STRATIGRAPHIC FRAMEWORK AND DEPOSITIONAL SEQUENCES IN THE LOWER SILURIAN REGIONAL OIL AND GAS ACCUMULATION, APPALACHIAN BASIN: FROM ASHLAND COUNTY, OHIO, THROUGH SOUTHWESTERN PENNSYLVANIA, TO PRESTON COUNTY, WEST VIRGINIA

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INTRODUCTION

The Lower Silurian regional oil and gas accumulation was named by Ryder and Zagorski (2003) for a 400-mi (mile)-long by 200-mi-wide hydrocarbon accumulation in the central Appalachian basin of the Eastern United States and Ontario, Canada (fig. 1*A*). 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). The dominant reservoirs in this 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 (fig. 1*A*), a more proximal eastern facies of the "Clinton" sandstone and Medina Group in central Pennsylvania and central West Virginia (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 the 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 having many characteristics of a basin-center accumulation (Davis, 1984; Zagorski, 1988, 1991; Law and Spencer, 1993); and (3) a central and 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*A*). Whereas the supply of oil and gas in the central and western hybrid-conventional part of the regional accumulation continues to decline because of the many wells drilled there since the late 1880s, except in the Lake Erie offshore (de Witt, 1993), new gas continues to be discovered in the deeper, eastern basin-center part (Zagorski, 1991; Pees, 1994; Petroleum Information Corporation, 1994). In the easternmost part, only small quantities of gas have been produced from the Tuscarora Sandstone because of its generally poor reservoir quality and because of the low energy (Btu) content of the gas (Avary, 1996). Much of the gas produced from the Tuscarora Sandstone is trapped in fractured reservoirs.

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 parts of New York, Pennsylvania, Ohio, and West Virginia. The locations of the cross sections are shown in figures 1*A* and *B*, and results are reported in Keighin (1998), Ryder (2000), 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 *E–E′* discussed in this report is about 235 mi long, trends northwestward approximately normal to the depositional strike of the Lower Silurian sandstone system, and extends through large stretches of the eastern basin-center and central and western hybrid-conventional parts of the Lower Silurian regional oil and gas accumulation. Of the remaining five cross sections (figs. 1*A* and *B*), four trend northwestward (approximately normal to the depositional strike of the Lower Silurian sandstone system) and one (*A–A′*) trends north-northeastward (parallel to and, in part, oblique to the depositional strike). Several of these cross sections (*E–E′* and *F–F′*) traverse the entire Lower Silurian regional oil and gas accumulation.

CONSTRUCTION OF THE CROSS SECTION

Section *E–E′* was constructed from 72 wells (fig. 1*B* and table 1). The wells are approximately 1 to 5 mi apart, although in southwestern Pennsylvania the maximum distance between wells is about 65 mi (fig. 1*B*). Uppermost Ordovician, Lower Silurian, and lowermost Upper Silurian strata are correlated between the wells by using gamma-ray, density, and neutron borehole geophysical logs. Of the 72 wells used to construct section *E–E′*, 39 are shown in this report with their accompanying gamma-ray logs. The datum for most of section *E–E′* is the base of the Reynales Limestone (described later in the text).

Perforated intervals and the results of initial production flow of natural gas are available for most of the 72 wells and are shown on section *E–E′* and in table 1. The 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 *E–E′* were taken largely from oil-and-gas-field maps produced by State geological surveys and oil and gas agencies (DeBrosse and Vohwinkel, 1974; Harper and others, 1982; Cardwell, 1982).

GENERAL STRATIGRAPHY

The chronostratigraphic position and nomenclature of Lower Silurian units and adjoining uppermost Ordovician and lowermost Upper Silurian units along section *E–E′* are shown in figure 2. The information presented in figure 2 is based, in part, on the following publications: (1) Patchen and others (1985) and Brett and others (1990) for regional perspective; (2) Knight (1969), Horvath (1970), Horvath and others (1970), Nelson and Coogan (1984), and McCormac and others (1996) for Ohio; (3) Heyman (1977), Piotrowski (1981), Berg and others (1983), and Laughrey (1984) for Pennsylvania; and (4) Smosna and Patchen (1978) and Avary (1996) for West Virginia.

Silurian strata correlated on section *E–E′* 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. U.S. Geological Survey (USGS)-approved revisions to the Niagaran Provincial Series by Brett and others (1995) 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. 2), 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 "Clinton" 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. Also, in this study, the terms Medina sandstone and "Clinton" sandstone are applied to equivalent units in adjoining West Virginia (see well 66). In Pennsylvania, equivalent units of the Medina sandstone and "Clinton" sandstone are the Whirlpool Sandstone and Grimsby Sandstone, respectively, of the Medina Group (Hettinger, 2001) (fig. 2).

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 the Cabot Head Shale of the Medina Group in western Pennsylvania (Ryder, 2000; Hettinger, 2001) (fig. 2). The Cabot Head Shale (upper) probably does not have an equivalent in Pennsylvania and West Virginia (fig. 2). The Brassfield Limestone is located in central and southern Ohio and grades eastward into the Medina sandstone and Cabot Head Shale (lower) (fig. 2). The Medina sandstone and Brassfield Limestone rest unconformably on the Upper Ordovician Queenston Shale (fig. 2). This unconformity of regional scope is named 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 (lower and upper), and Medina sandstone and equivalent Medina Group along section *E–E′* is between 200 and 210 ft (feet). These thicknesses are typical for the "Clinton" sandstone-Medina Group interval penetrated in wells located in Carroll (wells 55–63) and Jefferson (well 65) Counties, Ohio, and probably in Beaver County (well 67), Pennsylvania. Also, Coogan (1991) reported similar total "Clinton" sandstone thicknesses in eastern Ohio. Knight (1969) recognized this depocenter of "Clinton" sandstone-Medina Group strata as the Canton embayment (fig. 1*A*). The Canton embayment, as defined by Knight (1969), is about 30 ft greater than the maximum thicknesses indicated by section *E–E′* because it includes several carbonate units that overlie the "Clinton" and Medina sandstones. West of the Canton embayment, the combined "Clinton"-Cabot Head (lower)-Brassfield units thin to between 155 and 175 ft in Ashland County, Ohio (wells 1 and 5).

As shown in figure 2, the combined Medina sandstone, Cabot Head Shale (lower), and "Clinton" sandstone are replaced by the Tuscarora Formation in southwestern and central Pennsylvania (Berg and others, 1983) and by the Tuscarora Sandstone in northern and central West Virginia (Smosna and Patchen, 1978; Avary, 1996). The Tuscarora Sandstone (Formation) is interpreted in this report to rest disconformably on the Upper Ordovician Juniata Formation or on 50- to 100-ft-thick transition beds between the two units (Piotrowski, 1981; Berg and others, 1983) (fig. 2). This disconformity is thought to be the eastward extension of the Cherokee unconformity (fig. 2), although it contradicts Diecchio (1985) who interpreted a conformable contact between the Tuscarora and Juniata in northern West Virginia. The upper 115 ft of the Tuscarora Formation in southwestern Pennsylvania, which contains a higher percentage of shale, mudstone, and siltstone beds, is named the Castanea Member (Piotrowski, 1981; Castle, 1998). In West Virginia, the Castanea Member is replaced by the lower part of the Cacapon Sandstone Member of the Rose Hill Formation (Smosna and Patchen, 1978).

East of a hinge zone located about midway between wells 67 and 68 (fig. 1*B*), the Tuscarora Sandstone (Formation) thickens to about two times that of the combined "Clinton"-Cabot Head (lower)-Medina units and the equivalent Medina Group. The Tuscarora is about 475 ft thick in Fayette County, Pennsylvania (well 68), and about 325 to 380 ft thick in Preston County, West Virginia (wells 69–72). If the Tuscarora-Juniata transition beds are included, the total thickness of the Tuscarora interval is about 630 ft in well 68 and about 355 to 450 ft in wells 69 through 72. Likewise, the Rose Hill Formation thickens across the hinge zone to about 610 ft in Fayette County, Pennsylvania (well 68).

Thin, widespread carbonate units in the Clinton Group of Pennsylvania and equivalent strata in Ohio and West Virginia are recognized here in ascending order as the unnamed limestone (dolomite), Reynales Limestone (Dolomite), Dayton Limestone (Dolomite), and Irondequoit Limestone (Dolomite) (fig. 2). Commonly, these units are dolomite and are identified as such in Pennsylvania (Heyman, 1977; Berg and others, 1983) and West Virginia (Patchen and others, 1985). Gray shale associated with the carbonates generally is less than 20 ft thick except for the 30- to 70-ft-thick Rochester Shale (Member) that overlies the Irondequoit Limestone in Ohio and southwestern Pennsylvania. The Reynales and Irondequoit Limestones, as revised by Brett and others (1990, 1995) in New York, have been extended southward into Pennsylvania (Piotrowski, 1981; Pees, 1983; Laughrey, 1984; Ryder, 2000; Hettinger, 2001) and Ohio (Ryder, 2000; Hettinger, 2001). In contrast, the

Dayton Limestone (Horvath, 1970; Horvath and others, 1970; McDowell, 1983) and unnamed limestone are southern Ohio units that have been extended into central and eastern Ohio by Ryder (2000; this study) and into southwestern Pennsylvania and northern West Virginia. 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 *E–E′* other than to indicate a post-"Clinton" sandstone age. For example, in eastern Ohio, the Packer shell as used by Seibert (1987) and Hill and others (1992) consists of three limestone units that are assigned separate names in this report (see well 62).

The combined carbonate, shale, and mudstone units of the Clinton Group in Pennsylvania and equivalent strata in Ohio correlate with the Rose Hill Formation, a 235- to 610-ft-thick, shale-dominated and mudstone-dominated unit in southwestern Pennsylvania and northern West Virginia (Berg and others, 1983; Smosna and Patchen, 1978). At the southern end of section *E–E′*, the lower 240 to 320 ft of the Rose Hill Formation is dominated by sandstone and siltstone of the Cacapon Sandstone Member. The Cacapon Sandstone Member is equivalent to the Castanea Member of the Tuscarora Formation, unnamed limestone (dolomite) equivalent, unnamed shale equivalent, Reynales Limestone (Dolomite) equivalent, unnamed shale equivalent, and Dayton Limestone (Dolomite) equivalent. Commonly the sandstone units in the Rose Hill Formation, and locally the carbonate units, are very hematitic. The Irondequoit Limestone (Dolomite) on section *E–E′* pinches out southeastward (between wells 67 and 68) into shale of the upper part of the Rose Hill Formation.

The unconformity at the base of the Dayton Limestone in Ohio (see well 55 at 5,371 ft) is interpreted by Kleffner (1985) on the basis of conodont assemblages and by Brett and others (1990, 1995) and Hettinger (2001) on the basis of regional stratigraphic relations (fig. 2). In this report, this unconformity is extended into southwestern Pennsylvania and northern West Virginia, where it is interpreted to underlie one of the upper sandstone units of the Cacapon Sandstone Member (fig. 2; also see well 71 at 7,116 ft).

The Lower Silurian Keefer Formation (Sandstone) overlies the Rose Hill Formation in central and southwestern Pennsylvania and northern West Virginia (Smosna and Patchen, 1978, 1980; Berg and others, 1983; Meyer and others, 1992) (fig. 2). In this report, the Pennsylvania and West Virginia Keefer is differentiated from the slightly younger Keefer Sandstone in southern and eastern Ohio (Horvath and others, 1970) because of their contrasting stratigraphic positions with respect to the Rochester Shale. The Keefer Formation (Sandstone) of Pennsylvania and West Virginia is overlain by the Rochester Member-Rochester Shale Member as used by Berg and others (1983) and Smosna and Patchen (1978) whereas the Keefer Sandstone of eastern Ohio is underlain by the Rochester Shale as used by Nelson and Coogan (1984) (fig. 2). The 200- to 400-ft-thick Lower and Upper Silurian Lockport Dolomite and its McKenzie Member equivalent extend across the top of cross section *E–E′*. Unconformities interpreted by Brett and others (1990) at the base of the Irondequoit Limestone and the Lockport Dolomite in Ohio are not recognized in this report.

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 *E–E′* (fig. 2). The base and top of sequence 1 are defined, respectively, by the Cherokee unconformity of Dennison and Head (1975) (1,C on *E–E′*) (1=unconformity 1 of Hettinger, 2001; C=Cherokee unconformity of Dennison and Head, 1975) and unconformity 3 of Hettinger (2001) (3,T on *E–E′*) (3=unconformity of Hettinger, 2001; T= "Tuscarora unconformity" of Bambach (1987) and Dorsch and others, 1994) (fig. 2). Both unconformities probably resulted from a fall in eustatic sea level. Sequence 3, which directly overlies sequence 1, begins with unconformity 3,T and ends at the unconformity at the base of the Dayton Limestone and an equivalent sandstone unit in the upper part of the Cacapon Sandstone Member (fig. 2). An intermediate sequence, sequence 2 of Hettinger (2001), located in the middle of the Tuscarora in central Pennsylvania and 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 section *E–E′* prior to the deposition of sequence 3. 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 undefined systems tract (fig. 2).

Sequence 1 in this report correlates with sequence 1 of Hettinger (2001) and sequence I of Ryder (2000). Sequence 3 in this report correlates with, and replaces, sequence II of Ryder (2000). Moreover, sequence 3 in this report is similar to sequence 3 of Hettinger (2001), except for slight differences in the stratigraphic position of the top of the transgressive systems tract. This report places the top of the transgressive systems tract at a maximum flooding surface (mfs) (fig. 2), whereas Hettinger (2001) placed it at the unconformity at the base of the Dayton Limestone. The transgressive systems tract of sequence 3, as used in this report, is succeeded by an undefined systems tract (fig. 2).

By comparison, 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 of this report and Hettinger (2001). As defined by Brett and others (1990), sequence I extends from the Cherokee unconformity to an unconformity at the base of the Clinton Group (fig. 2). However, the Clinton Group basal unconformity of Brett and others (1990) is interpreted in this report to be a ravinement surface (fig. 2) caused by marine transgression rather than a sequence boundary caused by a fall in eustatic sea level. Combined sequences II and III of Brett and others (1990) that extend from their Clinton Group basal unconformity (ravinement surface (rv) in figure 2) to the Dayton Limestone basal unconformity constitute the approximate upper part of sequence 3 of this report.

Sequence 1

Transgressive Systems Tract

The approximate stratigraphic position of the transgressive systems tract (**tst**) is shown on section *E–E′* between wells 1 and 5, wells 61 and 62, wells 62 and 63, and wells 70 and 71 and in figure 2. 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 Formation (Sandstone) and the maximum flooding surface in the Brassfield Limestone, the Cabot Head Shale (lower), and at the top of the basal sandstone unit in the Tuscarora. Moreover, this systems tract correlates with the transgressive systems tract recognized by Castle (1998), Ryder (2000), and Hettinger (2001). 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 *E–E′*, is located at the base of the transgressive systems tract. This 10- to 15-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 50). In western New York and northwestern Pennsylvania, equivalent sandstone units have been interpreted by Metzger (1981) and Laughrey (1984) to be a sublittoral sheet sandstone deposit. 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 (equivalent to the Medina sandstone) was deposited in a northwestward-flowing braided fluvial system.

Following the interpretations for the Whirlpool Sandstone by Laughrey (1984), Middleton and others (1987), Castle (1998), and Hettinger (2001) (sections *B–B′* and *C–C′*), the Medina sandstone is interpreted on section *E–E′* to be a shoreface and sublittoral sheet sandstone, with a basal braided fluvial component. In the vicinity of section *E–E′*, the Medina sandstone is thinner and more argillaceous and (or) silty than the Whirlpool Sandstone of northwestern Pennsylvania (Hettinger, 2001) and the Medina sandstone of southeastern Ohio (Ryder, 2000). This region of thin and argillaceous Medina sandstone along *E–E′* is located near the zero-sand area on the net sandstone map (thickness of >50 percent "clean sandstone" on the gamma-ray log) of Boswell and others (1993). At the western end of section *E–E′*, the Medina sandstone becomes very calcareous and is replaced between wells 39 and 41 by the basal sandy part of the Brassfield Limestone.

The Whirlpool Sandstone is very thin to absent in Beaver County, Pennsylvania (well 67), but probably reappears southeast of the hinge zone as an equivalent basal sandstone unit (shown in gold) in the Tuscarora Formation. This basal Tuscarora sandstone unit probably rests unconformably on Tuscarora-Juniata transition beds and ranges in thickness from about 20 to 50 ft (wells 68–72). Similarly, Brett and others (1990), Castle (1998), and Hettinger (2001) have correlated the Medina sandstone and Whirlpool Sandstone with the lower part of the Tuscarora Formation. However, according to Castle (1998), the top of the Whirlpool-equivalent basal Tuscarora unit is located at 7,420 ft rather than at 7,425 ft as shown on section *E–E′* (well 72). Although Cotter (1982, 1983) and Hettinger (2001) interpreted the basal Tuscarora in central Pennsylvania as channeled coast, coastal lagoon, and barrier beach inlet deposits, the predominance of upward-decreasing ("cleaner") gamma-ray log responses (wells 68–70) suggests that, on section *E–E′*, the basal Tuscarora consists largely of shoreface and subtidal deposits. A marine shoreface interpretation by Castle (1998) for interval 7,425 to 7,437 ft, part of a 273-ft core (7,164–7,437 ft) in well 72, further supports the shoreface and subtidal origin for the basal Tuscarora unit.

The Cherokee unconformity, labeled 1,C along *E–E′*, is considered to be disconformable in nature and marked by sandstone and siltstone of probable Early Silurian age that abruptly overlie red beds of Late Ordovician Queenston Shale. Moreover, the Cherokee unconformity probably extends eastward where it is located between the Tuscarora and Tuscarora-Juniata transition beds of possible earliest Early Silurian age (fig. 2; *E–E′* between wells 68 and 72). Also, cross sections by Heyman (1977) show an unnamed unconformity at the top of the Queenston Shale in well 66 of this study. According to Dennison and Head (1975), the Cherokee unconformity was caused by a fall in eustatic sea level that was largely independent of the 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 *E–E′* 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 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) near the lower third of the Cabot Head Shale in northwestern Pennsylvania. The same maximum flooding surface is identified in the Cabot Head Shale (lower) and extended across the top of the basal sandstone unit of the Tuscarora (fig. 2; section *E–E′*).

Highstand Systems Tract

The stratigraphic position of the highstand systems tract is shown in figure 2 and on section *E–E′* (between wells 1 and 5, wells 61 and 62, wells 62 and 63, and wells 70 and 71). This systems tract, that is correlative with the highstand systems tract recognized by Ryder (2000) and Hettinger (2001), 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 *E–E′*). Where the 3,T unconformity is absent, the top of the highstand systems tract is marked by a ravinement surface (fig. 2, section *E–E′*). The sequence boundary unconformity and ravinement surface are described in the following text regarding 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 and Grimsby Sandstone constitute the majority of the highstand systems tract. Shown in light yellow on section *E–E′*, they are 35 to 50 ft thick and commonly have upward-decreasing ("cleaner") gamma-ray log responses (see well 25 between 3,706 and 3,646 ft; well 28 between 3,780 and 3,751 ft; and well 59 between 5,606 and 5,538 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, and appear to downlap across the underlying Cabot Head Shale. Castle (1998) assigned similar depositional environments to this sandstone interval, but he emphasized shelf-bar complexes that originated on a tide-dominated and wave-dominated shelf. The depositional patterns of the coarsening-upward sandstone sequence identified on section *E–E′* are nearly identical to the stacked westward-prograding shoreface sandstones recognized by Hettinger (2001).

Exceptions to the predominant upward-coarsening sandstone units in this interval are 10- to 30-ft-thick sandstones with symmetrical gamma-ray log signatures (see well 61 between 6,072 and 6,041 ft and well 62 between 6,085 and 6,079 ft, for example) or with slight upward-increasing gamma-ray log signatures with a flat base (see well 44 between 4,522 and 4,503 ft and well 65 between 6,705 and 6,692 ft). Possibly, these sandstone units could be retrogradational shoreface and tidal channel deposits in sequence 2 of Hettinger (2001). Also, the abnormally thick, detached sandstone body in well 25 between 3,706 and 3,669 ft could be part of Hettinger's sequence 2.

The lower to middle part of the "Clinton" sandstone and Medina Group, shown in light yellow, correlates with a 60- to 130-ft-thick interval in the Tuscarora Sandstone (Formation) (see wells 68–72). This part of the Tuscarora is dominated by 10- to 30-ft-thick, composite sandstone beds that generally display upward-decreasing gamma-ray log responses. Interval 7,425 to 7,384 of a 273-ft core in well 72 is described by Castle (1998) as containing amalgamated, fine-grained to coarse-grained, cross-stratified sandstone with vertical burrows, shale clasts, and local thin interbeds of shale. The cored interval is interpreted by Castle (1998) to consist of estuarine and marine sandstone deposits. Judging from the log signatures, the core interpretation by Castle (1998), outcrop interpretations by Cotter (1982, 1983), and subsurface correlations by Hettinger (2001), the yellow interval in the Tuscarora is recognized here to consist largely of shoreface and shelf sand-wave deposits.

Sequence 3

Basal Sequence Boundary

Sequence 3 begins with a basal sequence unconformity (labeled 3,T on *E–E′*) 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. 2).

In this study, the sequence 3 basal unconformity is extended into the Tuscarora Sandstone (Formation) by using upward-increasing gamma-ray log signatures with abrupt bases (for example, 11,110 ft in well 69 and 7,632 ft in well 71) and the contact between estuarine and marine deposits described in core in well 72 (7,384 ft) by Castle (1998). Very likely, unconformity 3 correlates with the "Tuscarora unconformity" interpreted by Bambach (1987) and Dorsch and others (1994) in southwestern Virginia and adjoining West Virginia where retrogradational deposits of the upper part of the Tuscarora rest in sharp contact on progradational deposits of the lower part of the Tuscarora. However, several differences may exist between the two unconformities. First, the retrogradational strata above the "Tuscarora unconformity" in Virginia and West Virginia are interpreted by Bambach (1987) and Dorsch and others (1994) to have been deposited in lower shoreface to nearshore environments; in contrast, retrogradational strata above unconformity 3 in Pennsylvania and northern West Virginia are interpreted by Hettinger (2001) and this author to have been deposited in fluvial-estuarine environments. Second, the "Tuscarora unconformity" in Virginia and West Virginia has been attributed to isostatic rebound during the Taconic orogeny (Dorsch and others, 1994), whereas unconformity 3 is attributed to a relative fall in base level (Hettinger, 2001; this report).

At the western end of section *E–E′* (between wells 1 and 41), where the unconformity 3,T is absent, the basal boundary of sequence 3 coincides with a ravinement surface (see Eastern Ohio column in fig. 2). This ravinement surface correlates with the one previously interpreted by Ryder (2000) and Hettinger (2001). Erosional by definition, the surface originated during the marine transgression of the subaerially exposed shoreface sandstone and offshore marine shale of the underlying highstand systems tract (see Walker, 1992, and Shanley and others, 1992, for other examples of a ravinement surface). Between wells 41 and 44, the ravinement surface cuts upsection above unconformity 3,T to follow the top of the "Clinton" sandstone (between wells 45 and 66), Grimsby Sandstone (well 67), and the Tuscarora Formation (well 68). Between wells 69 and 72, the ravinement surface is located about 75 to 80 ft above the top of the Tuscarora Sandstone. 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 "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 approximate stratigraphic position of the transgressive systems tract is shown in figure 2 and on section *E–E′* (between wells 1 and 5, wells 61 and 62, wells 62 and 63, and wells 70 and 71). This systems tract is located in the interval between the basal sequence 3 unconformity and the maximum flooding surface in the unnamed shale underlying the Reynales Limestone (see transgressive systems tract label between wells 62 and 63). At the western end of section *E–E′* where the basal sequence 3 unconformity is absent and the maximum flooding surface is obscure because the unnamed shale is absent, the systems tract is located between a ravinement surface and the base of the Reynales Limestone (see transgressive systems tract label between wells 1 and 5).

Composite sandstone units in the middle to upper part of the "Clinton" sandstone and Grimsby Sandstone constitute the majority of the transgressive systems tract in sequence 3. Shown in orange on section *E–E′*, they are 50 to 100 ft thick and display spike-shaped and (or) upward-increasing (higher clay content) gamma-ray log responses (see well 51 between 4,948 and 4,868 ft; well 57 between 5,608 and 5,522 ft; and well 65 between 6,665 and 6,583 ft, for example). 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. Although Castle (1998) interpreted these sandstones as tidal channel and shelf-bar deposits he emphasized their association with a prograding marine 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, suggests 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 and Medina Group are correlated here with a 150- to 230-ft-thick, sandstone-dominated interval in the Tuscarora Formation (Sandstone), also shown in orange on section *E–E′*. Blocky to upward-increasing gamma-ray log responses (wells 68–72) and the presence of a 200-ft-thick interval of fluvial and estuarine deposits in the core from well 72 (Castle, 1998) support this correlation.

A composite unit of shale, siltstone, mudstone, and thin sandstone in the upper part of the "Clinton" sandstone and Grimsby Sandstone, shown in dark green on section *E–E′*, rests conformably on the fluvial and estuarine sandstone deposits between wells 48 and 67. In eastern Ohio (between wells 48 and 65), northernmost West Virginia (well 66), and western Pennsylvania (well 67), the composite unit ranges in thickness from about 10 to 60 ft. In northwestern Pennsylvania, Laughrey (1984) interpreted a fine-grained unit in the upper 35 ft of the Grimsby Sandstone (correlative with the shale, siltstone, mudstone, and thin sandstone unit) 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. The interpretations by Laughrey (1984) and Castle (1998) are applied here (section *E–E′*) to the shale, siltstone, mudstone, and thin sandstone unit shown in dark green and to the sandstone unit shown in light green. This unit in the upper part of the "Clinton" sandstone and upper part of the Grimsby Sandstone correlates with the Castanea Member of the Tuscarora Formation (well 68) and the lower part of the Cacapon Sandstone Member of the Rose Hill Formation (wells 69–72) (fig. 2, section *E–E′*). The Castanea Member consists of mudflat and coastal sand deposits (Cotter, 1982, 1983) and intertidal flat and subtidal deposits (Castle, 1998).

At the western end of section *E–E′* (between wells 1 and 50), in the distal part of the Lower Silurian sandstone depositional system, a 15- to 80-ft-thick deepening-upward succession of interbedded sandstone, shale, sandy dolomite, and the unnamed limestone occurs between the ravinement surface and the Reynales Limestone. The sandstone, shale, and sandy dolomite in this unit belong to the middle and upper parts of the "Clinton" sandstone and the overlying Cabot Head Shale (upper). The 5- to 18-ft-thick sandstones and 16- to 24-ft-thick sandy dolomite of the "Clinton" sandstone (shown in stippled light yellow and stippled light 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. The eastward continuation of the ravinement surface between wells 50 and 67 is marked by the sharp contact between tidal-flat deposits shown in dark green and the overlying unnamed limestone (dolomite). In well 68, the ravinement surface is located between tidal-flat deposits of the Castanea Member (shown in dark and light green) and an overlying unnamed dolomite unit.

INITIAL RESERVOIR PERFORMANCE

Section *E–E′* traverses the entire Lower Silurian regional oil and gas accumulation (fig. 1*A*) where drilling depth to gas and (or) oil production ranges from about 2,443 ft (well 3) to about 11,580 ft (well 68) (table 1). Nearly all of the petroleum-producing zones have been stimulated by at least one stage of hydrofracturing. The approximate boundary between the basin-center and hybrid-conventional parts of the Lower Silurian regional oil and gas accumulation (Ryder and Zagorski, 2003) crosses section *E–E′* near well 45 (figs. 1*A* and *B*). As an approximate measure of variability in reservoir performance and character across section *E–E′*, the initial production flow (IPF) of gas, oil, and water was recorded for each well (table 1). 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 value of 65 thousand cubic feet of natural gas (MCFG) per day and range from 10 MCFG per day (well 64) to 1,500 MCFG per day (well 3) (table 1). Three wells in the "Clinton" sandstone on section *E–E′* had a gas IPF equal to or exceeding 500 MCFG per day. Two of these higher yield gas wells (3 and 33) are located in the hybrid-conventional part of the regional accumulation, whereas one well (49) is located in the basin-center part. There are no obvious differences between the depositional character (facies or systems tracts) of reservoirs in these three wells and the character in nearby wells having low to modest yields. In fact, the only obvious correlation seems to be the year that the wells were drilled. All three higher yield wells were drilled prior to 1980 as were seven of the eight wells with an IPF of 150 MCFG per day or more (table 1). These data suggest that wells completed prior to 1980 had higher flow rates because there was less interference from nearby wells with overlapping drainage areas. Also, these IPF data show no compelling correlation between gas production and a specific part of the Lower Silurian regional oil and gas accumulation. For example, the median IPF value for wells in the hybrid-conventional part of the regional accumulation is only slightly greater than the median IPF value for wells in the basin-center part (68 versus 50 MCFG per day, respectively).

Recorded oil IPFs in the "Clinton" sandstone along section *E–E′* have a median value of 4 barrels of oil (BO) per day and range from 1 BO per day in numerous wells (for example, wells 39, 48, and 59) to 240 BO per day in well 23 (table 1). The importance of hydrofracturing is indicated in well 12 where oil flow increased from a trace to 5 BO per day after stimulation (table 1). The largest oil fields on section *E–E′*, the East Canton field (between wells 50 and 57) and the Wooster field (between wells 22 and 26), have reported IPFs as high as 75 and 240 BO per day, respectively. The East Canton oil field is anomalous because it is located in the gas-dominated basin-center part of the regional accumulation. Ryder and Zagorski (2003) suggested that the presence of oil in this region is related to incomplete oil-to-gas transformation during the formation of basin-center gas. Thick sequence 3 fluvial and estuarine sandstones in the East Canton field (section *E–E′*) may account for the abnormally large size of the field, an interpretation that is supported by Sitler (1985) who reported that the best petroleum production comes from these deposits. Also, the updip pinchout of the fluvial-estuarine sandstones between wells 41 and 44 probably contributed to the subtle entrapment of oil at the East Canton field. Sitler's observation cannot be confirmed with the IPF data in table 1 because the perforated zones in the "Clinton" sandstone at East Canton span the unconformity and, thus, allow the mixing of petroleum from both the fluvial-estuarine sandstones and underlying shoreface sandstones.

The Tuscarora Formation (Sandstone) on section *E–E′* produces gas from the Heyn pool (well 68) in southwestern Pennsylvania and the Leadmine field (wells 71 and 72) in northern West Virginia. Also, gas produced from the Tuscarora Sandstone in wells 71 and 72 may be commingled with gas from the Cacapon Sandstone Member. IPFs from the Tuscarora range from 313 MCFG per day in well 68 to 16,300 MCFG per day in well 72. According to Avary (1996), both fields are characterized by anticlinal traps and fracture-enhanced porosity. Furthermore, Wescott (1982) demonstrated that secondary intergranular and interlaminar porosity, as great as 23 percent in well 72 (7,237 ft), in the Leadmine field may complement fracture porosity to increase the reservoir quality of the Tuscarora. Perforated intervals along section *E–E′* suggest that gas is produced from one or more depositional sequences in the Tuscarora reservoir ranging from shoreface sandstone in the highstand systems tract of sequence 1 to fluvial-estuarine and tidal flat sandstone in the transgressive systems tract of sequence 3. High interlaminar porosity in the Tuscarora Sandstone at 7,237 ft in well 72 (Wescott, 1982) suggests that fluvial-estuarine deposits may be a potentially important reservoir.

Water (brine) production, ranging from 1 to 1,000 barrels of water (BW) per day, is associated with the oil and gas in Ohio (see wells 1, 10, 45, 55, 57, and 65, for example). Except for well 1 with an IPF of 1,000 BW per day, the produced-water IPFs are generally greater in the basin-center part of the Lower Silurian regional oil and gas accumulation than in the hybrid-conventional part. However, this distribution of produced water is contrary to the basin-center gas model proposed by Ryder and Zagorski (2003). Probably the greater-than-expected water IPFs in the basin-center part are greatly influenced by the anomalous East Canton oil field and perhaps by the presence of water introduced during hydrofracturing of the reservoir.

CONCLUSIONS

1. The approximately 235-mi-long cross section *E–E′*, normal to depositional strike, from central Ohio, through southwestern Pennsylvania, 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 hydrocarbon reservoirs in Ohio include, in ascending order, the following stratigraphic units: 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, and "Clinton" sandstone interval thickens abruptly eastward across a hinge zone in southwestern Pennsylvania and grades into a sandstone-dominated unit named the Tuscarora Formation (Sandstone). The upper part of the Tuscarora in Pennsylvania is characterized by an interval having increased amounts of shale and siltstone called the Castanea Member. In West Virginia, the Castanea Member is replaced by the lower part of the Cacapon Sandstone Member.

3. Regionally extensive carbonate and shale units overlie the "Clinton" sandstone, Medina Group, and Tuscarora Sandstone (Formation) along most of the cross section. In ascending order, the carbonate units consist of an 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 about three times thicker in Pennsylvania and West Virginia than it is in Ohio. In Pennsylvania and West Virginia this interval is named the Rose Hill Formation and it overlies the Tuscarora. The carbonate units either pinch out into shale in the Rose Hill Formation or are replaced by sandstone beds, commonly hematite bearing, that constitute the upper part of 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 200 to 210 ft. In central Ohio this interval thins to about 120 ft partly because its lower part is replaced by the Brassfield Limestone. The equivalent Tuscarora Sandstone (Formation) ranges in thickness from 325 to 475 ft in southwestern Pennsylvania and northern West Virginia.

5. Two sequences (1 and 3) and three systems tracts are identified in the "Clinton" sandstone-Medina sandstone, Medina Group, and Tuscarora Sandstone (Formation) along section *E–E′*. The lower sequence, defined as sequence 1, consists of (a) a lower transgressive systems tract with a shoreface sandstone, a 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) an undefined systems tract. 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 at the top of the basal sandstone unit of the Tuscarora Sandstone (Formation).

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 tidally influenced deposits (Hettinger, 2001). This previously unrecognized unconformity was probably caused by a fall in eustatic sea level at the Rhuddanian-Aeronian boundary as interpreted 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 not recognized in central Ohio. Here, the base of the upper transgressive systems tract is defined by a ravinement surface, a surface of minor subaerial exposure and shoreline erosion, that follows the top of shoreface deposits of the underlying highstand systems tract. Beginning in eastern Ohio, the ravinement surface cuts progressively across the top of fluvial and estuarine deposits and overlying tidal-flat deposits of the "Clinton" sandstone and continues eastward across the top of the Castanea Member of the Tuscarora Sandstone (Formation). A maximum flooding surface, identified in the shale unit overlying the unnamed limestone, tentatively marks the top of the upper transgressive systems tract.

9. Of the stratigraphic units shown on *E–E′*, 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 2,443 ft in central Ohio to about 6,606 ft in eastern Ohio. Small amounts of gas are produced from the Tuscarora Sandstone (Formation) at about 11,580 ft in southwestern Pennsylvania and at about 7,208 ft in northern West Virginia.

10. Initial production flow (IPF) of petroleum recorded for each well along section *E–E′* 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 value of 65 MCFG per day and range from 10 MCFG per day to 1,500 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 East Canton and Wooster oil fields where they are as high as 75 BO and 240 BO per day, respectively. The East Canton oil field is an anomaly because it is located in the gas-dominated basin-center part of the regional accumulation. Gas IPFs ranging from 313 to 16,300 MCFG per day were reported from the Tuscarora Formation (Sandstone). Very likely, the greatest of these IPF values is influenced by open fracture systems.

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