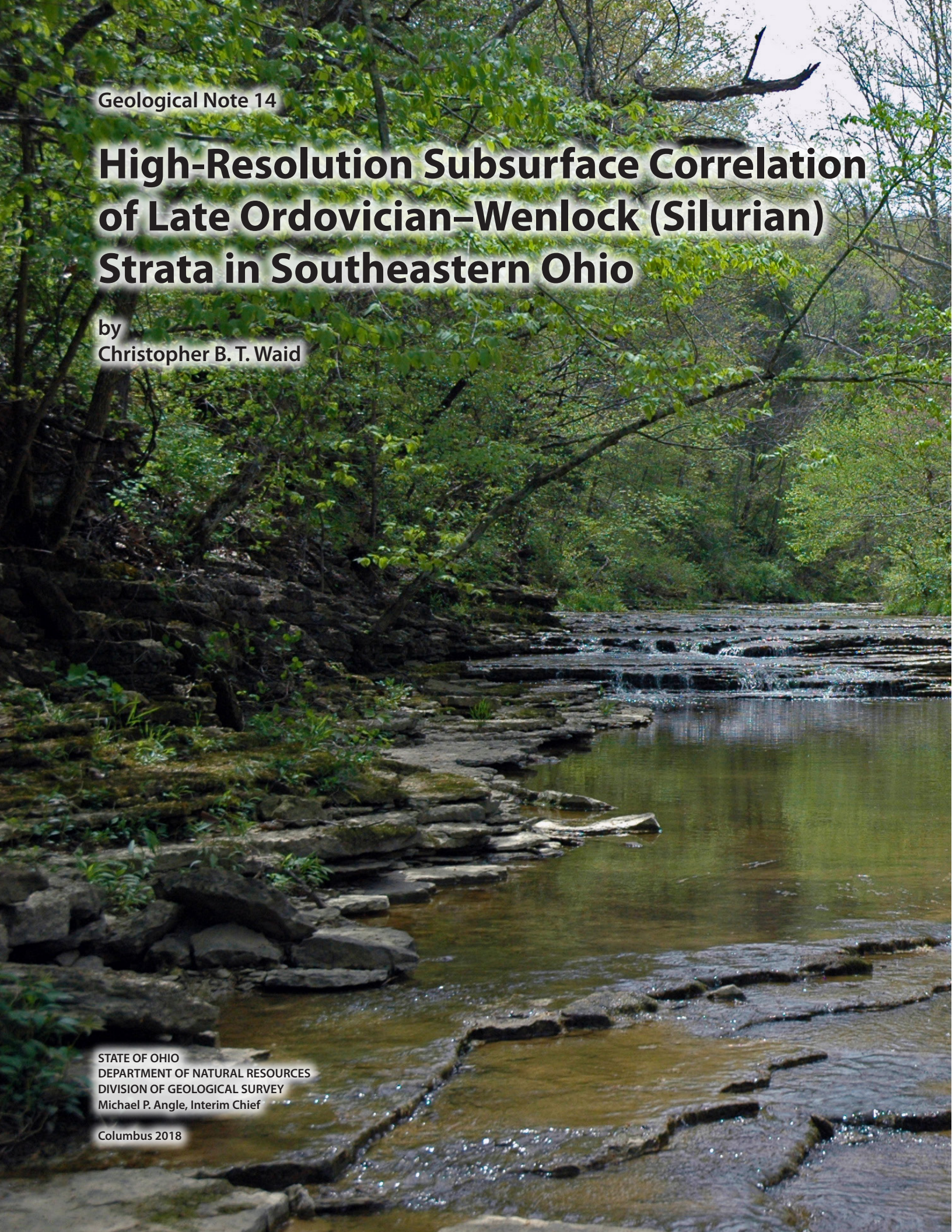




Geological Note 14

High-Resolution Subsurface Correlation of Late Ordovician–Wenlock (Silurian) Strata in Southeastern Ohio

by
Christopher B. T. Waid

STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Michael P. Angle, Interim Chief

Columbus 2018



ODNR DIVISION OF GEOLOGICAL SURVEY
2045 MORSE RD., BLDG. C-1
COLUMBUS, OHIO 43229-6693

(614) 265-6576
(614) 447-1918 (FAX)
geo.survey@dnr.state.oh.us
www.OhioGeology.com

SCIENTIFIC AND TECHNICAL STAFF OF THE DIVISION OF GEOLOGICAL SURVEY

Administration

Michael P. Angle, MS, *Interim State Geologist and Division Chief*
May Sholes, MBA, *Financial Analyst Supervisor*

Geologic Mapping & Industrial Minerals Group

J. D. Stucker, MS, *Geologist Supervisor*
Douglas J. Aden, MS, *Geologist*
Mohammad Fakhari, PhD, *Geologist*
Franklin L. Fugitt, BS, *Geologist*
Melinda Higley, PhD, *Geologist*
T. Andrew Nash, MS, *Geologist*
Brittany D. Parrick, BS, *Geology Technician*
Christopher E. Wright, MS, *Geologist*

Ground Water Resources Group

James M. Raab, MS, *Geologist Supervisor*
Curtis J. Coe, MS, *Geologist*
Scott C. Kirk, BS, *Environmental Specialist*
Craig B. Nelson, MS, *Hydrogeologist*
Mark S. Pleasants, MS, *Hydrogeologist*
Mitchell W. Valerio, MS, *Environmental Specialist*

Energy Resources Group

Paul N. Spahr, MS, *Geologist Supervisor*
Erika M. Danielsen, MS, *Geologist*
Samuel R. W. Hulett, MS, *Geologist*
Isaac Smith, MS, *Geologist*
Michael P. Solis, MS, *Geologist*
Christopher B. T. Waid, MS, *Geologist*

Geologic Hazards Group

D. Mark Jones, MS, *Geologist Supervisor*
Daniel R. Blake, MS, *Geologist*
Jeffrey L. Deisher, AAS, *Geology Technician*
Jeffrey L. Fox, MS, *Seismologist*

Geologic Records Center & Library

Lisa F. Long, MLIS, *Librarian/Archivist*
Madge R. Fitak, BS, *Customer Service Specialist*
Sylvia R. Halladay, MLS, *Librarian*
Shirley A. Rogers, MLIS, *Library Assistant*

Publications & Outreach

Mark E. Peter, MS, *Paleontologist*



High-Resolution Subsurface Correlation of Late Ordovician– Wenlock (Silurian) Strata in Southeastern Ohio

by
Christopher B. T. Waid

Geological Note 14

STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Michael P. Angle, Acting Chief

Columbus 2018



Disclaimer: The statements, findings conclusions and recommendations are those of he author and do not necessarily reflect the view of the Ohio Department of Natural Resources.

Editing: Charles R. Salmons

Graphic design and layout: David S. Orr

Front cover: Exposure of the thin-bedded Brassfield Formation along Lick Fork Creek in Adams County, Ohio. Photo by Charles Salmons

Recommended bibliographic citation: Waid, C.B.T., 2018, High-resolution subsurface correlation of Late Ordovician–Wenlockian (Silurian) strata in southern and southeastern Ohio: Columbus, Ohio, Department of Natural Resources, Division of Geological Survey Geological Note 14, 34 p., 5pl.

CONTENTS

Abstract	1
Introduction.....	1
Geological and environmental background.....	4
Sequence stratigraphy.....	5
Silurian stratigraphy of Ohio.....	6
Previous work: Overview of surface and subsurface stratigraphy.....	7
Surface units.....	7
Drakes Formation.....	7
Centerville Formation.....	7
Brassfield Formation.....	7
Belfast Member.....	7
Lower massive, thin bedded, and upper shaly Brassfield.....	8
Upper massive Brassfield (Rose Run iron ore).....	8
Drowning Creek Formation.....	9
Plum Creek Shale Member.....	9
Oldham Member.....	9
Alger Formation.....	9
Lulbegrud Member.....	9
Waco Member.....	10
Estill Member.....	11
Noland Formation.....	11
Bisher Formation.....	11
Subsurface units.....	11
Medina sand.....	11
"Clinton sands".....	12
Packer Shell.....	12
Cabot Head Shale.....	12
Rochester Shale.....	12
Methodology and results.....	12
Building the Adams County composite gamma-ray curve.....	12
Cross sections.....	14
Discussion.....	14
Comparison of Adams County and Aristech core gamma curves.....	14
Regional correlation.....	16
Proposed nomenclature revisions.....	19
Conclusions.....	21
Acknowledgements.....	22
References cited.....	22
Appendix A Spectral gamma-ray data from Adams County.....	27

FIGURES

1. Correlation and nomenclature chart for exposed Silurian of southern Ohio.....	2
2. Nomenclature chart for the subsurface of Ohio and surrounding regions.....	2
3. Paleogeographic and study area maps.....	3
4. Generalized correlation diagram of Silurian strata in Adams, Scioto, and Athens Counties.....	4
5. Chronostratigraphic diagram of the lower part of the Silurian System.....	6
6. Map showing localities and sections in Adams County used to create composite gamma-ray curve.....	13
7. Elevation and satellite imagery map of sections at the Brush Creek Motorsport Complex locality.....	14
8. Composite spectral gamma-ray log from the outcrops of Adams County.....	15
9. Comparison of gamma-ray logs from Adams County and Scioto County (Aristech Core).....	16
10. Photograph of potential type section for proposed Whippoorwill formation.....	20

TABLES

1. Hierarchy of depositional sequences.....	5
2. Location of sections used in creation of Adams County gamma log.....	13

PLATES

1. Stratigraphic cross section A–A’ 30

2. Stratigraphic cross section B–B’ 32

3. Stratigraphic cross section C–C’ 32

4. Stratigraphic cross section D–D’ 33

5. Stratigraphic cross section E–E’ 34

ABBREVIATIONS USED IN THIS GEOLOGICAL NOTE

Units of Measure		Stratigraphic Rank ¹ and Lithology	
American Petroleum Institute units	API	Formation	Fm
foot (feet)	ft	Member	Mbr/mbr
kilometer(s)	km	Shale	Sh
mega-annum (million years ago)	ma	Dolostone/Dolomite	Dol
meter(s)	m	Limestone	Ls
mile(s)	mi	Other Abbreviations and Symbols	
million years	my	Gamma Ray	GR
percent	%	Gamma-ray radiation	γ
parts per million	ppm	Potassium	K
thousand years	ky	Thorium	Th
		Uranium	U
		North American Commission on	
		Stratigraphic Nomenclature	NACSN
		1	Lower case indicates informal status of geological unit

High-Resolution Subsurface Correlation of Late Ordovician–Wenlock (Silurian) Strata in Southeastern Ohio

by
Christopher B. T. Waid

ABSTRACT

Silurian strata are one of the most valuable geological resources of the state of Ohio—they contain extensive natural gas and oil, salt deposits, and are a major source of aggregate material. Despite their importance, the fine-scale subsurface correlations of these units is poorly understood. Subsurface correlations have been complicated by several factors, particularly the development of several formal nomenclature schemes in different parts of the state, the incorrect and/or inconsistent application of formal unit terminology in subsurface studies, and the entrenchment of informal drillers' terms in geological literature. Advances in stratigraphic understanding of the Silurian units exposed in Ohio and in New York have allowed for a precise, often member-scale chronostratigraphic correlations between the two regions. A handheld, gamma-ray spectrometer was used to aid in bringing these member-scale correlations into the subsurface of southern and southeastern Ohio. A composite gamma log was created from exposures of the Brassfield, Noland, Alger, and Bisher Formations in central Adams County. The gamma log was then compared to the lithostratigraphic units to identify patterns that can be used to distinguish the units in the subsurface. Additional lithological control for the gamma signatures of each unit in slightly deeper depositional environments was provided by comparing the well logs and core from the Aristech #4 well in southeastern Scioto County. The gamma curve from Adams County was added as a pseudo well to the geological software program Petra, and the units from Adams County were correlated to 140 wells throughout Adams, Scioto, Pike, Ross, Jackson Lawrence, Gallia, Vinton, Meigs, and Athens Counties. Five cross sections were created across the study region. The cross sections show how depositional conditions for each unit varied across the study region, from the carbonate-dominated area on the flank of the Cincinnati Arch in the west, to the clastic dominated, deeper water deposits to the east. Several nomenclature revisions are proposed to reduce disconformities internal to formations. The Centerville Formation is reduced to member status. The Belfast Member is removed from the Brassfield Formation, and combined with the underlying Centerville Member to form the Whippoorwill formation. The Rose Run iron ore

(upper massive Brassfield) is removed from the Brassfield Formation, and assigned as the basal member of the Noland Formation. The Lulbegrud Member is removed from the Alger Formation, and reassigned as the uppermost member in the Noland Formation. Correlation of these units into the subsurface allows the traditional subsurface nomenclature used in southern/southeastern Ohio to be placed in a precise chronostratigraphic context.

INTRODUCTION

Silurian strata are a valuable and diverse geological natural resource to the state of Ohio. The "Clinton sands" have been producing oil and gas for over a century—over 95 million barrels of oil and 8.7 trillion cubic feet of natural gas have been extracted, and up to 279 million barrels of oil are recoverable through secondary recovery methods (Riley and others, 2011). The Lockport Group has been a minor gas-producing unit in the central and eastern part of the state (Riley and others, 2004). Even though production has decreased from these units, they hold potential for natural gas storage, brine injection, and carbon dioxide sequestration. Silurian carbonate units such as the Brassfield Formation, Dayton Formation, and Lockport Group are extensively quarried for aggregate and cement production, and together form the primary aquifer in north-central and northwestern Ohio. Additionally, the thick halite deposits of the Salina Group in the subsurface of eastern Ohio are an important source of salt. Partly because of the economic value of these units, drillers' terminology and misapplied formal stratigraphic terminology from surrounding states became entrenched in geological literature on the Silurian stratigraphy of Ohio. Additionally, regional variation in depositional facies, differential erosion, and scarce index fossils caused separate nomenclatures to develop in western/southwestern Ohio, southern Ohio, and in the subsurface of central and eastern Ohio.

The various and inconsistent nomenclature for the Silurian of Ohio (figs. 1, 2) complicates high-resolution correlations with surrounding states, and, in particular, with the subsurface Silurian of Ohio. Precise, chronostratigraphically meaningful correlations combined with historical hydrocarbon and aggregate production data form the basic framework necessary for gaining a more accurate understanding of the paleoenvironmental

Orton (1870)		Foerste (1935)	Rexroad and others (1965)	McDowell (1983)*	Hull (1990)**	Brett and Ray (2005); McLaughlin and others (2008)	Sullivan and others (2014a; 2016)	This Report
Niagara Group	Guelph	Peebles			Peebles	Peebles		Peebles
	Blue Cliff	Lilley			Lilley	Lilley		Lilley
	West Union	Bisher		Bisher	Bisher	Bisher		Bisher
	Niagara Shales	Ribolt						
		Alger		Estill	Estill	Estill		Estill
		Dayton	Dayton	Dayton	Dayton/Waco	Waco		Dayton equiv.
		Oldham	undiff.	undiff.	Lulbegrud	Lulbegrud		upper shale
	Dayton Stone	Plum Creek			Oldham	Oldham		orange
					Plum Creek	Plum Creek		white
					upper massive	upper massive		
	Clinton Limestone			Brassfield	thin-bedded	thin-bedded		
					lower massive			
					Belfast			
Cincinnati Group	Richmond	Richmond	Drakes	Drakes	Drakes			Drakes

FIGURE 1. Correlation and nomenclature chart for the exposed Upper Ordovician and Silurian of southern Ohio. Text in italics indicates member/submember status. WHP = Whippoorwill, BFLD = Brassfield, DC = Drowning Creek. Roman numerals indicate third-order depositional sequences. After Sullivan and others (2014a).

*Current official nomenclature of the U.S. Geological Survey

**Current official nomenclature of the Ohio Geological Survey

¹Hull (1990) does not explicitly group the Bisher, Lilley, and Peebles within the Lockport Formation, but it is implied based on his correlation chart.

Brunton and Brintnell (2011)		Hull (1990)*			Horvath (1967, 1969)	Brett and others (1990, 1995)	
Ontario		Northwestern Ohio	Drillers' terms	Southeastern Ohio	SE Ohio & West Virginia	New York	Seq. ¹
Clinton Group	Rochester Sh	Rochester Sh	Niagaran shale	Rochester Sh	Bisher	Decew Dol	V
	Irondequoit Ls				Estill	Rochester Sh	
	Rockaway Dol					Irondequoit Ls	IV
	Merriton Ls	Dayton	packer shell	Dayton		Rockaway Dol	
Catact Group	Thorold Ss & Cabot Head Sh	Cabot Head Sh	stray Clinton	Clinton Fm	Waco/Dayton	Williamson Sh	III
			red Clinton			Merriton Ls	
			white Clinton			Wolcott Furnace & Sauquoit Fm	
		Manitoulin Dol	Medina sands			Sodus Sh (upper & lower)	II
	Manitoulin Dol				Lulbegrud Sh	Reynales Ls	
					Oldham Ls	Neahga Sh	I
					Plum Creek/Cabot Head Sh & "Clinton" sands	Kodak Ss	
					Brassfield & "Clinton" sands	Cambria Sh	
						Thorold Ss	
						Grimsby Fm	
						Devils Hole Ss	
						Power Glen Sh	
						Whirlpool Ss	

FIGURE 2. Nomenclature chart for the subsurface of Ohio and surrounding regions. Chart does not indicate lithostratigraphic or chronostratigraphic correlation between each region.

*Current official nomenclature of Ohio Geological Survey

¹Sequences of Brett and others (1990) correlated to the updated type Niagaran nomenclature of Brett and others (1995).

conditions and subsequent geological events necessary for the deposition and preservation of natural resources. The application of sequence stratigraphy and integrated bio- and chemo-stratigraphy (for examples, see Brett and others, 1990, 2012; Brett and Ray, 2005; McLaughlin and others, 2008; Sullivan and others, 2014a, 2016) has greatly improved the chronostratigraphic precision (often within ≈ 500 ky) of correlations of exposed Silurian strata from western to southern Ohio, and to the classic Silurian reference sections of New York. The Silurian outcrops of Ohio and New York are separated by roughly 400 miles, and the lithology of many chronostratigraphically equivalent units can be considerably different. Since the transition between different depositional environments occurs somewhere in the subsurface between the two regions, subsurface correlations must be at a similar resolution to study where these depositional facies transitions occur, how the facies changed through time, and the impact these factors had on natural resource accumulation.

Correlations using the high-resolution stratigraphic framework developed at the surface is more challenging in the subsurface. Geophysical well logs are often the only data available—cores are rare, especially in the deeper parts of the basin, and many of the subtle features used to distinguish thin units are not visible in well cuttings. As a result, the correlations made in most subsurface research in eastern Ohio are at a much coarser resolution (formation and group scale) than at the surface, particularly with Paleozoic-scale subsurface mapping projects (for examples, see Ryder and others, 2009; Carter and others, 2010). Even studies specifically focused on the Silurian often use a mixture of drillers' terms and New York/Ontario nomenclature in the subsurface of Ohio (for examples, see Janssens, 1977; Ryder, 2000, 2006; Hettinger, 2001).

Establishing subsurface Silurian correlations at a resolution similar to outcrops is part of ongoing work by the Ohio Geological Survey to unify Silurian nomenclature across the state. It is possible to make subsurface correlations at resolutions comparable to outcrop studies through careful comparison of geophysical log data with lithological data. Subtle patterns in gamma-ray and bulk density logs indicative of small stratigraphic units can be identified and used for highly precise correlations over large areas. Comparing geophysical data with lithology is generally easy with cores, since most cored wells also have associated geophysical logs. Geophysical data from outcrops is less common, which limits direct comparisons between stratigraphic reference sections and subsurface geophysical logs.

The Ohio Division of Geological Survey purchased a handheld gamma-ray spectrometer to facilitate comparison of the geophysical characteristics of stratigraphic reference sections with subsurface well log data. A composite gamma-ray log was created from the Silurian reference exposures comprising the Medina and Clinton Groups

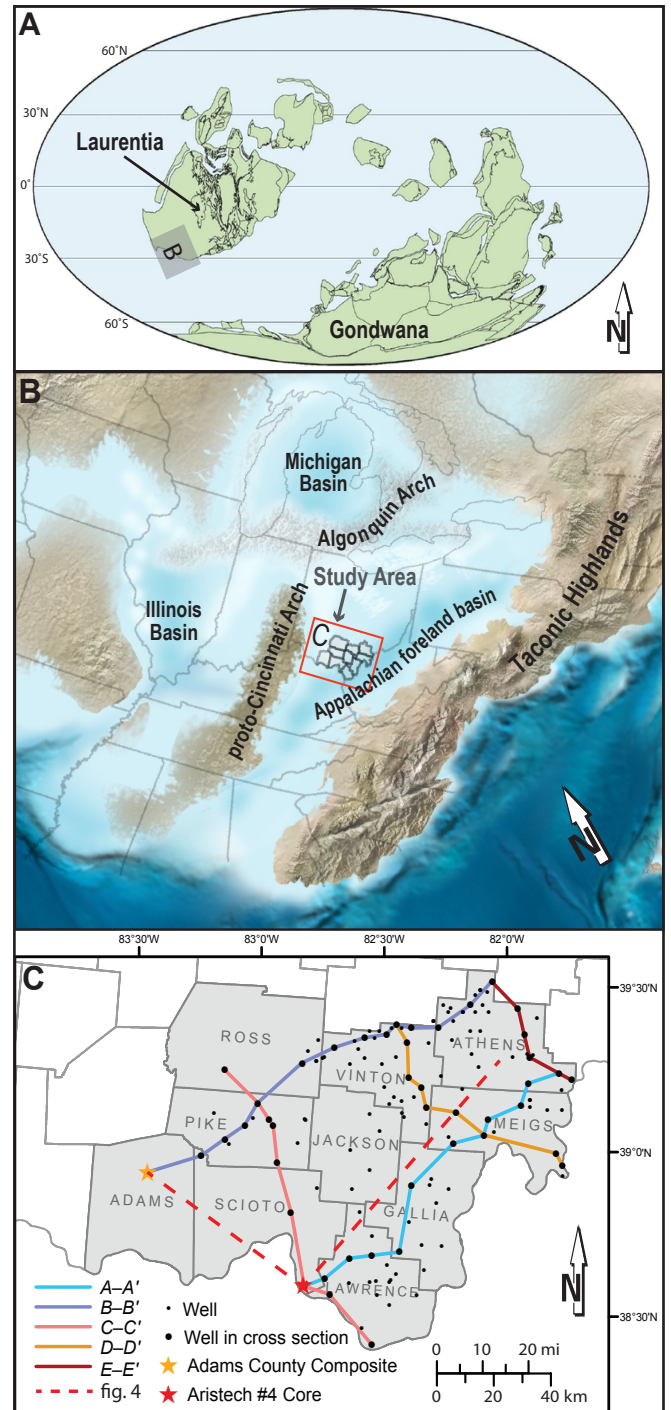


FIGURE 3. (A) Paleogeographic map showing the distribution of continental-scale landmasses during the early Silurian. Gray shaded area represents the extent of map B. Map modified from Torsvik and Cocks (2013). (B) Paleogeographic map of eastern Laurentia during the Ludlow Epoch. This is younger than the time interval of this study, but the general geographic features were the same. The study area spans basinal depositional settings in the east, to shallower ramp depositional settings in the west. Map modified from Blakey (2013). (C) County map of the study area showing the location of wells used for correlations and cross section lines.

(Late Ordovician through Wenlock) in Adams County (fig. 3). This data, when combined with lithological and geophysical data from the core from the Aristech #4 well (Aristech Core) in southeastern Scioto County (fig. 3), allows for outcrop-scale subsurface correlation of lower Silurian strata throughout southern and southeastern Ohio, and provides a useful framework for continued work on unifying Silurian nomenclature throughout the state (fig. 4).

Geological and Environmental Background

Ohio was located approximately 30° south of the equator, on the western flank of the Appalachian foreland basin during the latest Ordovician through mid-Silurian (fig. 3). The foreland basin began to form during the early phases of the Taconic Orogeny in the Early to Middle Ordovician (Van Staal and others, 1998). Subsidence associated with Taconic orogenic phases continued into the earliest Silurian, and created a broad foreland basin that extended into Michigan (Ettensohn and Brett, 2002). The “proto-Cincinnati Arch” or Findlay-Algonquin Arch (fig. 3) was the forebulge of the foreland basin system, and acted as the western boundary of the basin (Ettensohn, 2008). During the early to middle Llandovery a period of tectonic quiescence was associated with eastward migration of the foreland basin depocenter, perhaps a

result of static load relaxation (Goodman and Brett, 1994; Ettensohn and Brett, 1998). The Salinic Orogeny began during the late Llandovery, and reshaped the Appalachian foreland basin. The axis of the basin migrated westwards, and the strong uplift of the Algonquin Arch separated the Appalachian foreland basin from the Michigan Basin and created a strong regional unconformity at which much of the mid to lower Clinton strata were removed (Ettensohn and Brett, 1998). Orogenic activity along the eastern margin of Laurentia continued for more than a hundred million years, during the ensuing Acadian and Alleghenian orogenies, until the formation of Pangea during the Permian (Ettensohn, 2008).

Both the Taconic and Salinic orogenies were comprised of numerous phases of heightened orogenic activity, basin subsidence, and cratonward migration of the foreland basin axis, which were then followed by tectonic quiescence, static load relaxation, and eastward migration of the foreland basin. The orogenic phases drastically raised and lowered regional sea level, causing unconformities and pronounced shifts in depositional environments (Goodman and Brett, 1994; Ettensohn and Brett, 1998). The orogenic phases also influenced the general lithology of the strata. Clastic deposition dominated during times of heightened orogenic activity due to increased erosion rates on the

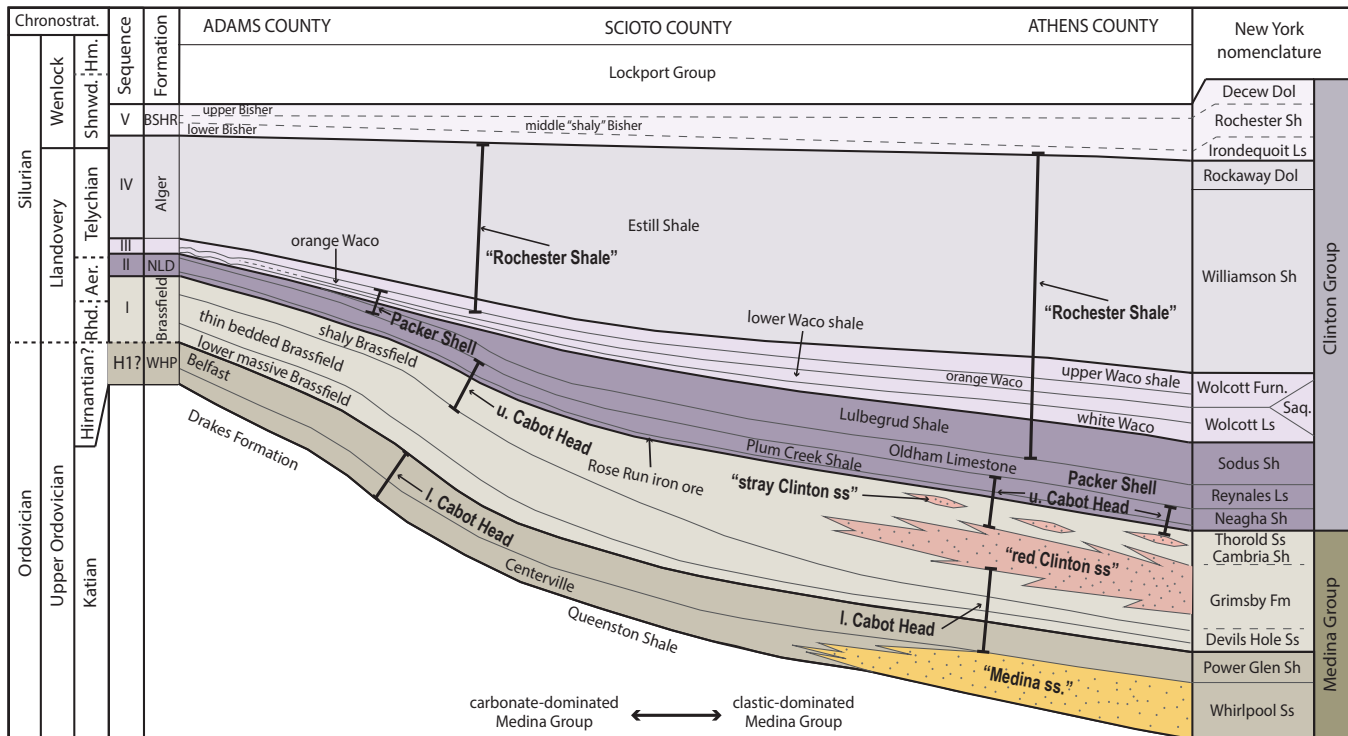


FIGURE 4. Generalized correlation diagram from the Silurian outcrops of Adams County, to the Aristech Core in Scioto County, and to the subsurface of northeast Athens County. Sequence stratigraphic framework and correlations to New York primarily based on Brett and others (1990), Brett and Ray (2005), and McLaughlin and others (2008). The transition between the Brassfield carbonate facies and the clastic “Medina/Clinton” sands facies occurs in Scioto County. Units in bold represent subsurface terminology as applied to southern Ohio. The stratigraphic extent of the Rochester Shale, upper Cabot Head, and the lower Cabot Head represent their use in most subsurface correlations, not their stratigraphic extents in their type areas. Saq. = Saquoit Formation, Furn. = Furnace, Rhd. = Rhuddanian, Aer. = Aeronian, Shnwd. = Sheinwoodian, Hm. = Homerian, Chronostrat. = chronostratigraphy.

Taconic highlands. These included coarse conglomerates and sandstone in eastern deltaic areas and thick mud-dominated successions in the basin center. Carbonate deposition in shallower environments dominated during intervals of reduced tectonic activity and highland erosion.

Global climate and associated eustatic sea-level variation also impacted depositional environments throughout the basin. Climate cooled perhaps as a result of increased silicate weathering rates, which removed carbon dioxide from the atmosphere during the Taconic Orogeny (Kump and others, 1999). Rapid deposition and preservation of organic matter during the Katian Age of the Late Ordovician further reduced carbon dioxide, initiating icehouse conditions (Saltzman and Young, 2005). Ice volume continued to increase throughout the remainder of the Ordovician, and reached its peak during the Hirnantian Age. Rapidly changing climate conditions, fluctuating sea levels, and metal poisoning are some of the likely causes of a series of extinction events bracketing the Ordovician/Silurian boundary (Finnegan and others, 2012; Vandenbroucke and others, 2015). Global sea level gradually rose during the Llandovery Epoch as the climate slowly returned to greenhouse conditions, and then gradually fell throughout the remainder of the Silurian (Johnson, 2006; Munnecke and others, 2010). Shorter cycles of sea level fluctuations were superimposed on the long-term eustatic trends throughout the Silurian, particularly during the early Silurian, probably due to glacial advances and retreats. Depositional facies changes caused by these relatively short-term fluctuations in sea level are the basis of sequence stratigraphy; a useful framework for basin-scale correlations across different depositional environments.

Sequence Stratigraphy

Sequence stratigraphy is a useful technique for chronostratigraphic correlations of geological units across different depositional facies, especially when biostratigraphic and chemostratigraphic data are scarce. Instead of correlating individual units based solely on lithology, sequence stratigraphy relies on correlating stratigraphic patterns of lithological change caused by sea-level variations. In regions with relatively shallow water conditions, the boundaries of stratigraphic sequences are marked by unconformities. There are numerous Earth processes that cause sea-level rise and fall, each occurring over different lengths of time. Researchers classify sequences into a hierarchy of orders based on sequence duration (for examples, see Vail and others, 1977; Bush and Rollins, 1984; Brett and others, 1990; Catuneanu, 2009). Table 1 contains a summary of sequence hierarchy and potential mechanisms for sequence formation, primarily from Miall (2010) and Bouilila and others (2011).

The mechanisms that cause first- and second-order sequences are fairly well understood, and represent tectonoeustatic sea-level variation related to varying rates of ocean floor spreading. The stratigraphic effects

TABLE 1. *Hierarchy of depositional sequences*

Order	Duration (my)	Term	Cause
1	200–400	Supersequence	Supercontinent formation cycle
2	10–100	Sloss sequence, Megasequence	Changes in mid-ocean-ridge spreading rate
3	1–10	Sequence	Regional tectonism, Milankovitch forcing
4	0.16–1	Parasequence set/cyclothem	Milankovitch forcing, regional tectonism, sedimentation patterns
5	0.01–0.1	Parasequence	Milankovitch forcing, sedimentation patterns

of these long-term global sea-level changes can be used for meaningful chronostratigraphic correlation between continents (albeit at very low temporal resolution). Third-order sequences are more poorly understood, and can be caused by a variety of regional and global mechanisms. Regional tectonics, particularly cycles of tectonic loading and basin subsidence followed by basin relaxation, can cause sequences deposited over 1–10 my (Miall, 2010). Third-order sequences formed through tectonic activity would therefore represent only local variations in relative sea-level, which can rarely be used for chronostratigraphic correlations across different basins. There are also eustatic sea-level variations that occur in the 1–10 my timeframe. It was well known that variations in the orbital parameters of the Earth contribute to high-frequency (< ≈400 ky) sea-level cycles corresponding to fourth- and fifth-order sequences (for examples, see Hays and others, 1976; Heckel, 1994, 2008), but it was not clear if lower frequency orbital variations could cause the 1–10 my third-order sequences. Recent advances in quantitative orbital tuning have produced evidence that together variations in the axial tilt of the Earth and variation of the eccentricity of the Earth's orbit can impact global sea-level at 1–3 my periodicities. Bouilila and others (2011) determined that third-order Cenozoic and Mesozoic passive margin sequences were controlled by 1.2 my axial obliquity modulations during icehouse conditions, and 2.4 my orbital eccentricity modulations during greenhouse conditions. In very tectonically active regions, such as the Appalachian foreland basin during the Late Ordovician through Silurian, third-order eustasy is likely at least partially obscured by regional sea-level changes brought about by orogenic activity (Ettensohn, 2008).

Brett and others (1990, 1998) developed a sequence stratigraphic framework that significantly increased the precision of correlations of the Silurian succession of western New York and Ontario (northern Appalachian Basin) to other regions. Brett and others (1990) originally separated the Silurian of the northern Appalachian Basin into seven third-order sequences, with each sequence corresponding to a group or subgroup, and the parasequence sets (termed subsequences) within

each third-order sequence generally corresponding to formations. Even if these sequences represent regional sea-level variation due to tectonism, they can be used for fairly precise chronostratigraphic correlations within and around the Appalachian Basin. Most Silurian stratigraphic research in the Appalachian Basin since Brett and others (1990) used various chronostratigraphic data to refine and extend this sequence stratigraphic framework into neighboring states, including Ohio (figs. 1, 4; for examples, see Brett and others., 1998; Brett and Ray, 2005; McLaughlin and others, 2008; Cramer, 2009).

Silurian Stratigraphy of Ohio

Nomenclature of Silurian rocks in Ohio is almost entirely derived from surrounding states. Terms for subsurface units in eastern Ohio are loosely based on New York/Ontario terminology, while the current terminology used for the exposed Silurian higher on the Cincinnati Arch (southern and southwestern/western Ohio) is primarily from Kentucky and Indiana. Lack of exposures between southern and western/southwestern

Ohio, combined with a paucity of index fossils and slight lithological differences, led to the development of two mostly distinct nomenclatures for the exposed Silurian of Ohio (see Foerste, 1897, 1906, 1935). Since then, steady accumulation of biostratigraphically useful conodont and brachiopod data, combined with the relatively new techniques of sequence- and chemostratigraphy allow for more precise correlations between units in southern and western/southwestern Ohio, providing a uniform chronostratigraphic framework for high-resolution correlations between the regions. The nomenclature of southern Ohio will be used in this report (fig. 1), because the subsurface Silurian of Ohio, particularly in southeastern Ohio, is lithologically more similar to the Silurian of southern Ohio than that of western/southwestern Ohio. See Brett and Ray (2005), McLaughlin and others (2008), Cramer (2009), Kleffner and

others (2012), Brett and others (2012), and Sullivan and others (2014a, 2016) for further information regarding the nomenclature and correlation of the Silurian of western Ohio.

The high-resolution stratigraphic framework developed in southern Ohio and Kentucky is not often used in the subsurface of southeastern Ohio. Instead, oftentimes inconsistent and incorrectly applied terminology from New York and Ontario is used by most researchers. Nomenclature from New York and Ontario is commonly used in the subsurface of Ohio for several reasons. New York was the first state to develop consistent and regionally applicable lithostratigraphic and paleontological framework for the Silurian in the northern Appalachian Basin (Vanuxem, 1842; Hall, 1852), and New York terminology became the primary stratigraphic framework for surrounding states in the late 1800s. The Silurian of New York eventually served as the basis for the North American Provincial Series—regional chronostratigraphic

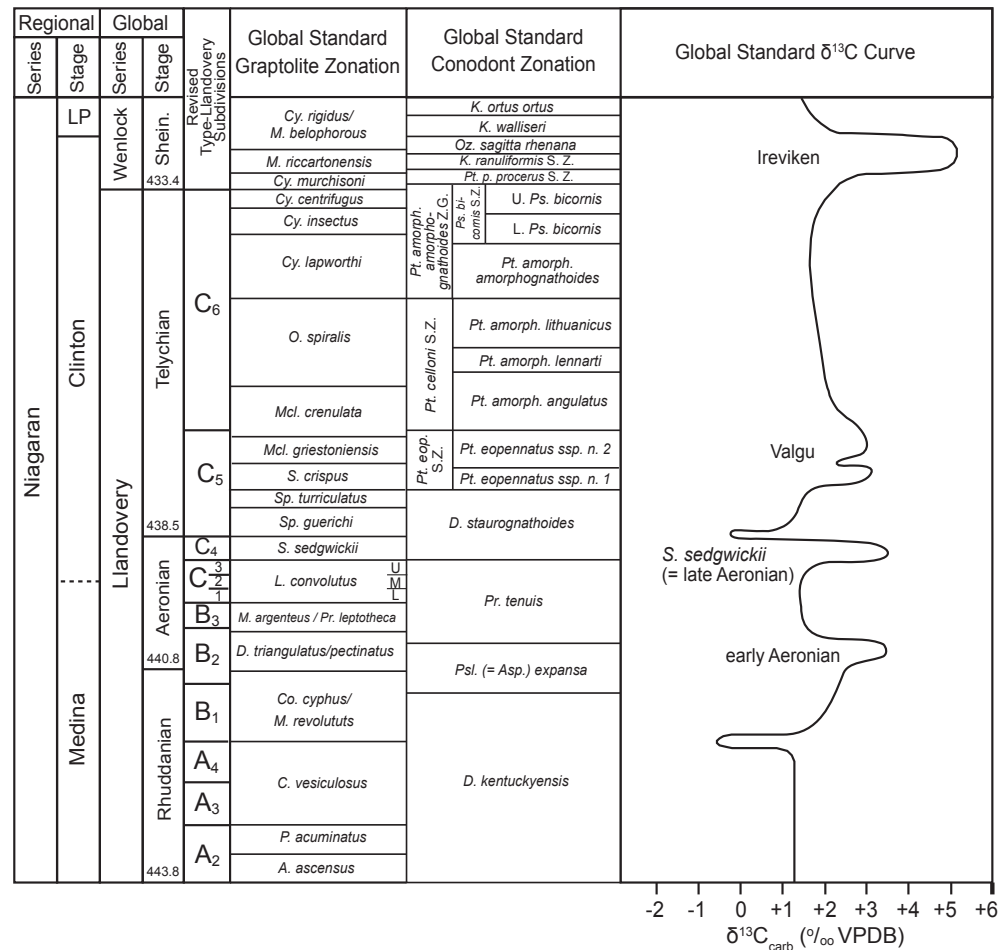


FIGURE 5. Chronostratigraphic diagram of the lower part of the Silurian System. LP = Lockport, Shein = Sheinwoodian, S.Z. = Superzone. Z.G. = Zonal Group. Global and regional series and stages, conodont zonation, and global standard $\delta^{13}\text{C}$ curve modified from Cramer and others (2011). Correlation of conodont and graptolite zonation from Melchin and others (2012). Correlation of Type Llandovery subdivisions from Davies and others (2013, 2016). Figure modified from Waid and Cramer (2017).

units used until recently for Silurian correlations in the United States (Cramer and others, 2011; fig. 5). Units from New York were correlated into Ohio by Orton (1870, 1871), who applied broad, approximately group-rank New York terminology to the Silurian of western and southern Ohio (fig. 1). Some of his correlations were incorrect, particularly his correlation of the lower “flinty” Clinton Limestone (presently termed Brassfield Formation) with the Clinton Group rocks of New York (fig. 1). Shortly after Orton’s reports, northeast Ohio experienced an oil and gas boom focused on lower Silurian strata. Industry geologists and drillers adopted Orton’s terms, and New York nomenclature remained entrenched in subsurface research within Ohio, even after the major stratigraphic revisions of Foerste (1935). In the northwest and central part of Ohio, the lowermost subsurface Silurian strata show more lithological similarities with Ontario than New York, so some Ontario terminology is used in addition to New York terminology (fig. 2). Stratigraphic nomenclature and the chronostratigraphic understanding of Silurian strata in New York and Ontario have been updated considerably since the early 1900s (for example, see Brett and others, 1995), while the correlations and nomenclature of subsurface Silurian in Ohio have remained mostly unchanged (fig. 2). Horvath (1964, 1967, 1969) used a combination of lithological data from cores and cuttings, and geophysical data from well logs to create the most precise and accurate subsurface correlations of subsurface Silurian strata in Ohio (fig. 2). Horvath predominantly used nomenclature from southern Ohio, with the exception of “Cabot Head Shale,” a term from Ontario. The correlations of this report expand upon those of Horvath (1967, 1969), with some revisions and clarifications based primarily on subsequent biostratigraphic and sequence stratigraphic information.

PREVIOUS WORK: OVERVIEW OF SURFACE AND SUBSURFACE STRATIGRAPHY

The extensive and widely variable nomenclature used for the Silurian at the surface and subsurface warrants a brief overview and discussion, in stratigraphic order, of the most recent (for example, Sullivan and others, 2014a) chronostratigraphic understanding and nomenclature used for these units. The Ohio Geological Survey generally followed the units of McDowell (1983) for geological mapping of Silurian units in southern Ohio (fig. 1). Also see figure 1 for broad-scale sequence stratigraphic interpretations for these units.

Surface Units

Drakes Formation

The Drakes Formation consists of medium grey siltstones, silty, sparsely fossiliferous silty dolostones, and greenish gray to maroon red silty shale. The maroon shales (upper part of Preachersville Member) represent distal tongues of the Queenston shale of New York. The unit preserves very few biostratigraphically useful fossils, but Grahn and Bergström (1985) assigned the unit to the

Katian Stage (Late Ordovician) based on the presence of the chitinozoan *Ancyrochitina merga* (Jenkins, 1970). The Preachersville Member may be Hirnantian if it correlates to a position high in the Queenston Shale, where the ascending limb of the Hirnantian isotope carbon excursion (HICE) was recorded by Bergström and others (2011) in southern Ontario.

Centerville Formation

The Centerville is a poorly understood unit, first identified by Foerste (1931) as strata that occasionally occur between the Elkhorn Formation ($\approx$ Drakes Formation) and the Belfast Member of the Brassfield Formation. The unit is present in southern Ohio, where it is a bluish-gray silty shale interbedded with gray (weathering to tan), slightly calcareous siltstone beds. The chronostratigraphic position of the unit is uncertain due to a lack of biostratigraphically useful fossils. It is separated from underlying strata by the global-scale Cherokee Unconformity of Dennison and Head (1975). McLaughlin and others (2008) assigned the unit to the lowermost Silurian, but subsurface correlations of the unit to the Whirlpool Sandstone (see plates 1, 3–5) indicate that it is likely Hirnantian (Upper Ordovician). The Whirlpool Sandstone was long thought to be the lowest Silurian unit in the New York type region (Brett and others, 1995), but recent chitinozoan evidence indicates a late Katian to Hirnantian position for the unit (Schröer and others, 2016).

Brassfield Formation

The Brassfield Formation is a widely recognized unit, spanning from western Tennessee, Kentucky, Ohio, and Indiana. The lithology of the unit is widely variable across such a large geographical area, so local informal members are commonly used. Additionally, the unit as presently recognized is diachronous—the so called “red Brassfield” on the western side of the Cincinnati Arch is almost entirely younger than the Brassfield on the eastern side of the Arch (Ettensohn and others, 2013) and is probably equivalent to the Oldham Member of Kentucky (McLaughlin and others., 2008). The Brassfield contains one formal and four informal members at its type area in central Kentucky (Ettensohn and others, 2013). All of the members present in the type area are also present in southern Ohio.

Belfast Member

The Belfast Member is the only formal member of the Brassfield Formation. It is composed of two distinct units. The lower unit, sometimes termed Belfast A (McLaughlin and others, 2008), is roughly 1 ft thick, heavily bioturbated glauconitic packstone of skeletal fragments. The upper unit (Belfast B) consists of thin, silty limestones interbedded with silty, calcareous shales that become more dominant higher up in the unit. The Belfast Member is characterized by the presence of hardgrounds, indicated by *Thalassinoides* burrows and *Trypanites* borings, which require firm to lithified sediment to be preserved. Glauconite accumulations indicate slow deposition.

Despite the apparently slow deposition, biostratigraphically useful fossils are extremely rare from both Belfast units. *Distomodus kentuckyensis* (Branson and Branson 1947), *Ozarkodina hassi* (Pollock, Rexroad, and Nicoll 1970), and *Icriodella discreta* Pollock, Rexroad, and Nicoll (1970) were reported from the Belfast Member by Cooper (1975). This fauna is indicative of the *D. kentuckyensis* Zone, which has traditionally been interpreted to begin at the Hirnantian/Rhuddanian boundary (fig. 5). However, these three species first occur in close succession (Zhang and Barnes, 2002), in Hirnantian strata (Kleffner and others, 2005; Bergström and others, 2011), so they do not necessarily indicate a Silurian position for the Belfast.

Grahn and Bergström (1985) recovered the chitinozoan *Conochitina* cf. *C. iklaensis* Nestor (1980) in three samples of the Belfast. True *C. iklaensis* occurs in the *Coronograptus cyphus* through *Lituigraptus convolutus* graptolite biozones, which correlate to the uppermost Rhuddanian through most of the Aeronian stages (fig. 5). If the *Conochitina* cf. *C. iklaensis* specimens of Grahn and Bergström (1985) have the same stratigraphic range as true *C. iklaensis*, then the unit is Rhuddanian or Aeronian. Since it is not the same species, however, the chronostratigraphic assignment of the Belfast remains unclear. Brett and others (2014) and Sullivan and others (2016) assign the Belfast B to the lowermost Rhuddanian, and do not include the Belfast A unit in their chronostratigraphic diagrams.

The chronostratigraphic uncertainty of the unit makes correlations to the Silurian successions of New York and Ontario difficult. Brett and Ray (2005) correlate the Belfast A to the Whirlpool Sandstone, and the Belfast B to the Power Glen Shale. Horvath (1967) did not correlate each member of the Brassfield Formation separately, and correlated the entire Brassfield to the Manitoulin Formation in Essex County, Ontario. If Horvath's correlation is correct, then the Belfast Member correlates to the lower part of the Manitoulin Formation. Bergström and others (2011) report HICE $\delta^{13}\text{C}$ values in the lower part of the Manitoulin Formation, with the descending limb of the excursion occurring in the middle part of the unit, and consider the entire Manitoulin Formation on the Bruce Peninsula and on Manitoulin Island to be Hirnantian. Therefore, if Horvath's correlation of the Brassfield is correct, the Belfast Member most likely occupies a Hirnantian chronostratigraphic position.

Lower massive, thin bedded, and upper shaly Brassfield

The lower massive Brassfield overlies the Belfast Member. It is considerably more massive and resistant to weathering than the underlying Belfast B. The unit is a generally fossil-rich, massive packstone to grainstone with evidence of hardgrounds. Occasional golf ball- to fist-sized nodules and thin, patchy beds of pale gray to white chert are present. The contact between the lower massive Brassfield and overlying thin bedded Brassfield is gradational in the Brassfield type area of central

Kentucky, and is usually placed at the lowest occurrence of consistently thin (3-6 in) beds (for example, see Ettensohn and others, 2013). The thin bedded Brassfield consists of thin dolomite-bio-wacke- to packstones interbedded with slightly calcareous, medium gray shales. The thin bedded Brassfield becomes progressively shalier up-section, and grades into the overlying upper shaly Brassfield.

Cooper (1975) recovered *D. kentuckyensis*, *I. discreta*, and *O. hassi* from the lower massive, thin bedded, and shaly Brassfield, placing it within the *D. kentuckyensis* biozone (Hirnantian through Aeronian). Brachiopods from the lower massive Brassfield indicate a late Rhuddanian to early Aeronian position (Berry and Boucot, 1970). The relative abundance of *O. hassi* and *D. kentuckyensis* changes from the lower massive Brassfield to the thin bedded and upper shaly Brassfield. *O. hassi* is the dominant platform species in the upper half of the lower massive Brassfield. *D. kentuckyensis* (including *D. sp. cf. D. kentuckyensis* in Cooper, 1975) is dominant in the thin bedded and shaly Brassfield. Limestones in the upper shaly member are characterized by another distinctive index fossil, the cogwheel shaped crinoid columnal *Floricolumnus*; this interval, the so-called "Bead bed," has been traced southward into southern Kentucky, to eastern Tennessee and northward to the vicinity of Dayton, Ohio (Thomka and Brett, 2017).

The lower massive, thin bedded, and shaly Brassfield members roughly correlate to the Devils Hole Sandstone, Grimsby Formation, Thorold Sandstone, Cambria Shale, and Kodak Sandstone (fig. 4; Brett and Ray, 2005). Horvath (1967) correlates the Brassfield to the Manitoulin Formation of Ontario, which is considered by Bergström and others (2011) to be entirely Hirnantian. However, brachiopods from the lower massive through upper shaly Brassfield are most likely Silurian (Berry and Boucot, 1970). This means that either the Manitoulin Formation in the subsurface of Essex County, Ontario contains younger strata than the Manitoulin exposed to the north on Bruce Peninsula and Manitoulin Island, that the Manitoulin at the sections studied by Bergström and others (2011) is not entirely Hirnantian, or that the lower massive through upper shaly Brassfield were deposited after the Manitoulin Formation.

Upper massive Brassfield (Rose Run iron ore)

The upper massive Brassfield is distinct from the underlying members of the Brassfield Formation. It is a reddish, hematitic packstone interbedded with minor gray shale. A thin glauconitic and phosphatic lag bed occurs at the base of the unit. The basal bed of the upper massive Brassfield in central Kentucky, termed the "bead bed" by some researchers (fig. 1), and historically termed the "Rose Run Ironstone" or "Rose Run iron ore" (Foerste, 1906), contains abundant, distinctive, cogwheel shaped crinoid columnals (Ettensohn and others, 2013). In contrast to the type area, in Adams County the lowermost bed of the upper massive Brassfield does not contain the distinctive crinoid "beads." However, a subtle glauconitic lag occurs

at the base, and the unit is distinctively more hematitic and fossiliferous than the limestone interbeds within the underlying upper shaly Brassfield.

Brett and Ray (2005) consider the upper massive Brassfield to represent the transgressive systems tract of sequence II, and correlate it to the Densmore Creek Phosphate Bed—a transgressive lag deposit at the base of the Maplewood Shale (equivalent to the Neagha Shale in fig. 4) which represents the base of sequence II in west-central New York (LoDuca and Brett, 1994). Conodont data provides some slight evidence supporting this correlation. Similar to the lower members of the Brassfield, *O. hassi*, *D. kentuckyensis*, and *I. discreta* were the most abundant platform conodonts recovered from the upper massive Brassfield (Cooper, 1975). Interestingly, the only interval throughout the entire Brassfield Formation where *I. discreta* is the most abundant species occurs in the lowest two feet of the upper massive member. Above that, *O. hassi* becomes the most abundant of the three species. The same faunal pattern occurs in New York, where Waid and Over (2015) recovered an *I. discreta*-dominated fauna from the Densmore Creek Phosphate Bed that transitioned to an *O. hassi*-dominated fauna in a higher unit (Budd Road Phosphate Bed).

Drowning Creek Formation

The mapping-scale Drowning Creek Formation was formally recognized by McDowell (1983) and the U.S. Geological Survey in Estill County, central Kentucky. Included as members within the formation were the Brassfield, Plum Creek Shale, and Oldham Limestone. The Plum Creek Shale and Oldham Limestone were not recognized in northern Kentucky and southern Ohio. In southern Ohio, the members were defined, in ascending order, as the Brassfield Member, “undifferentiated,” and the Dayton Dolomite Member (McDowell, 1983; Hull, 1990). Stratigraphic research since the formation was erected indicates that, in central Kentucky, the formation encompasses several disconformities/unconformities, including the boundary between sequences I and II. In northern Kentucky/southern Ohio, the Drowning Creek Formation contains even more unconformities, as it includes strata representative of sequence I, II, and III (Brett and Ray, 2005). In southern Ohio, Sullivan and others (2014a) removed the Waco Member (Dayton Dolomite Member of the Drowning Creek of McDowell, 1983) from the Drowning Creek Formation and placed it in the Alger Formation, and changed the Brassfield to formation status, thereby eliminating one of the internal unconformities.

Plum Creek Shale Member

The Plum Creek Shale is the lowest member of the Drowning Creek Formation as designated by Sullivan and others (2014a). In southern Ohio, the Plum Creek Shale consists of thin dolostones interbedded with greenish gray silty and calcareous shales. The interbedded carbonate beds are distinctly less ferruginous than the underlying upper massive Brassfield or the overlying Oldham Member.

Cooper (1975) recovered conodonts indicative of the *Distomodus kentuckyensis* biozone from the Plum Creek Shale (“shale with limestone interbeds” of his report). Brett and Ray (2005) correlate the Plum Creek Shale to the shaly parts of the Neagha and Maplewood Shales of New York.

Oldham Member

The Oldham is the highest member of the Drowning Creek Formation as defined by Sullivan and others (2014a, 2016). The Oldham is very thin in southern Ohio, and consists of several three- to four-inch-thick ferruginous and dolomitic wacke- to packstones with occasional shale partings. Its lower contact with the interbedded shales and dolostones of the Plum Creek Shale is subtle, and is placed at the top of the highest shale of the Plum Creek. The very limited conodont data from the unit indicate a *Distomodus kentuckyensis* biozone fauna (Rexroad, 1967; Nicoll and Rexroad, 1968), and Brett and Ray (2005) and Ettensohn and others (2013) correlate it to the Reynales Limestone of New York. Chitinozoans suggest an uppermost Aeronian to Telychian age for the top of the Oldham (J. Verniers, pers. comm. to C.E. Brett).

Alger Formation

The Alger Formation was erected by Foerste (1906), and revised by McDowell (1983). It includes, in ascending order, the Lulbegrud Shale, Waco, and Estill Members. The Alger Formation of McDowell (1983) was limited to south of Bath County, Kentucky, and correlated to parts of the Drowning Creek and Estill Shale Formations of north-central Kentucky/southern Ohio. Sullivan and others (2014a) extended the Alger Formation north into Ohio, and recognized as members within it the Lulbegrud Shale, Waco Member, and Estill Shale. However, a large, third-order sequence boundary below the Waco Member truncates the Lulbegrud in northern Kentucky and southern Ohio (McLaughlin and others, 2008; Sullivan and others 2016).

Lulbegrud Member

The Lulbegrud Member is not present in Adams County, but is present south-central Kentucky (Ettensohn and others, 2013; Sullivan and others 2014a), and in the subsurface in adjacent counties to the east (Horvath, 1967; this study). In its type area, the Lulbegrud overlies the Oldham Member, and consists of sparsely fossiliferous, greenish gray, clay-rich shales with some discontinuous dolomitic zones (Ettensohn and others, 2013). Brett and Ray (2005) and McLaughlin and others (2008) correlate the Lulbegrud to the Sodus Shale in west-central New York (fig. 4) based on sequence stratigraphic patterns.

The biostratigraphic evidence for this correlation is tenuous. Verniers and others (2012) recovered from the Sodus a conodont and chitinozoan fauna indicative of the late Aeronian to early Telychian *Distomodus staurognathoides* conodont biozone, and Kleffner (1997, personal communication to Brett and others, 1998) reports conodonts indicative of the *Pterospirifer celloni* zone from the upper Sodus Shale (refer to fig. 5). Brett and

others (1998) report that the lower Sodus Shale contains the brachiopod *Eocoelia* sp. cf. *E. intermedia*, and that the overlying Wolcott Limestone contains the brachiopod *E. curtisi* Zeigler (1966). If *E.* sp. cf. *E. intermedia* has the same stratigraphic range as true *E. intermedia* (Hall 1860), then it is restricted to the Aeronian stage. *E. curtisi* indicates a late Aeronian to Telychian age for the upper Sodus Shale, based on the stratigraphic range of the species in the type Llandovery area in Wales (Davies and others, 2013; Davies and others, 2016). Overall, the biostratigraphic data indicate that the Aeronian/Telychian boundary likely occurs somewhere within the Sodus Shale.

Biostratigraphic data is scarce from the Lulbeugrud—Huddle (1967) and McDowell (1983) assigned the unit to the upper part of Zone I through Zone II (approximately *Pt. celloni* zone) of Walliser (1964). However, Huddle (1967) did not specify the conodont species he used to determine his zonation, and neither Huddle (1967) nor McDowell (1983) illustrated any of the specimens used to assign this zonation.

The lack of illustrated specimens is problematic for two reasons. Firstly, Telychian conodont zonations based on species/subspecies of *Pterospirifer* was altered considerably by the updated taxonomy of Männik (1998, 2007), such that the “*Pt. celloni* zone” of previous authors corresponds to the *Pt. eopennatus* Superzone and *Pt. amorphognathoides angulatus* Zone (fig. 5). *Pt. eopennatus* looks very similar to *Pt. celloni*, so it is likely that the lower part of the “*Pt. celloni* zone” of past researchers corresponds to the *Pt. eopennatus* Superzone (Kleffner, in McLaughlin and others, 2008). But without illustrated specimens it cannot be determined which updated biozone the specimens of Huddle (1967) represent. Secondly, the conodont occurrences reported from the Colfax Section of McDowell (1983; plate 2) indicate widely contradictory ages for the Brassfield Formation through the Lulbeugrud Member. *Aulacognathus bullatus* (Nicoll and Rexroad 1968) has never been recorded below the Telychian Stage, yet McDowell (1983, plate 2, sample 7638-SD) reported it from the Brassfield alongside *Distomodus kentuckyensis* Branson and Branson (1947), and below *O. oldhamensis* (Rexroad 1967), both of which indicate an Aeronian or lower stratigraphic position. There are several possible reasons for this inconsistency. The specimen may have been misidentified as *A. bullatus*, but it is impossible to tell without an illustrated specimen. Another possibility is that it was correctly identified, but had accidentally been included in the Brassfield interval through contamination during the sample preparation process. The last possibility is that the range of *A. bullatus* extends considerably lower than is currently understood. However, this last possibility is highly unlikely—the species has never been recorded below Telychian strata in locations nearby (for example, see Nicoll and Rexroad, 1968) or in other sections globally (see Männik, 2007). McDowell (1983, plate 2, sample 7634-SD) also reports *O. polinclinata* (Nicoll and Rexroad

1968) from the same sample as *D. kentuckyensis* and *O. oldhamensis*. This co-occurrence is also odd, since the first occurrence of *O. polinclinata* has never been found below the uppermost *D. staurognathoides* Zone (Männik, 2007), which is well into the Telychian Stage (fig. 5). As with *A. bullatus*, *O. polinclinata* may have been misidentified, or may be present because of sample contamination. Again, it is impossible to tell without illustrated specimens. The most likely explanation, however, is that the Aeronian/Telychian boundary occurs somewhere within the middle of the sample interval. If this last scenario is true, then the Lulbeugrud Member is mostly in the Telychian Stage, and correlates to the Sodus Shale.

Waco Member

The Waco Member overlies the Lulbeugrud Member in south-central Kentucky and in the subsurface of counties to the east of Adams County. In Adams County, the Lulbeugrud was eroded, and the Waco Member overlies the Oldham Member of the Drowning Creek Formation. The type section designated by Foerste (1906) in Estill County, Kentucky no longer exists, so Sullivan and others (2014a) designated their “Irvine North” locality in Estill County, Kentucky, as their primary reference section. There, the Waco is composed of a basal carbonate beds containing abundant favositid corals and glauconite, an overlying thin shale package which is overlain by a heavily burrowed dolostone called the “*Teichichnus* bed,” which is in turn overlain by eight ft (2.5 m) of fossiliferous, fenestrate bryozoan rich shale and seven ft (2 m) of unfossiliferous shale (Sullivan and others, 2014a). The contact between the shaly, upper part of the Waco Member (upper Waco shale) and the Estill Member is “at the base of an interval of glauconitic mudstone overlying one or more bands of bright red shale” (Sullivan and others, 2014a, p. 256). The Valgu carbon isotope excursion was recorded in the fossiliferous part of the upper Waco shale (Sullivan and others, 2014a), which indicates a mid-Telychian chronostratigraphic position (fig. 5).

The lithology of the Waco Member in Adams County is slightly different than that in Estill County, Kentucky. Sullivan and others (2014a) divide the Waco Member into two informal submembers (fig. 1). The white Waco is a light gray glauconitic dolo-mud- to wacke-stone bearing occasional fossils. The orange Waco overlies the white Waco, and is a heavily bioturbated ferruginous dolomudstone. Based on carbon isotope profiles, the white Waco correlates to the basal carbonate beds through the top of the *Teichichnus* bed of Kentucky, and the orange Waco correlates to the fossiliferous shale part of the Waco Member in the type region (Sullivan and others, 2014a). Sullivan and others (2016) did not correlate any part of the “non-fossiliferous” shale portion of the upper Waco shale into Ohio, despite the presence of a thick band of red shale topped by a glauconitic mudstone at their Brush Creek locality (see fig. 9 in Sullivan and others, 2016). Herein, the “non-fossiliferous” upper Waco shale is tentatively recognized in Adams

County, Ohio, and its top is placed at the top of the first red shale/glaucinitic mudstone contact above the top of the orange Waco.

Most past researchers have correlated the Waco Member of Adams County as “the Dayton Limestone” or “Dayton Formation” (fig. 1) because of lithological and stratigraphic similarities to the Dayton Formation in its type area (Sullivan and others, 2014a). However, recent conodont, carbon isotope, and sequence stratigraphic research indicates that the Dayton Formation of western Ohio is considerably (1 third-order sequence) younger than the “Dayton” of Adams County, and the latter is chronostratigraphically equivalent to the Waco Member of Kentucky (Kleffner and others, 2012; Brett and others, 2012; Sullivan and others, 2014a). The true Dayton probably correlates to the dolomitic and glauconitic lower part of the Estill Member in Adams County (Cramer, 2009; Sullivan and others 2014a, 2016).

Sullivan and others (2016) tentatively correlate the white Waco and orange Waco to the Wolcott Limestone and Wolcott Furnace Hematite of New York, respectively (fig. 4). The correlation of the orange Waco to the Wolcott Furnace Hematite is supported by both conodont and isotope data. Kleffner, in McLaughlin and others (2008), reported conodonts indicative of the *Pterospirifer eopennatus* Superzone (fig. 5) from the Waco Member. Additionally, the Valgu carbon isotope excursion, which occurs within the *Pt. eopennatus* Superzone through the lower part of the *Pt. amorphognathoides angulatus* Zone (Munnecke and Männik, 2009; McAdams and others, 2017; Waid and Cramer, 2017), was recorded in the orange Waco (McLaughlin and others, 2012; Sullivan and others, 2014a). Conodonts indicative of the *Pterospirifer eopennatus* Superzone—*Ozarkodina polinclinata estonica* Männik (1992) and *Apsidognathus tuberculatus* ssp. n. 1 Männik (2007)—were recovered from the Wolcott Furnace Hematite in central New York (Sullivan, 2014b). Biostratigraphic support of correlation of the white Waco with the Wolcott Limestone of New York is more limited. Diagnostic conodonts have not been collected from the Wolcott, but the presence of *E. curtisi* (Brett and others, 1998) indicates a lower to middle Telychian stratigraphic position. A complication with this correlation is that the white Waco appears to be the basal unit of the sequence III in Ohio and Kentucky (Ettensohn and others, 2013; Sullivan and others, 2016), whereas the Wolcott Limestone was considered by Brett and others (1990) and Brett and Ray (2005) to represent the uppermost part (subsequence) of sequence II. However, the Wolcott may overlie a discontinuity, and overlying bryozoan-rich shales have a fauna comparable to that of the Waco shales, so reassignment to the base of sequence III seems entirely appropriate (C.E. Brett, pers. comm., 2018).

Estill Member

The Estill Member overlies the upper Waco shale. Its base is marked by a glauconite-rich greenish gray to green shale in southern Ohio and Kentucky (McDowell, 1983).

The Estill Member consists of alternating layers of green, gray, and red shale with occasional thin, silty dolostone beds in the lower part. Siltstone beds become more frequent toward the top of the formation in a coarsening-upward sequence. Iron oxide nodules, probably goethite pseudomorphs of pyrite nodules, ranging from pea to golf ball size become prevalent at the top of the Estill Member.

Conodont and isotope data indicates that Estill Member is within the *Pt. celloni* Superzone (fig. 5), and correlates to the Williamson Shale and Rockway Dolomite of New York (fig. 4; Kleffner, 1987; McLaughlin and others, 2008).

Noland Formation

The Noland Formation of Rexroad and others (1965) contains some of the units of both the Drowning Creek Formation and the Alger Formation. The lowest member of the Noland is the Plum Creek Clay, followed in ascending order by the Oldham Limestone, Lulbegrud Shale, and Waco Member (fig. 1). The term was abandoned by McDowell (1983) to follow contemporaneous geological mapping practices (see above).

Bisher Formation

The Bisher Formation overlies the Estill Member on a sharp, erosive surface. The Bisher Formation is often split up into three informal members—the lower, middle and upper Bisher (McLaughlin and others, 2008). The lower and upper Bisher are dolomitic and somewhat silty calcarenites that display varying types of cross bedding, ranging from symmetrical ripples and hummocky bedding to low angle cross stratification. The middle Bisher is generally more argillaceous than the lower or upper, and is fairly thin in Adams County. The uppermost few feet of the Bisher Formation consist of thin to medium bedded dolostones separated by shale partings. The contact between the Bisher Formation and overlying Lilley Formation is subtle in Adams County. The lowermost bed of the overlying Lilley Formation is a very thick, heavily cross bedded unit, distinguishing it from the underlying thin beds of the uppermost Bisher Formation. However, this contact is only obvious where weathering has made clear the bed thicknesses and sedimentary structures of the units.

Based on the presence of the Ireviken Excursion and the conodonts *Kockelella ranuliformis* (Walliser 1964) and *O. sagitta rhenana* (Walliser 1964), and stratigraphic facies changes, the three informal members correlate roughly to Irondequoit Limestone, Rochester Shale, and DeCew Dolomite of New York (see fig. 4; Kleffner, 1987; McLaughlin and others, 2008; Cramer and others, 2010; McLaughlin and others, 2012).

Subsurface Units

Medina sand

The Medina sand or Medina sandstone (fig. 2) is a widely used drillers’ term that refers to the sandstone unit

that rests on the Queenston Shale ($\approx$ Drakes Formation) in the subsurface of Ohio. The Medina can be traced northeast to New York, where it correlates to the Whirlpool Sandstone (Ryder, 2000; Brett and Ray, 2005). The “Medina sandstone” is picked consistently by different workers, (compare cross sections of Ryder, 2000, 2006; Hettinger, 2001; Riley and others, 2011), which allows for meaningful comparisons between different reports.

“Clinton sands”

The “Clinton sands” refers to a series of sandstones and shales in the subsurface of Ohio that correlate to several formations of the Medina Group in New York and not to the Clinton Group of that state. The interval is often subdivided into the subunits “white,” “red,” and “stray” Clinton sands, in ascending order. Brett and Ray (2005) correlate the white Clinton to the Devils Hole Sandstone, the red Clinton to the Grimsby Formation, and the stray Clinton to the Thorold Sandstone and Cambria Shale of New York (figs. 2, 4).

Packer Shell

The “Packer Shell” is a drillers’ term that refers to a thick limestone that separates the Clinton sands from overlying shales. The Packer Shell is actually different units in different parts of the state. In southern Ohio, the distinctive double-troughed gamma signature of the Aeronian Oldham Member (Horvath, 1964, 1967) corresponds to gamma signature of the Packer Shell of Ryder (2000). However, in central and northeastern Ohio, Kleffner (1985) recovered from the Packer Shell conodonts indicative of the Telychian *Pt. celloni* and *Pt. a. amorphognathoides* biozones, which means that there the Packer Shell correlates to the Dayton Formation of western Ohio.

Cabot Head Shale

The Cabot Head Shale (fig. 2) is a widely used term for fairly radioactive shales that occur in strata roughly equivalent to parts of the Medina Group of New York. At its type area, the Cabot Head Formation overlies the Manitoulin Formation, and correlates to most of the Medina Group (Power Glen Shale through Cambria Shale) of New York (Brett and others, 1990). Most subsurface reports from Ohio correlate an “upper” and a “lower” Cabot Head Shale. The lower Cabot Head generally corresponds to a radioactive shale above the Whirlpool Sandstone (“Medina sand”) or Brassfield Formation, and below the “Clinton sands” (fig. 4). The upper Cabot Head generally corresponds to a radioactive interval above the highest “Clinton” sandstone and below the Packer Shell. See Ryder (2000), and Riley and others (2011) for typical subsurface correlations of the lower and upper Cabot Head.

The stratigraphic extent of each unit depends on the geographic distribution of the various Clinton sands members, which complicates comparisons of the upper and lower Cabot Head between regions. Where the stray Clinton is present, the upper Cabot Head spans the top of the Plum Creek down to the top of the stray Clinton. Where the stray Clinton is absent, the upper Cabot Head extends down to the stratigraphically lower red Clinton (fig. 4). The same

scenario is true for the lower Cabot Head. The stratigraphic position of its top is dependent on whether or not the white Clinton is present. Where present, the top of the lower Cabot Head is placed at the base of the white Clinton. Where absent, the top of the lower Cabot Head is placed at the base of the stratigraphically higher red Clinton (fig. 4).

The lower Cabot Head, as defined in most subsurface investigations, generally correlates to the Power Glen Shale of New York (Ryder, 2000), which is consistent with the correlation of the lower part of the Cabot Head Formation in its type area. The upper Cabot Head, as correlated in most subsurface research, often encompasses the upper shaly member of the Brassfield through the Plum Creek Shale Member of the Drowning Creek Formation (see cross section of Ryder, 2000). The part of the subsurface “upper Cabot Head” that is equivalent to the Plum Creek correlates to a position higher than the upper Cabot Head Formation in southern Ontario.

Rochester Shale

The Rochester Shale is a formal unit from New York that is oftentimes applied incorrectly in the subsurface of southern Ohio (for examples, see Janssens, 1977; Ryder, 2000, 2006). In western New York, the Rochester Shale is the dominant shaly unit of the Clinton Group, reaching up to 120 ft thick. It is mostly a gray to dark gray calcareous mudstone with occasional interbedded carbonates. Based on conodont and carbon isotope evidence, the middle Bisher Formation in southern Ohio occupies approximately the same stratigraphic position as the Rochester Shale in New York (Rexroad and Nicoll, 1971; Kleffner, 1987; McLaughlin and others, 2012). The stratigraphically lower Estill Member is the dominant shale of Clinton Group strata in southern Ohio. The stratigraphic extent of the “Rochester Shale” in southern Ohio varies considerably between different subsurface investigations. In southern Ohio, Janssens (1977) extended the “Rochester” down to the Dayton Formation (see fig. 4). The unit Janssens termed the “Dayton” in southern Ohio is actually the Oldham Member, so his “Rochester” spans the Lulbegrud, Waco, and Estill Members, in ascending order. The stratigraphic extent of the subsurface “Rochester” of Ryder (2000; wells 1–19) in southern Ohio is more limited, spanning the base of the upper Waco shale to the top of the Estill Member.

METHODOLOGY AND RESULTS

Building the Adams County Composite Gamma-ray Curve

A composite gamma-ray log for the Silurian reference sections of Adams County was created using a Radiation Solutions® RS-230 handheld gamma-ray spectrometer with a Bismuth Germanate oxide detector crystal. The composite log is composed of data from eight stratigraphic sections in three localities (fig. 6, table 2). The Whippoorwill and Brush Creek Motorsports Complex (BCMC) localities are on Ohio State Route 41 between the towns of Peebles and West Union, and the Measley Ridge locality is on U.S. Highway 32, west of Peebles. Key beds or unit contacts

TABLE 2. Locations used for creation of Adams County gamma log

Location	Section	Latitude	Longitude	Data points	Footage (high)	Footage (low)	Units
Measley Ridge	2	38.93708	-83.451251	75	0	74	Bisher, Lilley, Lilley-Peebles Transition, base Peebles
Measley Ridge	1	38.938484	-83.450492	2	75	77.5	Top Estill & Base Bisher
Brush Creek Motorsport Complex	2	38.903673	-83.44761	30	80	152.5	Estill Shale
Brush Creek Motorsport Complex	1	38.90182	-83.44769	22	155	208	Waco & Estill shales
Whippoorwill	4	38.2169	-83.51147	34	209	245	Top l. m. Brassfield, t.b. and shaly Brassfield, Rose Run l.o., orange Waco
Whippoorwill	3	38.82349	-83.50742	6	246	251	lower massive Brassfield
Whippoorwill	2	38.821976	-83.50875	15	252	266	Centerville & Belfast
Whippoorwill	1	38.82349	-83.50742	11	267	277	Drakes

useful as stratigraphic tie points between sections were identified and marked, and could be used to correlate all of the sections, except for the two exposures at the BCMC locality, which could not be tied together.

The entire Estill Member, from the lower contact with the upper Waco shale to the upper contact with the Bisher Formation, is exposed at the two sections at the BCMC locality (figs. 6, 7). There are no marker beds useful for tying together the exposures, so the correlation of the sections was estimated using an elevation contour map (fig. 7). The contour lines were created in ArcGIS® from the Ohio Department of Natural Resources 2.5-ft resolution digital elevation model using the Spatial Analyst Contour function. The contours were then overlaid on satellite imagery (ArcGIS® online). The Estill Member exposed in section 1 was sampled starting at the lower contact with the Waco shale and ending at the tree line at approximately 730 ft (fig. 7). Section 2 was measured and sampled from the upper contact with the Bisher Formation down to approximately the 730 ft elevation line (fig. 7).

Spectral gamma-ray assays were taken at 1-ft increments for all of the units except for the Estill Member and the lower part of the shaly Lilley, where 2.5-ft sample spacing was used. Any rock or soil cover was trenched out to expose *in situ* rock.

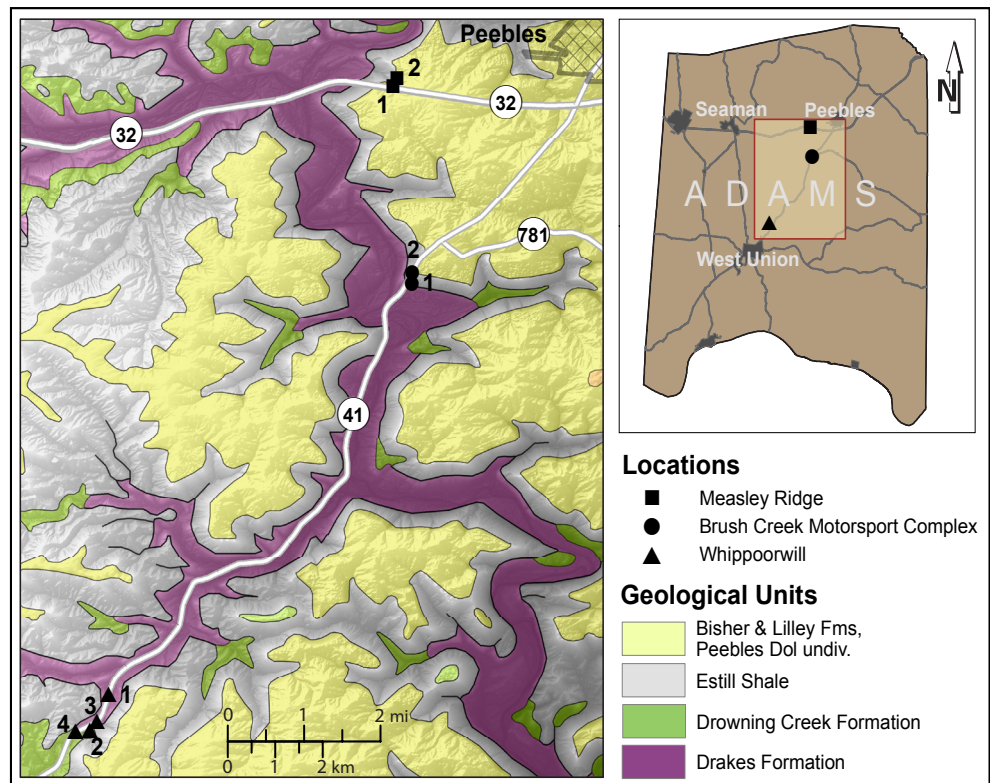


FIGURE 6. Map showing the localities and sections used for creating the composite gamma-ray log for the Silurian of Adams County, Ohio. Shading indicates topography, and colors represent units mapped by the Ohio Geological Survey (Slucher, 2006).

Exposure was generally very good, and only parts of the thin bedded Brassfield, Waco shale, and middle Bisher were covered (Appendix A). An assay time of 120 seconds was used for every sample, with the spectrometer firmly placed against the outcrops. After 120 seconds, potassium (K), uranium (U), and thorium (Th) concentrations were recorded. Following Doveton and Merriam (2004) and Ellis and Singer (2008), the concentrations of potassium, thorium, and uranium were used to estimate gamma radiation (γ) in API units by applying equation 1 (Appendix A).

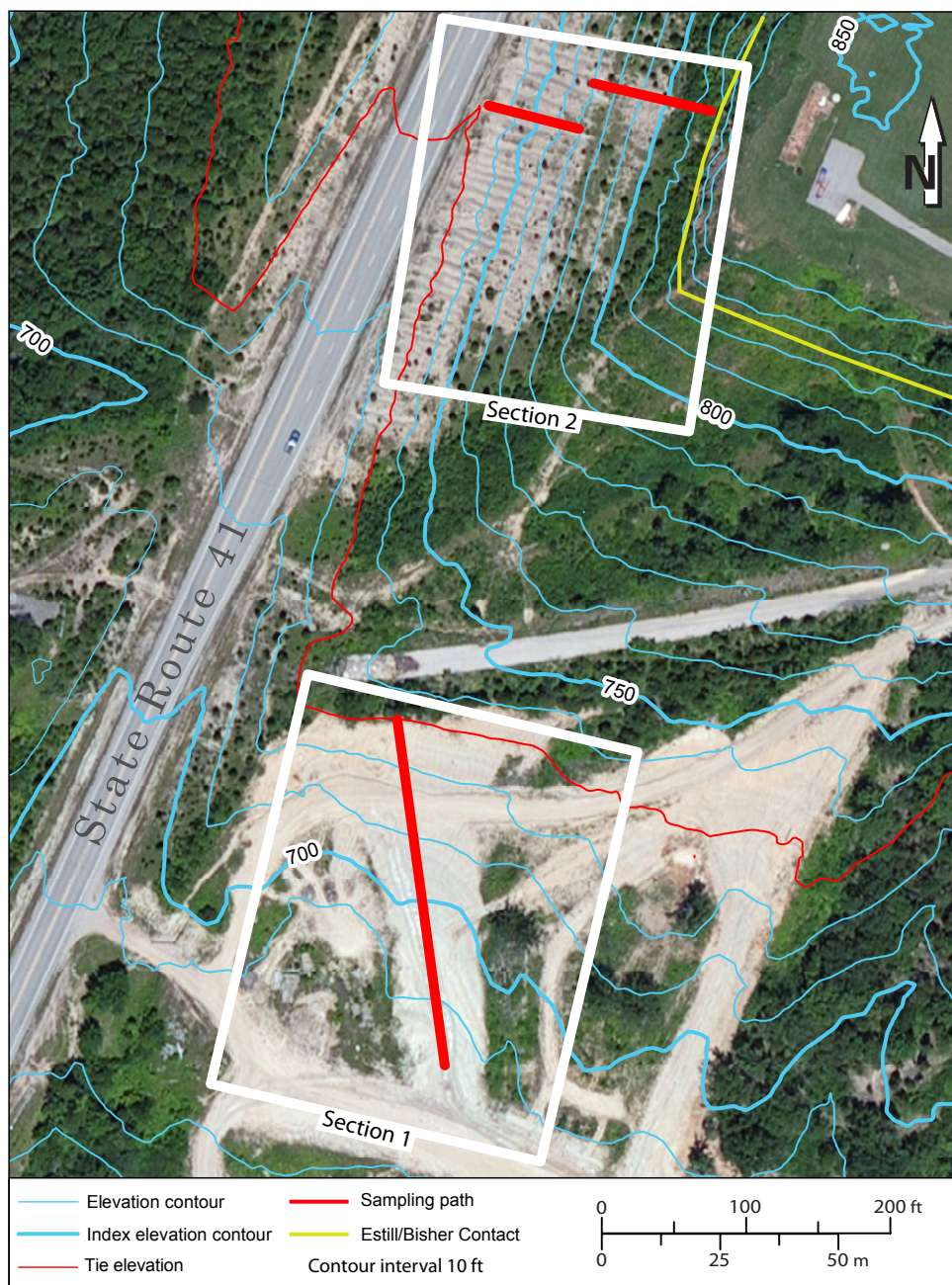


FIGURE 7. Elevation contour and satellite imagery map of the stratigraphic sections at the Brush Creek Motorsports Complex locality. Satellite imagery from ArcGIS online.

$$\gamma \text{ (API)} = 16K \text{ (\%)} + 4Th \text{ (ppm)} + 8U \text{ (ppm)} \quad (1)$$

The calculated gamma-ray values were then used to create a composite geophysical log (fig. 8). Formation boundaries were added to the log based solely on the lithological characteristics observed in the field. The composite gamma-ray data from Adams County were then imported into Petra®, and assigned to a pseudo-well, centered on the town of Peebles.

Cross Sections

Formation picks based on the combined lithological/

geophysical data from Adams County and the Aristech Core were correlated to 140 wells in the study area (fig. 3). Forty-five of those wells were selected to create five stratigraphic cross sections (plates 1–5) across the study area; cross sections A–A' and B–B' approximate depositional strike, and C–C', D–D', and E–E' run approximately parallel to depositional dip. The top of the orange Waco submember was used as the datum because it is consistent across the study area, and is easily identified by both lithological and gamma-ray characteristics in Adams County and in the Aristech Core.

DISCUSSION

Comparison of Adams County and Aristech Core Gamma Curves

The gamma-ray data from the outcrops of Adams County and the well log data (primarily gamma-ray, neutron density, and bulk density curves) from the Aristech Core were compared to their respective geological units to identify geophysical motifs characteristic of each unit. In general, the gamma-ray signatures are similar at each location (fig. 9). The strata of sequences I, IV, and V show only a slight thickness variation from Adams County to southeastern Scioto County, in contrast to sequences II and III, which are much thinner in Adams County. The units in Scioto County are generally

more argillaceous, which is reflected by higher relative gamma values, particularly in the Centerville–Plum Creek interval.

The Centerville Formation has a slightly different gamma signature at each location. In Adams County, gamma values generally decrease from the Centerville Formation's lower contact with the Drakes Formation to its upper contact with the basal bed of the Belfast Member. In Scioto County, the gamma values of the upper part of the Centerville Formation are slightly increased below the contact with basal "Belfast

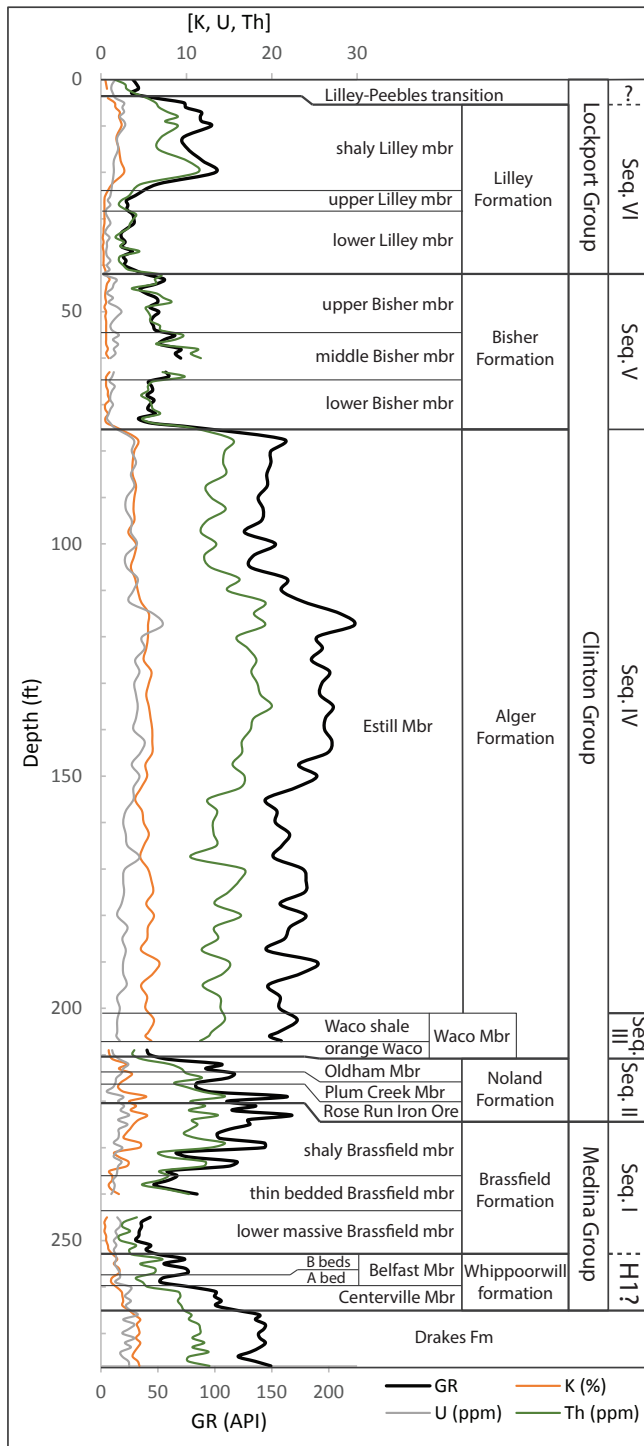


FIGURE 8. Composite spectral gamma-ray log from the outcrops of Adams County, Ohio. Formation boundaries are based on lithological data, and not the gamma curve. Gaps in the curve indicate covered sections. GR = Gamma ray.

A' bed of the Belfast Member. The different gamma signatures may indicate that the upper part of the Centerville was cut out in Adams County, or that there were slight differences in depositional facies between the two areas.

The gamma signature of the Belfast Member of the Brassfield Formation is nearly identical in both locations (fig. 9). The basal Belfast A bed of the member is characterized by low gamma values, and the more argillaceous Belfast B is characterized by two gamma peaks slightly elevated above the values of Belfast A. The lower massive Brassfield is similar in both locations, but with a more prolonged decrease of gamma values from the base of the unit in Scioto County. The gamma signature of the thin bedded Brassfield is similar in Adams and Scioto Counties. The gamma values within the upper shaly Brassfield are consistently elevated in Scioto County. In Adams County, they show a general increase up-section, with pronounced peaks and troughs that reflect the limestone interbeds within the upper shaly Brassfield. The absence of limestone interbeds in Scioto County is likely due to the progradation of clastic sediments from the Taconic Highlands. The upper massive Brassfield (Rose Run iron ore in fig. 9) has lower gamma values in Adams County than in Scioto County, where it is more argillaceous.

The Plum Creek exhibits very different gamma values in each location. The Plum Creek in Adams County is much more dolomitic than in Scioto County, which is reflected in lower gamma ray values. Additionally, in Scioto County the Plum Creek is divided by a clean sandstone that creates a pronounced trough in the gamma curve (fig. 9). The Oldham is characterized by generally low gamma values with a small gamma peak in the middle in both locations. The Lulbegrud is not present in Adams County, and in Scioto County is characterized by consistent, relatively high gamma values that slightly decrease in the upper part of the unit.

The orange Waco is more argillaceous in Scioto County than in Adams County, which is reflected in its higher gamma values. The underlying white Waco is not present in the Aristech Core, and is not present at the Whippoorwill locality, though it is present in other sections in Adams County (for examples, see Sullivan and others 2014a). The upper Waco shale is difficult to distinguish from the overlying Estill Member based on gamma values. In Adams County, the contact between the two is marked by a very glauconitic zone just above a band of brick-red shale. The brick-red shale is absent in Scioto County, but there is a glauconitic zone roughly 30 ft above the top of the orange Waco that likely marks the base of the Estill Member. Gamma values decrease slightly at the glauconitic zone in both locations, and this pattern can be tentatively used to distinguish the contact between the upper Waco shale and the Estill Member.

The gamma values of the Estill Member are higher and more variable in Adams County than in Scioto County (fig. 9). In Adams County, gamma values range from 126–224 API, with the lowest values occurring in the upper part of the unit, and the highest values occurring in the middle part of the unit. The gamma-ray values of the Estill Member in Scioto County are more consistent,

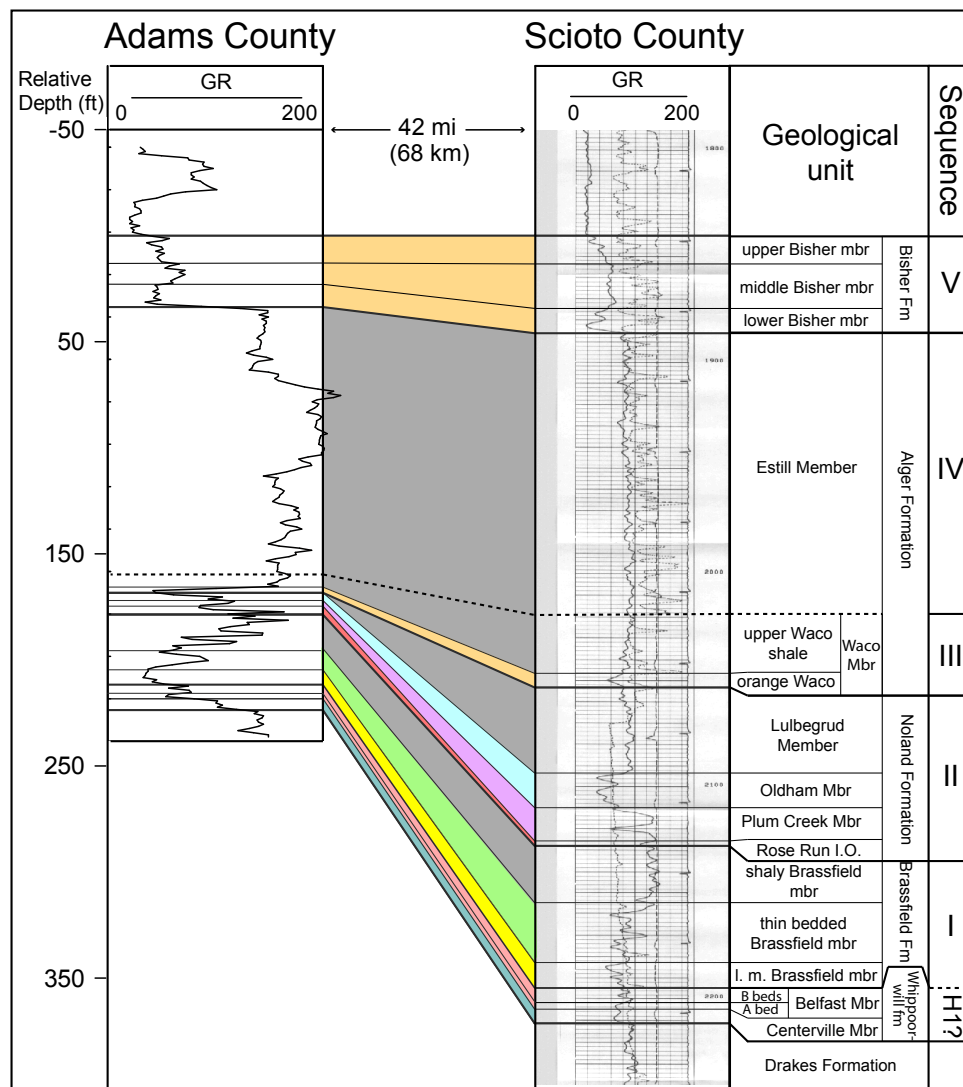


FIGURE 9. Comparison of gamma-ray logs from Adams and Scioto Counties (Aristech #4; API Number 34145601410000). Note the pronounced thickness variations of sequences II and III between the two locations.

ranging from approximately 90–100 API. The upper part of the Estill Member in Adams County is siltier than the middle or lower parts, which likely accounts in part for the lower gamma values. Additional factors that may have reduced the gamma values at the BCMS locality are that there the upper part of the Estill is exposed in a fairly gradual slope and is weathered. Because the Estill at the BCMS section is gently sloping, there was less rock to emit radiation above the gamma-ray spectrometer at each scanned point. The absence of radiation hitting the detector from above would slightly lower the gamma radiation detected by the spectrometer. The low-angle slope of the upper part of the Estill section also facilitated weathering and soil formation, which could also lower the amount of radiation emitted. Most weathering regimes deplete parent rock material of K and U, and leave Th in the weathered material/soil (Osmond and Ivanovich, 1992). If two out of

the three primary radioactive elements are depleted, the total gamma radiation emitted would therefore be reduced. The close correlation of K, U, and Th concentrations within the low-gamma upper part of the Estill, however, indicates that weathering likely did not appreciably affect the gamma values at the upper part of the BCMS section. If K and U were leached out of the Estill parent material, then their concentrations should decrease relative to the concentration of Th, which is not the case.

The Bisher Formation exhibits similar gamma characteristics in both locations. The contact of the lower Bisher with the underlying Estill Member is marked by a sharp decrease in gamma values. The gamma values of the argillaceous middle Bisher are elevated relative to the lower and upper Bisher. In general, the gamma values steadily decrease up-section in the upper Bisher. The argillaceous middle Bisher interval is nearly absent in Adams County, but is much thicker in Scioto County. Since the overall thickness of the Bisher Formation is similar in both locations, the difference in relative thickness of each of

the members is likely due to depositional facies variation. Adams County was under shallower conditions and was farther away from sediment sources than Scioto County, which would favor carbonate deposition.

Regional Correlation

Subsurface correlations at a member- to submember-scale were possible across the entire study area, in both carbonate-rich and clastic-rich depositional environments (plates 1–5). The gamma signatures of the units in Adams County are useful for correlations into shallower, more carbonate-dominated environments in the northern part of the study area (for example, see plate 2), and the geophysical log from the Aristech #4 well is useful for correlations in deeper environments with more clastic influence (plate 1). The units marking most of the sequence boundaries of Brett and Ray (2005) can be reliably

identified based on geophysical logs, and provide helpful guides for distinguishing the units within each sequence in different depositional environments.

Sequence I

The sharp decrease in gamma values from the Drakes Formation to the lower values of the Centerville Formation or Whirlpool Sandstone is a consistent marker throughout the study region (plates 1–5). The Centerville is a relatively thin, non-distinct formation that is mostly characterized by gamma values that decrease up-section. The Whirlpool Sandstone is also characterized by low gamma values, and can be distinguished from the Centerville by its bulk-density. With carbonates or siltstones, such as the Centerville, the trend of bulk density values will be opposite that of gamma values: when gamma values decrease, bulk density values will usually increase (see plate 1, wells 2, 3, and 6 for examples). Conversely, bulk density values of sandstones generally track the gamma values (see plate 1, wells 8–12 for examples). The contact between the Centerville and overlying Belfast Member is often subtle, but can usually be distinguished by the higher density of the Belfast A bed. The Centerville correlates to the Whirlpool in the northeastern half of the study area. The correlation is direct, because both the Centerville and Whirlpool are underlain by the Drakes Formation and appear, based on gamma-ray and bulk density trends, to be overlain by the Belfast in all parts of the study region (plates 1–5). Based on gamma-ray, bulk density, and occasional photoelectric factor curves, it appears that the Whirlpool is entirely sandstone in most parts of the study area, except in western Athens County (plate 1, wells 11, 12; plate 5, wells 2–6) and northeast Meigs County (plate 1, wells 9, 10; plate 4, wells 8, 9), where the uppermost part of the Whirlpool is argillaceous to shaly.

In some parts of the study area there is no distinct contact between the clean Belfast A and the more argillaceous Belfast B beds. Instead, the Belfast Member shows a general increasing trend in gamma values from bottom to top. The gradual “fining upward” trend is mostly consistent in the more clastic-dominated part of the study area to the northeast, though a pronounced contact is occasionally present (see northeastern parts of plates 1 and 2; plate 5). Overall, the gamma values of the Belfast generally increase to the northeast.

The lower massive Brassfield is characterized by very low gamma values and high density in the southwestern part of the study area. The unit becomes thinner towards the northeast, and higher gamma values indicate that it is more argillaceous (plate 1, note the decreasing thickness and increasing gamma values from the southwest towards the northeast), though it can still be distinguished from the underlying Belfast Member and overlying thin bedded Brassfield. The thin-bedded Brassfield becomes much thinner and more consistently argillaceous from the outcrop in Adams County and the core in Scioto County to the northeast. In most of Meigs and Athens Counties,

the gamma values of the thin-bedded Brassfield are the nearly identical to the overlying upper shaly Brassfield. In areas where the gamma values are similar, the top of the thin bedded Brassfield was placed at distinctive increases of bulk density that likely indicate higher carbonate content relative to the overlying upper shaly Brassfield. The combined thickness of the lower massive, thin bedded, and shaly Brassfield is roughly the same throughout the entire study area, but the thicknesses of each member changes relative to the other members. The upper shaly Brassfield becomes much thicker in the northeastern part of the study area, where the lower massive and thin bedded Brassfield are thin. The upper shaly Brassfield is thinner in areas where the lower massive and thin bedded Brassfield are thicker (plates 3–5, note thickness trends along depositional-dip). Throughout most of the study area, the upper shaly Brassfield more closely resembles that from the Aristech Core than the upper shaly Brassfield of Adams County.

Brett and Ray (2005) considered the Belfast Member to be equivalent to the Whirlpool Sandstone, and thus the basal unit of sequence I (as currently defined). They did not separate out the Centerville from the Belfast, and subsurface correlations indicate that the entire Belfast Member overlies the Whirlpool Sandstone. Therefore, the basal unit of sequence I in Ohio, as presently defined, is the Centerville Formation, and the Belfast Member likely correlates to at least part of the Power Glen Shale of New York (fig. 4). The Belfast interval in the study region does not become shaly enough to have gamma values as high as those of the Power Glen Shale. The cross section of Ryder (2000) does extend from southeastern Ohio to New York, and it appears that the Belfast can be traced to the Power Glen Shale. In the study region, the Clinton sand interval appears to correlate to the upper shaly Brassfield (plates 1–5, fig. 4), which generally corresponds to the correlations of Brett and Ray (2005) for the remaining units of sequence I.

The recent recovery of Ordovician chitinozoans and acritarchs from the Whirlpool Sandstone and Power Glen Shale (Schroer and others, 2016), assuming that they are not reworked, and the presence of the HICE in the Manitoulin necessitates a reinterpretation of sequence I of Brett and Ray (2005) in both New York and Ohio. If the correlations of the Centerville Formation to the Whirlpool Sandstone and the Belfast Member to the Manitoulin-Power Glen Shale are correct, then there likely is a significant unconformity or depositional hiatus between the Belfast Member and the lower massive member of the Brassfield, and this contact may represent the actual Ordovician/Silurian boundary. Based on the chronostratigraphic interpretations of Brett and others (2014) and Sullivan and others (2016), who place the upper part of the Belfast Member in the Rhuddanian, there is an approximately 2 my gap between the Belfast Member and the lower massive Brassfield. If the Belfast is indeed Hirnantian, as indicated by subsurface correlations to the Manitoulin Formation and

Power Glen Shale, then the amount of missing time is even greater. There is no reason why a depositional sequence cannot occur over a systemic boundary, but an internal unconformity spanning the majority of the total duration of the sequence (based on the chronostratigraphy of Sullivan and others, 2016) necessitates extensive reinterpretation. The Centerville and Belfast Member, and their correlative units in New York should be removed from sequence I of Brett and others (1990). A new sequence notation is necessary for the Centerville/Belfast and the equivalent Manitoulin/Whirlpool/Power Glen interval. Following the third-order sequence notation of Holland and Patzkowsky (1996) for Ordovician strata of eastern North America (for example, C1 for the first sequence of the Cincinnati Stage), the notation "H1" should be used Centerville/Belfast and Manitoulin/Whirlpool/Power Glen interval to reflect their Hirnantian position.

Sequence II

The Rose Run iron ore (upper massive Brassfield) is, in general, a consistent marker for the base of sequence II in southern and southeastern Ohio. The relatively high gamma signature of the Rose Run iron ore throughout the study area is more similar to values from Scioto County, where the unit is consistently argillaceous, than the low gamma values from Adams County, where the unit contains beds of fairly clean carbonate interbedded with thin shales. The gamma signature of the typical Rose Run iron ore in the study area is subtle, so it is difficult to identify the unit based solely on gamma curves. The density characteristics of the Rose Run iron ore are the most useful features for identification. Where iron rich, the unit produces a very sharp spike in bulk density values that is extremely useful for correlation (see plate 1, well 5–8). Many wells do not have bulk density logs, and the iron-rich nature of the unit appears to be patchy in the subsurface. The density spike is absent or reduced in many parts of the study region (see plate 4, compare bulk density values for the Rose Run iron ore of wells 6–8), which complicates correlations. Where bulk density values were absent or not useful, the boundaries of the Rose Run iron ore were estimated using gamma logs, and characteristics from nearby wells with prominent bulk-density spikes. The thickness of the Rose Run iron ore is very consistent across the entire study area.

The gamma signature of the Plum Creek Shale is variable across the study area. In shallower paleoenvironments the unit contains patchy dolostone interbeds (see plate 1, well 8), and in Scioto and Lawrence Counties, the Plum creek is split by a ten-ft-thick clean sandstone (plate 1, wells 1–3). The thickness of the Plum Creek Shale is widely variable across the study region, ranging in thickness from three ft in Adams County to 25 ft in Athens County. The Oldham Member has a very distinctive gamma signature. In most wells, the gamma values for the unit are low, but with a small shale gamma spike (mid-Oldham shale) in the middle of the unit (for examples, see plate 1, wells 1–3). The relative thickness

of the carbonates above and below the shale change throughout different parts of the study area, which causes the mid-Oldham shale to appear to occur higher or lower in the unit (compare positions of mid-Oldham shale in wells along plate 1). In most places the thickness of the mid-Oldham shale represents much less than a half of the total thickness of the Oldham, but in deeper paleoenvironments it can constitute more than half of total thickness (plate 5, wells 5 and 6). The contact between the Oldham Member and the overlying Lulbegrud Member is represented by a sharp increase in gamma values from the clean upper carbonate of the Oldham Member below to the high gamma values of the Lulbegrud Member above. The thickness of the Lulbegrud Member is very consistent in the southeastern part of the study area, but the unit thins rapidly up-dip (see plates 3–5) where it is removed by the unconformity at the sequence II/sequence III boundary.

Sequence II is composed of two fourth-order transgressive/regressive subsequences in New York (Brett and others, 1990), and that appears to be the case in southern Ohio as well (Brett and Ray, 2005). The Rose Run iron ore and Plum Creek Shale represent a transgressive and regressive couplet that correlates to the Densmore Creek Phosphate Bed and Maplewood Shale of New York. The second subsequence in Ohio is represented by the Oldham Member and Lulbegrud Member, which correspond to the Reynales Limestone and Sodus Shale of New York. Brett and others (1990) include the Wolcott Limestone as the uppermost unit of sequence II in New York, because it and underlying units are truncated by a regionally angular unconformity at the base of sequence III. If the Wolcott does indeed represent the late highstand deposits of sequence II, then there are no equivalent units in Ohio. However, Sullivan and others. (2014a, 2016) reinterpret the Wolcott as a probable transgressive carbonate deposit, which should probably be assigned to the base of Sequence III.

Sequence III

Sequence III is represented by the Waco Member of the Alger Formation in southern and southeastern Ohio. The base of sequence III is marked by the white Waco where present in Adams County, and by the overlying orange Waco where it is absent. The white Waco is absent at the Whippoorwill section in Adams County, and in the Aristech Core in Scioto County. Since the both the white and orange Waco are present in other sections in Adams County, it is possible that a minor unconformity exists between the white and orange Waco, or that the white Waco was deposited only in topographic lows on the Sequence II/III erosive surface. If the tentative identification and correlation of the white Waco in southeastern Ohio is correct, then the Waco Member in Ohio matches the general lithological pattern of the Waco Member in Kentucky. In Kentucky, the white and orange (*Teichichnus* bed) parts of the Waco Member are separated by a thin shale (lower Waco shale, herein), and the orange Waco is overlain by a thicker shale unit (upper Waco shale). The

presence of an unconformity is supported by subsurface correlations from deeper-water paleoenvironments to shallower environments, because orange Waco appears to cut down through the lower Waco shale and white Waco towards Scioto and Adams Counties. Sequence III appears to be composed of two smaller, fourth-order subsequences. The white Waco and the lower Waco shale, and the orange Waco and upper Waco shale each represent transgressive/regressive cycles superimposed on the third-order sequence.

The contact between the upper Waco shale and the overlying shales of the Estill Member is difficult to distinguish based on well log data because it occurs at a shale/shale contact. In both Adams and Scioto Counties, the glauconitic base of the Estill occurs at an inflection point where gamma values start to decrease up section. This inflection point occurs in most wells, and is tentatively used to mark the contact between the upper Waco shale and the Estill Member (dashed line on plates 1–5). If this contact is correct, the upper Waco shale is, in general, slightly more radioactive than the Estill Member, and this characteristic may be a useful characteristic for distinguishing the units in other parts of the basin.

The orange Waco appears to correlate with the Wolcott Furnace Hematite of New York, and the white Waco possibly correlates to the Wolcott Limestone (Sullivan and others 2014a, 2016). The biostratigraphic evidence used to correlate the white Waco and Wolcott Limestone is inconclusive—the white Waco is constrained to the *Pt. eopennatus* Superzone, whereas the brachiopods of the Wolcott Limestone only indicate a general Telychian stratigraphic position. The biostratigraphic data from the two units do not preclude direct correlation, but they don't support a direct correlation either. The correlation of the white Waco to the Wolcott is followed in this report (fig. 4) to remain consistent with the most recent interpretations (Ettensohn and others, 2013; Sullivan and others, 2016).

Sequence IV

Sequence IV is represented by the Estill Member, including probable Dayton Formation equivalents, in southern and southeastern Ohio. Gamma values are consistently high throughout the entire unit, though usually slightly lower than the underlying upper Waco shale. In some areas (plate 2, wells 1–3) the base of the Estill contains some intervals with slightly lower gamma values, likely representing slightly increased carbonate input. This interval with lower gamma values likely correlates to the Dayton Formation of western Ohio, a correlation supported by conodont and carbon isotope evidence (Kleffner, 1987; Cramer, 2009; Kleffner and others, 2012). Brett and Ray (2005) correlate the Estill to, in ascending order, the Second Creek Phosphate Bed, Williamson Shale, and the Rockway Dolomite of New York. The glauconitic zone at the base of the Estill represents slow deposition during sea-level rise, which may correspond to the phosphatic lag deposits of the Second Creek Phosphate

Bed. The Williamson is more radioactive and thinner than the Estill Member of southeastern Ohio. Facies similar to the Rockway Dolomite do not occur in southern Ohio. Brett and Ray (2005) consider the Rockway Dolomite to represent the late Highstand systems tract (deposits during sea-level fall or forced regression). The slightly siltier upper part of the Estill Member also indicates falling sea-level, and likely correlates, at least in part, to the Rockway.

Sequence V

The Bisher Formation comprises sequence V in southern and southeastern Ohio. The gamma values of the unit are highly variable across the study region, and it is often difficult to distinguish from the overlying Lilley Formation. The Bisher generally represents carbonate shoal deposits above storm-weather wavebase, so pronounced lateral facies variation (reflected in highly variable gamma characteristics) is not surprising. In general, though, the three members of the Bisher can be distinguished, and have similar gamma signatures to the Adams County section and the Aristech Core (compare plates 1–5 to fig. 9). The Bisher becomes much thinner and loses the typical elevated gamma values of the middle Bisher in the eastern half of Pike County (plate 2, wells 4–7; plate 3, wells 2–5) and in Ross County (plate 2, well 6; plate 3, well 1). It is possible that this region represents a carbonate shoal that was thicker than those in surrounding regions, where water energy was too high for argillaceous material to settle out during the deposition of the middle Bisher. The Bisher is also atypical in the northeastern part of the study area (plate 1, wells 7–12; plate 4, wells 5–9, plate 5, wells 2–6). The bulk density curves in this area slightly track the gamma curve, which likely indicates fairly thin and calcareous sandstone interbeds. Brett and Ray (2005) correlate the lower part of Bisher Formation to the Keefer Sandstone of Pennsylvania and West Virginia, so the sandstone interbeds in parts of Vinton, Athens, and Meigs Counties likely represent the westernmost extent of the sandstone into southeastern Ohio.

Proposed Nomenclature Revisions

The chronostratigraphic precision that the Silurian units of southern Ohio can be correlated to the well-known reference sections in New York, and throughout the subsurface of southeastern Ohio, is much greater than when these units were first formally defined in the late 1800s. These correlations allow for the recognition of numerous unconformities, including large third-order sequence boundaries, in the middle of some formations as they are currently defined. According to the North American Stratigraphic Code (NACSN, 2005, p. 1,566), time-concepts should be avoided when defining lithostratigraphic units. However, the North American Commission on Stratigraphic Nomenclature also state that “the establishment of formal [lithostratigraphic] units that straddle known, identifiable, regional disconformities is to be avoided, if at all possible.” The accumulation of several

decades of biostratigraphic and chemostratigraphic data combined with the sequence stratigraphic framework of the Appalachian Basin certainly makes it possible to define the lower Silurian units of southern Ohio and Kentucky such that they avoid disconformities. Furthermore, it is beneficial for comparisons to the New York reference sections if chronostratigraphically equivalent units occupy similar stratigraphic ranks.

The following revisions to the stratigraphic nomenclature of southern Ohio (see fig. 1) are recommended. Formal recognition of these units will require further investigation of the lateral extents of these units (including in the subsurface), lithostratigraphic relationships with Silurian units in other parts of the state, and recognition of adequate type sections for revised or newly formalized units.

The Belfast Member should be removed from the Brassfield Formation because a disconformity, likely spanning several million years, separates it from the overlying lower massive Brassfield. The boundary between the Belfast and Brassfield can be distinguished by a sharp change from relatively thin and argillaceous beds to thicker units containing extensive chert stringers and nodules, both of which mark the base of the lower massive Brassfield. The Centerville Formation should be reduced in rank to member status, because it is too thin to be delineated at the scale (1:24,000) of geological mapping in the region (NACSN, 2005, p. 1,567). Assigning the Centerville and Belfast to the same formation is the simplest grouping of the units, because it avoids the Cherokee unconformity between the Centerville member and underlying Drakes Formation, and the unconformity between the Belfast Member and the lower massive Brassfield. There are numerous excellent continuous exposures of both members in south-central Adams County along Ohio State Route 41. The term “Whippoorwill formation” is proposed because the best of these exposures (fig. 10) occurs along Lick Fork Creek east of State Route 41 in the village of Whippoorwill (Whippoorwill section 2; table 2). The creek is accessible behind Lick Fork Church.

The use of the term Drowning Creek Formation should be abandoned in favor of the Noland Formation. As shown in fig. 1, the Drowning Creek Formation, as revised by Sullivan and others (2014a), shares more units in common with the older Noland Formation (Rexroad and others, 1965) than the Drowning Creek Formation of McDowell (1983). Additional stratigraphic revisions to the Rose Run

iron ore and the Lulbegrud Member, proposed herein, are also more similar to the original meaning of the Noland Formation than the Drowning Creek Formation.

The Rose Run iron ore (“upper massive Brassfield”) represents the transgressive deposits of sequence II, and should be removed from the Brassfield Formation to avoid having a sequence boundary within the Brassfield Formation. The Rose Run iron ore should be added to the Noland Formation (as revised herein). In southern Ohio, the unit can be distinguished from the limestone interbeds in underlying upper shaly Brassfield by its hematitic nature and occasional glauconite zones. Additionally, a new name should be adopted for the unit to avoid confusion with the well-known Late Cambrian–Early Ordovician Rose Run Formation.

The Lulbegrud Member (uppermost unit of sequence II in Ohio) should be removed from the Alger Formation and added to the Noland Formation. This re-assignment removes the sequence II/sequence III boundary from within the Alger Formation, and places it in between the Noland and Alger Formations. The contact between the Noland Formation and the Alger Formation occurs at the base of the white Waco when it is present, or the orange Waco when the white Waco is absent. This contact between the Noland Formation and the Alger Formation is obvious where the Waco Member overlies the Lulbegrud Member, but is more difficult to identify when the Waco overlies Oldham Member or the Rose Run iron ore. The white Waco can be distinguished from the Oldham Member or Rose Run iron ore on the basis of color and fossil content including abundant tabulate corals (Sullivan and

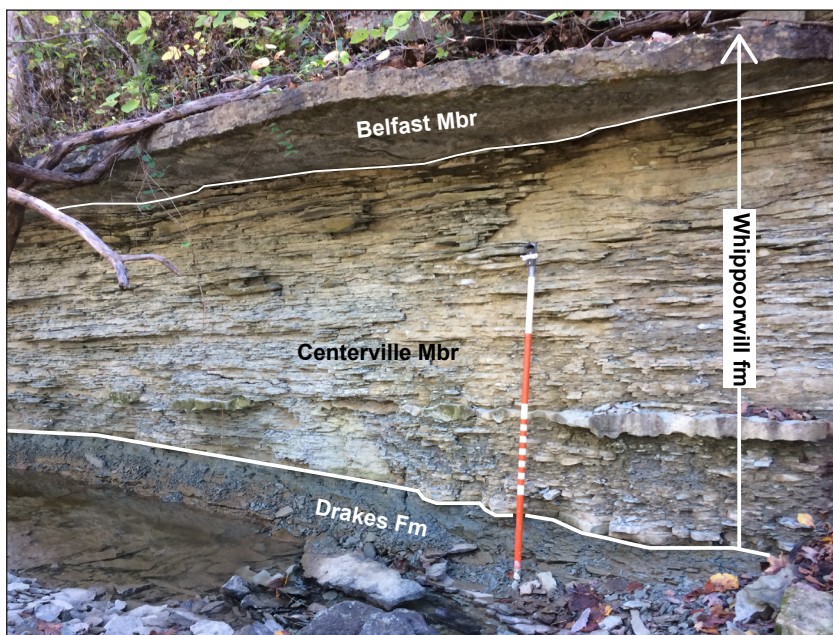


FIGURE 10. Photograph of potential type section for the proposed Whippoorwill formation at section 2 of the Whippoorwill locality. The section is on the east bank of Lick Fork Creek, Adams County. The Belfast A bed is exposed in this photograph. Belfast B beds are partially covered by vegetation, but are fully exposed approximately 15 ft south along the creek. Scale staff = 5 ft.

others, 2014a). The white Waco is very light-colored and crystalline, in contrast to the reddish Oldham Member or Rose Run iron ore. The orange Waco has sparse and poorly preserved fossils and is heavily bioturbated to massive, in contrast to the fossil rich, thin-to-medium bedded, Rose Run iron ore and Oldham Member.

The informal “upper Waco shale” unit of the Waco Member of the Alger Formation is tentatively recognized in Adams County. The upper contact of the unit occurs between the top of a dark red band of shale and bright green, glauconitic shale. If the carbonate unit tentatively correlated as the white Waco in the subsurface (plates 1, 3–5) is indeed the white Waco, then the shale in between the white Waco and the orange Waco represents a fourth informal unit within the Waco Member (see fig. 4). This shale is tentatively termed the “lower Waco shale.” The Alger Formation, as defined herein, still contains a sequence bounding unconformity. The lithological similarity of the upper Waco shale and the Estill Member makes consistent differentiation of the members difficult, particularly in the subsurface, and precludes separation of the units into separate formations.

The Medina and Clinton Groups of New York are recognized in Ohio. Under the proposed revisions, the Whippoorwill and Brassfield formations comprise the Medina Group (fig. 4). In northwestern Ohio, the strata occupying the Medina Group interval are formally recognized as part of the Cataract Group of Ontario by the Ohio Geological Survey (Hull, 1990). Some researchers extend the Cataract Group to the subsurface of eastern and southern Ohio (for example, Janssens, 1977; Wickstrom and others, 2005; Carter and others, 2010; Riley and others, 2011), whereas other researchers, as well as the USGS, assign the strata to the Medina Group (for example, Castle, 2001; Hettinger, 2001). The Cataract Formation of Schuchert (1914) in its type area along the Credit River in Ontario, and the Cataract Group as defined by Brunton (2008), are nearly chronostratigraphically equivalent to the Medina Group of west-central New York (Brett and others, 1990, 1995). Despite their equivalence, the use of “Medina Group” is preferred in the eastern half of Ohio for two reasons. The first is to be consistent with USGS nomenclature conventions in which the Medina is recognized at group level, whereas the Cataract is only recognized at a formation level in Michigan and Indiana (USGS geologic names lexicon). The second is that, in industry, the use of Cataract Group/Formation is generally restricted to the Michigan Basin, (AAPG-COSUNA), and the type areas for two out of the three formations comprising the Cataract Group (Manitoulin Dolomite and Cabot Head Formation) are on the northeast rim of the Michigan Basin. The term “Cataract Group” could still be used in northwest Ohio, which encompasses the southern rim of the Michigan Basin.

The term “Medina Sandstone” of Ohio should be abandoned in favor of the term “Whirlpool Sandstone,”

because it is clearly correlative with the Whirlpool Sandstone of New York, and it is easily distinguishable from the other sandstone units within the Medina Group. Again it should be noted that the “Clinton sands” of Ohio belong to the Medina Group and are not correlative with the Clinton Group of New York; for this reason the use of “Clinton sands” should be avoided where correlation of the New York units (Devils Hole, Grimsby, Thorold, Cambria and Kodak) is possible.

The Noland, Alger, and Bisher Formations comprise the Clinton Group in Ohio (fig. 4). The Clinton Group is often informally divided into lower, middle, and upper parts (for examples, see Gillette, 1947; Brett and others, 1990; LoDuca and Brett, 1994; Brett and others, 1995). Though informal, these subdivisions are useful as allostratigraphic units—the lower Clinton corresponds to sequence II, the middle Clinton to sequence III, and the upper Clinton to sequences IV and V (Brett and others, 1990). In Ohio, the Noland Formation represents the lower Clinton Group. The Waco Member of the Alger Formation represents the middle Clinton Group. The Estill Member of the Alger Formation and the Bisher Formation collectively represent the upper Clinton Group.

CONCLUSIONS

Advances in stratigraphic techniques and a steady accumulation of chronostratigraphic data over the past few decades allow for subdivision of lower Silurian strata in southern Ohio far more precise than the stratigraphic framework formally recognized and mapped by the U.S. Geological Survey and the Ohio Geological Survey. Over the stratigraphic interval equivalent to the Medina and Clinton Groups, the U.S. Geological Survey recognizes five units and the Ohio Geological Survey recognizes three units, whereas 16 regionally-traceable units can be recognized over the same interval based on updated chronostratigraphic information. These 16 members, submembers, and beds of southern Ohio can be grouped into a broader-scale stratigraphic hierarchy that is chronostratigraphically meaningful as well as lithostratigraphically divisible. Under the proposed revisions, the Brassfield, Noland, and Bisher Formations will each represent one 3rd-order sequence, and the Alger Formation will represent two 3rd-order sequences.

Regardless of larger-scale stratigraphic hierarchy, all of the 16 units observable in outcrop can be traced throughout the subsurface of southern and southeastern Ohio—a vast improvement in precision over traditional subsurface units from the same stratigraphic interval. Recognizing the units from Adams County in the subsurface allows the drillers’ terms and incorrectly applied New York and Ontario units to be placed in proper stratigraphic context. The “Rochester Shale” in the subsurface of southern/southeastern Ohio generally corresponds to the Lulbeugrud Member through Estill Member, or the upper Waco shale through the Estill

Member. The “Packer Shell” usually corresponds to the Oldham Member where the Lulbegrud is present, and the Oldham through the white/orange Waco where the Lulbegrud is absent. The upper Cabot Head Shale corresponds to the Plum Creek down to the top of the stray Clinton or red Clinton sands, depending on if the “stray Clinton” is present or not. The various “Clinton sands” intertongue with strata correlative lithostratigraphically to the upper shaly Brassfield. The chronostratigraphic correlation of individual “Clinton sands” units to the members of the Brassfield is uncertain, but they generally appear to span the same interval as the thin-bedded and upper shaly Brassfield. The lower Cabot Head Shale spans from the top of the Brassfield up to the lowest “Clinton sand” in regions where the Whirlpool Sandstone is absent. Where the Whirlpool Sandstone is present, the lower Cabot Head Shale extends from the top of the Whirlpool to the base of the lowermost “Clinton sand” and appears to be equivalent to the Power Glen Shale of western New York and southern Ontario.

ACKNOWLEDGMENTS

The technical and stylistic reviews of Michael Solis, Paul Spahr, and Chuck Salmons are greatly appreciated. Dr. Carlton Brett provided valuable assistance in the field, and provided a very thorough and helpful external review of the manuscript. Funding for this research was provided by the Ohio minerals severance tax.

REFERENCES

- Bergström, S.M., Kleffner, M.A., Schmitz, Birger; and Cramer, B.D., 2011, Revision of the Ordovician-Silurian boundary in southern Ontario: regional chronostratigraphic implications of $\delta^{13}\text{C}$ chemostratigraphy of the Manitoulin Formation and associated strata: *Canadian Journal of Earth Science*, v. 48, no. 11, p. 1447–1470.
- Berry, W.B.N., and Boucot, A.J., 1970, Correlation of the North American Silurian rocks: Boulder, Colo., Geological Society of America Special Paper 102, 289 p.
- Blakey, R.C., 2013, Key time slices of North American geologic history: Colorado plateau Geosystems, Inc.
- Boucot, A.J., Chen Xu, and Scotese, C.R., 2013, Phanerozoic Paleoclimate: An Atlas of Lithologic Indicators of Climate *in*, Nichols, G.J. and Ricketts, Brian, eds., *Concepts in Sedimentology* No. 11: Tulsa, Okla., Society for Sedimentary Geology (SEPM), 478 p.
- Boulila, Slah; Galbrun, Bruno; Miller, K.G., Pekar, S.F., Browning, J.V., Laskar, Jaques, and Wright, J.D., 2011, On the origin of Cenozoic and Mesozoic “third-order” eustatic sequences: *Earth-Science Reviews*, v. 109, p. 94–112.
- Branson, E.B., and Branson, C.C., 1947, Lower Silurian conodonts from Kentucky: *Journal of Paleontology*, v. 21, no. 6, p. 549–556.
- Brett, C.E., Baarli, B.G., Chowns, T., Cotter, E., Driese, S., Goodman, W.M., and Johnson, M.E., 1998, Early Silurian condensed intervals, ironstones, and sequence stratigraphy in the Appalachian foreland basin, *in* Landing, E. and Johnson, M.E., eds., *Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes*: Albany, New York, New York State Museum Bulletin 491, p. 89–143.
- Brett, C.E., Cramer, B.D., McLaughlin, P.I., Kleffner, M.A., Showers, W.J., and Thomka, J.R., 2012, Revised Telychian-Sheinwoodian (Silurian) of the Laurentian mid-continent—building uniform nomenclature along the Cincinnati Arch: *Bulletin of Geosciences*, v. 87, no. 4, p. 733–753.
- Brett, C.E., Goodman, W.M., and LoDuca, S.T., 1990, Sequences, cycles, and basin dynamics in the Silurian of the Appalachian Foreland Basin. *Sedimentary Geology*, v. 69, no. 3–4, p. 191–244.
- Brett, C.E. and Ray, D.C., 2005, Sequence and event stratigraphy of Silurian strata of the Cincinnati Arch region—Correlations with New York-Ontario successions: *Proceedings of the Royal Society of Victoria*, v. 117, no. 2, p. 175–198.
- Brett, C.E., Tepper, D.H., Goodman, W.M., LoDuca, S.T., and Eckert, Bea-Yeh, 1995, Revised stratigraphy and correlations of the Niagaran Provincial Series (Medina, Clinton, and Lockport Groups) in the type area of western New York: Reston, Virg., U.S. Geological Survey Bulletin 2086, 66 p.
- Brett, C.E., Thomka, J.R., Sullivan, N.B., and McLaughlin, P.I., 2014, Anatomy of a compound sequence boundary—A karstic unconformity in the Cincinnati Arch region: *GFF*, v. 136, no. 1, p. 42–47.
- Brunton, F.R., 2009, Update of revisions to the early Silurian stratigraphy of the Niagara Escarpment—integration of sequence stratigraphy, sedimentology, and hydrogeology to delineate hydrogeologic units, *in* Summary of Field Work and Other Activities, 2009: Ontario Geological Survey, Open File Report 6240, p. 25–1–25–20.
- Brunton, F.R., and Brintnell, Candace, 2011, Final update of early Silurian stratigraphy of the Niagara Escarpment and correlation with subsurface units across southwestern Ontario and the Great Lakes Basin, *in*, Easton, R.M., Burnham, O.M., and (6) others, eds., *Summary of Field Work and Other Activities 2011: Sudbury, Ontario*, Ontario Geological Survey Open File Report 6270, p. 30–1–30–11.
- Bush, R.M., and Rollins, H.B., 1984, Correlation of Carboniferous Strata using hierarchy of transgressive-regressive units: *Geology*, v. 12, no. 8, p. 471–474.
- Carter, K.M., Kostelnik, Jaime; Laughrey, C.D., and (14) others, 2010, Characterization of geologic sequestration opportunities in the MRCSP Region; Middle Devonian-middle Silurian formations—Phase I task report: Columbus, Ohio, Battelle Memorial Institute, MRCSP Phase II deliverable for Department of Energy grant DE-FC26-05NT42589, 350 p., accessible at <http://www.mrcsp.org/phase-ii-geologic-reports>.
- Cooper, B.J., 1975, Multielement conodonts from the Brassfield Limestone (Silurian) of southern Ohio: *Journal of Paleontology*, v. 49, no. 6, p. 984–1008.
- Cramer, B.D., 2009, Application of integrated high-resolution biochemostratigraphy to Paleozoic chronostratigraphic correlation—recalibrating the Silurian system: Ph. D. dissertation, Ohio State University, 289 p.
- Cramer, B.D., Brett, C.E., Melchin, M.J., Männick, Peep; Kleffner, M.A., McLaughlin, P.I., Loydell, D.K., Munnecke, Axel; Jeppsson, Lennart; Corradini, Carlo; Brunton, F.R.,

- and Saltzman, M.R., 2011, Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphy: *Lethaia*, v. 44, p. 185–202.
- Cramer, B.D., Kleffner, M.A., Brett, C.E., McLaughlin, P.I., Jeppsson, Lennart; Munecke, Axel; Samtleben, Christian, 2010, Paleobiogeography, high-resolution stratigraphy, and the future of Paleozoic biostratigraphy—Fine-scale diachroneity of the Wenlock (Silurian) conodont *Kockelella walliseri*: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 294, p. 232–241.
- Davies, J.R., Waters, R.A., Molyneux, S.G., Williams, Mark; Zalasiewicz, J.A., and Vandenbroucke, T.R.A., 2016, Gauging the impact of glacioeustasy on a mid-latitude early Silurian basin margin, mid Wales, UK: *Earth-Science Reviews*, v. 156, p. 82–107.
- Davies, J.R., Waters, R.A., Molyneux, S.G., Williams, Mark; Zalasiewicz, J.A., Vandenbroucke, T.R.A., and Verniers, Jacques, 2013, A revised sedimentary and biostratigraphical architecture for the Type Llandovery area, central Wales: *Geological Magazine*, v. 150, no. 2, p. 300–332.
- Dennison, J.M., and Head, J.W., 1975, Sea-level variations interpreted from the Appalachian Basin Silurian and Devonian: *American Journal of Science*, v. 275, p. 1,089–1,120.
- Doveton, J.H., and Merriam, D.F., 2004, Borehole petrophysical chemostratigraphy of Pennsylvanian black shales in the Kansas subsurface: *Chemical Geology*, v. 206, no. 3–4, p. 249–258.
- Ellis, D.V., and Singer, J.M., 2008, *Well Logging for Earth Scientists*: New York, Springer, 699 p.
- Ettensohn, F.R., 2008, Appalachian foreland basin in eastern United States *in*, Miall, Andrew, ed., *The Sedimentary Basins of the United States and Canada, Volume 5*: New York, Elsevier, p. 105–179.
- Ettensohn, F.R., and Brett, C.E., 1998, Tectonic components in third order Silurian cycles: Examples from the Appalachian Basin and global implications, *in* Landing, E., ed., *New York State Museum Bulletin 491*, p. 143–162.
- Ettensohn, F.R., and Brett, C.E., 2002, Stratigraphic evidence from the Appalachian Basin for continuation of the Taconian orogeny into Early Silurian time: *Physics and Chemistry of the Earth*, v. 27, p. 279–288.
- Ettensohn, F.R., Lierman, R.T., Mason, C.E., Andrews, W.M., Hendricks, R.T., Phelps, D.J., and Gordon, L.A., 2013, The Silurian of central Kentucky, U.S.A.—Stratigraphy, palaeoenvironments, and palaeoecology: *Memoirs of the Association of Australasian Paleontologists*, v. 44, p. 159–189.
- Finnegan, Seth; Heim, N.A., Peters, S.E., and Fischer, W.W., 2012, Climate change and the selective signature of the Late Ordovician mass extinction: *Proceedings of the National Academy of Sciences*, v. 109, no. 18, p. 6829–6834.
- Foerste, A.F., 1897, A report on the geology of the Middle and Upper Silurian rocks of Clark, Jefferson, Ripley, Jennings, and southern Decatur counties, Indiana: Indianapolis, Ind., Indiana Department of Geology and Natural Resources Annual Report 21, p. 212–288.
- Foerste, A.F., 1906, The Silurian, Devonian and Irvine Formations of east-central Kentucky, with an account of the clays and limestones: Lexington, Ky., Kentucky Geological Survey Bulletin 7, 269 p.
- Foerste, A.F., 1931, The Silurian fauna of Kentucky, *in*, Jilison, W.R., ed., *Paleontology of Kentucky*: Frankfort, Kentucky, The Kentucky Geological Survey, p. 167–212.
- Foerste, A.F., 1935, Correlation of Silurian formations in southwestern Ohio, southeastern Indiana, Kentucky, and Tennessee: *Bulletin of the Scientific Laboratories of the University of Denison* No. 30, p. 119–205.
- Gillette, Tracy, 1947, The Clinton of western and central New York: Albany, N.Y., New York State Museum Bulletin 341, 191 p.
- Goodman, W.M. and Brett, C.E., 1994, Tectonic vs. eustatic controls on the stratigraphic architecture of the Silurian northern Appalachian Basin, *in* Dennison, J.M. and Ettensohn, F.M. eds. *Society of Economic Paleontologists and Mineralogists. Special Publication, Concepts in Sedimentology and Paleontology*, 4.
- Grahn, Yngve, and Bergström, S.M., 1985, Chitinozoans from the Ordovician-Silurian boundary beds in the eastern Cincinnati region in Ohio and Kentucky: *Ohio Journal of Science*, v. 85, no. 4, p. 175–183.
- Hall, James, 1852, *Palaeontology of New York Volume II—Containing descriptions of the organic remains of the lower middle division of the New-York System, equivalent in part to the Middle Silurian rocks of Europe*: Albany, N.Y., C. Van Benthuysen, 784 p.
- Hall, James, 1860, Descriptions of new species of fossils from the Silurian rocks of Nova Scotia: *Canadian Naturalist and Geologist*, v. 5, p. 144–159.
- Hays, J.D., Imbrie, John, Shackleton, N.J., 1976, Variations in the Earth's orbit—Pacemaker of the Ice Ages: *Science*, v. 194, no. 4270, p. 1,121–1,132.
- Heckel, P.H., 1994, Evaluation of evidence for glacio-eustatic control over marine Pennsylvanian cyclothems in North America and consideration of possible tectonic effects, *in* Dennison, J.M., and Ettensohn, F.R., eds., *Tectonic and eustatic controls on sedimentary cycles: Society for Sedimentary Geology (SEPM), Concepts in Sedimentology and Paleontology* No. 4, p. 65–87.
- Heckel, P.H., 2008, Carboniferous Period, *in* Ogg, J.G., Ogg, G., and Gradstein, F.M., eds., *The concise geologic time scale*: Cambridge, U.K., Cambridge University Press, 177 p.
- Helfrich, C.T., 1975, Silurian conodonts from the Wills Mountain Anticline, Virginia, West Virginia, and Maryland: *Geological Society of America Special Paper 161*, 82 p.
- Hettinger, R.D., 2001, Subsurface correlations and sequence stratigraphic interpretations of Lower Silurian strata in the Appalachian basin of northeast Ohio, southwest New York, and northwest Pennsylvania: U.S. Geological Survey Geologic Investigations Series Map I-2741, 1 sheet, scale about 1:2,000,000, text 22 p.
- Holland, S.M., and Patzkowsky, M.E., 1996, Sequence stratigraphy and long-term lithologic change in the Middle and Upper Ordovician of the eastern United States, *in*, Witzke, B.J., Ludvigsen, G.A., and Day, J., eds., *Paleozoic Sequence Stratigraphy—Views from the North American Craton*: Boulder, Colo., Geological Society of America Special Paper 306, p. 117–130.

- Horvath, A.L., 1964, Stratigraphy of the Silurian rocks of southern Ohio and adjacent parts of West Virginia, Kentucky, and Indiana: Columbus, Ohio, Ph. D. dissertation, The Ohio State University, 155 p.
- Horvath, A.L., 1967, Relationships of lower Silurian strata in Ohio, West Virginia, and northern Kentucky: The Ohio Journal of Science, v. 67, no. 6, p. 341–359.
- Horvath, A.L., 1969, Relationships of middle Silurian strata in Ohio and West Virginia: The Ohio Journal of Science, v. 69, no. 6, p. 321–342.
- Huddle, J.W., 1967, Silurian conodonts from Kentucky: U.S. Geological Survey Professional Paper 575-A, p. A116.
- Hull, D.N., 1990, revised by Larsen, G.E., 2000, and Slucher, E.R., 2004, Generalized column of bedrock units in Ohio: Columbus, Ohio, Department of Natural Resources, Division of Geological Survey, 1p.
- Janssens, Adriaan, 1977, Silurian rocks in the subsurface of northwestern Ohio: Columbus, Ohio, Ohio Department of Natural Resources, Division of Geological Survey, Report of Investigations 100, 96 p.
- Johnson, M.E., 2006, Relationship of Silurian sea-level fluctuations to oceanic episodes and events: GFF, v. 128, no. 2, p. 115–121.
- Jenkins, W.A.M., 1970, Chitinozoa from the Ordovician Sylvan Shale of the Arbuckle Mountains, Oklahoma: Palaeontology, v. 13, p. 261–288.
- Kleffner, M.A., 1985, Conodont biostratigraphy of the stray “Clinton” and “Packer Shell” (Silurian, Ohio subsurface) and its bearing on correlation: Columbus, Ohio, Ohio Geological Society—The New Clinton Collection, p. 219–230.
- Kleffner, M.A., 1987, Conodonts of the Estill Shale and Bisher Formation (Silurian, southern Ohio)—Biostratigraphy and distribution: The Ohio Journal of Science, v. 87, n. 3, p. 78–79.
- Kleffner, M.A., Bergström, S.M., and Schmitz, B., 2005, Revised chronostratigraphy of the Ordovician/Silurian boundary interval in eastern Iowa and northeastern Illinois based on $\delta^{13}\text{C}$ chemostratigraphy: Iowa Geological Survey Guidebook Series, v. 24, p. 46–49.
- Kleffner, M.A., Cramer, B.D., Brett, C.E., Mikulic, D.G., Kluessendorf, Joanne, Johnson, and Thomas, 2012, Lower Silurian of western Ohio—The case of the disappearing Dayton, and unique Midwestern co-occurrence of pentamerid brachiopods with the Gravalymene celebra trilobite association in the Springfield Formation, in Sandy, M.R., and Goldman, Daniel, eds., On and Around the Cincinnati Arch and Niagara Escarpment—Geological Field Trips in Ohio and Kentucky for the GSA North-Central Section Meeting, Dayton, Ohio: Boulder, Colo., Geological Society of America, p. 1–18.
- Kump, L.R., Arthur, M.A., Patzkowsky, M.E., Gibbs, M.T., Pinkus, D.S., and Sheehan, P.M., 1999, A weathering hypothesis for glaciation at high atmospheric pCO_2 during the Late Ordovician: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 152, p. 173–187.
- LoDuca, S.T., and Brett, C.E., 1994, Revised stratigraphic and facies relationships of the lower part of the Clinton Group (middle Llandoveryan) of western New York State, in Landing, Ed, ed., Studies in Paleontology in Honor of Donald W. Fisher: New York State Museum Bulletin 481, p. 161–182.
- Miall, A.D., 2010, The Geology of Stratigraphic Sequences: Berlin, Springer Link, 522 p.
- Männik, Peep, 1992, Taxonomy of the conodont species Ozarkodina polinclinata (Nicoll et Rexroad) in the Silurian of Estonia: Proceedings of the Estonian Academy of Science, Geology, v. 41, p. 54–62.
- Männick, Peep, 1998, Evolution and taxonomy of the Silurian conodont *Pterospirifer*: Palaeontology, v. 41, p. 1001–1050.
- Männik, Peep, 2007, An updated Telychian (Late Llandovery, Silurian) conodont zonation based on Baltic faunas: Lethaia, v. 40, no. 1, p. 45–60.
- McAdams, N.E.B., Bancroft, A.M., Cramer, B.D., and Witzke, B.J., 2017, Integrated carbon isotope and conodont biochemostratigraphy of the Silurian (Aeronian–Telychian) of the East-Central Iowa Basin, Iowa, USA: Newsletters on Stratigraphy, v. 50, p. 391–416.
- McDowell, R.C., 1983, Stratigraphy of the Silurian outcrop belt on the east side of the Cincinnati Arch in Kentucky, U.S. Geological Survey Professional Paper 1151-F, 2 plates, 27 p.
- McLaughlin, P.I., Cramer, B.D., Brett, C.E., and Kleffner, M.A., 2008, Silurian high-resolution stratigraphy on the Cincinnati Arch: Progress on recalibrating the layer-cake, in Maria, A.H. and Counts, R.C., eds., From the Cincinnati Arch to the Illinois Basin: Geological Field Excursions along the Ohio River Valley: Boulder, Colo., Geological Society of America Field Guide 12, p. 119–180.
- McLaughlin, P.I., Emsbo, Poul; Brett, C.E., 2012, Beyond black shales—the sedimentary and stable isotope records of oceanic anoxic events in a dominantly oxic basin (Silurian; Appalachian Basin, USA): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 367–368, p. 153–177.
- Melchin, M.J., Sadler, P.M., and Cramer, B.D., 2012, Chapter 21—The Silurian Period, in, Gradstein, F., Ogg, J., Schmitz, M., and Ogg, G., eds., The Geologic Time Scale 2012: New York, Elsevier, p. 525–588.
- Munnecke, Axel; Calner, Mikael; Harper, D.A.T., Servais, Thomas, 2010, Ordovician and Silurian seawater chemistry, sea level, and climate: A synopsis: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 296, p. 389–413.
- Munnecke, Axel; Männick, Peep, 2009, New biostratigraphic and chemostratigraphic data from the Chicotte Formation (Llandovery, Anticosti Island, Laurentia) compared with the Viki core (Estonia, Baltica): Estonian Journal of Earth Sciences, v. 3, p. 159–169.
- NACSN (North American Commission on Stratigraphic Nomenclature), 2005, North American Stratigraphic Code: AAPG Bulletin, v. 89, no. 11, p. 1,547–1,591.
- Nestor, V., 1980, Middle Llandoveryan chitinozoans from Estonia: Eesti NSV Teaduste Akadeemia, Keemia Geoloogia, v. 29, p. 136–141.
- Nicoll, R.S., and Rexroad, C.B., 1968, Stratigraphy and conodont paleontology of the Salamonie Dolomite and Lee Creek member of the Brassfield Limestone (Silurian) in southeastern Indiana and adjacent Kentucky: Bloomington,

- Ind., Indiana Geological Survey Bulletin 40, 73 p.
- Orton, E.F.B., 1870, Part III—Report on geology of Montgomery County: Columbus, Ohio, Ohio Division of Geological Survey Report of Progress for 1869, p. 139–164.
- Orton E.F.B., 1871, The geology of Highland County: Columbus, Ohio, Ohio Division of Geological Survey Report of Progress for 1870, p. 253–310.
- Osmond, J.K., and Ivanovich, M., 1992, Uranium-series mobilization and surface hydrology, *in*, Ivanovich, M. and Harmon, R.S., eds., *Uranium-Series Disequilibrium—Applications to Earth, Marine and Environmental Sciences*: Oxford, U.K., Clarendon Press, p. 259–289.
- Pollock, C.A., Rexroad, C.B., and Nicoll, 1970, Lower Silurian conodonts from northern Michigan and Ontario: *Journal of Paleontology*, v. 44, p. 743–764.
- Rexroad, C.B., 1967, Stratigraphy and conodont paleontology of the Brassfield (Silurian) in the Cincinnati Arch area and adjacent states: Bloomington, Ind., Indiana Geological Survey Bulletin 36, 64 p.
- Rexroad, C.B., Branson, E.R., Smith, M.O., Summerson, C.H., and Boucot, A.J., 1965, The Silurian formations of east-central Kentucky and adjacent Ohio: *Kentucky Geological Survey Bulletin* 10, no. 2, 34 p.
- Rexroad, C.B., and Nicoll, R.S., 1971, Summary of conodont biostratigraphy of the Silurian System of North America, *in*, Sweet, W.C., and Bergström, S.M., eds., *Symposium on Conodont Biostratigraphy*: Boulder, Colo., Geological Society of America Memoir 127, p. 207–225.
- Riley, R.A., Baranoski, M.T., and Wickstrom, L.H., 2004, Oil and gas fields map of Ohio: Columbus, Ohio, Ohio Division of Geological Survey PG-1, scale 1:500,000.
- Riley, R.A., Wicks, J.L. and Perry, C.J., 2011, Silurian “Clinton” sandstone reservoir characterization for evaluation of CO₂-EOR potential in the East Canton Oil Field, Ohio: Columbus, Ohio, Ohio Department of Natural Resources, Division of Geological Survey.
- Ryder, R.T., 2000, Stratigraphic framework and depositional sequences in the lower Silurian regional oil and gas accumulation, Appalachian Basin—from Jackson County, Ohio, through northwestern Pennsylvania, to Orleans County, New York: Reston, Virg., U.S. Geological Survey Miscellaneous Investigation Series Map I-2726, 2 sheets, 8 p. text.
- Ryder, R.T., 2006, Stratigraphic framework and depositional sequences in the lower Silurian regional oil and gas accumulation, Appalachian Basin—from Licking County, Ohio to Fayette County, West Virginia: Reston, Virg., U.S. Geological Survey Scientific Investigations Map 2916, 2 sheets.
- Ryder, R.T., Crangle, R.D., Trippi, M.H., Swezey, C.S., Lentz, E.E., Rowan, E.L., and Hope, R.S., 2009, Geologic cross section D–D’ through the Appalachian Basin from the Findlay Arch, Sandusky County, Ohio, to the Valley and Ridge Province, Hardy County, West Virginia: U.S. Geological Survey Scientific Investigations Map 3067, 2 sheets, 52 p. text.
- Saltzman, M.R., and Young, S.A., 2005, Long-lived glaciation in the Late Ordovician? Isotopic and sequence-stratigraphic evidence from western Laurentia: *Geology*, v. 33, no. 2, p. 109–112.
- Schröer, Laurenz; Vandenbroucke, T.R.A., Hints, Olle; Steeman, Thomas; Verniers, Jacques; Brett, C.E., Cramer, B.D., and McLaughlin, P.I., 2016, A Late Ordovician age for the Whirlpool and Power Glen formations, New York: *Canadian Journal of Earth Sciences*, v. 53, n. 7, p. 739–747.
- Schuchert, Charles, 1914, Medina and Cataract Formations of the Siluric of New York and Ontario: U.S. Geological Survey Bulletin, v. 45, p. 277–320.
- Slucher, E.R. (principal compiler), Swinford, E.M., Larsen, G.E., and others, with GIS production and cartography by Powers, D.M., 2006, Bedrock geologic map of Ohio: Columbus, Ohio, Ohio Division of Geological Survey Map BG-1, version 6.0, scale 1:500,000.
- Sullivan, N.B., Brett, C.E., McLaughlin, P.I., Kleffner, M.A., Cramer, B.D., 2014a, Correlation of the Waco Member of the Alger Shale Formation (Silurian; Llandovery; Telychian) in east-central Kentucky and south-central Ohio: *GFF*, v. 136, no. 1, p. 254–258.
- Sullivan, N.B., Kleffner, M.A., Brett, C.E., 2014b, Conodont biostratigraphy, paleoecology, and taphonomy of the Second Creek Bed and Wolcott Furnace Hematite (Clinton Group) in west central New York State: *Palaeontologia Electronica*, v. 17, iss. 1, p. 1–19.
- Sullivan, N.B., McLaughlin, P.I., Brett, C.E., Cramer, B.D., Kleffner, M.A., Thomka, J.S., Emsbo, Poul., 2016, Sequence boundaries and chronostratigraphic gaps in the Llandovery of Ohio and Kentucky—The record of early Silurian paleoceanographic events in east-central North America: *Geosphere*, v. 12, no. 6, p. 1–20.
- Torsvik, T.H., Cocks, R.M., 2013, New global palaeogeographical reconstructions for the Early Palaeozoic and their generation: *Geological Society Memoirs*, v. 38, p. 5–24.
- Thomka, J.R., and Brett, C.E., 2017, Insights into the taxonomy and paleoecology of the ‘bead bed’ crinoid (Echinodermata: Crinoidea) based on new material from the Lower Silurian Brassfield Formation of east-central Kentucky: *Palaios*, v. 32, p. 762–768.
- Vail, P.R., Mitchum, R.M., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubbs, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level: American Association of Petroleum Geologists Memoir 26, p. 49–212.
- Vandenbroucke, T.R.A., Emsbo, P., Munnecke, A., Nuns, N., Duponchel, L., Lepot, K., Quijada, M., Paris, F., Servais, T., and Kiessling, W., 2015, Palaeozoic plankton are harbingers of mass extinction: *Nature Communications*, v. 6.7966, 7#p. DOI: 10.1038/ncomms8966
- Van Staal, C.R., Dewey, J.F., Miocail, C. M., McKerrow, and McKerrow, W.S., 1998, The Cambrian–Silurian tectonic evolution of the northern Appalachians and the British Caledonides—History of a complex, west and southwest Pacific-type segment of Iapetus, *in*, Blundell, D.J., and Scott, A.C., eds., *Lyell—The past is the key to the present*: Geological Society Special Publication 143, p. 199–242.
- Vanuxem, Lardner, 1842, *Geology of New York—Part III, Survey of the third geological district*: Albany, N.Y., New

- York State Museum, 306 p.
- Verniers, Jacques; Van de Moortel, I., Steeman, T., Mortier, J., Vandenbroucke, T.R.A., Cramer, B.D., and Kleffner, M.A., 2012, The Tryon Park controversy—a combined chitinozoan and conodont restudy, *in*, Cramer, B.D., and Brett, C.E., eds., IGCP 591 Annual Meeting: Cincinnati, Ohio, IGCP Annual Meeting Abstract Volume.
- Waid, C.B.T., and Cramer, B.D., 2017, Global chronostratigraphic correlation of the Llandovery Series (Silurian System) in Iowa, USA, using high-resolution carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) chemostratigraphy and brachiopod and conodont biostratigraphy: *Bulletin of Geosciences*, v. 92, no. 3, p. 373–390.
- Waid, C.B., and Over, D.J., 2015 (print 2016), Aeronian (Llandovery, Silurian) conodonts from the Densmore Creek Phosphate Bed and the Budd Road Phosphate Bed, Clinton Group, western New York State: *Canadian Journal of Earth Sciences*, v. 53, no. 7, p. 645–650.
- Walliser, Otto, 1964, Conodonten des Silurs: *Abhandlungen des Hessischen Landesamtes für Bodenforschung*, v. 41, p. 1–106.
- Wickstrom, L.H., Venteris, E.R., Harper, J.A., and (26) others, 2005, Characterization of geologic sequestration opportunities in the MRCSP Region—Phase I task report: Ohio Department of Natural Resources, Division of Geological Survey Open-File Report 2005-1, 152 p.
- Zeigler, A.M., 1966, The Silurian brachiopod *Eocoelia hemispherica* (J. de C. Sowerby) and related species: *Palaeontology*, v. 9, p. 523–543.
- Zeigler, A.M., Hansen, K.S., Johnson, M.E., Kelly, M.A., Scotese, C.R., van der Voo, R., 1977, Silurian continental distributions, paleogeography, climatology, and biogeography: *Tectonophysics*, v. 40, no. 1–2, p. 13–51.
- Zhang, Shunxin, and Barnes, C.R., 2002, A new Llandovery (early Silurian) conodont biozonation and conodonts from the Becscie, Merrimack, and Gun River formations, Anticosti Island, Quebec: *Journal of Paleontology*, v. 76 (sp. 57), p. 1–46.

APPENDIX A. Spectral gamma-ray data from Adams County
(see fig. 6, fig. 7, and table 2 for location and section information)

Depth (ft)	K (%)	U (ppm)	Th (ppm)	Gamma (API)	Location	Section	Unit Contacts
0	0.5	1.7	1.6	28	MR	2	Base Peebles at 0.9'
1	0.6	1.3	2.8	31.2	MR	2	
2	0.7	1.2	3	32.8	MR	2	
3	0.6	1.4	4	27.2	MR	2	
4	0.8	1.7	5.4	48	MR	2	
5	1.6	2.7	6.4	72.8	MR	2	Base Lilley-Peebles transition beds
6	1.7	2.5	6.8	74.4	MR	2	
7	2.2	2.7	7.8	88	MR	2	
8	2.1	2.2	9	87.2	MR	2	
9	2.3	2.7	7.5	88.4	MR	2	
10	2.4	2.8	9	96.8	MR	2	
12.5	1.8	1.9	7	72	MR	2	
15	2.1	2	6.7	76.4	MR	2	
17.5	2.3	1.5	10.1	89.2	MR	2	
20	2.7	1.5	11.3	100.4	MR	2	
22.5	1.3	1.3	4.7	50	MR	2	
25	0.5	1.1	3.3	30	MR	2	upper Lilley/shaly Lilley
26	0.4	0.8	2.4	22.4	MR	2	
27	0.4	1.1	2.1	23.6	MR	2	
28	0.4	0.6	2.9	22.8	MR	2	
29	0.4	0.6	4.1	27.6	MR	2	
30	0.4	0.9	3.8	28.8	MR	2	Base upper Lilley
31	0.4	1.1	3.4	28.8	MR	2	
32	0.3	0.7	3.2	23.2	MR	2	
33	0.3	0.5	2.3	18	MR	2	
34	0.2	1	1.7	18	MR	2	
35	0.3	0.7	2.7	21.2	MR	2	
36	0.2	0.7	2.3	18	MR	2	
37	0.3	0.6	4.5	27.6	MR	2	
38	0.3	0.7	2.3	19.6	MR	2	
39	0.3	1.1	2.1	22	MR	2	
40	0.3	0.7	2.6	20.8	MR	2	
41	0.5	1	3.3	29.2	MR	2	
42	0.6	0.3	7	40	MR	2	Base lower Lilley at 42.5'
43	1	1.8	6.3	55.6	MR	2	
44	0.7	1.5	6.4	48.8	MR	2	
45	0.6	1.3	3.6	34.4	MR	2	
46	0.5	0.7	6.4	39.2	MR	2	
47	0.5	1.4	7.3	48.4	MR	2	
48	0.6	0.9	8.2	49.6	MR	2	
49	0.4	1.9	5.3	42.8	MR	2	
50	0.6	2.4	5.5	50.8	MR	2	
51	0.5	1.9	5.8	46.4	MR	2	
52	0.6	1.4	5.8	44	MR	2	
53	0.6	1.1	6.9	46	MR	2	
54	0.6	1.3	7	48	MR	2	
55	0.6	2.1	9.6	64.8	MR	2	
56	0.6	1.4	8.7	55.6	MR	2	
57	0.6	2	6.5	51.6	MR	2	
58	0.8	1.5	11.3	70	MR	2	
59	0.6	1.7	10.5	65.2	MR	2	
60	0.9	1.1	11.7	70	MR	2	Base upper Bisher
61	covered	covered	covered	covered	MR	2	
62	covered	covered	covered	covered	MR	2	
63	1	1.5	7.2	56.8	MR	2	
64	0.6	1.3	9.8	59.2	MR	2	Base middle Bisher
65	0.6	1	6.1	42	MR	2	
66	0.6	1.6	5.5	44.4	MR	2	
67	0.8	1.3	5.5	45.2	MR	2	
68	0.8	1.1	4.7	40.4	MR	2	
69	0.96	1.1	5.6	46.56	MR	2	
70	0.5	1.4	5.9	42.8	MR	2	
71	0.5	1.1	6.1	41.2	MR	2	
72	0.8	0.9	6.9	47.6	MR	2	

Depth (ft)	K (%)	U (ppm)	Th (ppm)	Gamma (API)	Location	Section	Unit Contacts
73	0.5	0.7	4.8	32.8	MR	2	
74	0.7	1.1	6.1	44.4	MR	2	
75	1.9	1.6	10.6	85.6	MR	1	Base lower Bisher
77.5	4.3	3.8	15.4	160.8	MR	1	
80	3.9	3.6	14.5	149.2	BCMC	2	
82.5	3.7	4.1	14.3	149.2	BCMC	2	
85	3.7	3.5	14.6	145.6	BCMC	2	
87.5	4.1	3.9	12.3	146	BCMC	2	
90	3.9	3	12.9	138	BCMC	2	
92.5	3.8	2.9	14.6	142.4	BCMC	2	
95	3.9	3.6	12.4	140.8	BCMC	2	
97.5	3.2	3.5	11.7	126	BCMC	2	
100	4.1	4.2	13.5	153.2	BCMC	2	
102.5	3.9	2.9	12.1	134	BCMC	2	
105	3.5	3	12.8	131.2	BCMC	2	
107.5	4	4.3	16.2	163.2	BCMC	2	
110	4.3	3.8	14.8	158.4	BCMC	2	
112.5	4.7	3.3	19.2	178.4	BCMC	2	
115	5.6	6.1	17.9	210	BCMC	2	
117.5	5.5	7.2	19.2	222.4	BCMC	2	
120	5.5	4.8	15.9	190	BCMC	2	
122.5	5.3	5.1	17.2	194.4	BCMC	2	
125	5	4	18.2	184.8	BCMC	2	
127.5	5.9	4.5	17.6	200.8	BCMC	2	
130	5.6	3.9	18.3	194	BCMC	2	
132.5	5.3	4.1	18.7	192.4	BCMC	2	
135	5.6	4.3	20	204	BCMC	2	
137.5	5.8	4.1	17.9	197.2	BCMC	2	
140	6	3.8	17.5	196.4	BCMC	2	
142.5	6	5.1	16.5	202.8	BCMC	2	
145	6	4.6	16.5	198.8	BCMC	2	
147.5	5.2	3.6	15.4	173.6	BCMC	2	
150	5.4	4.5	16.8	189.6	BCMC	2	
152.5	4.7	3.8	16.3	170.8	BCMC	2	
155	4	3.8	12.5	144.4	BCMC	1	
157.5	4.8	2.9	13.6	154.4	BCMC	1	
160	5	2.6	13.1	153.2	BCMC	1	
162.5	5.6	2.9	13.2	165.6	BCMC	1	
165	5	3.1	13.5	158.8	BCMC	1	
167.5	4.6	4.5	10.5	151.6	BCMC	1	
170	5.5	2.8	16.7	177.2	BCMC	1	
172.5	5.9	2.6	16.2	180	BCMC	1	
175	6.1	2.7	14.9	178.8	BCMC	1	
177.5	5.3	2.4	13.3	157.2	BCMC	1	
180	6.2	1.9	16.4	180	BCMC	1	
182.5	5.5	3.1	13.3	166	BCMC	1	
185	5.4	2.5	13.7	161.2	BCMC	1	
187.5	4.7	2.9	11.8	145.6	BCMC	1	
190	6.8	2.6	15	189.6	BCMC	1	
192.5	6.1	2.6	14.3	175.6	BCMC	1	
195	4.7	3	11.9	146.8	BCMC	1	
197.5	5.4	1.9	13.9	157.2	BCMC	1	
200	5.2	2.2	14	156.8	BCMC	1	
202.5	6.2	1.9	14.5	172.4	BCMC	1	
205	5.6	1.9	13	156.8	BCMC	1	Base Estill
206	5.2	1.8	12.6	148	BCMC	1	
207	5.9	2.2	11.6	158.4	BCMC	1	Base upper Waco shale at 207.5'
208	covered	covered	covered	covered	BCMC	1	
209	0.9	1.3	3.9	40.4	WHP	4	
210	1	1.5	3.7	42.8	WHP	4	Base orange Waco
211	1.4	2.2	4.9	59.6	WHP	4	
212	3	3.2	8	105.6	WHP	4	Base Oldham at 212.4'
213	2.1	2.6	9.4	92	WHP	4	
214	3.6	2.4	10	116.8	WHP	4	
215	3.1	1.8	11.8	111.2	WHP	4	
216	2.3	1.7	8.6	84.8	WHP	4	Base Plum Creek
217	2	1.4	10.1	83.6	WHP	4	

Depth (ft)	K (%)	U (ppm)	Th (ppm)	Gamma (API)	Location	Section	Unit Contacts
218	2.7	0.7	12	96.8	WHP	4	
219	5.3	2.6	14.5	163.6	WHP	4	
220	3.3	2	10.5	110.8	WHP	4	Base Rose Run iron ore
221	4.1	2.7	12.2	136	WHP	4	
222	3.5	2.3	10.3	115.6	WHP	4	
223	5.4	3.3	13.7	167.6	WHP	4	
224	4.4	2	10.7	129.2	WHP	4	
225	3.8	3.1	11.3	130.8	WHP	4	
226	3.4	2.1	10.5	113.2	WHP	4	
227	2.9	2.1	9.7	102	WHP	4	
228	2.7	2	11.3	104.4	WHP	4	
229	4.6	1.5	14.5	143.6	WHP	4	
230	4.5	2.5	12.8	143.2	WHP	4	
231	1.6	1.8	6.8	67.2	WHP	4	
232	2.1	1.5	7.8	76.8	WHP	4	
233	3.2	2.4	12.2	119.2	WHP	4	
234	3	2	12	112	WHP	4	
235	1	1.9	6.9	58.8	WHP	4	
236	1.3	1.8	7.9	66.8	WHP	4	Base shaly Brassfield @ 236.3'
237	1.3	1.4	6.9	59.6	WHP	4	
238	0.9	1.6	4.8	46.4	WHP	4	
239	1.2	1.5	7.8	62.4	WHP	4	
240	2.1	1.2	10.3	84.4	WHP	4	
241	covered	covered	covered	covered	WHP	4	
242	2.5	1.9	9.2	92	WHP	4	
243	covered	covered	covered	covered	WHP	4	
244	covered	covered	covered	covered	WHP	4	
245	0.7	1.9	4.2	43.2	WHP	4	Base thin bedded Brassfield at 245.2'
246	0.4	2.3	2.7	35.6	WHP	3	
247	0.5	2.2	2.5	35.6	WHP	3	
248	0.4	1.7	3.4	33.6	WHP	3	
249	0.6	1.9	2.1	33.2	WHP	3	
250	0.6	1.5	2.3	30.8	WHP	3	
251	0.8	1.8	4.1	43.6	WHP	3	
252	0.9	1.5	3.3	39.6	WHP	2	Base lower massive Brassfield
253	1.4	1.7	3.6	50.4	WHP	2	
254	1.9	1.8	7.2	73.6	WHP	2	
255	1.5	1.6	4.6	55.2	WHP	2	
256	2.1	1.9	6.3	74	WHP	2	
257	2.1	2.2	6.2	76	WHP	2	
258	1.3	2.2	4.1	54.8	WHP	2	Base Belfast B at 258.9'
259	1.2	1.7	4.9	52.4	WHP	2	
260	1.8	3.5	5.5	78.8	WHP	2	Base Belfast A
261	2.4	3.3	9	100.8	WHP	2	
262	2.5	2.8	9.3	99.6	WHP	2	
263	2.6	3.5	9	105.6	WHP	2	
264	2.5	2.9	9.4	100.8	WHP	2	
265	3.3	3.4	9.7	118.8	WHP	2	
266	3.9	4.3	10.6	139.2	WHP	1	Base Centerville
267	4.6	2.6	10.3	135.6	WHP	1	
268	4.2	3.9	11.4	144	WHP	1	
269	4.4	3.3	11.6	143.2	WHP	1	
270	4.5	2.5	11.6	138.4	WHP	1	
271	4.1	3.9	10.7	139.6	WHP	1	
272	4.6	2.8	12.1	144.4	WHP	1	
273	4.3	3.5	10.7	139.6	WHP	1	
274	3.9	2.3	12.6	131.2	WHP	1	
275	3.7	2.5	10.3	120.4	WHP	1	
276	4.3	3.2	10.2	135.2	WHP	1	
277	4.5	3.3	12.7	149.2	WHP	1	

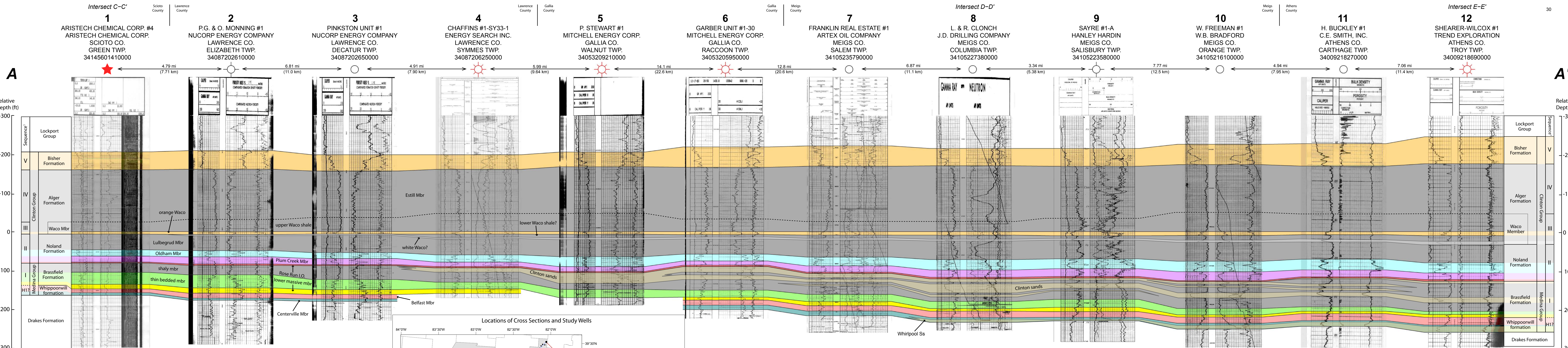


Plate 1
Cross section A-A' illustrating Ordovician and Silurian strata from Scioto County to Athens County.

Datum = top of orange Waco

¹Sequences after:
Brett, C.E. and Ray, D.C., 2005. Sequence and event stratigraphy of Silurian strata of the Cincinnati Arch region—Correlations with New York-Ontario successions: *Proceedings of the Royal Society of Victoria*, v. 117, no. 2, p. 175–198.
McLaughlin, F.L., Cramer, B.D., Brett, C.E., and Kleffner, M.A., 2008. Silurian high-resolution stratigraphy on the Cincinnati Arch—Progress on recalibrating the layer-cake, in: Maria, A.H., and Counts, R.C., eds., *From the Cincinnati Arch to the Illinois Basin—Geological Field Excursions along the Ohio River Valley*: Boulder, Colo., Geological Society of America Field Guide 12, p. 119–180.

B

Relative Depth (ft)

-200
-100
0
100
200

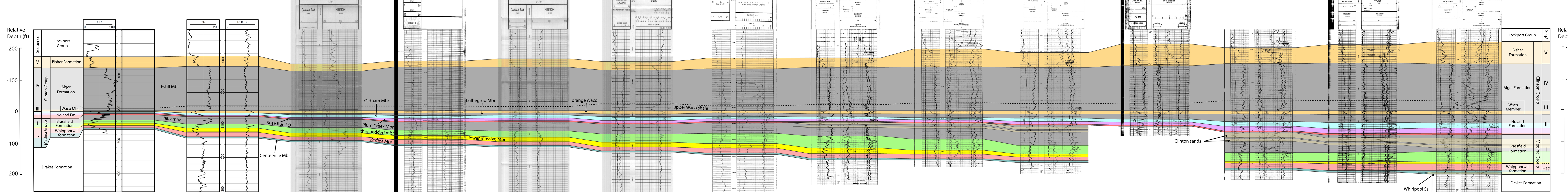
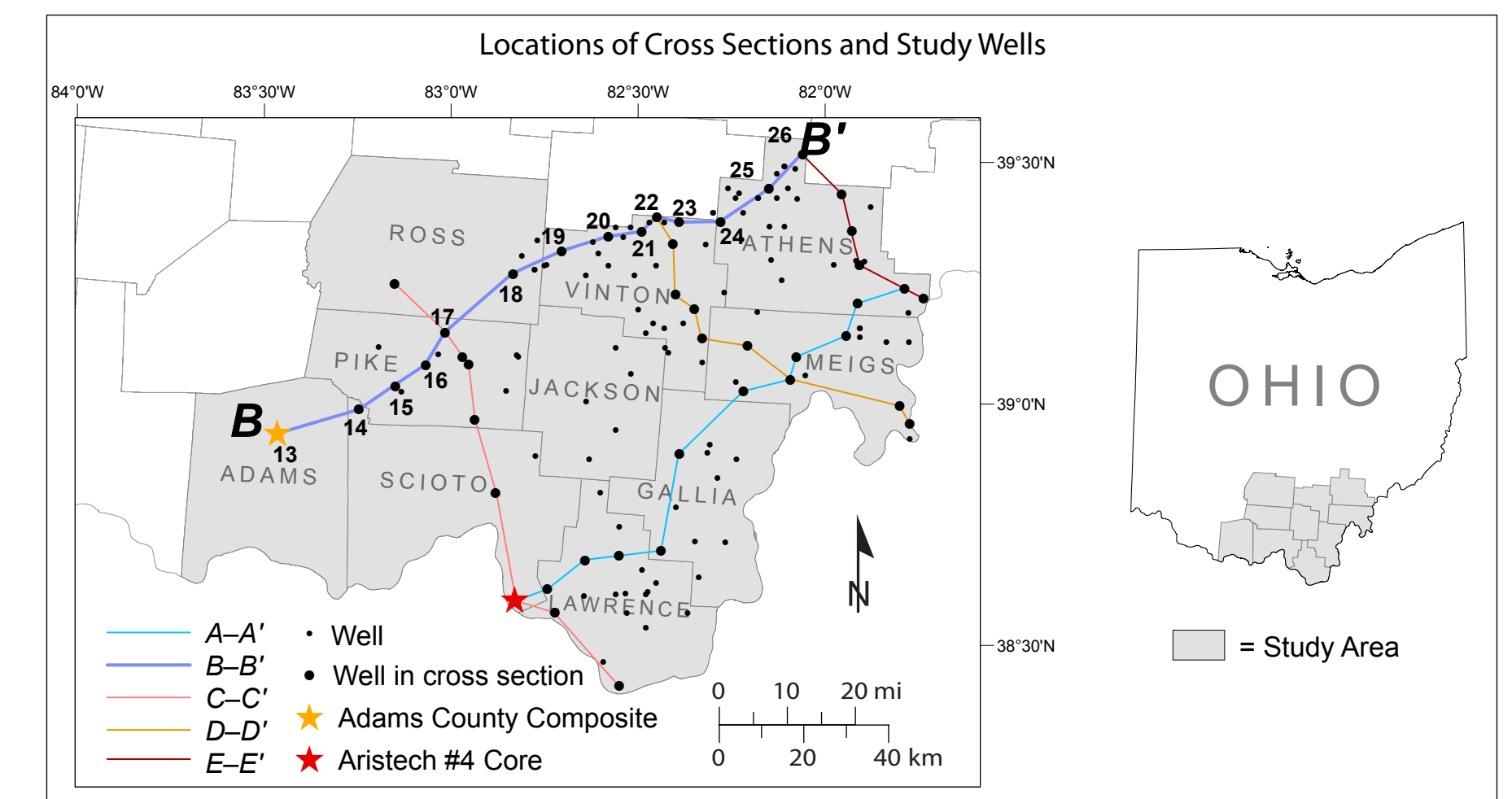


Plate 2

Cross section B-B' illustrating Ordovician and Silurian strata from Adams County to Athens County.

Datum = top of orange Waco



Abbreviations

- Mbr Member (lowercase = informal status)
- Fm Formation (lowercase = informal status)
- I.O. Iron Ore
- Ss Sandstone

Well Type

- Location only
- Adams County Composite
- Gas well
- Dry hole
- Tentative unit boundary

B'

Relative Depth (ft)

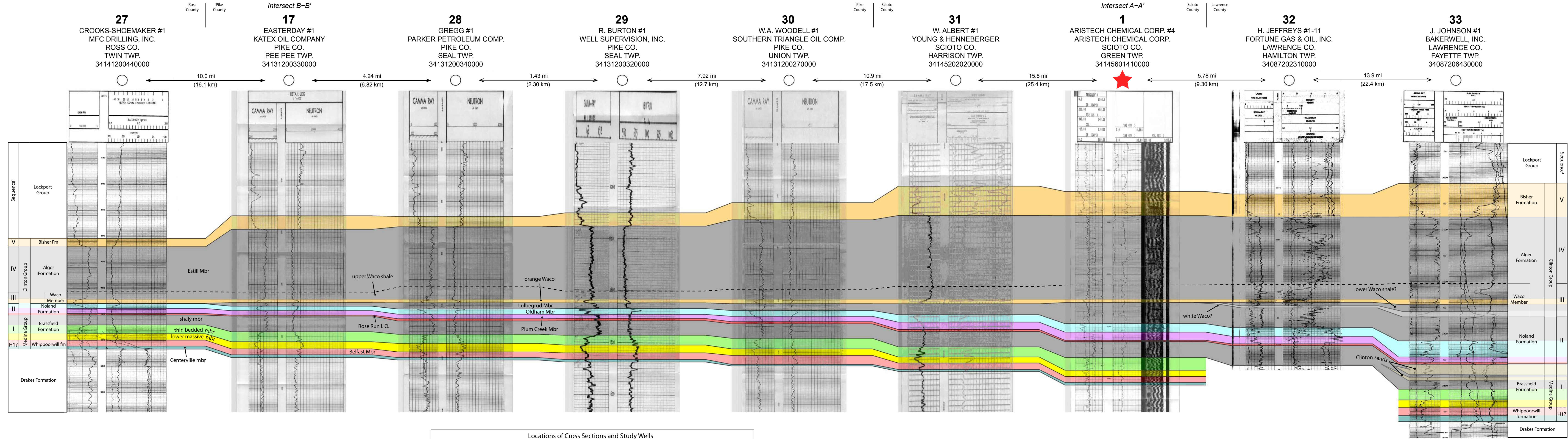
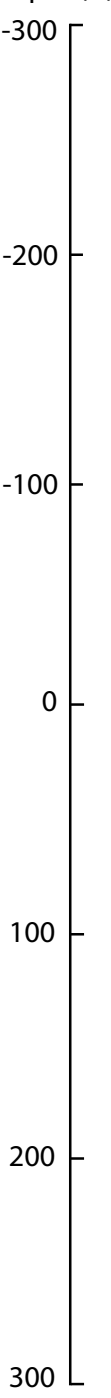
-200
-100
0
100
200

*Sequences after:

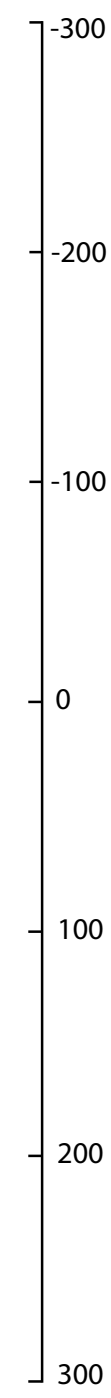
Brett, C.E. and Ray, D.C., 2005. Sequence and event stratigraphy of Silurian strata of the Cincinnati Arch region—Correlations with New York-Ontario successions; Proceedings of the Royal Society of Victoria, v. 117, no. 2, p. 175–198.
McLaughlin, P.I., Cramer, B.D., Brett, C.E., and Kleffner, M.A., 2008. Silurian high-resolution stratigraphy on the Cincinnati Arch—Progress on recalibrating the layer-cake, in: Maria, A.H., and Counts, R.C., eds., From the Cincinnati Arch to the Illinois Basin—Geological Field Excursions along the Ohio River Valley: Boulder, Colo., Geological Society of America Field Guide 12, p. 119–180.

C

Relative Depth (ft)



Relative Depth (ft)

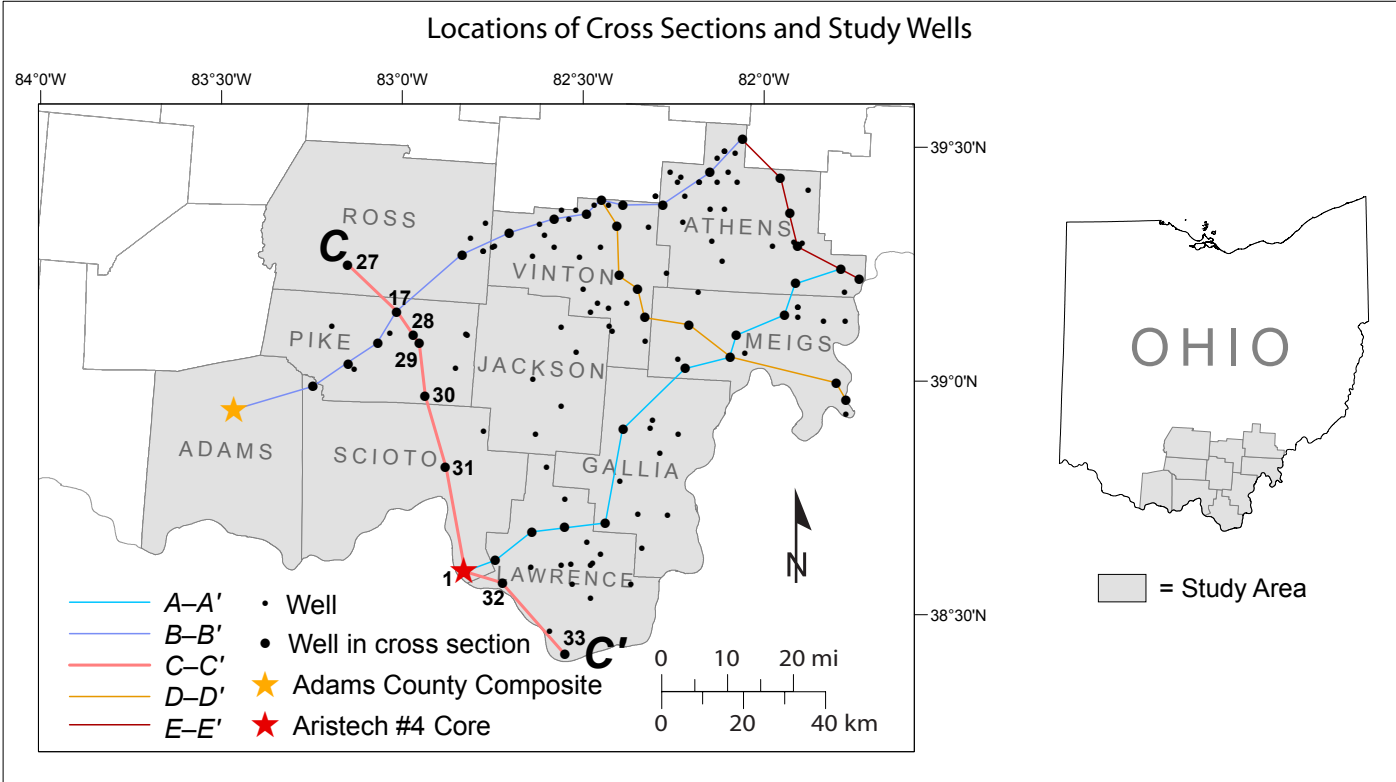


C'

Plate 3

Cross section C–C' illustrating Ordovician and Silurian strata from Ross County to Lawrence County.

Datum = top of orange Waco



Abbreviations

- Mbr Member (lowercase = informal status)
- Fm Formation (lowercase = informal status)
- I.O. Iron Ore

Well Types

- Location only
- ⊕ Well status unknown
- ★ Aristech Core

----- Tentative unit boundary

¹Sequences after:

Brett, C.E. and Ray, D.C., 2005. Sequence and event stratigraphy of Silurian strata of the Cincinnati Arch region—Correlations with New York-Ontario successions: Proceedings of the Royal Society of Victoria, v. 117, no. 2, p. 175–198.
McLaughlin, P.I., Cramer, B.D., Brett, C.E., and Kleffner, M.A., 2008. Silurian high-resolution stratigraphy on the Cincinnati Arch—Progress on recalibrating the layer-cake, in: Maria, A.H., and Counts, R.C., eds., From the Cincinnati Arch to the Illinois Basin—Geological Field Excursions along the Ohio River Valley: Boulder, Colo., Geological Society of America Field Guide 12, p. 119–180.

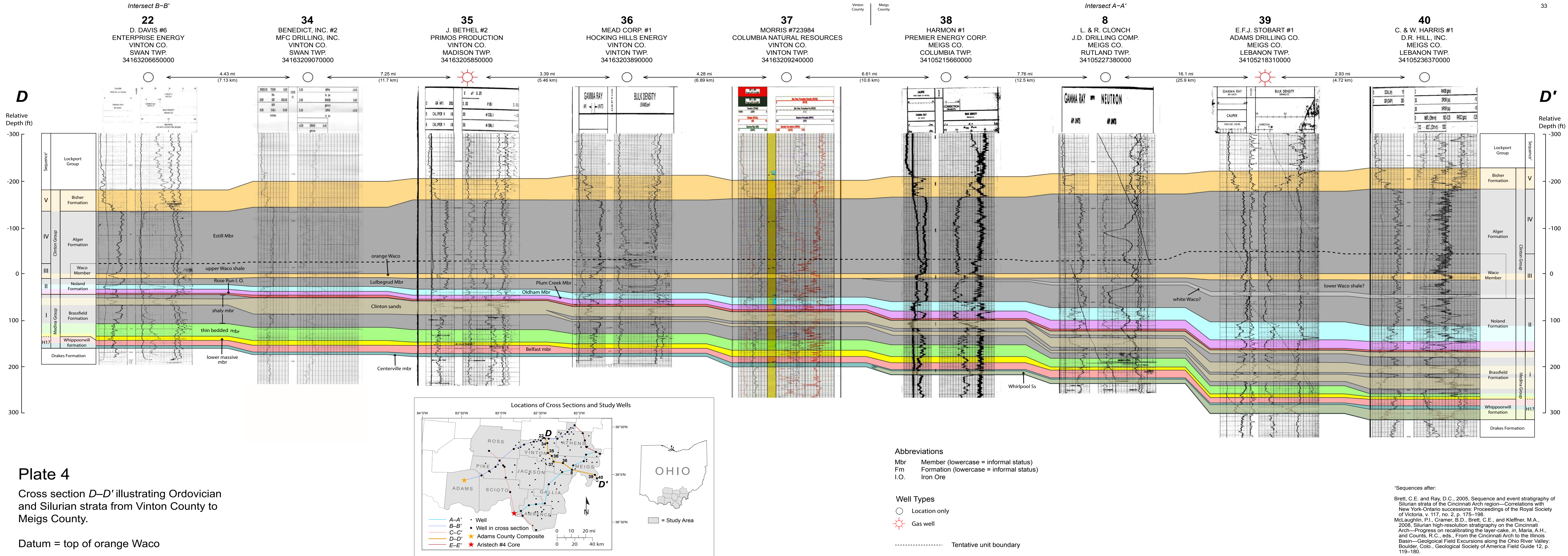


Plate 4

Cross section *D–D'* illustrating Ordovician and Silurian strata from Vinton County to Meigs County.

Datum = top of orange Waco

B. DOCIE #1
WALLICK PETROLEUM COMP.
ATHENS CO.
TRIMBLE TWP.
34009225570000

MAXWELL #1
BENATTY CORP.
ATHENS CO.
AMES TWP.
34009227220000

RAM #4
STRATA CORP.
ATHENS CO.
ROME TWP.
34009229380000

H. MCDANIEL #3
STRATA CORP.
ATHENS CO.
ROME TWP.
34009229250000

SHEARER-WILCOX #1
TREND EXPLORATION
ATHENS CO.
TROY TWP.
34009218690000

E. MISNER #1
ENERGY SEARCH, INC.
ATHENS CO.
TROY TWP.
34009234520000

E

Relative
Depth (ft)

-300

-200

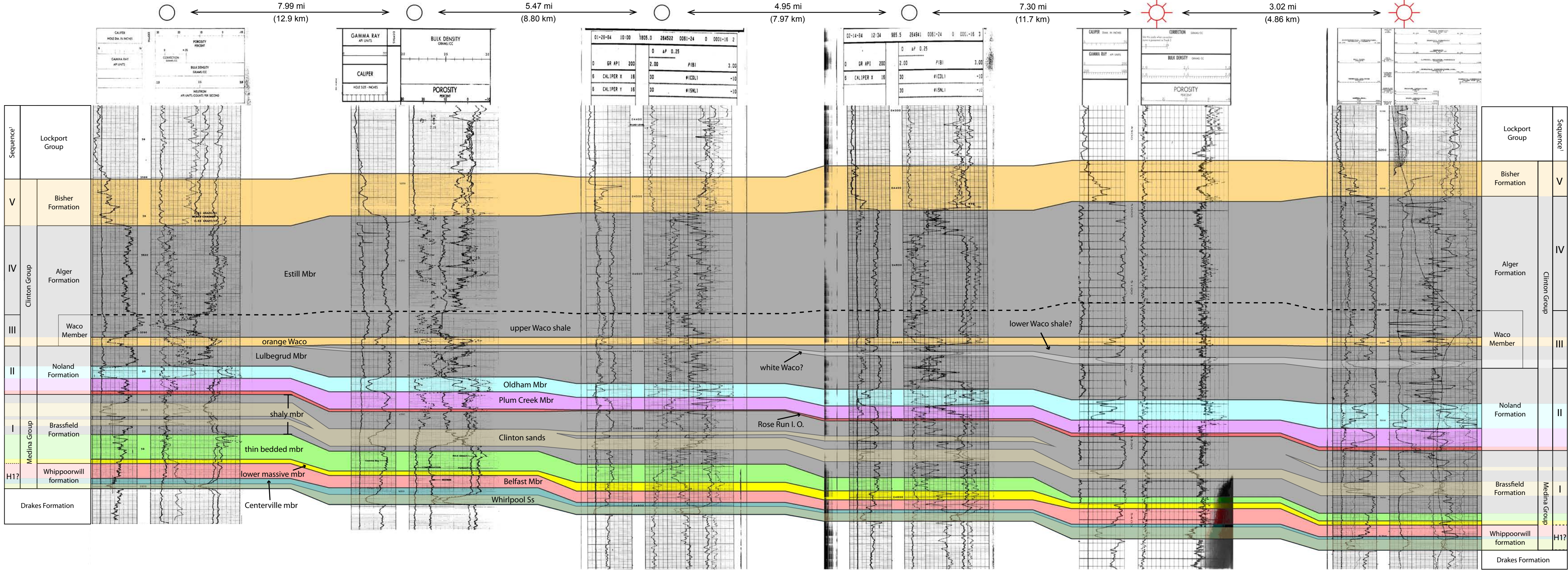
-100

0

100

200

300



Relative
Depth (ft)

-300

-200

-100

0

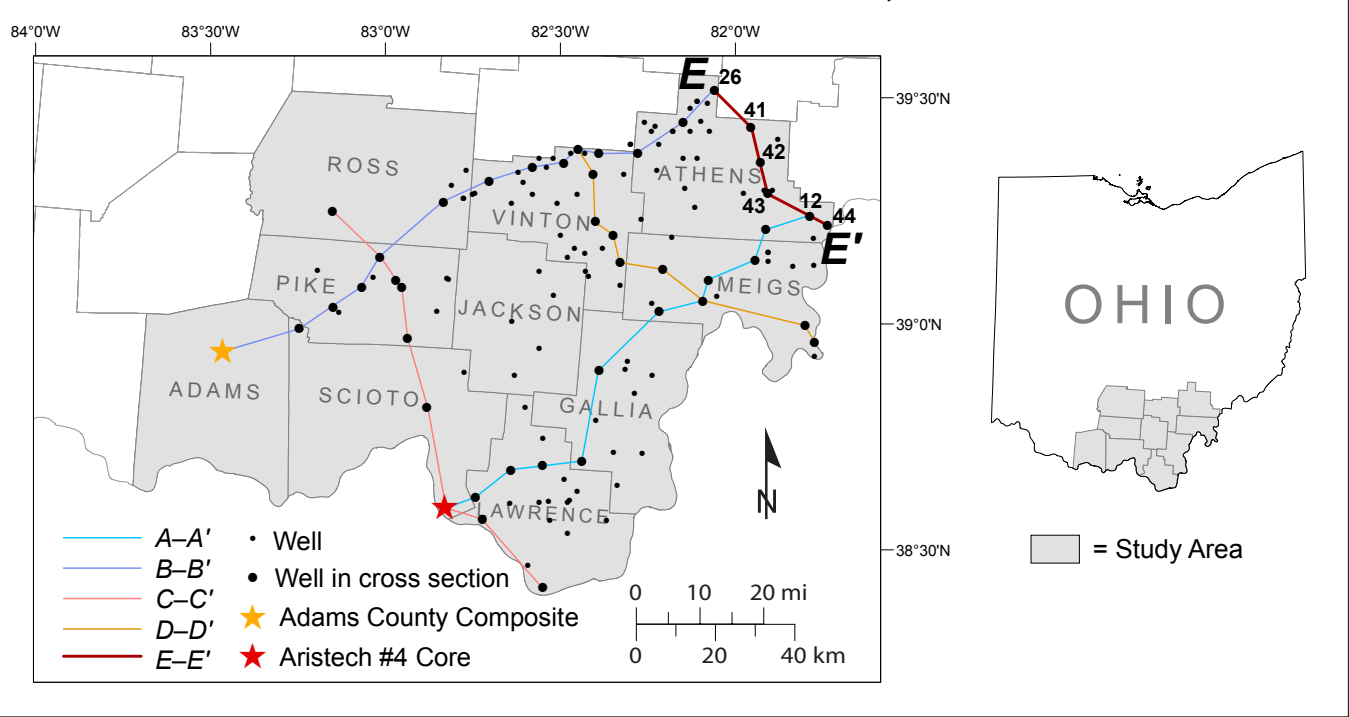
100

200

300

E'

Locations of Cross Sections and Study Wells



Abbreviations

Mbr Member (lowercase = informal status)
Fm Formation (lowercase = informal status)
I.O. Iron Ore
Ss Sandstone

Well Type

○ Location only
☀ Gas well

----- Tentative unit boundary

¹Sequences after:

Brett, C.E. and Ray, D.C., 2005, Sequence and event stratigraphy of Silurian strata of the Cincinnati Arch region—Correlations with New York-Ontario successions: Proceedings of the Royal Society of Victoria, v. 117, no. 2, p. 175–198.
McLaughlin, P.I., Cramer, B.D., Brett, C.E., and Kleffner, M.A., 2008, Silurian high-resolution stratigraphy on the Cincinnati Arch—Progress on recalibrating the layer-cake, in Maria, A.H., and Counts, R.C., eds., From the Cincinnati Arch to the Illinois Basin—Geological Field Excursions along the Ohio River Valley: Boulder, Colo., Geological Society of America Field Guide 12, p. 119–180.

Plate 5

Cross section E–E' illustrating Ordovician and Silurian strata across Athens County.

Datum = top of orange Waco

