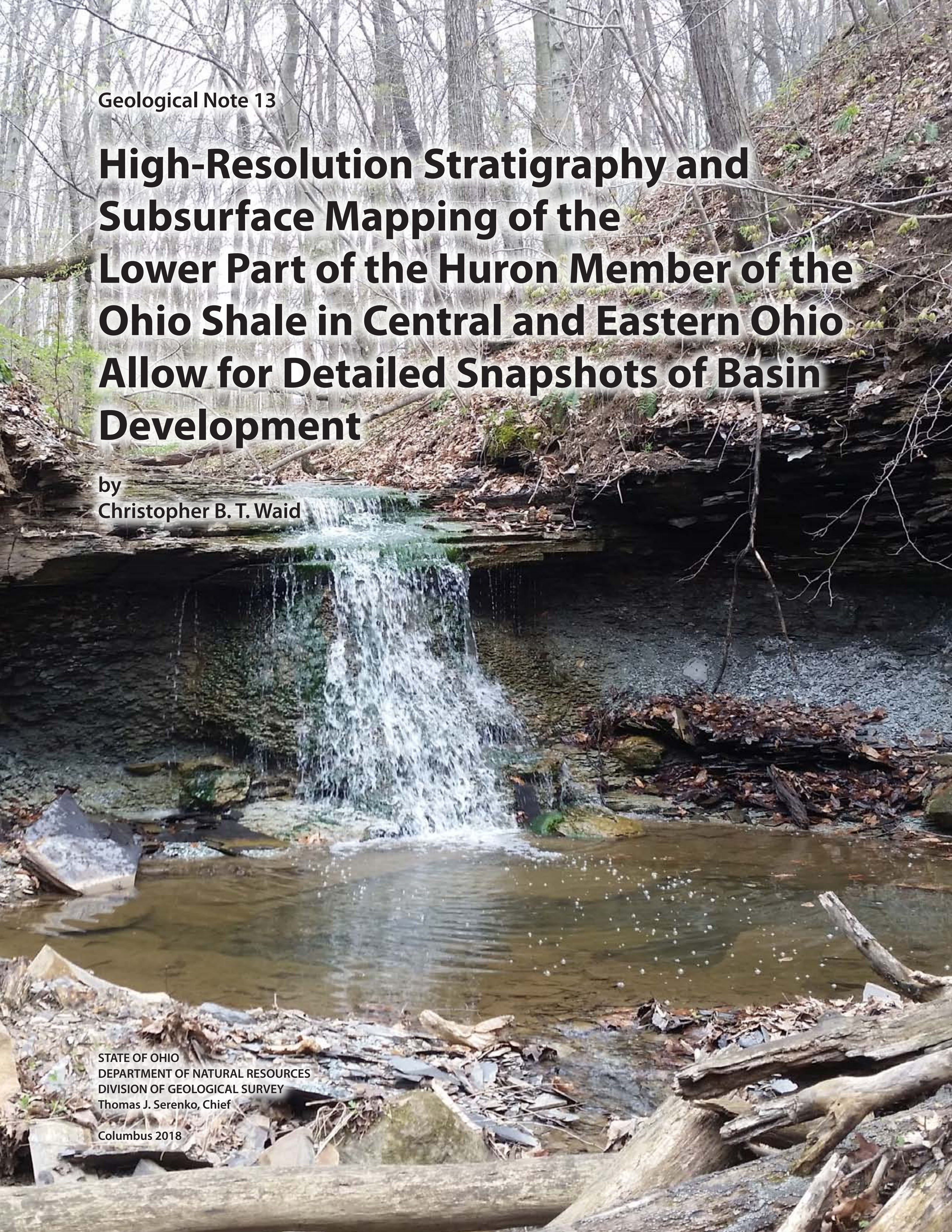

Geological Note 13

High-Resolution Stratigraphy and Subsurface Mapping of the Lower Part of the Huron Member of the Ohio Shale in Central and Eastern Ohio Allow for Detailed Snapshots of Basin Development

by
Christopher B. T. Waid

STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Thomas J. Serenko, Chief

Columbus 2018

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Disclaimer: This report was prepared by the Ohio Department of Natural Resources, Division of Geological Survey under DOE Cooperative Agreement No. DE-FC26-05NT42589 from the U.S. Department of Energy, National Energy Technology Laboratory, administered through Battelle Memorial Institute. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy, the Ohio Department of Natural Resources, or Battelle Memorial Institute.

Editing: Charles R. Salmons
Graphic design and layout: David S. Orr

Front cover: Contact of the Upper Olentangy Shale with the overlying Huron Member of the Ohio Shale at Shale Hollow Park, Lewis Center, Ohio. Photograph by Mohammad Fakhari.

Recommended bibliographic citation: Waid, C.B.T., 2018, High-resolution stratigraphy and subsurface mapping of the lower part of the Huron Member of the Ohio Shale in central and eastern Ohio allow for detailed snapshots of basin development: Columbus, Ohio Department of Natural Resources, Division of Geological Survey Geological Note 13, 18 p., 2 pls.

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ABBREVIATIONS USED IN THIS GEOLOGICAL NOTE

Units of Measure

foot (feet)	ft
grams per cubic centimeter	g/ccm
kilometer(s)	km
mega-annum (million years ago)	ma
mile(s)	mi
million years	my
percent by weight	wt%
thousand years	ky

Lithologic and/or Stratigraphic Units*

Formation	Fm
Member	Mbr/mbr
Shale	Sh

Geologic Terms

Akron Magnetic Boundary	AMB
Cambridge Cross-Strike Structural Discontinuity	CCSSD
Frasnian	Frasn.
Northwest Columbiana bathymetric high	NWCBH
Total organic carbon	TOC

Other Abbreviations

Consortium for Continental Reflection Profiling	COCORP
Enhanced gas recovery	EGR
Gamma ray	GR
Midwest Regional Carbon Sequestration Partnership	MRCSP
Ohio Department of Natural Resources	ODNR

*Lowercase lithologic and stratigraphic names and abbreviations indicate informal status of a unit.

High-Resolution Stratigraphy and Subsurface Mapping of the Lower Part of the Huron Member of the Ohio Shale in Central and Eastern Ohio Allow for Detailed Snapshots of Basin Development

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Christopher B. T. Waid

ABSTRACT

The Ohio Department of Natural Resources, Division of Geological Survey was involved (2003–2017) in the collaborative, multistate Midwest Regional Carbon Sequestration Partnership project, administrated by Battelle Memorial Institute and funded by the U.S. Department of Energy, to evaluate the utility of strata in the Appalachian Basin for carbon utilization and sequestration. Part of this research project involved developing a high-resolution stratigraphic framework for the organic-rich Upper Devonian shale interval in Ohio that will allow precise characterization of the hydrocarbon production and carbon sequestration potential of numerous shale units of this interval. The organic-rich lower part of the Huron Member of the Ohio Shale (Famennian Stage, Devonian System) is one of the units of interest for unconventional development and carbon storage in Ohio. A repetitive stacking pattern of black and gray shale throughout the lower part of the Huron Member (lower Huron submember) is interpreted to reflect cyclical glacio-eustatic sea-level variation. Two third-order depositional sequences, subdivided into eight glacio-eustatic sea-level cycles in the lower Huron submember, were regionally identified and correlated using gamma-ray and bulk density values in 789 well logs. The tops were correlated from wells throughout central and eastern Ohio using Petra® software, and ArcGIS® software was used to create isopach maps for each cycle. Thickness variations from cycle to cycle indicate that movement along basement-penetrating faults was a major structural control of local basin bathymetric characteristics during the deposition of the lower Huron submember. In particular, sinistral movement along the Smith Township, Suffield, Akron, and Highlandtown fault systems created a zone of contractional overstepping that led to a persistent paleobathymetric high during the deposition of cycles 1–4. Three unnamed normal faults in Belmont County appear to have been reactivated during the deposition of sequence 2 and influenced the development of a sub-basin. Finally, overall depositional strike changed dramatically after cycle 4, becoming parallel to the Akron magnetic boundary in the north and parallel to the Cambridge Cross-Strike Structural Discontinuity in the south. Furthermore, the cycles most likely represent the 413-ky eccentricity Milankovitch cycle, based on biostratigraphic information and transgressive-regressive sequences. The ability to constrain the timing of fault motion to sub-million-year time slices highlights the utility of high-resolution stratigraphy for analysis of localized basin subsidence and provides a useful step towards a greater understanding of the geologic controls of high-quality source rock deposition and preservation.

INTRODUCTION

The Ohio Department of Natural Resources (ODNR), Division of Geological Survey (Ohio Geological Survey) participated in the multistate Midwest Regional Carbon Sequestration Partnership (MRCSP) funded by the Department of Energy under the administration of Battelle Memorial Institute. The main goal of this project in Ohio was to broadly characterize geologic units in the study region (fig. 1) that have potential for carbon sequestration. In addition to traditional reservoirs, organic-rich shale units show promise for sequestering carbon dioxide (CO_2). Although shale has very low permeability, CO_2 can be injected into stimulated fractures. The nano-scale pore spaces within the shale and organic particles act as a molecular sieve, and the CO_2 molecules adsorb to the walls of the pore space (Kang and others, 2011). Additionally, CO_2 is effective as an injection chemical for enhanced gas recovery (EGR) from organic-rich geological units, such as black shales and unmineable coal seams. Carbon dioxide bonds more readily with organic particles, such as kerogen and bitumen, than methane, so it will expel methane that is adsorbed within organic pore spaces. Initial research into EGR using CO_2 injection primarily focused on coal bed methane (White and others, 2005; Robertson, 2010), where it was found that CO_2 replaces methane at an approximate ratio of 2:1.

Thick shale sequences were deposited in the Appalachian Basin during the Devonian Period (fig. 1). Rapid increases in accommodation space, through combinations of tectonic subsidence and eustatic sea-level rise, allowed for widespread environments conducive to shale deposition. Water was deep enough to allow fine particles to settle out of the water column, and sea-level

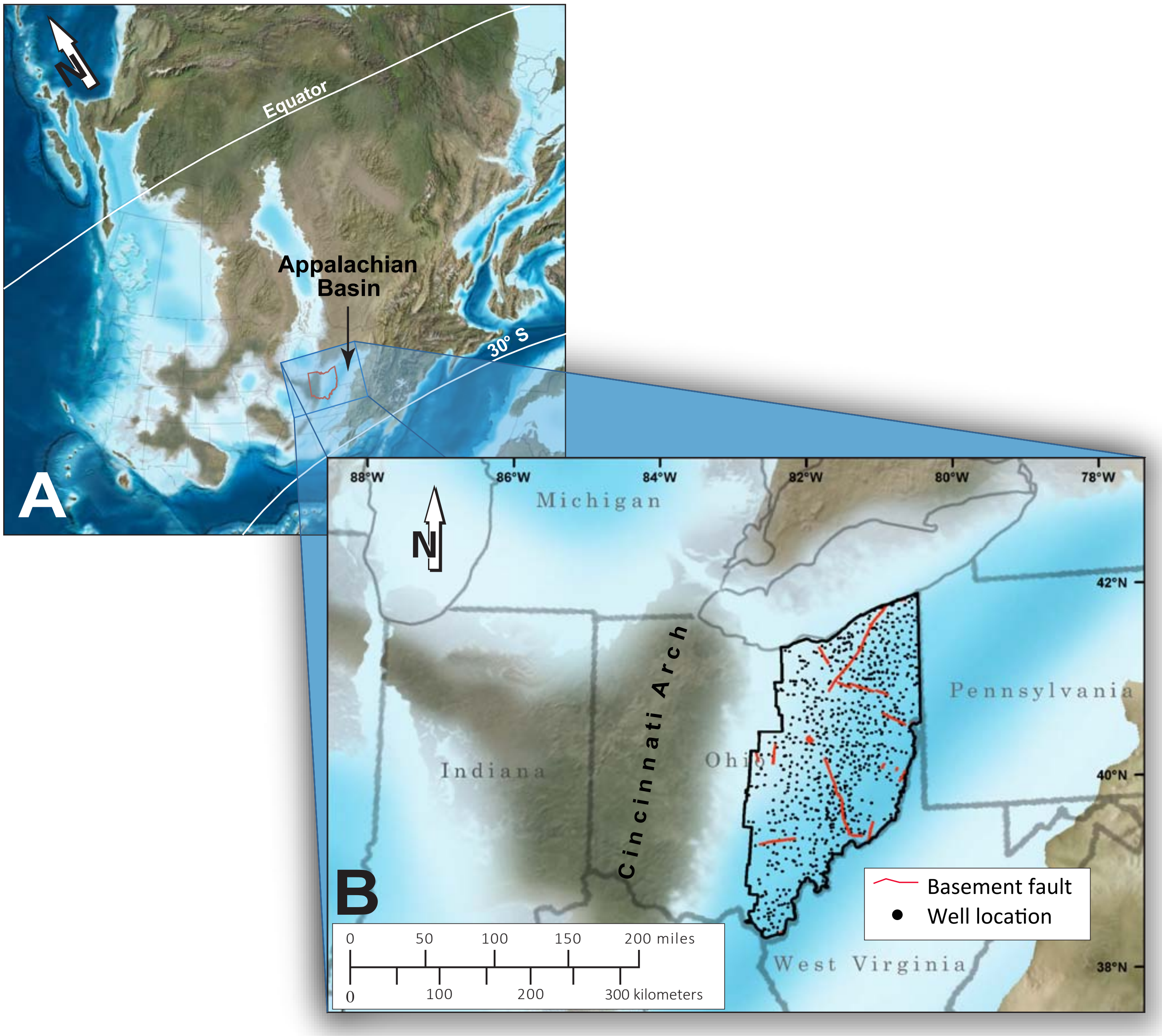


FIGURE 1. (A) Late Devonian (≈375 Ma) paleogeographic map of North America with (B) a close-up showing the modern study region (eastern Ohio) and surrounding states. North arrow, latitude, and longitude of panel B are present day. Study region outlined in black. Images modified from Blakey (2013).

transgressions stranded more coarsely grained sediment farther shoreward. Biochemical conditions within the basin were occasionally favorable for widespread deposition and preservation of organic material within some of the shale units, such as the Marcellus Formation, Genesee Formation, Rhinestreet Member of the West Falls Formation, and the Ohio Shale (fig. 2).

In Ohio, the organic-rich lower part of the Huron Member (fig. 3) of the Ohio Shale, informally correlated as the lower Huron submember (fig. 4), is one of the most promising units for unconventional development and carbon sequestration. The unit contains the highest net thickness of organic-rich strata of all the members of the Ohio Shale (de Witt and others, 1993). It has variable but generally high (1 to >10%) total organic carbon (TOC) composition (Milici and Swezey, 2014; Ohio Geological Survey, unpub. data, 2017). The lower Huron is deep enough (>2,500 ft below the surface) throughout enough of the state to store CO_2 and to have the thermal maturity necessary to produce hydrocarbons (Repetski and others, 2008; Hackley and others, 2013). In addition to its natural resource potential, the Huron Member also has significant scientific value. The unit was deposited immediately after the main pulse of the Late Devonian mass extinction interval near the Frasnian/Famennian boundary (Sepkoski, 1996), so it may be useful for studying biogeochemical conditions within the Appalachian Basin during the extinction recovery interval.

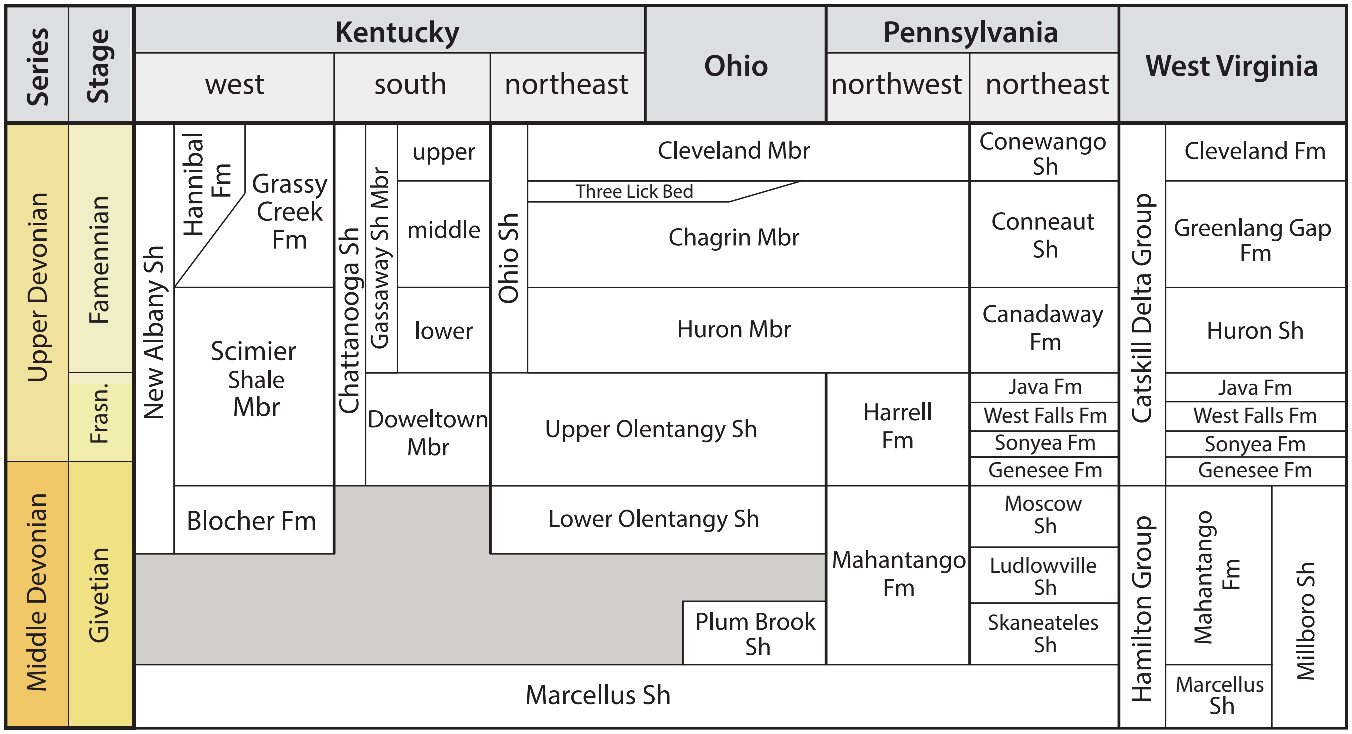


FIGURE 2. Generalized correlation diagram of Middle and Upper Devonian units in Ohio and surrounding states. Frasn. = Frasnian. Modified from Alshahrani and Evans (2014, fig. 1).

The lower Huron submember has not been correlated at a precision high enough to fully understand the stratigraphic and geographic distribution of elevated TOC, nor for the unit to be useful for modern paleoenvironmental research. The lower Huron submember must necessarily be subdivided into mappable units of higher chronostratigraphic precision than the submember itself to determine how the basin evolved during deposition. Additionally, the chronostratigraphic precision of the lower Huron submember is not high enough to provide insight at the resolution that modern paleoenvironmental research is conducted. Many aspects of ecosystem recovery (for example, carbon and phosphate biogeochemical cycles, oxygen levels) can vary on relatively short (<1 my) timescales—a much smaller interval of time than represented by the lower Huron submember as a whole.

Detailed subdivision, correlation, and subsurface mapping of the lower Huron submember is therefore necessary for gaining a better understanding of the effects of basin development on the geographic and stratigraphic distribution of TOC sweet spots. This framework will also provide the foundation for the lower Huron submember to be subdivided into more precise "time slices," increasing the resolution at which changes in the biochemical and climatic conditions can be studied within the unit. The cyclical variations in radioactivity present throughout the lower Huron (fig. 4) provide useful markers for correlations and are used to develop a high resolution stratigraphic framework for the submember.

Geological and Environmental Setting

The Appalachian Foreland Basin spanned tropical to subtropical latitudes during the Devonian Period (fig. 1). The basin initially was formed by the Taconic Orogeny during Middle Ordovician time and was reshaped by several orogenic intervals by the end of the Devonian (Ettensohn, 2008). The Acadian Orogeny began during the latest Silurian Period when the Avalonia Terrain and associated island arcs collided with the (present-day) eastern margin of Laurentia (Ettensohn, 2008). The eastern part of Ohio was on the distal edge of the Acadian foredeep, which sloped up towards the west to the back bulge of the foreland basin system, represented in Ohio by the Cincinnati Arch (Ettensohn, 2008). Extensive basement fault systems throughout Ohio (fig. 1; Baranoski, 2013) likely localized some of the strain associated with basin subsidence and evolution.

The last of the four main Devonian tectophases of the orogeny decelerated in the northern (present-day New York) region of the Laurentian margin by the early Famennian (Ver Straeten, 2010). This led to a general decline in relative sea level in the northern part of the Appalachian Basin because of reduced basin subsidence and an influx of clastic sediments eroded from the Acadian highlands (Ettensohn, 2008). A transition from greenhouse to icehouse climate conditions occurred at approximately the same time, which further decreased sea level (Sandberg and others, 2002; Brezinski and others, 2009). Most of the ice likely was restricted to the paleocontinent of

Gondwana, but the presence of iceberg-rafted dropstones in Famennian strata of the Appalachian Basin indicates that there may have been some ice on Laurentia as well (Brezinski and others, 2009).

The Late Devonian Mass Extinction, one of the so-called "Big Five" global extinctions, occurred in several phases before and after the Frasnian/Famennian boundary. The most pronounced pulse of extinction, termed the "Kellwasser Event," occurred just prior to the Frasnian/Famennian boundary (Klapper and others, 1993) and is often marked by two globally synchronous black shale deposits. The factors and events leading to the extinction interval remain controversial, but the general cause appears to be changes in the oceanic biogeochemical system that both led to and was exacerbated by a transition from greenhouse to icehouse climate conditions (Algeo and others, 1995; Algeo and Scheckler, 1998; Murphy and others, 2000; Averbuch and others, 2005). Plants with extended root systems began colonizing the land in earnest during the middle part of the Devonian Period and increased the rate of continental weathering (Algeo and others, 1995). The higher rate of continental weathering increased the flux of nutrients into the ocean (Algeo and others, 1995; Algeo and Scheckler, 1998), as well as the rate of continental silicate weathering (Averbuch and others, 2005). The influx of nutrients into the ocean rapidly increased primary productivity and carbon burial, leading to extensive oceanic anoxia and eutrophication (Murphy and others, 2000). The combined effects of silicate weathering and the increased rate of carbon burial rapidly reduced the amount of CO_2 in the atmosphere, leading to global cooling, as the eutrophic conditions caused by excess nutrients in the oceans led to the collapse of carbonate-shelf ecosystems adapted to oligotrophic conditions. The combination of major oceanic geochemical changes and rapid climate change led to the extended ecosystem collapse and extinction (Algeo and Sheckler, 1998).

Stratigraphy of the Huron Member of the Ohio Shale

The Ohio Shale (Famennian Stage; fig. 2) is the youngest of the Devonian shale formations in Ohio and overlies the Java Formation (equivalent in part to Upper Olentangy Shale) throughout the study region. The Ohio Shale is composed (in ascending stratigraphic order) of the Huron, Chagrin, and Cleveland Members throughout its entire geographic extent. A relatively thin, very organic-rich unit termed the Three Lick Bed separates the Chagrin and Cleveland Members throughout the central part of Ohio, but eastwards it becomes indistinguishable from the gray shale of the Chagrin Member.

The Huron Member becomes exceptionally thick towards the center of the Appalachian Basin, so it often is divided into informal "submembers" to make correlations more precise. In subsurface investigations, the Huron often is split into the lower and upper Huron submembers, based primarily on gamma-ray (GR) well logs (fig. 3). The low-gamma middle part of the Huron is sometimes defined as the "middle Huron" (for example, see Wickstrom and others, 2005). The lower Huron is the most consistently radioactive submember, showing high GR values representing organic-rich black shale throughout the extent of the unit. The middle Huron exhibits lower GR values than the lower Huron submember and essentially represents the lowermost tongue of the Chagrin Member (Wickstrom and others, 2005). It is mainly gray shale and siltstone and represents a progradation of clastic sediments from the Acadian Highlands during a pronounced sea-level lowstand. The lithology of the upper Huron is the most varied of the submembers. Towards the western edge of the Appalachian Basin, the upper Huron is a very organic-rich, radioactive black shale. The organic content of the upper submember decreases towards the basin axis, and in eastern Ohio it becomes nearly indistinguishable from the gray shale and siltstone of the middle Huron and overlying Chagrin. In most parts of the study region, each submember shows consistent stacking of alternating layers of rocks with higher and lower radioactivity (figs. 3, 4), interpreted to represent cyclical alternations in the amount of TOC.

The lower Huron submember is thickest in Ohio, extends into westernmost Pennsylvania and New York, and southward into eastern Kentucky and northern West Virginia (Roen, 1984). It becomes very thick (≈1,000 ft) in the deeper parts of the Appalachian Basin, and zones with very high TOC appear to occur at different stratigraphic intervals in different parts of the study region. The stratigraphic and geographic variation in the TOC concentration is not surprising, given the factors that led to the deposition and preservation of organic material within the lower Huron. Unlike the Marcellus Formation, the Huron Member was not deposited in completely anoxic and euxinic conditions, where organic material was readily preserved everywhere in the basin. Rather, it was deposited under predominantly suboxic conditions, where rapidly deposited organic material created occasional zones of anoxia and organic preservation across the basin (Perkins and others, 2008). Since most of the water column was oxic to suboxic, the circulation (and stagnation) patterns of bottom waters could have played an extremely important role in influencing where organic carbon was preserved. The paleobathymetry of the basin during deposition of the lower Huron submember may have played an important role in influencing bottom-water circulation patterns and therefore, the distribution of TOC sweet spots.

Limited biostratigraphic data from the lower Huron submember makes it difficult to determine how much time the submember represents, but it was likely deposited over the course of approximately 3 my. Over and Rhodes (2002) constrained the base of the formation in central Ohio to the Middle *Palmatolepis triangularis* conodont

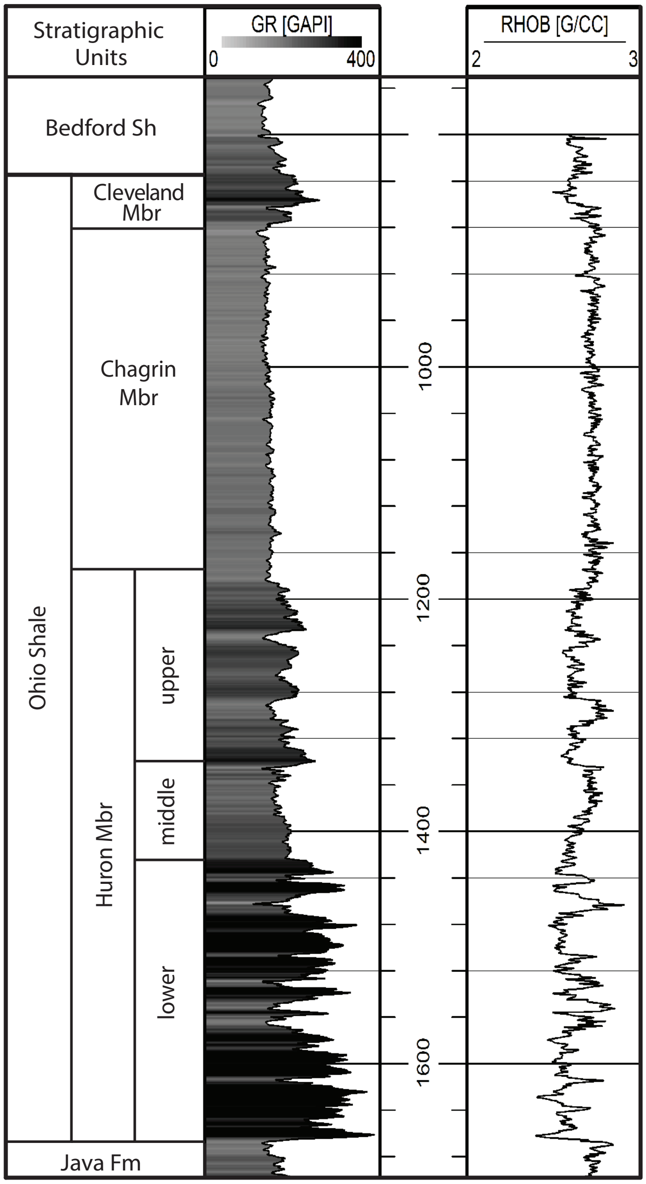


FIGURE 3. Wireline gamma-ray and bulk density log for the Ohio Shale in Licking County. Color shading corresponds to gamma value and generally represents alternating layers of black and gray shale. Well log from Wolford #1 (API 34089225810000) well in Licking County, Ohio.

biozone, but there is no direct conodont data constraining the top of the submember in central and eastern Ohio. Based on lithostratigraphic correlations to the approximately coeval Gassaway Member of the Chattanooga Shale (fig. 2), the top of the lower Huron is likely within the lower part of the Upper *P. crepida* conodont biozone (Fuentes and others, 2002; Over, 2007). This corresponds to an interval of approximately 2.95–3.6 my, based on the chronometrically calibrated conodont zones of Buggisch and Joachimski (2006).

Milankovitch Cycles and Cyclostratigraphy

The lithological record of rapid sea-level changes throughout the deposition of the lower Huron provides a useful tool for high-resolution correlation and mapping of the unit. Rapid sea-level changes are often caused by variations in the orbital parameters of Earth. The eccentricity of Earth's orbit, degree of tilting of its axis, and direction that its rotational axis points all change in regular and cyclic intervals (eccentricity, obliquity, and precession cycles, respectively; Kutzbach, 1976). The eccentricity cycle has periodicities of 413 and ≈100 ky; the obliquity has a periodicity of 41 ky; and the precession cycle has a periodicity of ≈23 ky (van den Hewel, 1966; Girkin, 2005; Laskar and others, 2011). These variations in Earth's orbit influence where and how much insolation Earth receives from season to season. Depending on the configuration of continental landmass, the orbital variations can have profound effects on the average temperature of the planet (Hays and others, 1976). During icehouse conditions,

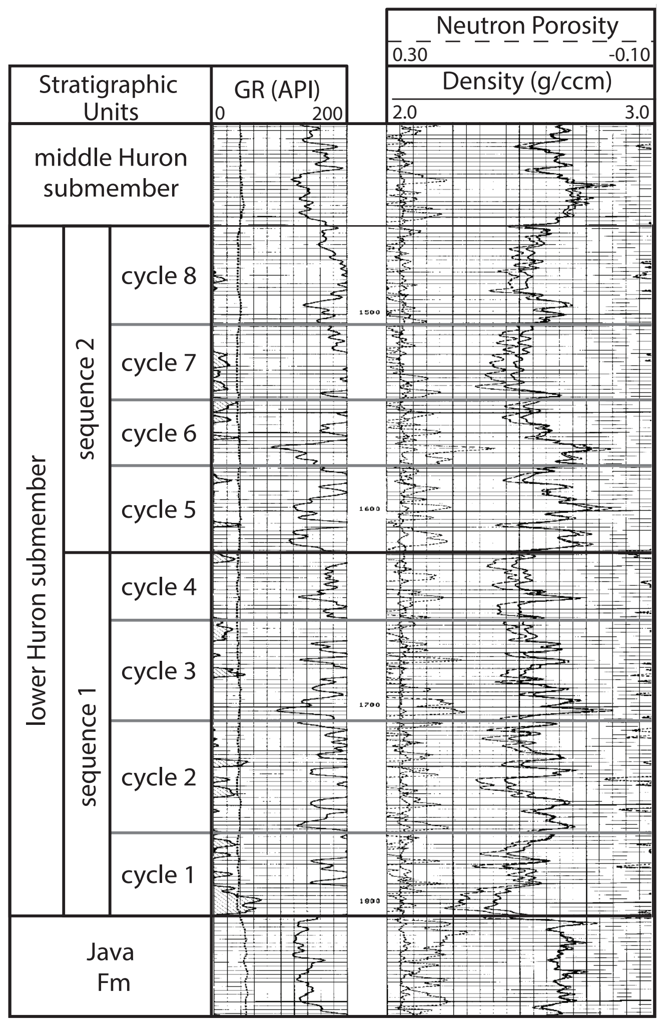


FIGURE 4. Example gamma-ray, neutron porosity, and bulk density log for the lower Huron submember. Note the pronounced cyclical variation of the gamma curve, and sharp change in bulk density curve at sequence boundary. Well log from Charles & Jean Call #3 (API 34153221450000) well in Summit County, Ohio.

temperature changes caused by Milankovitch cycles are the primary control on glacial vs. interglacial conditions and therefore, on geologically rapid sea-level fluctuations. The impact of Milankovitch cycles on the global climate during greenhouse conditions are subtler and likely influence the global distribution of arid and humid environments (Ellwood and others, 2000).

Cyclostratigraphy is the term for the use of cyclic changes in rock properties, caused by Milankovitch climate forcing, as a tool for correlation. Because sea level is relatively stable in greenhouse conditions, geochemical or geophysical proxies such as magnetic susceptibility (for example, see Crick and others, 1997) often are the only way to observe Milankovitch climatic effects on the rock record. The effects of Milankovitch cycles on the rock record are much more apparent during icehouse conditions. Rapid changes in sea level from glacial to interglacial periods create cyclical changes in lithology as depositional facies shift from deeper to shallower conditions and back again. Cyclothems—cyclic packages of terrestrial/nearshore rocks, nearshore limestones, and offshore shales (fig. 5)—are a common stratigraphic feature of Carboniferous strata in North America (Heckel, 2008). Extensive conodont and foraminifera biostratigraphic and carbon isotope chemostratigraphic data from Pennsylvanian cyclothems indicate that the cycles are glacioeustatic and predominantly controlled by eccentric Milankovitch forcing at 100 and 413 ky frequencies (Heckel, 1994; Chesnel and others, 2016).

The same principles that allow for the recognition and correlation of Carboniferous cyclothems can be applied to the lower Huron submember. Unlike the mixed terrestrial/nearshore and offshore marine deposits of classic North American Midcontinent cyclothems, the lower Huron consists of entirely offshore, deep-marine shale deposits. In this deep-water environment, glacioeustatic sea-level changes would have only a minor effect on the depositional facies of any given area. Consequently, Milankovitch climate cycles would create only subtle changes in lithology that may not be noticeable by visual inspection alone. However, the sea-level fluctuations had a pronounced effect on the deposition and preservation of TOC, which allows for the recognition of sea-level cycles using geophysical well logs. Sea-level transgressions increased the concentration of organic material relative to terrigenous sediment (Arthur and Sageman, 2005) and thus the TOC concentration. Gamma ray logs positively correlate with TOC values in the Devonian shales of the Appalachian Basin (Schmoker, 1980), therefore spikes in GR values can be interpreted to represent sea-level transgressions, and troughs interpreted to represent regressions.

METHODOLOGY AND RESULTS

A total of 789 well logs with measurement resolution high enough to distinguish cycles were selected from the study area (fig. 6). Petra® software was used to pick and

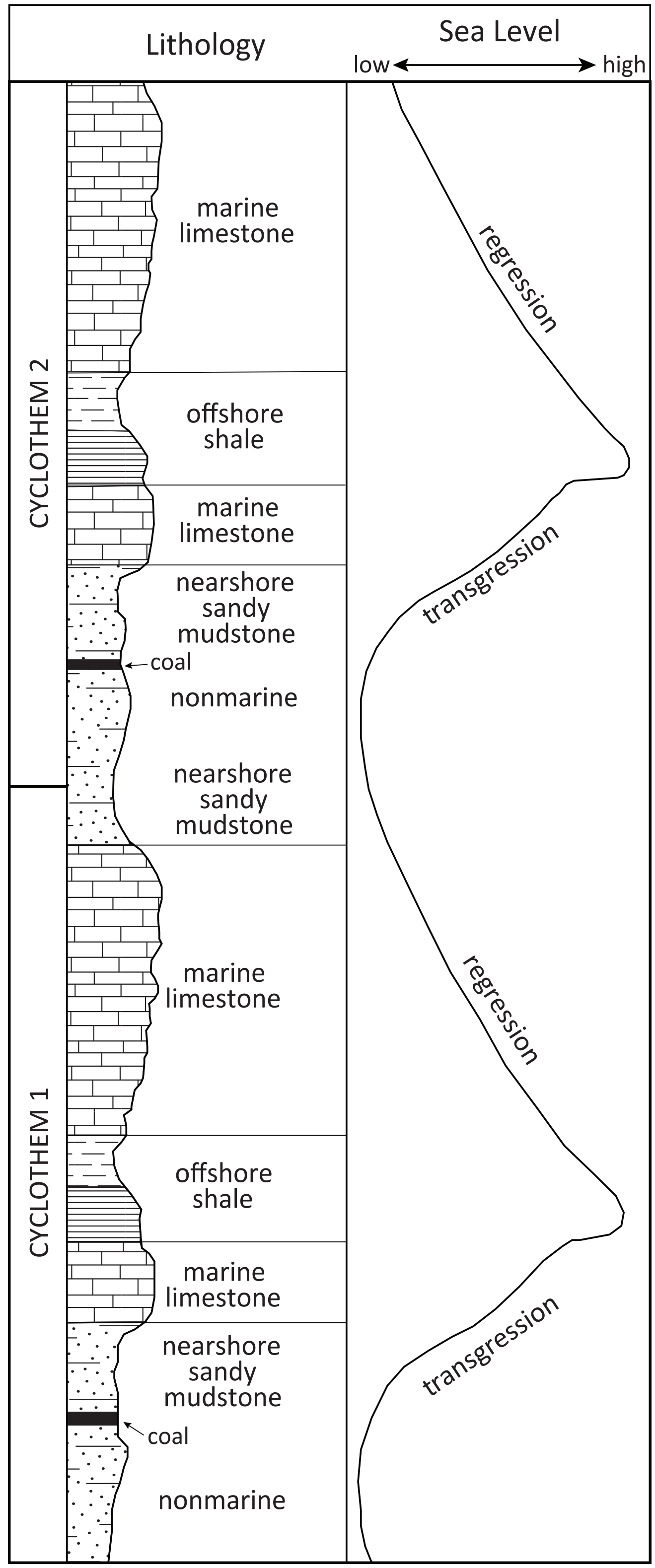


FIGURE 5. Idealized Pennsylvanian North American Midcontinent cyclothem. The repetitive lithological stacking pattern reflects glacially-driven fluctuations in sea level. Shape of sea-level curve from Heckel (2008).

correlate the top of each cycle. Cycle boundaries were placed at the beginning of gamma-ray troughs and bulk density spikes (interpreted as sea-level lowstands) to be consistent with the definition of cyclothem boundaries (compare figs. 4 and 5). Eight cycles can be reliably correlated across the study region (plates 1, 2), and 10 cycles can be distinguished along “shelf edge” locations. The general cyclical patterns of the gamma-ray logs are consistent across the study region. However, the fine-scale shapes of GR curves often vary from well to well, which can make it difficult to precisely (within ±10 ft) place cycle boundaries. The radioactivity of the shales is very highly dependent on the redox conditions of sediment-water interface during deposition, and slight differences in redox conditions across the study region at a given time could cause variation in the radioactivity of the rocks. Bulk density log curves are generally more consistent across different wells (see plates 1, 2), but they do not exhibit cyclical patterns as clear as the gamma-ray logs. Nonetheless, distinctive increases of the bulk density of the rock occur at most cycle boundaries and are useful for ensuring precise and consistent picks when the gamma logs are ambiguous. Bulk density curves are especially helpful for correlations in the easternmost portion of the study area, where the gamma-ray character of the cycles becomes much less distinctive (plates 1, 2).

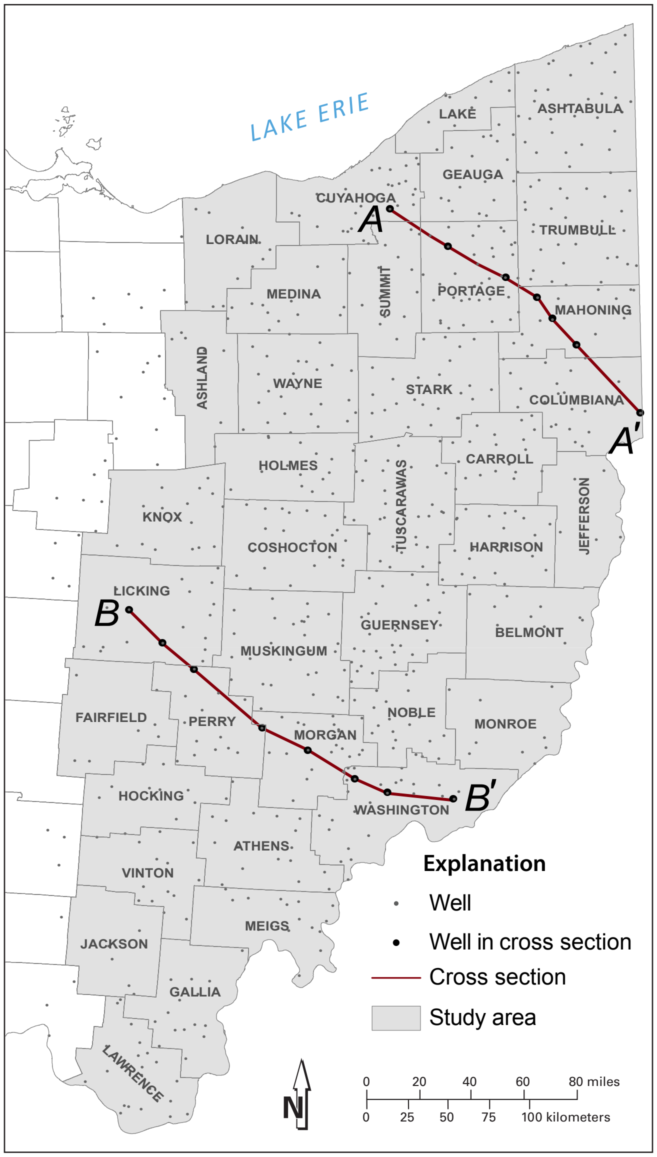


FIGURE 6. Map of Ohio showing study region, county names, well locations, and cross section lines. Cross section *A–A′* shown in plate 1. Cross section *B–B′* shown in plate 2.

After the cycle boundaries were picked across the study region, ESRI ArcMap® software was used to calculate the thickness of each cycle at each well. Isopach maps were created in ArcMap® using a simple kriging geostatistical model with constant trend removal. A lag size of 16,100 ft (average nearest neighbor = 15,922 ft) was used, with a neighborhood radius of 37,500 ft. Correlations between observed and model-predicted thicknesses were generally good, with RMS values ranging from 5.91 to 8.11 ft, and correlation coefficient values ranged from 0.939 to 0.986 (table 1). The surface data model then was exported as a raster file and contoured at a 10-ft interval in ArcMap®. The contour lines were hand edited in ArcGIS® to smooth angular contours and ensure consistency as much as possible with the data points. A new raster image then was created from the edited contour lines. Final maps were created using the edited contour lines and raster images[1] (fig. 7).

DISCUSSION

Two large transgressive–regressive sequences in the lower Huron submember can be distinguished both by the gamma and bulk density values on the well logs (fig. 4; plates 1, 2). The boundary between these sequences is marked by the lowest gamma values of the submember, as well as a sharp, positive shift in bulk density values. Both sequences have intervals of very high (>200 API) gamma values, but in general, sequence 1 has lower bulk density values than

TABLE 1. ***Isopach kriging model results for the lower Huron submember of the Ohio Shale***

Cycle	RMS error (ft)	Regression function
1	5.91	0.988X + 0.59
2	6.08	0.972X + 1.22
3	6.53	0.943X + 2.43
4	6.33	0.934X + 2.72
5	7.49	0.986X + 0.792
6	8.11	0.980X + 1.38
7	8.06	0.939X + 3.19
8	7.00	0.959X + 2.23

[1] Full-scale versions of the maps used in figure 7, as well as associated structure maps, are available from the ODNR Division of Geological Survey in print, Adobe® PDF, and ArcGIS® format as open-file maps OF 314–OF 321 (structure maps) and OF 328–OF 335 (isopach maps).

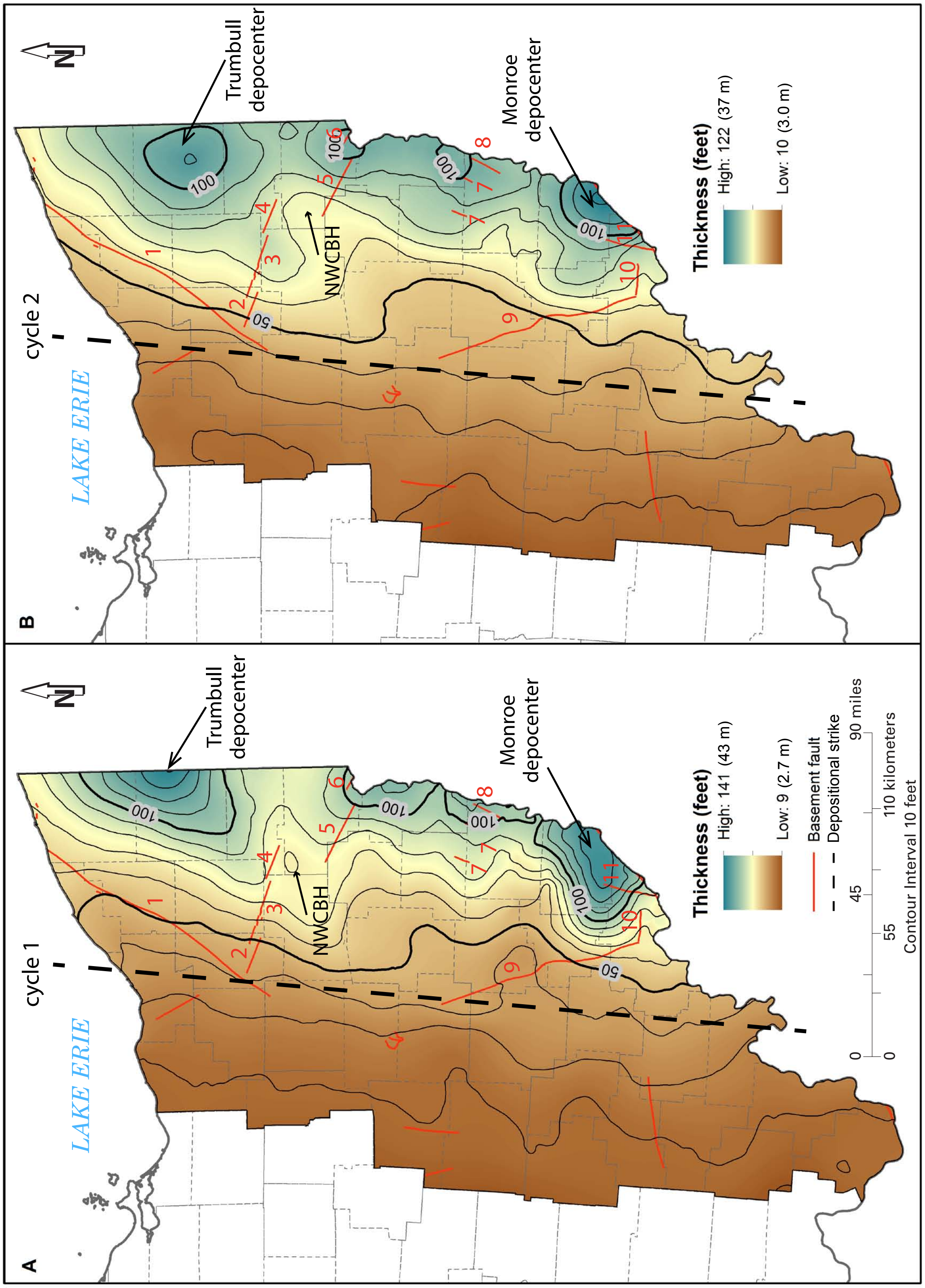
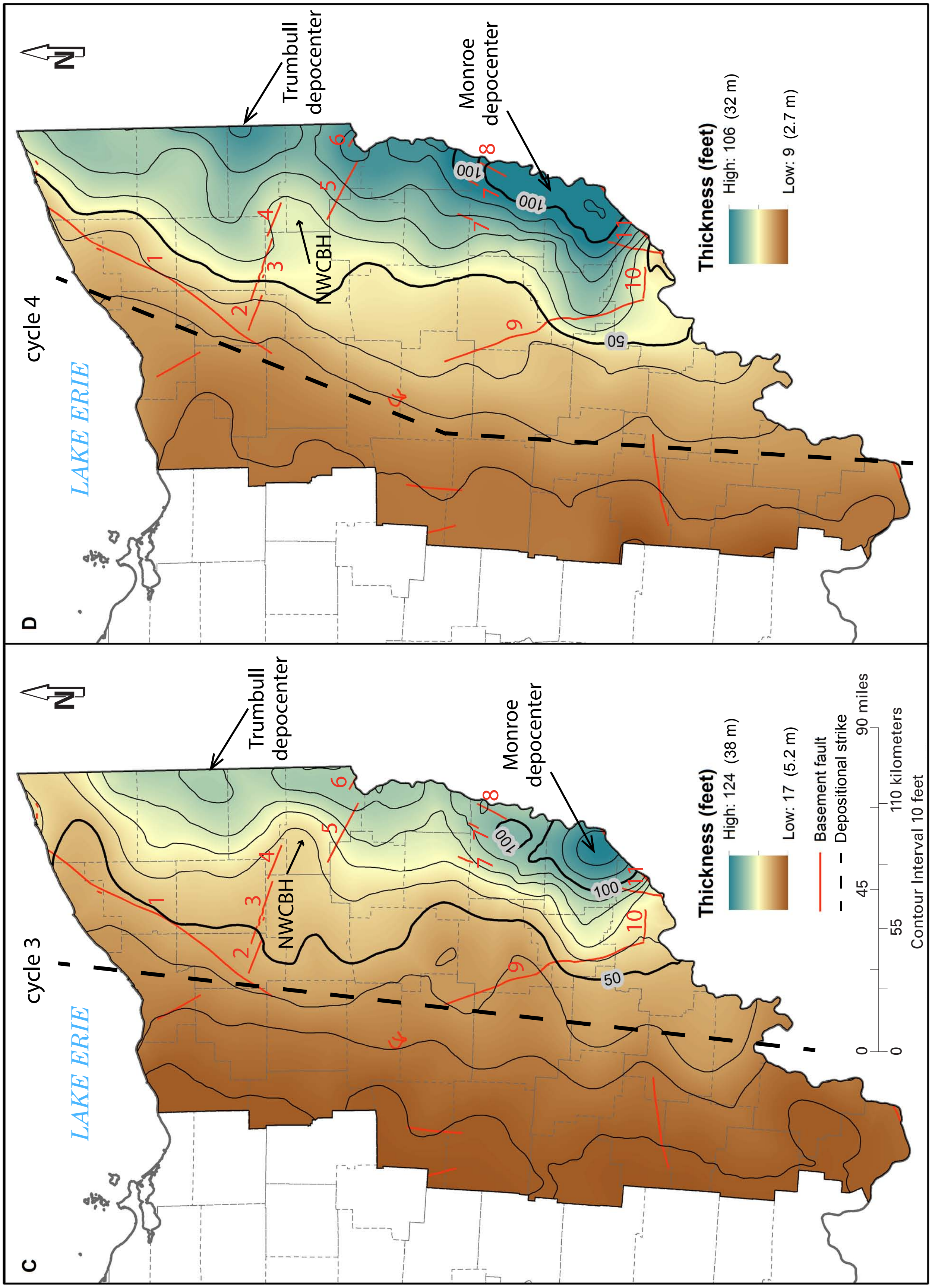
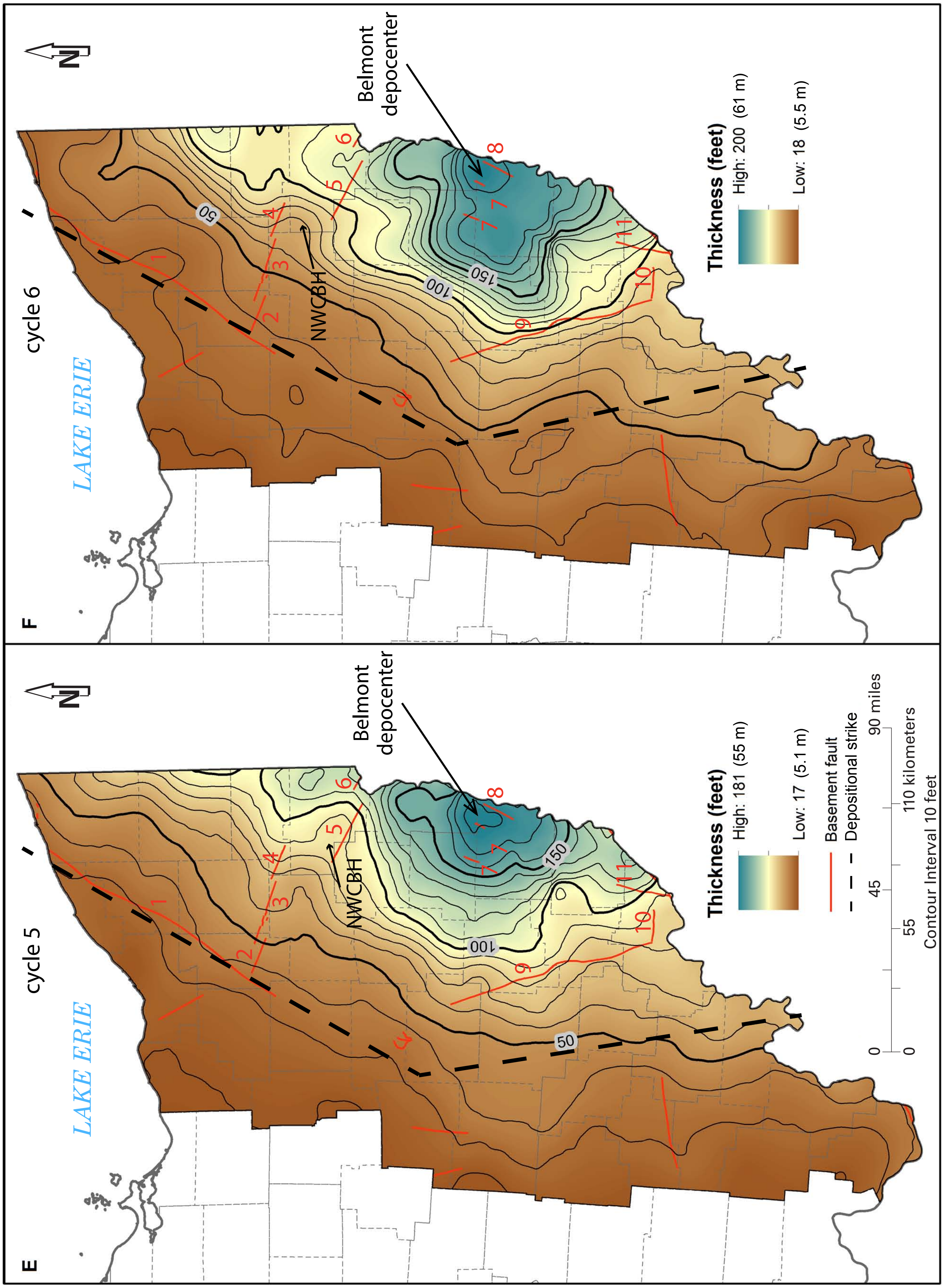
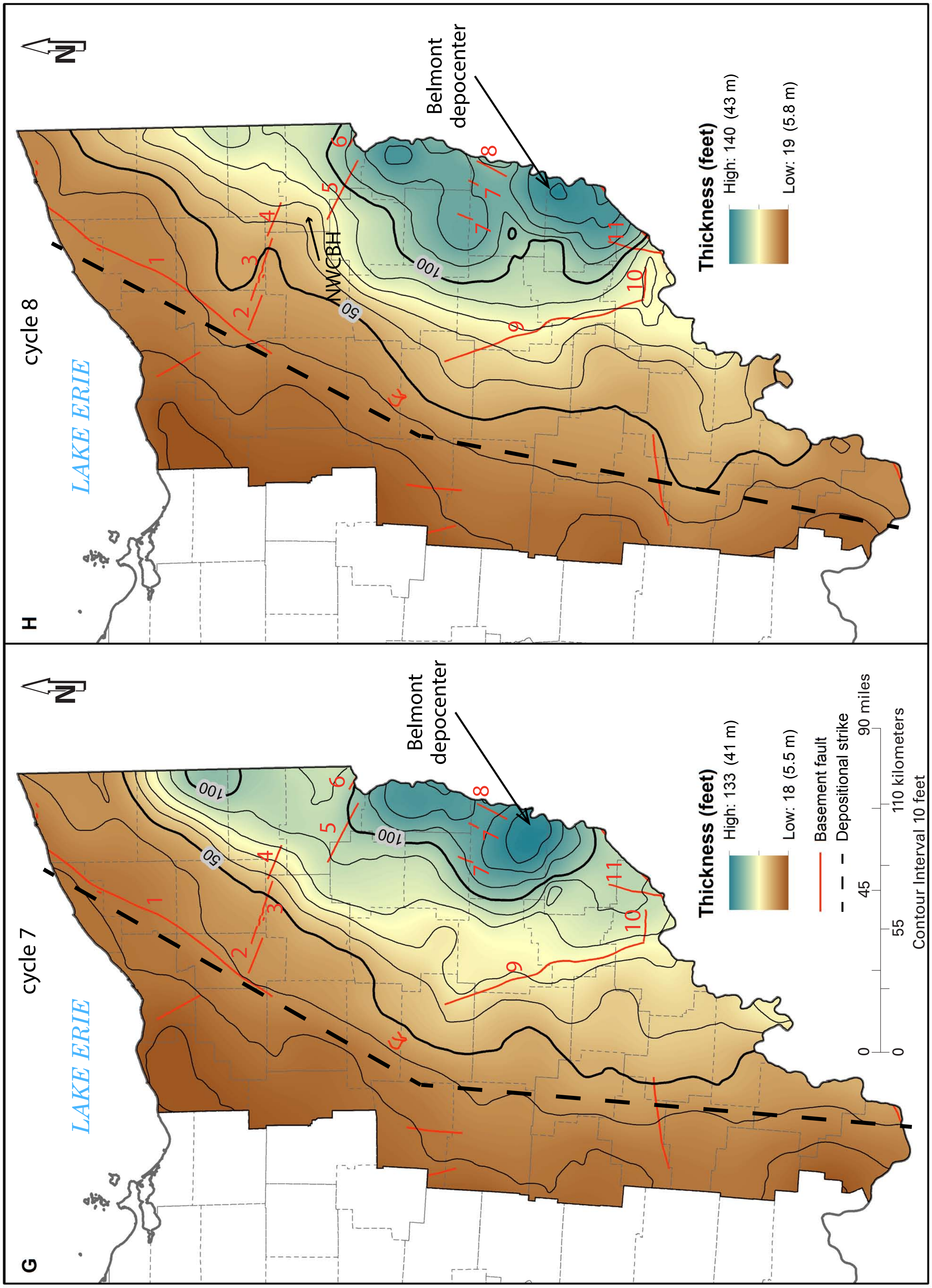


FIGURE 7. Thickness contour (isopach) maps (A–H) of each cycle within the lower Huron submember in eastern Ohio. NWCBH = northwest Columbiana bathymetric high. Basement faults from Baranoski (2013). 1–Akron magnetic boundary, 2–Akron Fault, 3–Suffield Fault System, 4–Smith Township Fault, 5–Highlandtown Fault, 6–Washington-Pittsburgh Cross-Strike Structural Discontinuity, 7–unnamed faults along COCORP (Consortium for Continental Reflection Profiling) seismic lines, 8–unnamed fault (Belmont County), 9–Cambridge Cross-Strike Structural Discontinuity, 10–unnamed faults (Washington County), 11–unnamed faults (Washington County).


D
cycle 4
LAKE ERIE
Trumbull depocenter
Monroe depocenter
NWCBH
Thickness (feet)
High: 106 (32 m)
Low: 9 (2.7 m)
C
cycle 3
LAKE ERIE
Trumbull depocenter
Monroe depocenter
NWCBH
Thickness (feet)
High: 124 (38 m)
Low: 17 (5.2 m)
Basement fault
Depositional strike
0 45 90 miles
0 55 110 kilometers
Contour Interval 10 feet


F
cycle 6
LAKE ERIE
Belmont depocenter
NWCBH
Thickness (feet)
High: 200 (61 m)
Low: 18 (5.5 m)
E
cycle 5
LAKE ERIE
Belmont depocenter
NWCBH
Thickness (feet)
High: 181 (55 m)
Low: 17 (5.1 m)
Basement fault
Depositional strike
0 45 90 miles
0 55 110 kilometers
Contour Interval 10 feet


H
cycle 8
LAKE ERIE
N
Belmont depocenter
NWCBH
50
100
1
2
3
4
5
6
7
8
9
10
11
Thickness (feet)
High: 140 (43 m)
Low: 19 (5.8 m)
G
cycle 7
LAKE ERIE
N
Belmont depocenter
50
100
Thickness (feet)
High: 133 (41 m)
Low: 18 (5.5 m)
Basement fault
Depositional strike
0 45 90 miles
0 55 110 kilometers
Contour Interval 10 feet

sequence 2. Because lower bulk density values generally correlate with higher TOC (Schmoker, 1979), sequence 1 of the lower Huron may have higher TOC content than sequence 2. The relative thickness of each sequence varies across the study region. Sequence 1 is thicker than sequence 2 in the north and vice versa in the south (plates 1, 2).

Eight smaller cycles within these two large sequences can be reliably distinguished across the study region based on gamma and bulk density logs (fig. 4). Cycles one and two can each be further subdivided into two cycles along strike in shelf-edge paleoenvironments. However, the additional cycles become too condensed to be distinguished in shallower paleoenvironments towards the Cincinnati Arch (plates 1, 2), likely because of only the transgressive phase of the cycles being deposited and/or preserved. In deeper-water paleoenvironments, the character of the gamma and bulk density curves used to distinguish the additional cycles diminishes to the point that they no longer can be reliably correlated. This is most likely caused by dilution of the organic material by sediments of the Acadian clastic wedge prograding from the east, thereby reducing the radioactive variability of the units.

The thickness maps for each cycle (fig. 7) indicate considerable depocenter migration throughout the lower Huron interval. Two main depocenters were present during the deposition of cycle 1 (fig. 7A). The northern depocenter (termed “Trumbull depocenter,” herein) was located primarily in present-day Trumbull County and southeastern Ashtabula County and extended slightly into northern Mahoning County. The southern depocenter (termed “Monroe depocenter,” herein) was located primarily in present-day Monroe County and extended slightly into northern Washington and southeastern Noble Counties. Depocenter configuration during cycle 2 (fig. 7B) was similar to cycle 1, but the depocenters were less pronounced, with less thickness variation. By the time cycle 3 (fig. 7C) was deposited, the Trumbull depocenter began to thin and the Monroe depocenter began to expand northwards from Monroe County into Belmont County. The northward migration of the Monroe depocenter continued during cycle 4 (fig. 7D), until it extended through Jefferson County and into southern Columbiana County, where it more or less connected to the remnants of the Trumbull depocenter. The most pronounced depocenter shift of the lower Huron occurred at the transition from sequence 1 to sequence 2 (cycle 4 to cycle 5). By the time cycle 5 (fig. 7E) was deposited, the Trumbull and Monroe depocenters were absent. A new depocenter (termed “Belmont depocenter,” herein) developed in present-day Belmont County and extended into southern Jefferson and Harrison Counties. The Belmont depocenter remained the primary zone of deposition for cycle 6 (fig. 7F) and began to segregate into smaller depocenters during cycles 7 and 8 (figs. 7G and 7H).

The locations and evolution of the depocenters can be attributed to tectonic activity along basement faults, changes in sediment patterns, or some combination of the two factors. Numerous basement-rooted faults located throughout the study region (see fig. 7) could have localized movement as the basin responded to changing tectonic conditions during the Acadian orogenic events. Terrain accretion on the eastern margin of North America moved progressively southward throughout the orogeny (Ettensohn, 1987), causing an overall southward migration of subsidence in the basin. As the primary tectonic stresses of the orogeny shifted southward, the direction and extent of movement along each basement fault could have changed, causing new sub-basin depocenters to develop. The migration of depocenters can also be explained through variations in sediment pathways from the Acadian highlands. Subsidence in the northern part of the Appalachian Basin (New York, northeastern Pennsylvania) began to decelerate by the beginning of the Famennian Stage (Ver Straeten, 2010). This reduced accommodation space available for sediments eroded from the Acadian highlands and allowed rapid progradation of the Catskill Delta complex westward across the basin (Ettensohn, 1985). Therefore, it is possible that the migration of depocenters observed in the lower Huron represents distal effects of changing drainage and circulation patterns on and around the delta complex. Understanding whether the depocenters reflect localized subsidence and increased accommodation space, or represent changes in sedimentation patterns, is crucial for paleobathymetric interpretations of the basin. If the depocenters represent localized zones of subsidence, then they would have been bathymetric lows that became filled in by sediment. Conversely, if they represent regions where sediment accumulated at a higher rate, then they would have been bathymetric highs.

The close association of depocenter development, regions of anomalously thin strata, and depositional strike with basement structures provides some evidence for considerable tectonic influence. Throughout cycles 1–5, strata in the region south of the Smith Township, Suffield, and Akron fault systems, and north of the Highlandtown Fault in northwestern Columbiana County, was conspicuously thinner than strata in surrounding areas (fig. 7A–E). This feature (termed “northwest Columbiana bathymetric high,” herein) is best explained by contractional overstepping between bounding sinistral strike-slip fault systems (fig. 8). Even if the contractional forces were not great enough to cause uplift, they appear to have counteracted the overall subsidence of the basin enough to reduce the amount of accommodation space that was created. The bathymetric high became less pronounced during cycles 6–8, which may indicate that fault movement slowed down or stopped as regional stress conditions changed.

The Belmont depocenter also appears to have been tectonically influenced. The thickest part of the depocenter is centered on three unnamed basement faults in northern Belmont County (faults 7 and 8 on fig. 7). Because the faults were oriented perpendicular to the direction of extensional stress in the Devonian Appalachian foreland basin, they would have been ideal for localizing extensional movement as normal faults during basin subsidence. The faults are very small (approximately 5–10 mi long; Baranoski, 2013) compared to the size of the Belmont depocenter. Their locations were based only on one seismic line, so their lateral extents and influence on sub-basin development may have been greater. The sudden appearance of this depocenter during cycle 5 (beginning of sequence 2) likely indicates that stress conditions of the basin significantly changed at the sequence boundary.

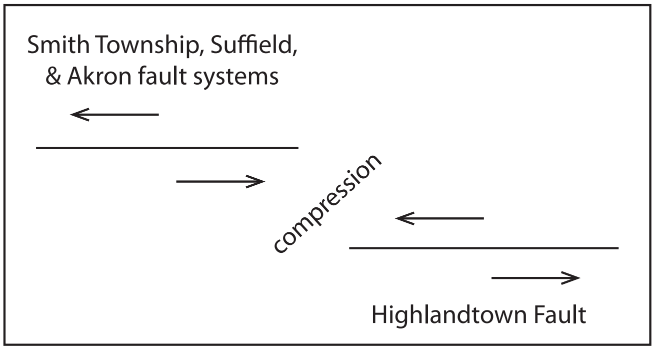


FIGURE 8. Simplified diagram illustrating contractional overstepping between the Smith Township, Suffield, and Akron fault systems and the Highlandtown Fault in Ohio. Arrows represent crustal motion. A zone of compression is created as the crust between each fault system is pushed together.

Large-scale changes in the depositional strike of the lower Huron that started in cycle 4 indicate significant tectonic influence on the overall shape of the basin in Ohio. During cycles 1–3, depositional strike over the entire region generally was oriented north–south (figs. 7A–C). Depositional strike in the northern half of the study area rotated clockwise during cycle 4 and became more-or-less parallel to the Akron magnetic boundary (AMB) through cycle 8 (structure 1 on fig. 7D–H). Depositional strike in the southern half of the study area rotated counterclockwise and became parallel to the Cambridge Cross-Strike Structural Discontinuity (CCSSD) during cycles 5 and 6 (structure 9 on figs. 7E–7F). Both the AMB and the CCSSD are regionally extensive discontinuities in basement lithology and/or structure. The AMB is a linear magnetic (geophysical) feature that exhibits elevated seismic activity (Seeber and Armbruster, 1993). It is unclear geologically what the boundary represents, but most researchers consider it a Proterozoic suture zone in Grenville basement rocks (Rankin and others, 1993). Clustered deep-seismic activity along the AMB indicates that it is heavily faulted. The CCSSD also is a suspected suture zone in Grenville basement rocks and has an extensive associated fault system (Root, 1996). Reactivation of the basement faults along the CCSSD impacted basin paleobathymetry and sedimentation patterns in the region throughout the Paleozoic (Root and Martin, 1995; Root, 1996). The fault and fracture systems of the AMB appear to have reactivated during cycle 4, and they remained a primary control on depositional strike throughout the deposition of the rest of the lower Huron submember. Normal movement along the faults associated with the CCSSD appears to have occurred during cycles 5 and 6, when depositional strike became parallel to the feature. The influence of faults associated with the CCSSD waned during cycles 7 and 8, and depositional strike in the southern part of Ohio rotated back to a more north–south direction.

The degree of tectonic influence on the development of the Monroe depocenter (sequence 1) is unclear. It appears to be bound to the west by the CCSSD, indicating that subsidence along the southern portion of the fault zone may have partially contributed to the depocenter development. The Trumbull depocenter (sequence 1) does not appear to be associated with any of the nearby basement structures. The depositional strike of the strata on the western end of the depocenter is parallel to the AMB during cycle 2, but not during cycles 1, 3, or 4, so it is more likely that the Trumbull depocenter reflects a region of increased sedimentation. The southern extent of the depocenter may have been restricted by the northwest Columbiana bathymetric high (see fig. 7A–7D).

Overall, the lower Huron submember represents approximately three million years. The two large sequences represent the third-order sequences of Vail and others (1977), which have durations of 1–3 my. The eight smaller cycles found within the two sequences likely represent one or both of the Milankovitch eccentricity frequencies (≈100 and 413 ky), but it is impossible to determine with certainty given the current amount of biostratigraphic information available for the unit. The unit was deposited over approximately 2.95–3.6 my. Divided by 8 cycles, this corresponds to 369 to 450 ky per cycle, which brackets the 413 ky eccentricity frequency. If the additional cycles observed in shelf-edge environments are included, this corresponds to 295 to 360 ky per cycle, which does not correspond to any of the Milankovitch frequencies. This may mean that the additional cycles observed at shelf-edge paleoenvironments represent other Milankovitch cycles (likely 100 ky cycles) superimposed on the 413 ky cycles. However, this scenario assumes that there are no stratigraphic breaks throughout the entire lower Huron submember. If there are stratigraphic breaks, either through erosion or nondeposition, it is possible that the cycles all represent 100 ky eccentricity frequencies, or even 23 ky and 41 ky precession and obliquity frequencies, with frequent missing intervals throughout the lower Huron submember.

Though nondeposition and/or erosion cannot be ruled out without biostratigraphic or chemostratigraphic evidence, the continuity of the cycles both along strike and down-dip across the study region provide some evidence that these effects were limited. Pronounced erosion would cause the cycles to appear to pinch out up depositional dip (to the west). Since eight of the cycles can be traced across the entire study region (plates 1, 2), significant erosive intervals within the lower Huron submember are unlikely. It is also unlikely that there were intervals of nondeposition that simultaneously affected the entire study region (≈18,500 mi^2 [48,000 km^2]). If deposition occurred in some areas and not in others, then strata would seem to appear and disappear along cross sections across the basin, which is not the case. Additional work providing more precise chronostratigraphic data throughout the unit, followed by quantitative time-series analysis and orbital tuning (for example, see Meyers and others, 2008) of the gamma-ray data is necessary to determine with more confidence which orbital cycles are represented in the lower Huron submember.

CONCLUSIONS

A high-resolution stratigraphic framework based on gamma-ray and bulk density well logs was constructed for the lower Huron submember of the Huron Member of the Ohio Shale. Two third-order depositional sequences representing approximately 1.5 my each are recognized in the lower Huron submember. Eight regionally correlative cycles are superimposed on the two main sequences and likely represent glacio-eustatic sea-level fluctuations corresponding to the long-eccentricity Milankovitch cycle. If this is the case, each cycle represents an approximately 413 ky time slice. Mapping these cycles allows for the most chronostratigraphically detailed reconstruction to date of the evolution of the Appalachian Basin in Ohio. Variations in thickness from cycle to cycle allow for identification of basement features that impacted subsidence patterns of the basin in Ohio. If each cycle represents ≈413 ky, the timing of structure reactivation and movement can be constrained with extremely high chronostratigraphic precision. The Smith Township, Suffield, Akron, and Highlandtown fault systems exhibited sinistral strike-slip movement during the deposition of cycles 1–5 of the lower Huron submember. Movement appears to have slowed down or ceased by cycle 6. The Belmont depocenter is centered on three unnamed faults that likely localized extensional movement during an interval of basin subsidence that occurred during the deposition of cycles 5–8. The same tectonic forces that led to the development of the Belmont depocenter appear to have reactivated faults associated with the Akron Magnetic Boundary during cycles 4–8 and faults associated with the Cambridge Cross-Strike Structural Discontinuity during cycles 5 and 6. The ability to reconstruct basin conditions at Milankovitch-scale time slices is an important step toward gaining a better understanding of the impact of tectonic forces on basin evolution and TOC preservation within the lower Huron submember.

ACKNOWLEDGMENTS

The technical contributions of Michael P. Solis and Kyle M. Metz, and the manuscript reviews of Julie Bloxson, Paul Spahr, Thomas Serenko, and Charles Salmons are greatly appreciated. Funding was provided by the Ohio minerals severance tax and grants from the U.S. Department of Energy, National Energy Technology Laboratory (DOE Cooperative Agreement No. DE-FC26-05NT42589) administrated by Battelle Memorial Institute.

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PLATE 1

Cross section *A–A′* illustrating the cycles of the lower Huron submember from Cuyahoga County to Columbiana County.

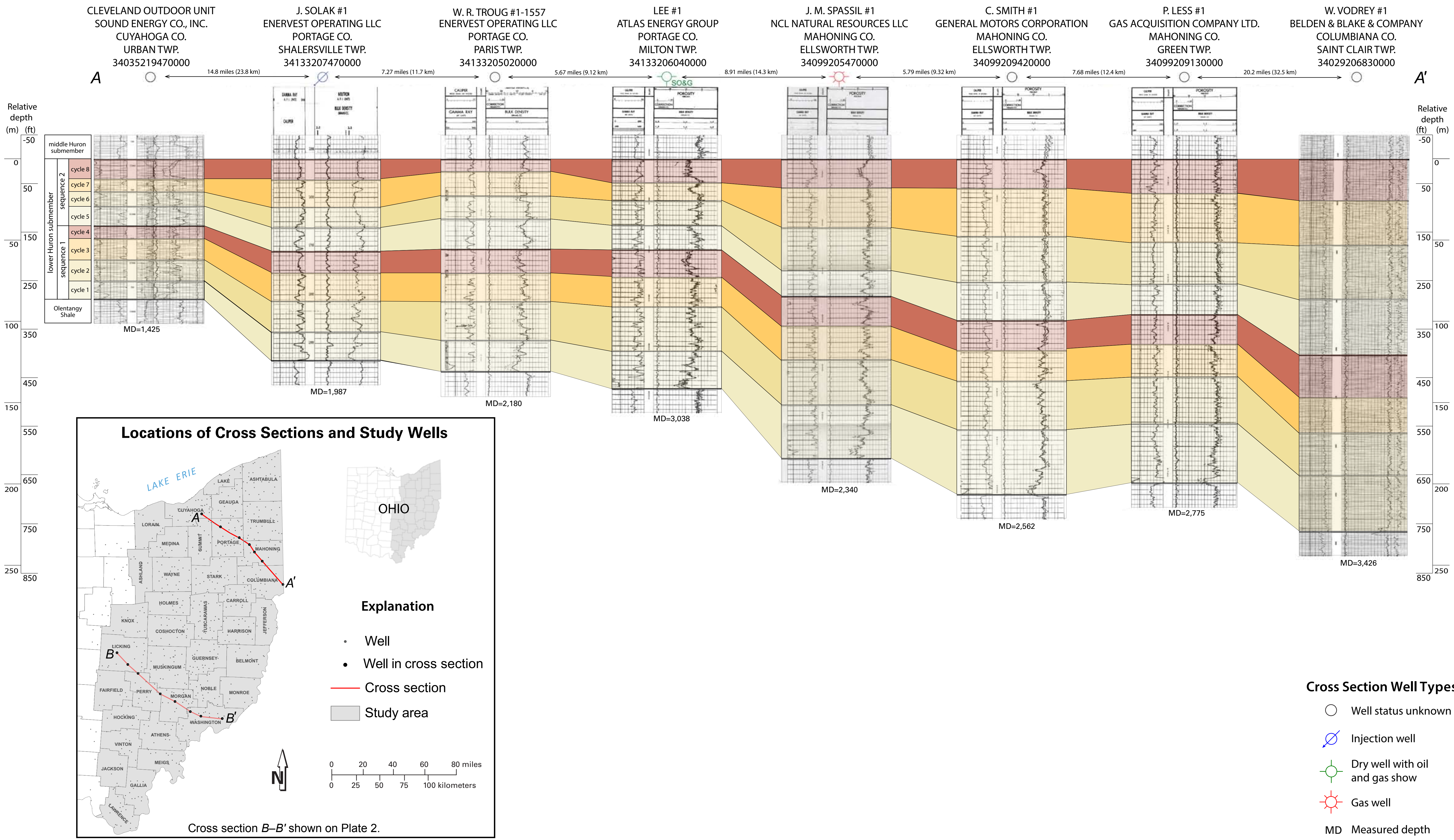
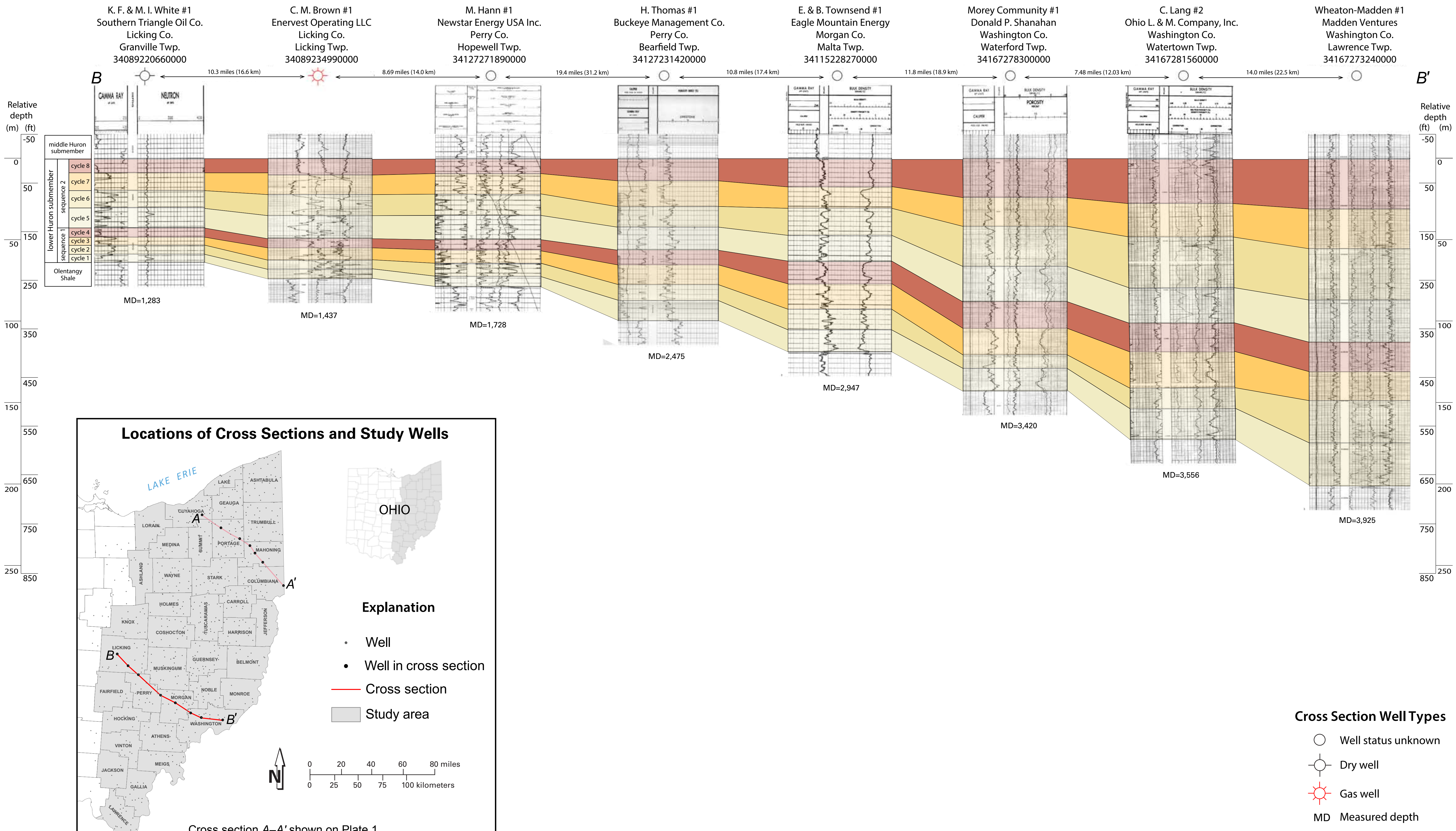


PLATE 2

Cross section *B–B′* illustrating the cycles of the lower Huron submember from Licking County to Washington County.



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