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

By Robert T. Ryder

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
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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

By Robert T. Ryder

Introduction

The Lower Silurian regional oil and gas accumulation was named by Ryder and Zagorski (2003) for a 400-mile (mi)-long by 200-mi-wide hydrocarbon accumulation in the central Appalachian basin of the Eastern United States and Ontario, Canada (fig. 1). From the early 1880s to 2000, approximately 300 to 400 million barrels of oil and eight to nine trillion cubic feet of gas have been produced from the Lower Silurian regional oil and gas accumulation (Miller, 1975; McCormac and others, 1996; Harper and others, 1999). Dominant reservoirs in the regional accumulation are the Lower Silurian "Clinton" and Medina sandstones in Ohio and westernmost West Virginia and coeval rocks in the Lower Silurian Medina Group (Grimsby Sandstone (Formation) and Whirlpool Sandstone) in northwestern Pennsylvania and western New York. A secondary reservoir is the Upper Ordovician(?) and Lower Silurian Tuscarora Sandstone in central Pennsylvania and central West Virginia (fig. 1), a more proximal eastern facies of the "Clinton" sandstone and Medina Group (Yeakel, 1962; Cotter, 1982, 1983; Castle, 1998). The Tuscarora Sandstone consists of a greater percentage of net sandstone than the "Clinton"-Medina interval, and typically Tuscarora sandstones are coarser grained (Yeakel, 1962).

The Lower Silurian regional oil and gas accumulation is subdivided by Ryder and Zagorski (2003) into the following three parts: (1) an easternmost part consisting of local gas-bearing sandstone units in the Tuscarora Sandstone that is included with the basin-center accumulation; (2) an eastern part consisting predominantly of gas-bearing "Clinton" sandstone-Medina Group sandstones that have many characteristics of a basin-center accumulation (Davis, 1984; Zagorski, 1988, 1991; Law and Spencer, 1993); and (3) a western part consisting of oil- and gas-bearing "Clinton" sandstone-Medina Group sandstones that is a conventional accumulation with hybrid features of a basin-center accumulation (Zagorski, 1999) (fig. 1). With the notable exception of the offshore part of Lake Erie (de Witt, 1993), the supply of oil and (or) gas in the hybrid-conventional part of the regional accumulation continues to decline because of the many wells drilled there since the late 1880s. However, new gas and local oil continues to be discovered in the deeper basin-center part (Zagorski, 1991; Pees, 1994; Petroleum Information Corporation, 1994). In general, only small quantities of gas have been produced from the Tuscarora Sandstone fields because of their generally poor reservoir quality and because of the low energy (Btu) content of the gas (Avary, 1996). Although fracture porosity is the dominant porosity type in the Tuscarora Sandstone gas reservoirs (Avary, 1996), there are several fields, such as Indian Creek (fig. 1), where intergranular porosity seems to be important (Bruner, 1983; Castle and Byrnes, 2005).

In order to better understand the character and origin of the Lower Silurian regional oil and gas accumulation and its component parts, six cross sections were drawn through the Lower Silurian strata in parts of New York, Ohio, Pennsylvania, and West Virginia. The locations of the cross sections are shown in figures 1 and 2, and results are reported in Keighin (1998), Ryder (2000, 2004), and Hettinger (2001). Each cross section shows the stratigraphic framework, depositional setting, sequence stratigraphy, and hydrocarbon-producing intervals of the Lower Silurian sandstone reservoirs and adjoining strata. Cross section *F–F′* presented here is about 215 mi long and trends northwestward, approximately normal to the depositional strike of the Lower Silurian sandstone system, and extends through large stretches of the basin-center and hybrid-conventional parts of the Lower Silurian regional oil and gas accumulation. Cross sections *B–B′*, *C–C′*, *D–D′*, and *E–E′* also trend northwestward (approximately normal to the depositional strike of the Lower Silurian sandstone system) whereas cross section *A–A′* trends north-northeastward (parallel to and, in part, oblique to the depositional strike) (figs. 1, 2). Cross sections *E–E′* and *F–F′* traverse nearly the entire width of the Lower Silurian regional oil and gas accumulation.

Construction of the Cross Section

Cross section *F–F′* was constructed from 105 wells (fig. 2; table 1). The wells are approximately 1 to 5 mi apart, although in central West Virginia the maximum distance between wells is about 20 mi (fig. 2). Uppermost Ordovician, Lower Silurian, and lowermost Upper Silurian strata are correlated between the wells by using gamma-ray, density, and neutron borehole geophysical logs and, in several cases, lithologic descriptions correlated with log curve characteristics. Of the 105 wells used to construct section *F–F′*, 50 are shown in this report with their accompanying gamma-ray logs. The datum for most of section *F–F′* is the base of the Reynales Limestone or the Dayton Limestone where the Reynales Limestone is missing due to erosion or pinch out (described later in the text).

Perforated intervals and the results of initial production flow of natural gas are available for most of the 105 wells and are shown on section *F–F′* and in table 1. Data shown in this report include the stratigraphic position of the reservoirs, the type(s) of fluid encountered in the wells, and the initial yields of petroleum volumes. Oil and gas fields identified on section *F–F′* were taken largely from oil-and-gas-field maps produced by State geological surveys and oil and gas agencies (DeBrosse and Vohwinkel, 1974; Cardwell, 1982).

General Stratigraphy

The chronostratigraphic position and nomenclature of Lower Silurian units and adjoining uppermost Ordovician and lowermost Upper Silurian units along section *F–F′* are shown in figure 3. Information presented in figure 3 is based, in part, on the following publications: (1) Regional perspective: Brett and others (1990); (2) Ohio: Knight (1969), Horvath (1970), Horvath and others (1970), McCormac and others (1996), and Ryder (2000, 2004); and (3) West Virginia: Smosna and Patchen (1978), Patchen and others (1985), Avary (1996), and Ryder (2004).

Silurian strata correlated on section *F–F′* belong to the Niagaran Provincial Series (Fisher, 1959; Rickard, 1975). According to Rickard (1975) and Brett and others (1995), this provincial series in western New York consists of the Medina, Clinton, and Lockport Groups. Revisions by Brett and others (1995) to the Niagaran Provincial Series, with approval of the U.S. Geological Survey (USGS), include the use of (1) the Medina Group instead of the Albion Group, (2) the Lockport Group instead of the Lockport Dolomite, and (3) two Eastern North American (Provincial) Series names (Lower and Upper) for the Silurian System instead of three (Lower, Middle, and Upper). In Ontario, Canada, the Clinton Group is recognized, but the Medina Group is replaced by the Cataract Group (Brett and others, 1995).

The lowermost Lower Silurian strata of Ohio consist of two informal units, the Medina sandstone and the “Clinton” sandstone (fig. 3), that were named by early drillers. These early drillers correctly correlated the Medina sandstone in Ohio with the type Medina Group of New York, but they miscorrelated the overlying “Clinton” sandstone with strata in the type Clinton Group of New York, when it should have been correlated with the type Medina Group (McCormac and others, 1996). Although this miscorrelation has caused confusion in nomenclature, the term continues to be widely used in the literature and by the oil and gas industry. Informal subdivisions of the “Clinton” sandstone such as the white, red, and stray Clinton sands (Pepper and others, 1953) are not used in this report.

Shale and carbonate units associated with the “Clinton” and Medina sandstones in Ohio consist of the Cabot Head Shale (lower and upper) (Knight, 1969) and the Brassfield Limestone (Horvath, 1970). The Cabot Head Shale (lower) in Ohio correlates with a shale unit near the base of the Tuscarora Sandstone in West Virginia, and the Cabot Head Shale (upper) correlates with a shale unit near the base of the Rose Hill Formation in West Virginia (fig. 3). The Brassfield Limestone is located in central and eastern Ohio and grades eastward into the Medina sandstone and Cabot Head Shale (lower) (fig. 3). The Medina sandstone and Brassfield Limestone rest unconformably on the Upper Ordovician Queenston Shale (fig. 3). This regional unconformity has several names: the Cherokee unconformity (Dennison and Head, 1975; Brett and others, 1990), basal unconformity (Castle, 1998), and unconformity 1 (Hettinger, 2001).

The maximum thickness of the combined “Clinton” sandstone, Cabot Head Shale, and Medina sandstone along section *F–F′* is between 170 and 180 feet (ft). These thicknesses are typical for wells located in Noble County (wells 60–90) and eastern Washington County (wells 91 and 92) in Ohio. Also, Coogan (1991) reported similar total “Clinton” sandstone-Cabot Head Shale-Medina sandstone thicknesses in this part of eastern Ohio. The 170 to 180 ft thickness values are located at the southern end of a “Clinton” sandstone depocenter recognized by Knight (1969) as the Canton embayment (fig. 1). Isopachs that define the Canton embayment (Knight, 1969) show that the “Clinton”-Cabot Head-Medina interval is about 30 ft greater than the maximum thicknesses indicated by section *F–F′* because the isopachs include several post-“Clinton” sandstone carbonate units (Packer shell discussed later in this section). The combined “Clinton”-Cabot Head-Brassfield (Medina equivalent) unit thins to about 130 ft in Licking County, Ohio (well 1).

As shown on the cross section and in figure 3, the combined Medina sandstone, Cabot Head Shale (lower), and “Clinton” sandstone are replaced largely by the Tuscarora Sandstone (Smosna and Patchen, 1978; Avary, 1996) in northwestern and central West Virginia. The Cherokee unconformity at the base of the Medina sandstone is interpreted in this cross section to extend eastward into West Virginia where it separates the Tuscarora Sandstone from the Upper Ordovician Juniata Formation (fig. 3). However, this disconformity between the Tuscarora and Juniata is controversial in northern West Virginia because Diecchio (1985), mainly using outcrop evidence, suggested that the contact is conformable. Future studies are required to resolve this debate. Also, a younger unconformity (unconformity 3 of Hettinger, 2001, and its possible equivalent, the “Tuscarora unconformity” of Dorsch and others, 1994) is recognized in this cross section. In central West Virginia this younger unconformity appears to have truncated the lower part of the Tuscarora Sandstone as well as the Cherokee unconformity (fig. 3; also see wells 101 and 105 on the cross section).

The Tuscarora Sandstone in central West Virginia (wells 97–99, 101) is overlain by a 25- to 30-ft-thick sandstone, shown in light green, at the base of the Rose Hill Formation. This sandstone unit is assigned to the lower part of the Cacapon Sandstone Member of the Rose Hill Formation (Smosna and Patchen, 1978) (fig. 3) and is equivalent to the Castanea Member of the Tuscarora Formation in Pennsylvania (Piotrowski, 1981; Castle, 1998; Ryder, 2004). The upper part of the Cacapon Sandstone Member is represented by a 25- to 50-ft-thick sandstone (shown in yellow with red stipples) and underlying shale and carbonate beds (fig. 3). The upper and lower parts of the Cacapon Sandstone Member are replaced northwestward, across arbitrary boundaries, by equivalent strata of the main body of the Rose Hill Formation (see wells 94, 96, and 97).

The change from the “Clinton” sandstone-Cabot Head Shale-Medina sandstone interval to the Tuscarora Sandstone occurs across a tectonic hinge zone (Ohio-West Virginia hinge zone of Ryder, 1992), located approximately between wells 92 and 94 (figs. 1, 2). Although the Tuscarora Sandstone shows little thickness change across the hinge zone, the overlying Rose Hill Formation increases to 520 ft (well 96) in West Virginia from a thickness of 355 ft (well 91) for equivalent strata in eastern Ohio. The Tuscarora-Rose Hill depocenter along section *F–F′* is located between wells 96 and 99 where the depocenter has a maximum thickness of about 700 ft in well 96. At the southeastern end of section *F–F′* (well 105), the Tuscarora-Rose Hill interval thins to about 410 ft.

Thin, widespread carbonate units between the “Clinton” sandstone and the Lockport Dolomite (or locally the Keefer Sandstone) in Ohio and in the equivalent Rose Hill Formation in West Virginia, are recognized here in ascending order as the unnamed limestone (dolomite), Reynales Limestone (Dolomite), Dayton Limestone (Dolomite), and Irondequoit Limestone (Dolomite) (fig. 3). Unnamed gray shale units associated with the carbonates in Ohio generally range in thickness from less than 20 ft to about 90 ft. The Rochester Shale between the Irondequoit Limestone and the Lockport Dolomite (or locally the Keefer Sandstone) is between 40 and 85 ft thick. At the northwestern end of section *F–F′* where the Irondequoit Limestone pinches out and the base of the Lockport Dolomite climbs upsection due to a facies change, the Rochester Shale is as thick as 135 ft (well 16). The Reynales and Irondequoit Limestones, originally defined in New York (Brett and others, 1990, 1995), have been extended southward into Ohio (Hettinger, 2001; Ryder, 2000, 2004). In contrast, the unnamed limestone and Dayton Limestone are southern Ohio units (Horvath, 1970; Horvath and others, 1970; McDowell, 1983) that have been extended northward in this study into eastern Ohio and northern West Virginia (Ryder, 2000, 2004). The unnamed limestone may be equivalent to the Oldham Limestone of south-central Ohio and northern Kentucky (Horvath, 1970; McDowell, 1983; Ryder, 2000). An informal driller’s term, the Packer shell, commonly is shown and described as a carbonate unit that overlies the “Clinton” sandstone (McCormac and others, 1996). Because this term usually is assigned indiscriminately to one or more carbonate units above the “Clinton” sandstone, it has no stratigraphic significance for section *F–F′* other than to indicate a post-“Clinton” sandstone age. In southeastern Ohio, the Packer shell, as used by Osten (1982) in western Noble County, consists of a single limestone unit that is assigned to the unnamed limestone in this report (see wells 66–70). Another informal driller’s term used by Osten (1982), the Casing shell, consisting of a limestone unit about 50 ft above the Packer shell, is assigned to the Dayton Limestone in this report (see wells 66–70).

The combined carbonate and shale units between the “Clinton” sandstone and the Lockport Dolomite (locally the Keefer Sandstone) in Ohio correlate with the shale-dominated Rose Hill Formation in central West Virginia (Smosna and Patchen, 1978). The Irondequoit Limestone in section *F–F′* pinches out southeastward near well 94 into shale of the upper part of the Rose Hill Formation whereas the Dayton and Reynales Limestones extend across the entire lower part of the Rose Hill Formation to the southeastern end of the section (fig. 3). The western end of the Reynales Limestone is truncated near well 64 by an unconformity at the base of the Dayton Limestone. The unnamed limestone below the Reynales Limestone consists of two units: a lower unit that pinches out southeastward near well 101 into shale of the Cacapon Sandstone Member of the Rose Hill Formation (Smosna and Patchen, 1978) and an upper unit that is replaced near well 96 by a sandstone unit of the Cacapon Sandstone Member. Commonly, the sandstone units in the Rose Hill Formation, and locally the carbonate units, are very hematitic.

The unconformity at the base of the Dayton Limestone in Ohio (see well 80 at 5,600 ft) is interpreted by Kleffner (1985) on the basis of conodont assemblages and by Brett and others (1990, 1995), Hettinger (2001), and Ryder (2000, 2004) on the basis of regional stratigraphic relations (fig. 3). In this report, this unconformity is extended into northwestern West Virginia (see well 94 at 7,458 ft and well 101 at 6,746 ft) on the basis of its probable regional extent into central Pennsylvania (Hettinger, 2001).

The Lower Silurian Keefer Sandstone overlies the Rose Hill Formation in northwestern and central West Virginia (Smosna and Patchen, 1978, 1980; Meyer and others, 1992) (fig. 3). In this report, the West Virginia Keefer is differentiated from the slightly younger Keefer Sandstone of eastern Ohio (Horvath and others, 1970) (fig. 3). The widespread Lower and Upper Silurian Lockport Dolomite and its McKenzie Limestone equivalent extend across the top of cross section *F–F′*. At the southeastern end of section *F–F′* the middle part of the McKenzie Limestone contains a 25- to 35-ft-thick unnamed sandstone unit (Smosna and Patchen, 1978), and the top of the McKenzie is overlain by the Upper Silurian Williamsport Sandstone. Unconformities interpreted by Brett and others (1990) in the middle of the Irondequoit Limestone in central and western New York and at the base of the Lockport Dolomite in southern Ohio are not shown in this report because they may be absent along cross section *F–F′*.

Sequence Stratigraphy and Depositional Environments of the “Clinton,” Medina, and Tuscarora Sandstones

Two depositional sequences, 1 and 3, are interpreted in the Lower Silurian strata of section *F–F′* (fig. 3). The base of sequence 1 is defined by the Cherokee unconformity of Dennison and Head (1975) (1,C on *F–F′*) (1=unconformity 1 of Hettinger, 2001; C=Cherokee unconformity of Dennison and Head, 1975, and Brett and others, 1990; basal unconformity of Castle, 1998). The top of sequence 1 is defined by unconformity 3 of Hettinger (2001) (3,T on *F–F′*) (3=unconformity 3 of Hettinger, 2001; T=“Tuscarora unconformity” of Dorsch and others, 1994) (fig. 3). Both unconformities probably resulted from a fall in eustatic sea level based on an apparent basinal shift in depositional environments. Sequence 3, which directly overlies sequence 1, extends from unconformity 3,T to the unconformity at the base of the Dayton Limestone and the Dayton Limestone (Dolomite) equivalent in the middle part of the Rose Hill Formation (fig. 3). An intermediate sequence, sequence 2 of Hettinger (2001), located in the middle of the Tuscarora in central Pennsylvania and in the “Clinton” sandstone and Cabot Head Shale (lower) in northeastern Ohio (see sections *B–B′* and *C–C′* by Hettinger, 2001), is not recognized in this report. Perhaps sequence 2 was eroded from the strata illustrated on section *F–F′* prior to the deposition of sequence 3 or was never deposited. Sequence 1 consists of a transgressive systems tract and an overlying highstand systems tract whereas sequence 3 consists of a transgressive systems tract and an overlying systems tract that was not evaluated (fig. 3). Sequences 1 and 3 in this report correlate, respectively, with sequences 1 and 3 of Hettinger (2001) and Ryder (2004). Moreover, sequences 1 and 3 in this report, Ryder (2004), and Hettinger (2001) replace sequences I and II of Ryder (2000).

A comparison of sequences 1 and 3 (this report) with sequences I, II, and III of Brett and others (1990) is shown in figure 3. The main difference is that sequence I of Brett and others (1990) consists of a single transgressive systems tract that includes all of sequence 1 and the lower part of sequence 3, an interval that extends from the Cherokee unconformity to the Clinton Group basal unconformity of Brett and others (1990). However, the Clinton Group basal unconformity of Brett and others (1990) is interpreted by Hettinger (2001) and Ryder (2000, 2004) to be instead a ravinement surface at the base of the Cabot Head Shale (upper) (fig. 3) caused by marine transgression rather than a fall in eustatic sea level (see Walker, 1992, and Shanley and others, 1992, for other examples of ravinement surfaces). Also, Hettinger (2001) and Ryder (2004, this report) reinterpreted the upper boundary of sequence I to coincide with unconformity 3 (Hettinger, 2001). Thus the stratigraphic interval of sequence 1 is reduced with respect to sequence I (Brett and others, 1990). Moreover this reinterpretation establishes sequence 3 as the equivalent of combined sequences I (part) II, and III (Brett and others, 1990) (fig. 3).

Sequence 1

Transgressive Systems Tract

The stratigraphic position of the transgressive systems tract (tst) is shown on section *F–F′* between wells 3 and 5, wells 18 and 20, wells 21 and 23, wells 55 and 58, wells 60 and 62, wells 72 and 74, and wells 98 and 99 and in figure 3. This systems tract is located in the interval between the Cherokee unconformity at the base of the Brassfield Limestone, the Medina sandstone, and the Tuscarora Sandstone and the maximum flooding surface (mfs) in the Brassfield Limestone, the Cabot Head Shale (lower), and above the top of the basal sandstone unit in the Tuscarora (fig. 3). Moreover, this systems tract correlates with the transgressive systems tract recognized by Castle (1998), Hettinger (2001), and Ryder (2000, 2004). Lithologic units and their interpreted depositional environments that constitute the systems tract are described in the following paragraphs.

The Medina sandstone, shown in gold on section *F–F′*, is located at the base of the transgressive systems tract. This 10- to 20-ft-thick basal sandstone unit is characterized by an upward-fining change in grain size judging from its upward-increasing (higher clay content) gamma-ray log response (see wells 45 and 72). In northwestern Pennsylvania, an equivalent sandstone unit, the Whirlpool Sandstone, has been interpreted by Laughrey (1984) to be a sublittoral sheet sandstone. Moreover, on the basis of outcrop studies in northwestern New York and adjoining Ontario, Canada, Middleton and others (1987) concluded that the lower part of the Whirlpool Sandstone was deposited in a northwestward-flowing braided fluvial system.

Following the interpretations of Laughrey (1984), Middleton and others (1987), Castle (1998), and those of Hettinger (2001) in sections *B–B′* and *C–C′* for the Whirlpool Sandstone, the Medina sandstone is interpreted on section *F–F′* as a shoreface and sublittoral sheet sandstone, with a basal braided fluvial component. At the northwestern end of section *F–F′*, the Medina sandstone becomes very calcareous and is replaced between wells 27 and 29 by the basal sandy part of the Brassfield Limestone.

The Medina sandstone correlates with an equivalent basal sandstone unit in the Tuscarora Sandstone (fig. 3). This basal Tuscarora sandstone unit rests unconformably on the Juniata Formation and ranges in thickness from about 10 to 15 ft (wells 94–99). At the southeastern end of section *F–F′*

(wells 101, 105), the basal sandstone unit of the Tuscarora is absent, probably because it was truncated by unconformity 3,T. Although Castle (2001) and Castle and Byrnes (2005) interpreted the Tuscarora Sandstone in central West Virginia as a deeply incised valley-fill deposit, they attributed the erosion to the basal unconformity (Cherokee unconformity) rather than to the 3,T unconformity presented in this study. On the basis of similar thicknesses and gamma-ray log responses, the basal Tuscarora sandstone unit and the Medina sandstone are interpreted here to have a similar depositional origin.

The Cherokee unconformity, labeled 1,C along section *F–F′*, is considered to be disconformable in nature and is marked by sandstone, siltstone, and sandy limestone of probable Early Silurian age that abruptly overlie red beds of probable Late Ordovician age (fig. 3; *F–F′* between wells 1 and 92). Moreover, the Cherokee unconformity probably extends eastward where it is located at the base of the Tuscarora Sandstone (fig. 3; *F–F′* between wells 94 and 101). According to Dennison and Head (1975), the Cherokee unconformity was caused by a short-term fall in eustatic sea level that was largely independent of the longer term Taconic orogeny and the classic angular unconformity between Middle-Upper Ordovician and Lower Silurian strata in eastern Pennsylvania (Pavlides and others, 1968; Rodgers, 1970).

The Medina sandstone on section *F–F′* grades upward into shale and mudstone of the Cabot Head Shale (lower) (Knight, 1969). Following Laughrey (1984), Brett and others (1995), and Castle (1998), these shale and mudstone units are interpreted on section *F–F′* as offshore marine deposits. Furthermore, on the basis of a high gamma-ray log response, Castle (1998) and Hettinger (2001) interpreted a maximum flooding surface (see Walker, 1992, for definition) near the lower third of the Cabot Head Shale (lower) in Ohio. The same flooding surface is identified in the Tuscarora Sandstone above the top of the basal sandstone unit (fig. 3; section *F–F′*).

Highstand Systems Tract

The stratigraphic position of the highstand systems tract is shown in figure 3 and on section *F–F′* (between wells 3 and 5, wells 18 and 20, well 21 and 23, wells 55 and 58, wells 60 and 62, wells 72 and 74, and wells 98 and 99). This systems tract, correlative with the highstand systems tract recognized by Hettinger (2001) and Ryder (2000, 2004), is located in the interval between the maximum flooding surface in the Cabot Head Shale (lower) and a sequence boundary unconformity defined by Hettinger (2001) (labeled 3,T on *F–F′*). Where the 3,T unconformity is absent, the top of the highstand systems tract is marked by a ravinement surface (fig. 3). The sequence boundary unconformity and ravinement surface are described in the section on sequence 3. Castle (1998) also recognized a highstand systems tract in this approximate stratigraphic interval but, unlike Hettinger (2001), he placed its top at a marine flooding surface rather than at a regional unconformity.

Composite sandstone units in the lower to middle part of the "Clinton" sandstone constitute the majority of the highstand systems tract. Shown in light yellow on section *F–F′*, they are 10 to 40 ft thick and commonly have upward-decreasing ("cleaner"/lower clay content) gamma-ray log responses (see well 27 between 3,505 and 3,488 ft and well 66 between 5,242 and 5,215 ft, for example). In northwestern Pennsylvania, these types of sandstones have been interpreted as barrier bar and tidal delta deposits (Laughrey, 1984) and shoreface deposits (Hettinger, 2001). The shoreface sandstone units interpreted by Hettinger (2001) become successively younger and overlap one another in a westerly direction, pinch out northwestward into offshore marine shale of the Cabot Head Shale (lower), and appear to downlap across the base of the Cabot Head Shale (lower). Castle (1998) assigned similar depositional environments to this sandstone interval, but he emphasized shelf-bar complexes that originated on a tide- and wave-dominated shelf. The depositional patterns of the coarsening-upward sandstone units identified on section *F–F′* are nearly identical to the stacked westward-prograding shoreface sandstones recognized on sections *B–B′* and *C–C′* by Hettinger (2001).

The lower to middle part of the "Clinton" sandstone, shown in light yellow, correlates with a 25- to 80-ft-thick sandstone interval in the Tuscarora Sandstone (see wells 94–99). This part of the Tuscarora is dominated by 10- to 35-ft-thick, individual and composite sandstone beds commonly with upward-decreasing gamma-ray log responses (see well 98 between 7,830 and 7,812 ft). In the same fashion as the transgressive systems tract deposits, the highstand systems tract deposits of the Tuscarora are interpreted here to be truncated by unconformity 3,T between wells 99 and 101. Judging from their log signatures that are similar to those in the lower and middle parts of the "Clinton" sandstone, the sandstones in the equivalent lower Tuscarora interval are interpreted here as shoreface deposits. Probable outcrop equivalents of the lower Tuscarora Sandstone interval in southwestern Virginia have been interpreted as proximal marine shelf (Bambach, 1987) and storm-dominated, shallow-marine deposits (Dorsch and others, 1994).

Sequence 3

Basal Sequence Boundary

Sequence 3 begins with a basal sequence unconformity (labeled 3,T on *F–F′*) that correlates with unconformity 3 of Hettinger (2001) in northwestern and central Pennsylvania, northeastern Ohio, and western New York. Hettinger (2001) proposed this previously unrecognized unconformity to account for the irregular truncation of shoreface sandstone deposits he observed, from well logs, in the underlying highstand systems tract of sequence 1. According to Hettinger (2001), erosion and paleovalley incision into the highstand systems tract that marks the unconformity was caused by a relative fall in base level. This suggested mechanism is supported by a fall in eustatic sea level interpreted by Ross and Ross (1996) at the Rhuddanian-Aeronian boundary (fig. 3).

In this study, the sequence 3 basal unconformity (unconformity 3 of Hettinger, 2001) is extended southeastward into the Tuscarora Sandstone by using upward-increasing gamma-ray log signatures with abrupt bases (for example, 7,714 ft in well 94 and 8,704 ft in well 97). In well 105 and probably well 101, the sequence 3 basal unconformity is interpreted to truncate all sequence 1 deposits of the Tuscarora and the underlying Cherokee unconformity (1,C) and, thus, place the upper part of the Tuscarora Sandstone directly on the Juniata Formation. Furthermore, the sequence 3 basal unconformity is correlated in this study with the "Tuscarora unconformity" recognized by Bambach (1987) and Dorsch and others (1994) in southwestern Virginia and adjoining West Virginia where retrogradational lower shoreface to nearshore deposits of the upper part of the Tuscarora rest in sharp contact on progradational storm-dominated shallow-marine deposits of the lower Tuscarora Sandstone. Consistent with this correlation, the Cherokee unconformity is interpreted here to reappear about 30 mi south of cross section *F–F′* near the West Virginia-Virginia border, where it forms the contact between the lower Tuscarora Sandstone and the transitional part of the Juniata Formation (Bambach, 1987). However, this interpretation contrasts with that of Bambach (1987), Dorsch and others (1994), and Castle (2001) because they correlated the "Tuscarora unconformity" with the Cherokee unconformity not with unconformity 3 of Hettinger (2001). Additional outcrop and subsurface data are required to resolve these divergent interpretations.

At the northwestern end of section *F–F′* (between wells 1 and 16, wells 21 and 36, and wells 60 and 62), where unconformity 3,T is absent, the sequence 3 basal unconformity merges with a ravinement surface (see Eastern Ohio column in fig. 3). This ravinement surface correlates with one previously interpreted by Hettinger (2001) and Ryder (2000, 2004). Erosional by definition, the surface originated during marine transgression of the subaerially exposed shoreface sandstone and offshore marine shale of the underlying highstand systems tract. In wells 18 to 20 and 38 to 58, the ravinement surface passes over unconformity 3,T and the top of sequence 3 fluvial-estuarine and tidal flat deposits in the "Clinton" sandstone, discussed in the following section, before returning to the top of the highstand systems tract deposits. Between wells 62 and 64 the ravinement surface again passes over unconformity 3,T and the top of sequence 3 fluvial-estuarine and tidal flat deposits in the "Clinton" sandstone (between wells 64 and 92) and the Tuscarora Sandstone/lower part of the Rose Hill Formation (between wells 92 and 105). Evidence for erosion and reworking along the ravinement surface is provided by a thin zone of fossiliferous, argillaceous, and clastic limestone described, in core, between the "first and second Clinton sands" in Hocking County, Ohio (Overbey and Henniger, 1971). Very likely, both partial subaerial exposure during the sea-level drop and shoreline advancement during the subsequent rise in sea level contributed to the erosion and reworking.

Transgressive Systems Tract

The stratigraphic position of the transgressive systems tract is shown in figure 3 and on section *F–F′* (between wells 3 and 5, wells 18 and 20, wells 21 and 23, wells 55 and 58, wells 60 and 62, wells 72 and 74, and wells 98 and 99). This systems tract is located in the interval between the sequence 3 basal unconformity and the maximum flooding surface in the unnamed shale underlying the Reynales Limestone (see transgressive systems tract label between wells 72 and 74). At the northwestern end of section *F–F′*, between wells 1 and 36, where the sequence 3 basal unconformity is largely absent and the maximum flooding surface is obscure because the pre-Dayton Limestone unconformity (fig. 3) has removed part or all of the unnamed shale, the systems tract is located between the ravinement surface and the base of the Dayton Limestone (see transgressive systems tract label between wells 3 and 5).

Composite sandstone units in the middle part of the "Clinton" sandstone constitute the lower part of the transgressive systems tract in sequence 3. Shown in orange on section *F–F′*, they are 10 to 65 ft thick and display spike-shaped and (or) upward-increasing (higher clay content) gamma-ray log responses (see well 64 between 5,244 and 5,225 ft, well 80 between 5,745 and 5,709 ft, and well 92 between 6,875 and 6,828 ft, for examples). In previous investigations these composite sandstone units have been interpreted as channel deposits associated with a prograding shoreline. For example, Osten (1982) and Laughrey (1984) interpreted them as distributary channels and braided fluvial channels, respectively, that were deposited more or less synchronously behind, across, and above a prograding marine shoreline. Castle (1998) interpreted the sandstones as tidal channels and shelf-bar complexes associated with a prograding shoreline. Similarly, coeval sandstone units in the outcrop belt of the Medina Group in northwestern New York and adjoining Ontario, Canada, have been interpreted by Duke and others (1991) as progradational shoreline deposits (subtidal and intertidal channels and shoals). A new interpretation by Hettinger (2001), adopted in this report, suggested that these channel sandstone units are fluvial and tidally influenced (estuarine) deposits that resulted from the backfilling of paleovalleys during a relative rise in base level. The paleovalleys were cut during the preceding relative fall in base (sea) level that formed unconformity 3. Van Wagoner and others (1990) and Reinson (1992) have described deposits of this nature in other regions of the world that formed during a relative rise in sea level.

The proposed fluvial and estuarine deposits in the "Clinton" sandstone are correlated here with a 35- to 85-ft-thick, sandstone-dominated interval in the Tuscarora Sandstone, also shown in orange on section *F–F′*. Blocky to upward-increasing gamma-ray log responses (wells 94–105) and the presence of incised valley-fill deposits of fluvial and estuarine origin in a core taken from the Tuscarora in Kanawha County, central West Virginia (Castle, 2001; Castle and Byrnes, 2005) support this correlation.

A thin shaley sandstone unit in the upper part of the "Clinton" sandstone, shown in light green on section *F–F′*, rests conformably on the fluvial and estuarine sandstone deposits in wells 48, 52–58, and 90–92. In eastern Ohio the sandstone unit ranges in thickness from about 10 to 20 ft. In northwestern Pennsylvania, Laughrey (1984) interpreted a correlative shale, siltstone, and sandstone unit in the upper 35 ft of the Grimsby Sandstone of the Medina Group as tidal-flat deposits with some evidence for fluctuating marine conditions. The same unit in northwestern Pennsylvania has been interpreted by Castle (1998) as an intertidal flat and subtidal deposit that is equivalent to the Castanea Member of the Tuscarora Formation. These interpretations by Laughrey (1984) and Castle (1998) are applied here to the shaley sandstone unit shown in light green on section *F–F′*. This unit in the upper part of the "Clinton" sandstone correlates with a similar sandstone unit of probable tidal-flat origin at the base of the main body of the Rose Hill Formation (well 94) and at the base of the Cacapon Sandstone Member (wells 96–101) (fig. 3).

Across most of section *F–F′*, a 12- to 60-ft-thick unit of interbedded sandstone, shale, and sandy dolomite occurs between the ravinement surface and the overlying Dayton Limestone (wells 1–9) and unnamed limestone (wells 10–90). This sandstone and shale unit belongs to the upper part of the "Clinton" sandstone and the overlying Cabot Head Shale (upper). The 4- to 25-ft-thick sandstones and 5- to 25-ft-thick sandy dolomite of the "Clinton" sandstone (shown in stippled yellow and stippled blue, respectively) are interpreted here as marine shelf and (or) nearshore marine deposits whereas the shales (shown in gray) are interpreted as offshore marine deposits. These deeper water deposits constitute the upper part of the transgressive systems tract of sequence 3. The overlying unnamed limestone and associated marine shales represent the final upward deepening of the transgressive systems tract of sequence 3. The upper sandstone in the Cacapon Sandstone Member (wells 97–99, 101, 105) that merges westward with the upper part of the unnamed limestone probably represents a minor progradational event in the overall retrogradational setting.

Initial Reservoir Performance

Section *F–F′* traverses most of the Lower Silurian regional oil and gas accumulation (fig. 1) where drilling depth to gas and (or) oil production ranges from about 2,705 ft (well 6) to about 7,082 ft (well 101) (table 1). Nearly all of the petroleum-producing zones have been stimulated by at least one stage of hydrofracturing. Section *F–F′* crosses the approximate boundary between the basin center and hybrid-conventional parts of the Lower Silurian regional accumulation (Ryder and Zagorski, 2003) near wells 38 and 41 (figs. 1, 2). As an approximate measure of variability in reservoir performance and character across section *F–F′*, the initial production flow (IPF) of gas, oil, and water was recorded for each well. Of particular interest is the identification of areas of high reservoir productivity that could be correlated with a specific depositional environment, depositional sequence, or part of the Lower Silurian regional oil and gas accumulation.

Recorded gas IPFs in the "Clinton" sandstone have a median of 150 thousand cubic feet of natural gas (MCFG) per day and range from 10 MCFG per day (wells 6 and 53) to 4,060 MCFG per day (well 26) (table 1). Twenty-two wells in the "Clinton" sandstone on section *F–F′* had a gas IPF equal to or exceeding 500 MCFG per day. Half of these higher yield gas wells (for example, wells 7, 26, and 38) are located in the hybrid-conventional part of the regional accumulation and half (for example, wells 49, 59, and 93) are located in the basin-center part. There are no obvious differences between the depositional character (facies or systems tracts) in these higher yield wells and that in nearby wells with low to modest yields. Also, there is no correlation between gas production and accumulation type because the median IPFs are the same for wells in the hybrid-conventional and basin-center parts of the regional accumulation (150 MCFG per day). The only variable that seems to correlate with initial gas production is the year that the well was drilled. For example, sixteen of the twenty-two higher yield wells were drilled prior to 1980 when initial pressures had not yet been diminished by extensive infill drilling (table 1). However, this relation does not apply to wells with IPFs less than 500 MCFG per day.

Recorded oil IPFs in the "Clinton" sandstone along section *F–F′* have a median value of 5 barrels of oil (BO) per day and range from a trace in several wells (for example, wells 26, 41, and 48) to 200 BO per day in well 13 (table 1). The importance of hydrofracturing is indicated in well 12 where oil flow increased from 4 to 30 BO per day after stimulation (table 1). The largest oil fields on section *F–F′*—Philo field (wells 43–45), Forest Glen field (wells 5–9), and Perryton field (wells 10–18)—have reported IPFs as high as 4, 100, and 200 BO per day, respectively (table 1). As predicted in the model for hydrocarbon accumulation proposed by Ryder and Zagorski (2003), oil is more abundant in the hybrid-conventional part of the Lower Silurian regional oil and gas accumulation (high-yield wells 9 and 13; median IPF≈10 BO) than in the basin-center part (median IPF=3 BO). Ryder and Zagorski (2003) suggested that the minor oil produced in the basin-center part of the regional accumulation, including Philo field and higher yield well 59 (IPF=50 BO), is related to incomplete oil-to-gas transformation during the formation of basin-center gas.

An IPF of 235 MCFG per day was recorded from the Tuscarora Sandstone in well 101 (table 1), located approximately 20 mi northeast of the Indian Creek field in Kanawha County, West Virginia (fig. 1). Gas with a high percentage of noncombustable CO_2 is trapped at the Indian Creek field on a northeast-plunging anticlinal nose (Avary, 1996). Other characteristics of the field include IPFs that average 8,172 MCFG per day and an ultimate recovery of 60 billion cubic feet (Avary, 1996). Primary intergranular porosity that averages 8.2 to 10.4 percent (Bruner, 1983; Avary, 1996), combined with open fractures (Avary, 1996), contribute to the unusually good

Tuscarora reservoir at Indian Creek field compared with other localities (Wescott, 1982; Castle and Byrnes, 2005). Perforated intervals at Indian Creek field and in well 101 along section *F–F′* indicate that the gas in the Tuscarora reservoir is produced from the basal fluvial-estuarine sandstone unit in the sequence 3 transgressive systems tract.

Water (brine) production, ranging from a trace to 4 barrels of water (BW) per day, is reported with the oil and gas in Ohio (wells 18, 19, 34, 36, 37, and 68). All of these water-producing wells, except for well 68, are located in the hybrid-conventional part of the Lower Silurian regional oil and gas accumulation as suggested in the basin-center gas model proposed by Ryder and Zagorski (2003). The higher-than-expected water IPF in well 68 in the basin-center part of the accumulation may have resulted from water introduced during hydrofracturing of the reservoir.

Summary and Conclusions

1. The approximately 215-mi-long cross section *F–F′*, normal to depositional strike, from central Ohio to northern West Virginia, shows the stratigraphic framework, nomenclature, and depositional sequences of the Niagaran Provincial Series (Lower and lower Upper Silurian).

2. Lower Silurian strata in Ohio include, in ascending order, the following stratigraphic units: the Medina sandstone, Cabot Head Shale (lower), “Clinton” sandstone, and Cabot Head Shale (upper). In central Ohio, the Brassfield Limestone replaces the Medina sandstone and part of the Cabot Head Shale (lower). The combined Medina sandstone, Cabot Head Shale (lower), and “Clinton” sandstone interval grades eastward across a hinge zone in western West Virginia into a sandstone-dominated unit named the Tuscarora Sandstone.

3. Regionally extensive carbonate and shale units overlie the “Clinton” sandstone and Tuscarora Sandstone along most of the cross section. In ascending order, the carbonate units consist of the unnamed limestone (dolomite), Reynales Limestone (Dolomite), Dayton Limestone (Dolomite), and Irondequoit Limestone (Dolomite). In Ohio, the 30- to 70-ft-thick Rochester Shale overlies the Irondequoit Limestone. The carbonate and shale interval is two to three times thicker in West Virginia than it is in Ohio. In West Virginia this interval is named the Rose Hill Formation and overlies the Tuscarora Sandstone. The carbonate units in Ohio extend into West Virginia as equivalent units in the Rose Hill Formation where they either continue across the entire section, pinch out into shale, or are replaced by sandstone beds, many of which are hematite bearing. For example, the unnamed limestone (dolomite) equivalent unit in the lower part of the Rose Formation is replaced at the southeastern end of the cross section by a sandstone interval called the Cacapon Sandstone Member of the Rose Hill Formation.

4. The thickest part of the combined “Clinton” sandstone, Medina sandstone, and Cabot Head Shale (lower and upper) interval is located in eastern Ohio where thicknesses range from about 170 to 180 ft. In central Ohio this interval thins to about 100 ft partly because its lower part is replaced by the Brassfield Limestone. The equivalent Tuscarora Sandstone ranges in thickness from 155 to 175 ft in western West Virginia.

5. Two sequences (1 and 3) and four systems tracts are identified in the “Clinton” sandstone-Medina sandstone and Tuscarora Sandstone along section *F–F′*. The lower sequence, defined as sequence 1, consists of (a) a lower transgressive systems tract with a shoreface sandstone, a basal braided fluvial component, and an overlying offshore marine shale and (b) an overlying highstand systems tract with westward-prograding shoreface sandstone and interbedded offshore marine shale. Sequence 3 consists of (a) a transgressive systems tract with fluvial and estuarine sandstone deposits overlain by tidal-flat deposits and (b) a systems tract that was not evaluated. Intervening sequence 2 of Hettinger (2001) is not recognized in this study.

6. The transgressive systems tract in sequence 1 rests unconformably on Queenston Shale and Juniata Formation red beds of probable Late Ordovician age. Dennison and Head (1975) named this unconformity the Cherokee unconformity and suggested that it was caused by a fall in eustatic sea level. The top of the transgressive systems tract is defined by a maximum flooding surface near the base of the Cabot Head Shale (lower) and above the top of the basal sandstone unit of the Tuscarora Sandstone.

7. The highstand systems tract in sequence 1 consists of shoreface sandstones of the “Clinton” sandstone that become younger and overlap one another in a westward direction and pinch out into offshore marine shale of the Cabot Head Shale (lower).

8. The base of the transgressive systems tract in sequence 3 is marked primarily by a regional unconformity that resulted from erosion into the underlying highstand systems tract. The resultant paleovalleys have been backfilled by fluvial and estuarine deposits (Hettinger, 2001). This previously unrecognized unconformity was probably caused by a fall in eustatic sea level at the Rhuddanian-Aeronian boundary described by Ross and Ross (1996). Moreover, this unconformity may correlate with the “Tuscarora unconformity” recognized in southwestern Virginia and adjoining West Virginia by Bambach (1987) and Dorsch and others (1994). Paleovalley incision and accompanying fluvial and estuarine deposits are uncommon in central Ohio. Here, the base of the transgressive systems tract in sequence is marked by a ravinement surface that follows the top of shoreface deposits of the underlying highstand systems tract. Minor subaerial exposure and shoreline erosion are associated with the

ravinement surface. Throughout most of eastern Ohio the ravinement surface follows the top of fluvial and estuarine deposits and overlying tidal-flat deposits in sequence 3 of the "Clinton" sandstone and continues eastward across the top of the Tuscarora Sandstone. A maximum flooding surface, identified in the shale unit overlying the unnamed limestone, marks the top of the transgressive systems tract.

9. Of the stratigraphic units shown on section *F–F′*, the "Clinton" sandstone is the major oil and gas producing interval. The drilling depth to oil and natural gas production in the "Clinton" sandstone varies from about 2,700 ft in central Ohio to about 7,000 ft in eastern Ohio. Although only a small amount of gas is produced from the Tuscarora Sandstone along section *F–F′*, larger quantities of gas are produced from the Tuscarora at Indian Creek field in nearby Kanawha County, central West Virginia (Avary, 1996). The Tuscarora gas in central West Virginia is produced at depths between 6,600 and 7,000 ft.

10. Initial production flow (IPF) of petroleum recorded for each well along section *F–F′* provides an estimate of the variability in reservoir performance across the Lower Silurian regional oil and gas accumulation. Gas IPFs from wells in the "Clinton" sandstone have a median of 150 MCFG per day and range from 10 to 4,060 MCFG per day. There is no obvious correlation between IPF and depositional facies, systems tracts, and basin-center–hybrid-conventional parts of the regional accumulation. Oil IPFs are highest in the Forest Glen and Perryton oil fields where they are as high as 100 and 200 BO per day, respectively. An IPF of 235 MCFG per day was reported from the Tuscarora Sandstone. Very likely, the highest of these IPF values is influenced by open fracture systems.

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