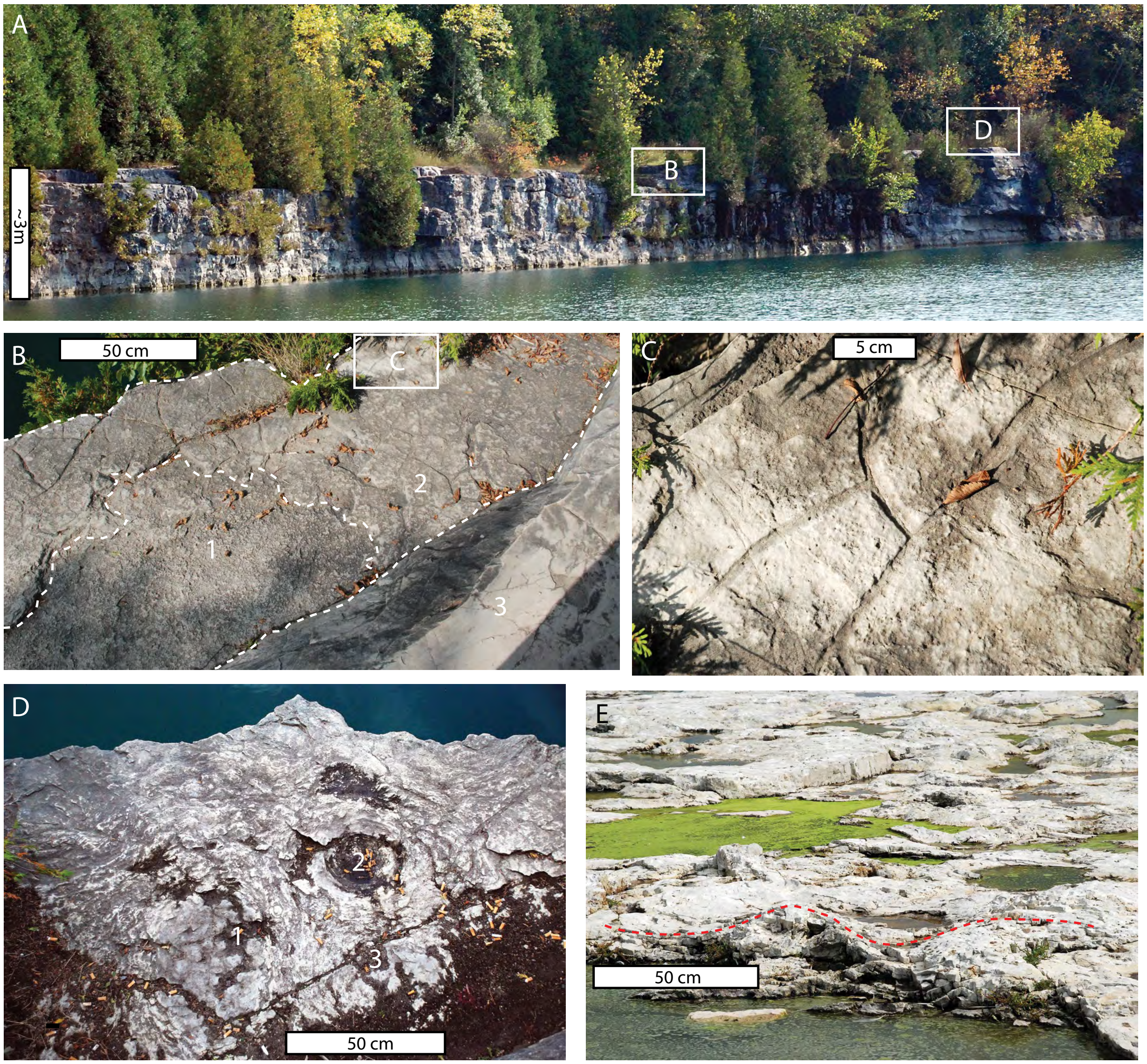
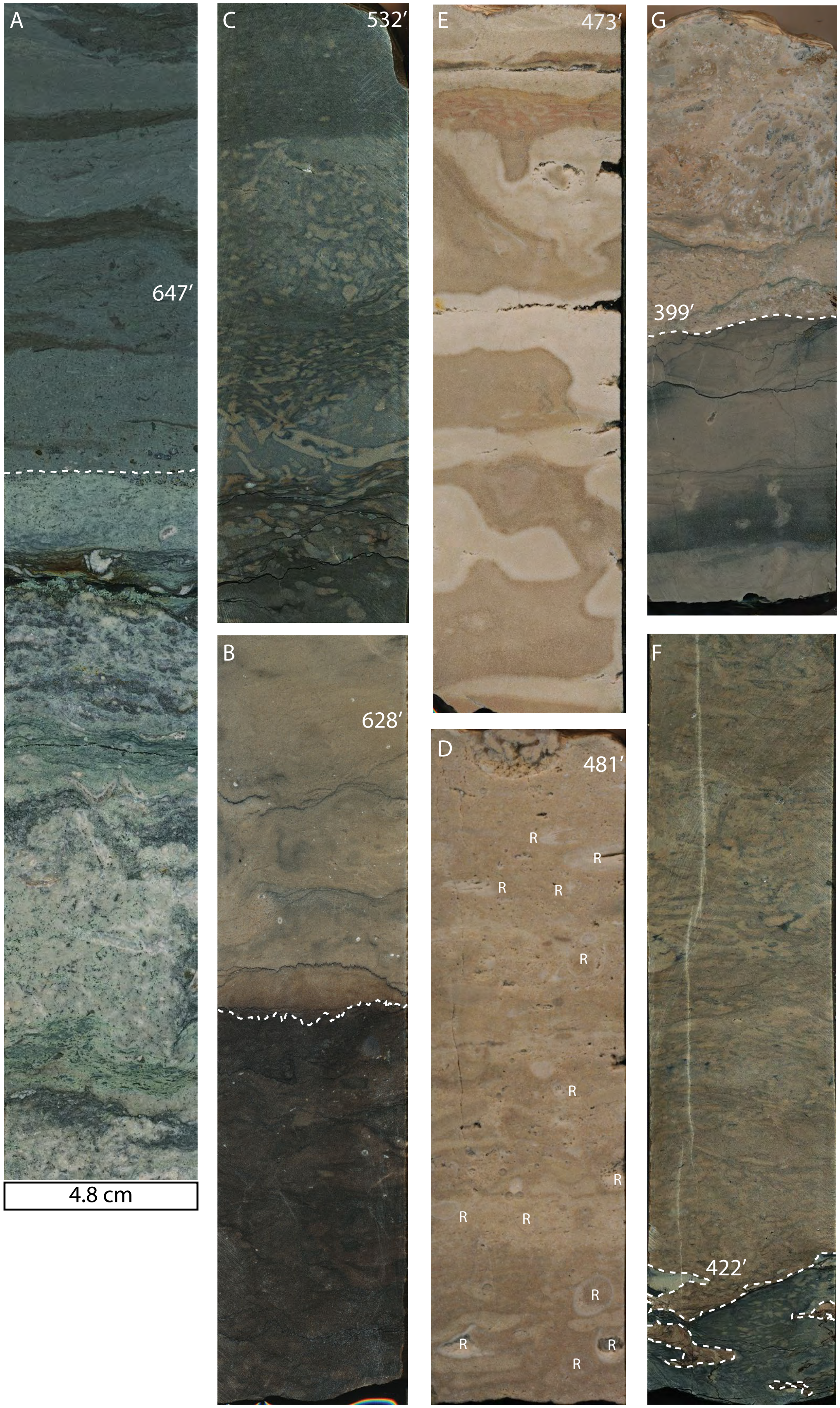


Figure 5. *Outcrop exposures at Quarry Park (A–D) and North Shore Park (E) in the city of Sheboygan.* **A.** *Southeastern exposed quarry face, about 10 feet (3 m) high, showing the location of close-ups B and D.* **B.** *Contact between fossiliferous dolowackestones to packstones (1), mudcracked surface (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′
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

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◀ **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.

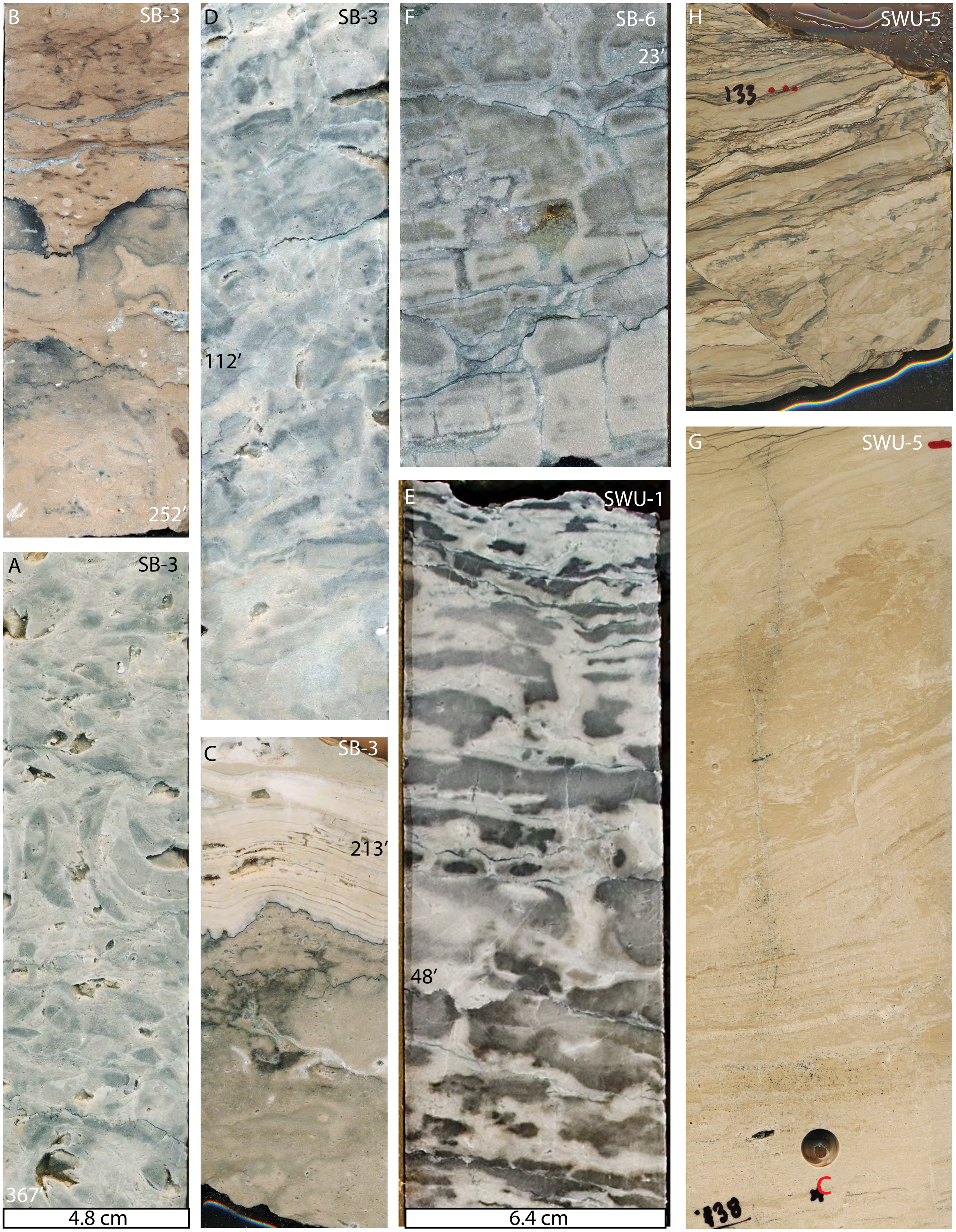
C. Dark gray fine-grained dolomudstone containing robust Chondrites *burrows, some compacted in more argillaceous zones: Lower Mayville Formation.*

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′
4.8 cm
C
SB-3
213′
E
SWU-1
48′
6.4 cm
G
SWU-5
C

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.

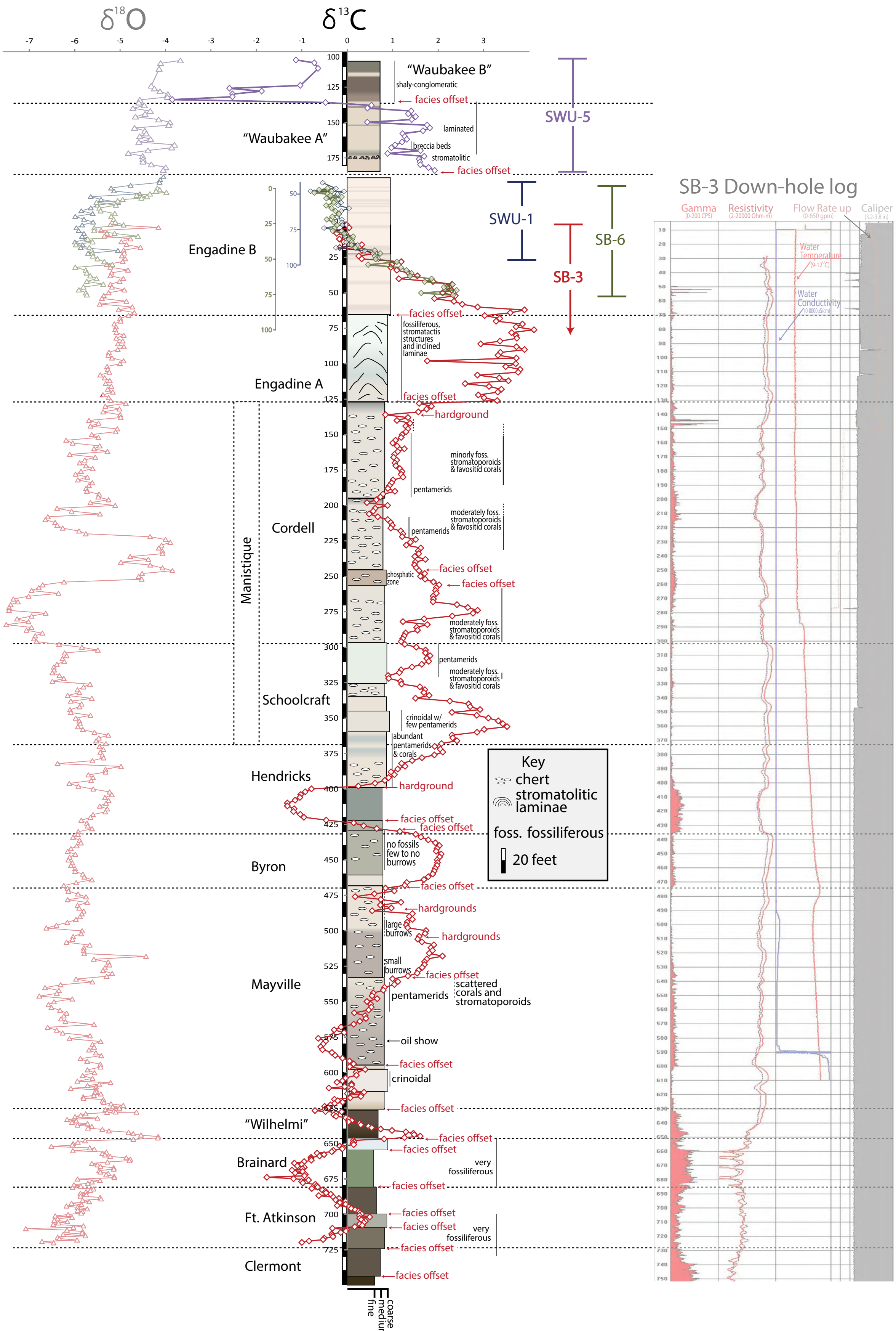
D. Inclined fabric of yellow to pink elongate sparry masses (incipient stromatactis structure?) interspersed in bluish-gray dolowackestone to dolopackstone with minor green clay stringers: Engadine Formation.

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.



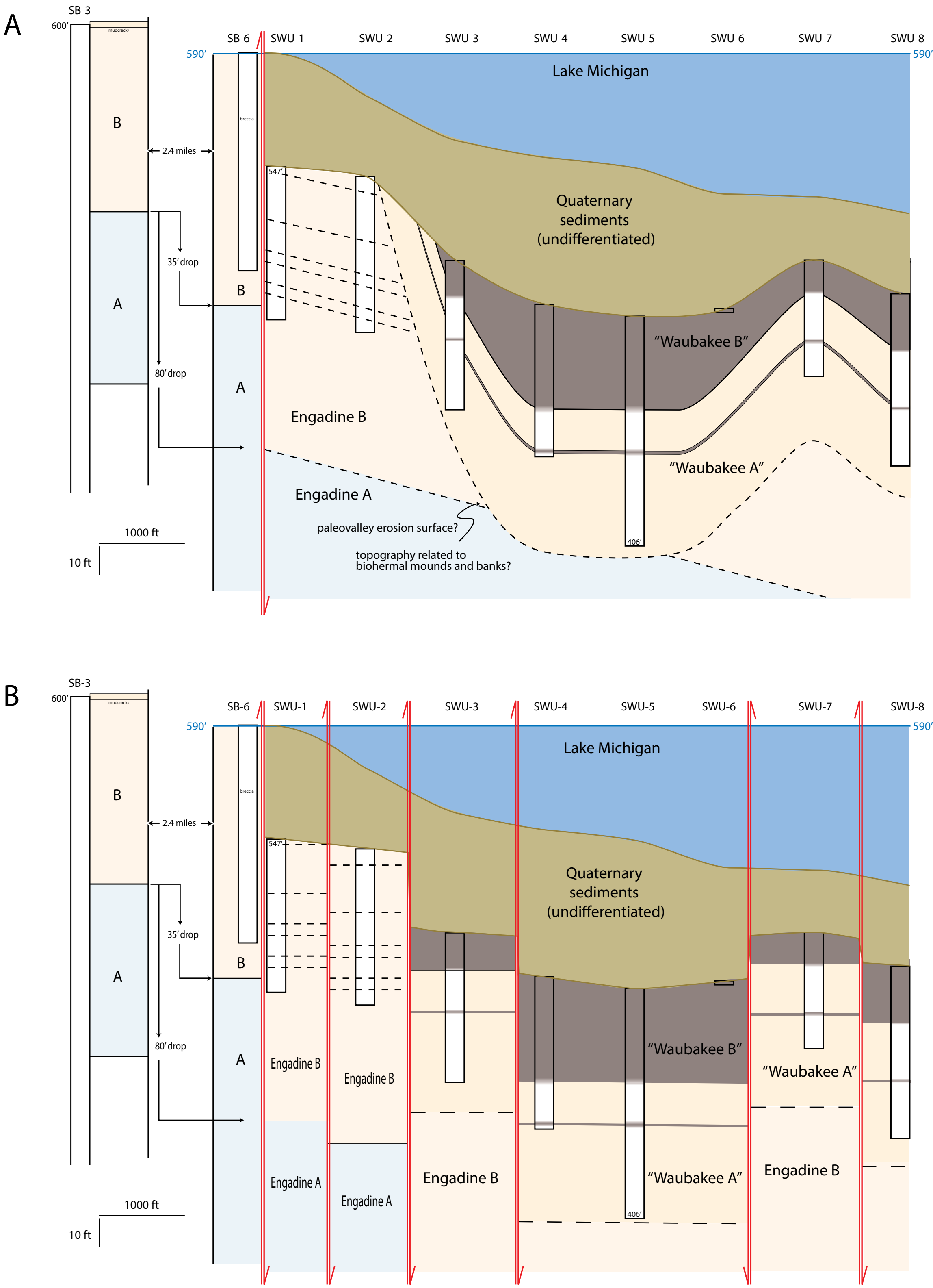
δ18O
δ13C
"Waubakee B"
shaly-conglomeratic
facies offset
laminated
"Waubakee A"
breccia beds
stromatolitic
SWU-5
SB-3 Down-hole log
Gamma
Resistivity
Flow Rate up
Caliper
Water Temperature
Water Conductivity
SWU-1
SB-6
SB-3
Engadine B
fossiliferous, stromatactis structures and inclined laminae
Engadine A
hardground
minorly foss. stromatoporoids & favositid corals
pentamerids
Manistique
Cordell
moderately foss. stromatoporoids & favositid corals
phosphatic zone
Schoolcraft
crinoidal w/ few pentamerids
abundant pentamerids & corals
Key
chert
stromatolitic laminae
foss. fossiliferous
20 feet
Hendricks
no fossils few to no burrows
Byron
hardgrounds
large burrows
small burrows
Mayville
pentamerids
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′
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′
590′
Lake Michigan
Quaternary sediments (undifferentiated)
547′
"Waubakee B"
"Waubakee A"
Engadine B
Engadine A
paleovalley erosion surface?
topography related to biohermal mounds and banks?
406′
B
SB-3
600′
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′
590′
Lake Michigan
Quaternary sediments (undifferentiated)
547′
"Waubakee B"
"Waubakee A"
"Waubakee A"
Engadine B
Engadine B
Engadine B
Engadine B
Engadine A
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).

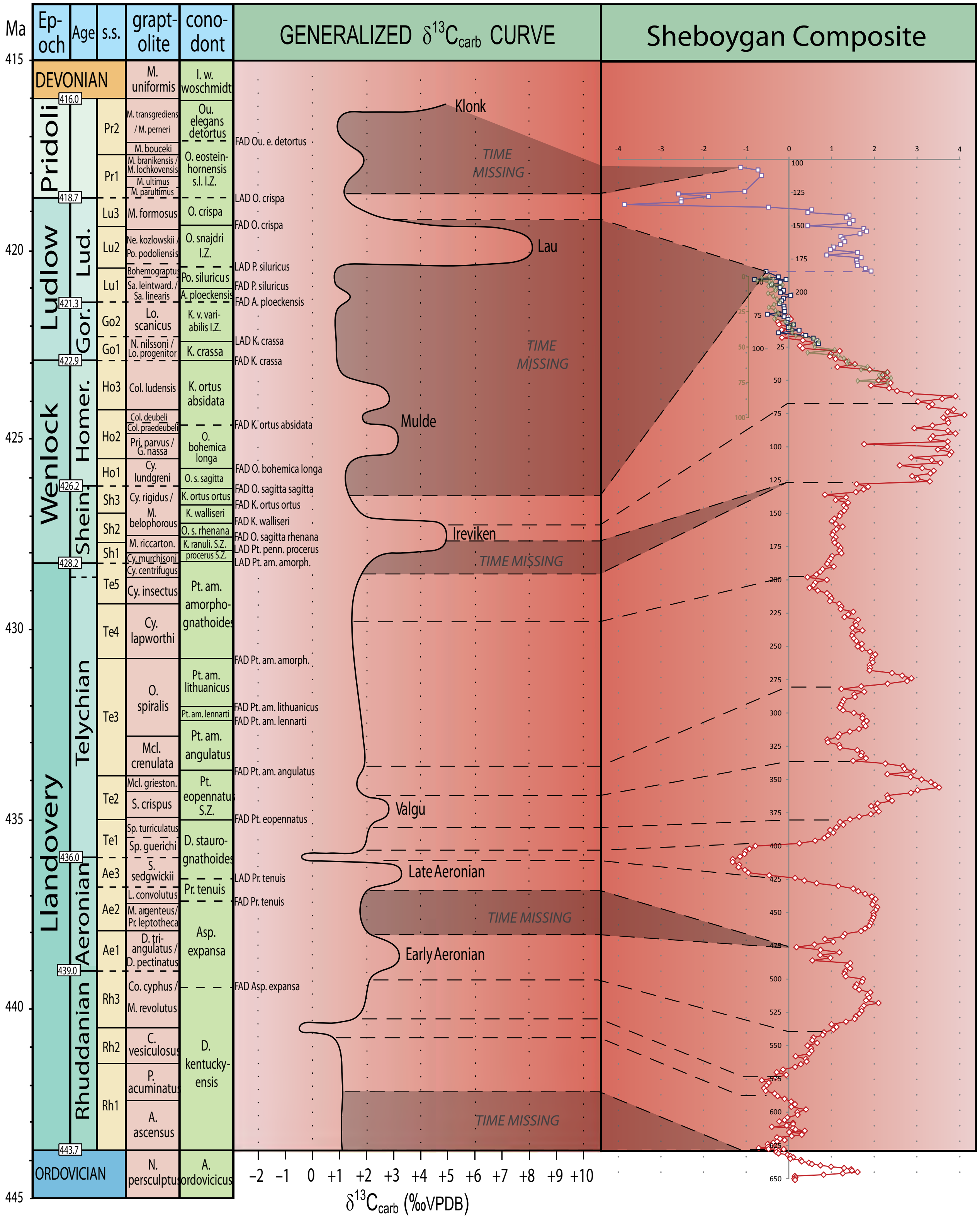


Figure 10. *Composite Sheboygan area carbon isotope curve (vertical axis in feet) against the global composite standard (vertical axis in millions of years; modified from Cramer and others, 2011a). Correlation of the carbon isotope curve to the composite curve is marked by dashed lines. Dark shaded areas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

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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.*

SB-1—*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.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)
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

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.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)
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

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.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)
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

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.)	$\delta^{13}C_{carb.}$ (‰)	$\delta^{18}O_{carb.}$ (‰)
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			