STRATIGRAPHIC FRAMEWORK AND DEPOSITIONAL SEQUENCES IN THE LOWER SILURIAN REGIONAL OIL AND GAS ACCUMULATION, APPALACHIAN BASIN: FROM JACKSON COUNTY, OHIO, THROUGH NORTHWESTERN PENNSYLVANIA, TO ORLEANS COUNTY, NEW YORK

By Robert T. Ryder

DISCUSSION

Introduction

Lower Silurian sandstone units constitute the reservoir rock for a regionally extensive oil and gas accumulation in the central Appalachian basin (fig. 1A). The accumulation, referred to here as the Lower Silurian regional oil and gas accumulation, has been drilled and produced since the early 1880's. To date, approximately 300 million barrels of oil and six to eight trillion cubic feet of gas have been produced from it in the United States and Ontario, Canada (McCormac and others, 1996; Miller, 1975; State oil and gas reports such as New York State Department of Environmental Conservation, 1998). The dominant reservoirs are the "Clinton" and Medina sandstones in Ohio and westernmost West Virginia and the Medina Group (Grimsby Sandstone/Grimsby Formation and Whirlpool Sandstone) in northwestern Pennsylvania and western New York. A secondary reservoir in the Lower Silurian regional oil and gas accumulation is the Upper Ordovician(?) and Lower Silurian Tuscarora Sandstone (fig. 1A), a more proximal eastern facies of the "Clinton" sandstone and Medina Group (Yeakel, 1962; Cotter, 1982; Castle, 1998).

On the basis of subtle variations, the regional accumulation is tentatively subdivided by Ryder (1998) into three parts: (1) an eastern gas-bearing part having many characteristics of basin-centered accumulation (Davis, 1984; Zagorski, 1988, 1991; Law and Spencer, 1993); (2) a western gas-bearing part having characteristics of discrete fields such as a gas-water contact; and (3) a central oil- and gas-bearing hybrid part having characteristics of both discrete and basin-centered accumulation (Zagorski, 1996) (fig. 1A). Whereas the oil and (or) gas in the hybrid and discrete parts of the regional accumulation in Ohio are largely depleted except in the Lake Erie offshore (de Witt, 1993), gas continues to be discovered in the deeper basin-centered part of the Appalachian basin (Zagorski, 1991; Pees, 1994; Petroleum Information Corporation, 1994). The Tuscarora Sandstone is tentatively identified here with the basin-centered part of the regional accumulation (fig. 1A). However, 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).

To better understand the character and origin of the regional oil and gas accumulation and its component parts, six cross sections were drawn through the Lower Silurian sequence in parts of New York, Ohio, Pennsylvania, and West Virginia. The locations of the cross sections are shown on figure 1A and B, and preliminary results are reported in Ryder and others (1996), Keighin and Hettinger (1997), and Keighin (1998). 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 A–A′ presented here is about 450 mi long and trends northeastward, approximately subparallel to the depositional strike of the Lower Silurian sandstone system. Moreover, section A–A′ extends through large stretches of the basin-centered and hybrid parts of the regional accumulation. The remaining five cross sections are oriented approximately normal to and in part oblique to the depositional strike of the Lower Silurian sandstone system and they connect with section A–A′ (fig. 1A and B). Two of these cross sections (E–E′ and F–F′) traverse the entire Lower Silurian regional oil and gas accumulation and its discrete, hybrid, and basin-centered parts.

Methodology, Oil and Gas Data, and Stratigraphic Nomenclature

Section A–A′ was constructed from 221 wells and one outcrop section (fig. 1B and table 1). Most commonly, the wells are 1 to 5 mi apart (fig. 1B). Uppermost Ordovician, Lower Silurian, and lowermost Upper Silurian strata are correlated between the wells by using gamma-ray, density, and neutron geophysical logs. Of the 221 wells used to construct section A–A′, 47 are shown in this report with their accompanying gamma-ray logs. The outcrop section at the northern end of section A–A′ was described by Duke and others (1991).

Perforated intervals and the results of initial production flow of natural gas from them are available for most of the 221 wells and are shown on section A–A′ and in table 1. These data are shown in this report to indicate the type(s) of fluid and natural gas encountered in the wells, their stratigraphic position, and their approximate volumes available for commercial production. Oil and gas fields identified on section A–A′ were taken largely from oil-and-gas-field maps produced by State geological surveys and oil and gas agencies (DeBrosse and Vohwinkel, 1974; New York State Department of Environmental Conservation, 1986; Pennsylvania Bureau of Topographic and Geologic Survey, 1994). Several field names were taken from the scientific literature (McCormac and others, 1996) and unpublished theses (Seibert, 1987; Zagorski, 1991).

A correlation chart (fig. 2) shows the chronostratigraphic position and nomenclature of Lower Silurian units and adjoining uppermost Ordovician and lowermost Upper Silurian units along section A–A′. Nomenclature used in this report generally follows that established by the State geological surveys of New York, Ohio, and Pennsylvania, however modifications and additions have been made. The following stratigraphic investigations of the Lower Silurian have contributed to this investigation through their usage of nomenclature and (or) their well documented subsurface cross sections: (1) Rickard (1975) and Brett and others (1990, 1995) in New York; (2) Knight (1969), Horvath (1970), Horvath and others (1970), Osten (1982), and

McCormac and others (1996) in Ohio; and (3) Heyman (1977), Piotrowski (1981), and Laughrey (1984) in Pennsylvania.

The lowermost Lower Silurian of Ohio consists of informal units, the Medina sandstone and the "Clinton" sandstone (fig. 2), that were named by early drillers. The "Clinton" sandstone in Ohio was miscorrelated by drillers with strata in the type Clinton Group of New York when in fact it is equivalent to the underlying type Medina Group of New York (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 here. Early drillers correctly identified the Medina sandstone in Ohio as a partial equivalent of the type Medina Group of New York.

In New York, equivalent units of the Medina sandstone and "Clinton" sandstone are the Whirlpool Sandstone and Grimsby Formation, respectively, of the Medina Group whereas, in Pennsylvania, they are the Whirlpool Sandstone and Grimsby Sandstone of the Medina Group (fig. 2). Additional units in the lowermost Lower Silurian of Ohio consist of the Brassfield Limestone (Horvath, 1970) and the Cabot Head Shale (lower and upper) (Knight, 1969). The Brassfield Limestone is located in central and southern Ohio and grades eastward into the Medina sandstone and Cabot Head Shale (lower) (fig. 2). Equivalent units of the Cabot Head Shale (lower) are the Power Glen Shale of the Medina Group in New York and the Cabot Head Shale of the Medina Group in Pennsylvania (fig. 2). Probably, the Cabot Head Shale (upper) does not have an equivalent unit in New York and Pennsylvania (fig. 2).

Thin, widespread carbonate units in the Clinton Group of New York and Pennsylvania, and equivalent strata in Ohio, are recognized here in ascending order as the unnamed limestone, Reynales Limestone, Dayton Limestone, and Irondequoit Limestone (fig. 2). Locally, these units may be highly dolomitic. The base of the Reynales Limestone is the datum for most of section A–A′. The Reynales and Irondequoit Limestones, originally defined in New York (Brett and others, 1990, 1995), have been extended southward into Pennsylvania (Piotrowski, 1981; Laughrey, 1984; Pees, 1983) and Ohio (this study). 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 northwestern Pennsylvania. The unnamed limestone may be equivalent to the Oldham Limestone of south-central Ohio and northern Kentucky (Horvath, 1970; McDowell, 1983). 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 A–A′ other than to indicate a post-"Clinton" 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 142) whereas, in southeastern Ohio, the Packer shell as used by Osten (1982) in well 68 (table 1) consists of a single limestone unit recognized as the unnamed limestone in this report (see adjoining well 69 on section A–A′).

Silurian strata correlated on section A–A′ 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 (fig. 2). 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).

Thickness, Depositional Environments, and Sequence Stratigraphy of the Medina Group

The maximum thickness of the Medina Group and equivalent strata (fig. 2) along section A–A′ is between 200 and 230 ft. These thicknesses for the Medina Group were determined from wells located in Carroll County (wells 117 and 120), Columbiana County (well 124), and Mahoning County (wells 132 and 142) in Ohio, and Lawrence County (well 145) and Mercer County (wells 147, 150, and 153) in Pennsylvania. Knight (1969) recognized this depocenter of Medina Group and equivalent strata as the Canton embayment. Isopachs that define the Canton embayment (Knight, 1969) are about 30 ft greater than the maximum thicknesses indicated by section A–A′ because the isopachs include the overlying basal carbonate units of the Clinton Group. The Medina Group thins northward from the depocenter to about 100 ft in Genesee County (well 220), New York, and equivalent strata thin southward to about 115 ft in Jackson County (well 2), Ohio. The Clinton Group and equivalent strata along section A–A′ are thickest in Athens, Washington, and Noble Counties, Ohio, where they range from 220 to 270 ft thick (wells 16–69). Regional basinward thickening of the Clinton Group accounts for most of this increased thickness. The relatively abrupt thickness change is only apparent because of the eastward bend in section A–A′ between wells 19 and 69 (fig. 1A and B).

The basal sandstone unit in the Medina Group in New York and Pennsylvania, the Whirlpool Sandstone, and the equivalent Medina sandstone in Ohio, shown in gold in section A–A′, is 10 to 20 ft thick with a well-defined low or "clean" gamma-ray log response (lower clay content) that gradually changes upward to a higher response (higher clay content) (see wells 147 and 166). This basal sandstone unit, with an upward-fining change in grain size as suggested by its characteristic upward-increasing gamma-ray log response, has been interpreted by Metzger (1981) and Laughrey (1984) to represent a sublittoral sheet sandstone. On the basis of outcrop studies in northwestern New York and adjoining Ontario, Canada, Middleton and others (1987) conclude 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 R.D. Hettinger (in Ryder and others, 1996), the Whirlpool Sandstone and Medina sandstone are interpreted in section A–A′ as shoreface and littoral sheet sandstone, with a basal braided fluvial component. Moreover, these sandstone units were deposited unconformably on the Upper Ordovician Queenston Shale (fig. 2). The unconformity at the top of the Queenston Shale is recognized as the Cherokee unconformity of Dennison and Head (1975) (see also Brett and others, 1990). The unconformity is regional in extent and may correlate with an angular unconformity between upper Middle-lower Upper Ordovician and Lower Silurian strata described in outcrop in eastern Pennsylvania and New York State by Rodgers (1970, p. 33 and 68). Along section A–A′, the unconformity is considered to be disconformable in nature and is marked by green, gray, and brown sandstone and siltstone of probable Early Silurian age that abruptly overlie red beds of probable Late Ordovician age. The angular unconformity and disconformity are products of the Middle to Late Ordovician Taconic orogeny (Rodgers, 1970; Drake and others, 1989). The Medina sandstone thins to 10 ft or less in Guernsey, Harrison, Carroll, and Columbiana Counties, Ohio (wells 87–124), and becomes very argillaceous and (or) silty. This region of sparse Medina sandstone appears as a zero-sand area on the net sandstone map (thickness of >50 percent clean sandstone on the gamma-ray log) of Boswell and others (1993). The Whirlpool Sandstone is absent at the northeastern end of section A–A′ where it is interpreted in this report to have been removed by erosion prior to the deposition of the Grimsby Formation. However, the possibility remains that the absence of the Whirlpool Sandstone was caused by nondeposition. At the southwestern end of section A–A′, the Medina sandstone becomes very calcareous and is replaced between wells 14 and 16 by the lowermost part of the Brassfield Limestone.

The Whirlpool Sandstone and Medina sandstone grade upward into: (1) shale and mudstone of the Cabot Head Shale (lower) (Knight, 1969) in Ohio, (2) the Cabot Head Shale (Berg and others, 1983) in Pennsylvania, and (3) the Power Glen Shale (Brett and others, 1995) in New York. Following Laughrey (1984), Brett and others (1995), and Castle (1998), these shale and mudstone units are interpreted on section A–A′ as offshore marine deposits. A maximum flooding surface (mfs) (see Walker, 1992) is interpreted near the middle of this shale and mudstone interval by Castle (1998).

The interval between the base of the Whirlpool Sandstone/Medina sandstone and the maximum flooding surface in the Cabot Head (lower)/Cabot Head/Power Glen Shales is interpreted as a transgressive systems tract by R.D. Hettinger (in Ryder and others, 1996) and Castle (1998). The Cherokee unconformity at the base of the transgressive systems tract is recognized as a sequence boundary by Brett and others (1990), R.D. Hettinger (in Ryder and others, 1996), and Castle (1998). The approximate position of the lower transgressive systems tract (tst) is shown on figure 2 and section A–A′ (between wells 6 and 9, wells 82 and 87, wells 150 and 153, and wells 187 and 197).

Composite sandstone units in the lower to middle part of the Grimsby Formation, Grimsby Sandstone, and "Clinton" sandstone, shown in light yellow on section A–A′, are 35 to 50 ft thick and commonly have upward-decreasing ("cleaner") gamma-ray log responses (see well 39 between 5,745 and 5,693 ft and well 109 between 6,322 and 6,273 ft, for examples). The log responses suggest that 10- to 20-ft-thick sandstone units in the composites tend to increase upwards in overall grain size and thickness (see well 39 between 5,745 and 5,733 ft, 5,733 and 5,715 ft, and 5,715 and 5,693 ft and well 109 between 6,322 and 6,308 ft, 6,308 and 6,296 ft, and 6,296 and 6,273 ft, for examples). Fifteen- to twenty five-ft-thick sandstones with blocky gamma-ray log signatures and a flat base also are present in the interval (see well 147 between 5,964 and 5,942 and well 202 between 4,002 and 3,984 ft, for examples). In northwestern Pennsylvania, Laughrey (1984) interprets this sandstone interval as deposits of barrier bar and tidal delta environments. In a preliminary version of section B–B′ (fig. 1A and B), R.D. Hettinger (in Ryder and others, 1996) interprets the lower and middle sandstone units in the Grimsby Formation as shoreface sandstones. The shoreface sandstone units interpreted by R.D. Hettinger become successively younger and overlap one another in a westerly direction, pinch out northwestward into offshore marine shale of the Power Glen Shale, and appear to downlap across the base of the Power Glen Shale. The barrier bar and tidal delta interpretation of Laughrey (1984) is consistent with the shoreface interpretation of Hettinger. Castle (1998) assigns similar depositional environments to this sandstone interval, but he emphasizes shelf-bar complexes that originated on a tide- and wave-dominated shelf. The depositional patterns of the coarsening-upward sandstone sequence identified in section A–A′ compare most favorably with the stacked westward-prograding shoreface sandstones recognized by R.D. Hettinger.

Composite sandstone units in the upper part of the "Clinton" sandstone, Grimsby Sandstone, and Grimsby Formation, shown in orange on section A–A′, are 50 to 100 ft thick with spike-shaped and (or) upward-increasing (higher clay content) gamma-ray log responses (see well 40 between 5,855 and 5,805 ft; well 76 between 5,453 and 5,412 ft; and well 97 between 5,811 and 5,695 ft, for examples). Commonly, 5- to 35-ft-thick sandstones within these composite sandstone units are characterized by an upward decrease in overall grain size and thickness of individual sandstone units (see well 40 between 5,855 and 5,826 ft and 5,826 and 5,805 ft; and well 147 between 5,902 and 5,875 ft, 5,875 and 5,856 ft, and 5,856 and 5,840 ft, for examples). The composite sandstone units in the upper part of the "Clinton" sandstone and Grimsby Sandstone have been interpreted, respectively, as distributary channels (Osten, 1982) and braided fluvial channels (Laughrey, 1984) that were deposited more or less synchronously behind, across, and above a prograding marine shoreline. Castle (1998) interprets the sandstones as tidal channels and shelf-bar complexes. Along the outcrop belt of the Medina Group in northwestern New York and adjoining Ontario, Canada, these sandstone units have been interpreted as subtidal and intertidal channels and shoals (Duke and others, 1991). A new interpretation by R.D. Hettinger (in Ryder and others, 1996) is adopted here that suggests that rather than being part of a continually prograding shoreline, these channel sandstone units constitute a combination of fluvial and tidally influenced estuarine deposits that resulted from the backfilling of paleovalleys previously cut during a eustatic fall in sea level. Evidence for this previously unrecognized unconformity in the Medina Group and "Clinton" sandstone is provided by a fall in eustatic sea level at the Rhuddanian-Aeronian boundary (Ross and Ross, 1996). The unconformity originally proposed by R.D. Hettinger is interpreted in this report to extend across section A–A′ from about well 39 to the outcrop section 222. A proposed ravinement surface truncates the unconformity between wells 39 and 40 and continues southwestward along section A–A′ at or near the top of the shoreface sandstone units and equivalent offshore marine shale. This surface is erosional in nature and originated during the marine transgression of a formerly subaerial environment and adjoining subtidal environments (see Walker, 1992; Shanley and others, 1992). Northeastward along section A–A′, the proposed ravinement surface follows the top of the fluvial and estuarine deposits (between wells 40 and 69), then cuts upsection to follow the top of the "Clinton" sandstone (between wells 69 and 142), Grimsby Sandstone (between wells 142 and 176), Grimsby Formation (between wells 176 and 202), and uppermost Medina Group (between wells 202 and outcrop section 222).

Following R.D. Hettinger, the stratigraphic interval between the maximum flooding surface and the unconformity at the base of the fluvial and estuarine deposits is interpreted here as a highstand systems tract. Southwest of well 39 where the unconformity is absent, the top of the highstand systems tract coincides with the proposed ravinement surface. As discussed later in the text, the ravinement surface in this part of section A–A′ also marks the base of an upper transgressive systems tract. The approximate stratigraphic position of the highstand systems tract is shown on figure 2 and section A–A′ (between wells 6 and 9, wells 82 and 87, wells 150 and 153, and wells 187 and 197). Together, the lower transgressive and highstand systems tracts constitute sequence I of this investigation (fig. 2). By comparison, sequence I of Brett and others (1990) involves a larger interval, consisting of a single transgressive systems tract, that extends from the Cherokee unconformity to the base of the Neahga Shale. Castle (1998) defines a highstand systems tract at about this stratigraphic position, but he places its top at a marine flooding surface in the uppermost part of the Grimsby Sandstone rather than at a regional unconformity in the middle part of the Grimsby Sandstone.

A composite unit of shale, siltstone, and thin sandstone in the upper part of the "Clinton" sandstone, Grimsby Sandstone, and Grimsby Formation, shown in dark green on section A–A′, rests conformably on the fluvial and estuarine sandstone deposits between wells 76 and 214. In northeastern Ohio (between wells 109 and 142), northwestern Pennsylvania (between wells 145 and 176), and westernmost New York (between wells 187 and 202) the composite unit ranges in thickness from about 30 to 60 ft. North of well 202 in western New York, the unit thins to 25 ft or less and incorporates two sandstone units shown in light green on section A–A′. These two sandstones correlate with the Thorold and Kodak Sandstones and the intervening shale correlates with the Cambria Shale (Brett and others, 1990, 1995). Near well 168 in northwestern Pennsylvania, Laughrey (1984) interpreted a fine-grained unit in the upper 35 ft of the Grimsby Sandstone—correlative with the shale, siltstone, and thin sandstone unit—as tidal-flat deposits with some evidence for fluctuating marine conditions. This 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 to the entire shale, siltstone, and thin sandstone unit shown in dark green on section A–A′. In New York, Brett and others (1995) cite lithologic descriptions for the Thorold Sandstone, Cambria Shale, and Kodak Sandstone that are consistent with deposition in a tidal-flat environment. The Thorold Sandstone consists of mottled, crossbedded channel deposits; the Cambria Shale has dessication cracks, ostracodes, and caliche horizons; and the Kodak Sandstone has rhythmic alternation of sandy and shaly interbeds.

At the southwestern end of section A–A′ (between wells 2 and 19), in the distal part of the Lower Silurian sandstone depositional system, a 25- to 40-ft-thick unit of interbedded sandstone and shale occurs between the ravinement surface and the unnamed limestone (Oldham Limestone(?)). Except for its lower one-third in well 2 which belongs to the Cabot Head Shale (lower), this sandstone and shale unit belongs to the upper part of the "Clinton" sandstone and the overlying Cabot Head Shale (upper). The 4- to 18-ft-thick sandstones (shown in stippled light yellow) of the "Clinton" sandstone are interpreted here as marine shelf and (or) nearshore marine deposits whereas the shales (shown in gray) are interpreted as offshore marine deposits. The interbedded sandstone and shale unit continues northeastward from well 19 to a pinch-out edge between wells 87 and 97. The unit thins progressively northeastward from well 39 where it begins to overstep fluvial and estuarine deposits of the backfilled paleovalleys (between wells 39 and 69) and overlying tidal-flat deposits (between wells 76 and 87). All that remains of the unit between wells 69 and 97 is a 6- to 10-ft-thick marine shale of the Cabot Head Shale (upper). The northeastward continuation of the ravinement surface beyond the pinch-out edge of the Cabot Head Shale (upper) is marked by the sharp contact between tidal-flat deposits shown in dark green and the overlying unnamed limestone (between wells 97 and 147) and Reynales Limestone (between wells 150 and 202). Between well 208 and the northern end of section A–A′, the ravinement surface is located at the base of the Neahga Shale. Phosphate pebbles and cobbles in the Densmore Creek Phosphate Bed at the base of the Neahga Shale (Brett and others, 1995) support the interpretation of a ravinement surface there.

Following R.D. Hettinger (in Ryder and others, 1996), the fluvial and estuarine deposits (shown in orange) are considered here to be the lower part of an upper transgressive systems tract that has onlapped a subaerially exposed highstand systems tract. Also following Hettinger, the unconformity at the base of the fluvial and estuarine deposits is considered to be a sequence boundary. Whether or not these fluvial and estuarine deposits are the product of a transgressive systems tract or a lowstand systems tract depends on one's view of the timing of paleovalley infilling with respect to sea level stand. For example, Van Wagoner and others (1990) argue that the maximum filling of an incised paleovalley occurs during a falling sea level whereas Reinson (1992) argues that maximum filling occurs during a rising sea level. The view of Reinson (1992) is favored in this study.

Southwestward of the limit of identified paleovalley incision and associated fluvial and estuarine deposits near well 39, the base of the upper transgressive systems tract coincides with the ravinement surface (see highstand systems tract marker between wells 6 and 9). Although there is no record of lowstand systems tract deposits or obvious incision into the uppermost part of the shoreface sandstones (between wells 14 and 39) and equivalent offshore marine shale (between wells 2 and 9), 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 nearby 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.

The upper transgressive systems tract in the southwestern part of section A–A′ between wells 2 and 39 is located between the ravinement surface and a proposed maximum flooding surface in the unnamed shale above the unnamed limestone (see upper transgressive systems tract marker between wells 6 and 9). In ascending stratigraphic order, units in the upper transgressive systems tract consist of interbedded marine shelf/nearshore marine shale of the upper part of the "Clinton" sandstone, offshore shale of the Cabot Head Shale (upper), the unnamed limestone, and the lower part of the unnamed shale. Northeastward, between wells 40 and 147, the upper transgressive systems tract consists of two parts: (1) a lower part with fluvial and estuarine deposits (shown in orange) and overlying tidal-flat deposits (shown in dark green) and (2) an upper part that is contiguous with the shallow- and offshore-marine deposits just described between wells 2 and 39. The upper part of the upper transgressive systems tract thins northward from a thickness of about 82 ft in well 39 to a zero edge between wells 147 and 150 and its constituent units progressively onlap the ravinement surface. In northwestern Pennsylvania and westernmost New York (between wells 150 and 202) the upper transgressive systems tract consists entirely of the fluvial and estuarine part. Here, the unnamed shale is absent and the maximum flooding surface coincides with the ravinement surface. The maximum flooding surface that marks the top of the upper transgressive systems tract reappears in the Neahga Shale between wells 202 and 208 and continues northward to the end of section A–A′.

The approximate stratigraphic position of the upper transgressive systems tract is shown on figure 2 and section A–A′ (between wells 6 and 9, wells 82 and 87, wells 150 and 153, and wells 187 and 197). This systems tract constitutes the lower part of sequence II of this investigation (fig. 2). The top of sequence II is tentatively placed at the regional unconformity at the base of the Dayton Limestone and Williamson Shale (fig. 2). This unconformity is identified by Kleffner (1985) on the basis of conodont assemblages and by Brett and others (1990, 1995) on the basis of regional stratigraphic relations. No systems tract is assigned in this study to the Reynales Limestone and underlying unnamed shale/Neahga Shale between the top of the upper transgressive systems tract and the tentative top of sequence II (fig. 2). By comparison, sequence II of Brett and others (1990) involves a smaller interval that extends from the base of the Neahga Shale to the top of the Reynales Limestone. Moreover, the unconformity at the base of the Dayton Limestone and Williamson Shale is considered by Brett and others (1990) to be associated with a younger sequence that they designate as sequence IV. Sequence III of Brett and others (1990) is located in central New York State and thus does not involve strata shown on section A–A′.

Although unconformities recognized by Brett and others (1990, 1995) at the base of the Irondequoit Limestone and Lockport Group are accepted in this study (fig. 2), they are not assigned to specific sequence boundaries. The unconformity at the base of the Irondequoit Limestone is shown on section A–A′ to extend across western New York and a large part of northwestern Pennsylvania (between wells 176 and 150) but the unconformity at the base of the Lockport Group is not shown because of its poorly defined contact with the underlying Decew Dolomite at the top of the Clinton Group.

Reservoir Performance as Indicated by Initial Production Flow of Natural Gas

Most of section A–A′ follows the gas-dominated, eastern margin of the Lower Silurian regional oil and gas accumulation (fig. 1A) where drilling depth to production ranges from about 1,000 ft (well 219) to about 6,650 ft (well 110). One indication of the variability in reservoir performance across section A–A′ is given by the initial production flow of gas and associated fluids that are measured after well completion. This parameter, usually expressed in thousands of cubic feet of natural gas (MCFG) per day, is recorded for each well (table 1) to see if patterns of high gas productivity emerge. The eventual objective is to link gas- and fluid-production characteristics in a given well or group of wells to specific geologic controls and (or) to specific parts of the regional accumulation (fig. 1A). Geologic controls of probable importance include depositional facies or systems tracts, thickness/geometry/continuity of sandstone bodies, diagenetic facies, sandstone composition, depth of burial, natural fractures, and structure (see Seibert, 1987; Keltch and others, 1990). This complex linkage is beyond the scope of the present investigation because, for one reason, long-term production data needed to calculate the estimated ultimate recovery (EUR) of gas for individual wells have not been compiled or are unavailable.

Natural gas is the dominant commodity produced in wells along section A–A′. Initial production flow of gas from individual wells ranges from 10 MCFG per day (well 97) to 6,670 MCFG per day (well 187). Nearly all of the gas-producing zones have been stimulated by at least one stage of hydraulic fracturing. Thirty-five wells on section A–A′ had an initial production flow of gas equal to or exceeding 1,000 MCFG per day. They are located in southeastern Ohio (well 22 in Athens County; wells 35 and 39 in Washington County; wells 48, 50, 58–60, 65, 67, 68, and 75 in Noble County), northwestern Pennsylvania (wells 158 and 159 in Mercer County; wells 162 and 163 in Venango County; well 170 in Crawford County; wells 173, 177, 179, 181, and 182 in Warren County), and western New York (wells 186–188, 196, 199–201, 203, 206, 208, and 209 in Chautauqua County; wells 215 and 216 in Erie County). There is no obvious depositional control (facies or systems tracts) on these 35 higher yield wells. However, because 22 of the 35 wells have been perforated in the Whirlpool Sandstone/Medina sandstone, in addition to the "Clinton"/Grimsby sandstones, there is a hint that high reservoir performance of the Whirlpool/Medina sandstone in the lower transgressive systems tract may be important for higher gas yields. Whether the 35 higher yield wells represent production "sweet spots" is yet to be established.

Water and oil are not reported from initial production flow tests in wells along section A–A′ in New York and Pennsylvania. An absence of produced water there may, in part, be related to State regulations which until recently did not require produced water to be reported. Small quantities of oil and (or) water (brine) are reported with the gas in Ohio (see wells 14, 26, 32, 48, 76, 97, 109, 117, and 124, for examples). Additional water production data are required to confirm the suggestion by Ryder (1998) that water volumes produced per well from the basin-centered part of the regional accumulation are less than those produced from the hybrid part (fig. 1A).

CONCLUSIONS

1. A 450-mi-long, depositional-strike-oriented cross section from southern Ohio, through northwestern Pennsylvania, to north-central New York, shows the stratigraphic framework, depositional sequences, and nomenclature of the Niagaran provincial series (Lower and lower Upper Silurian).

2. The Lower Silurian Medina Group of west-central and southwestern New York consists, in ascending order, of the following stratigraphic units: the Whirlpool Sandstone, Power Glen Shale, Grimsby Formation, Thorold Sandstone, Cambria Shale, and Kodak Sandstone. In northwestern Pennsylvania, the Medina Group consists of the same units except that the Power Glen Shale is named the Cabot Head Shale; the Grimsby Formation is named the Grimsby Sandstone; and the Thorold Sandstone, Cambria Shale, and Kodak Sandstone are absent. Correlative units of the Medina Group in eastern and central Ohio, in ascending order, are the Medina sandstone, Cabot Head Shale (lower), "Clinton" sandstone, and Cabot Head Shale (upper). In south-central Ohio, the Brassfield Limestone replaces the Medina sandstone and part of the Cabot Head Shale (lower).

3. The Whirlpool Sandstone, Grimsby Formation, Grimsby Sandstone, "Clinton" sandstone, and Medina sandstone are the major oil and gas reservoirs in the Lower Silurian regional oil and gas accumulation.

4. Regionally extensive carbonate units in the lower and middle parts of the Clinton Group overlie the Medina Group and its equivalents along most of the cross section. The Reynales and Irondequoit Limestones occur in western New York, northwestern Pennsylvania, and eastern and southern Ohio. The Dayton Limestone occurs stratigraphically between the Reynales and Irondequoit Limestones in eastern and southern Ohio and northwestern Pennsylvania and pinches out near the New York-Pennsylvania border. The unnamed limestone, stratigraphically lowest of the carbonate units, occurs in southern and eastern Ohio and pinches out in northwestern Pennsylvania.

5. The thickest part of the Medina Group and equivalent strata is located in northeastern Ohio and northwestern Pennsylvania. Thicknesses of the Medina Group and equivalent units in this depocenter range from about 200 to 230 ft. In northern New York, the Medina Group thins to about 100 ft whereas in southern Ohio an equivalent unit, the "Clinton" sandstone and the Cabot Head Shale (upper and lower) combined, thins to about 60 ft.

6. Three depositional intervals are identified in the Medina Group and equivalent strata: (1) A basal interval of shoreface sandstone with a braided fluvial component and overlying offshore marine shale constitutes a lower transgressive systems tract; (2) a middle interval of offshore marine shale overlain and intertongued with westward-prograding shoreface sandstone constitutes a highstand systems tract; and (3) an upper interval of fluvial and estuarine sandstone deposits overlain by tidal-flat deposits with local marine shale constitutes the largest part of an upper transgressive systems tract.

7. The lower transgressive systems tract rests unconformably on red beds of probable Late Ordovician age. This regional unconformity is the Cherokee unconformity of Dennison and Head (1975) and is a product of the Taconic orogeny (Rodgers, 1970). The top of the lower transgressive systems tract is defined by a maximum flooding surface near the base of the Cabot Head and Power Glen Shales.

8. The base of the upper transgressive systems tract is marked primarily by an unconformity of regional extent at the base of fluvial and estuarine sandstone deposits that have backfilled incised paleovalleys (R.D. Hettinger in Ryder and others, 1996). This previously unrecognized unconformity was probably caused by a fall in eustatic sea level at the Rhuddanian-Aeronian boundary (Ross and Ross, 1996). Paleovalley incision and accompanying fluvial and estuarine deposits are not recognized in southern Ohio. Here, the base of the upper transgressive systems tract 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. The ravinement surface continues across the remainder of the study area at the top of fluvial and estuarine deposits and overlying tidal-flat deposits. A maximum flooding surface above the base of the unnamed shale (overlying the unnamed limestone) and the equivalent Neahga Shale marks the approximate top of the upper transgressive systems tract.

9. Drilling depth to natural gas production along the cross section varies from 1,000 ft in northern New York to about 6,650 ft in eastern Ohio.

10. Initial production flow of gas is recorded for each well along section A–A′ to estimate the variability in reservoir performance across the regional oil and gas accumulation. Although beyond the scope of this investigation, the eventual objective is to link reservoir performance with specific geologic controls. Initial production values range from a minimum of 10 MCFG per day to a maximum of 6,670 MCFG per day. Reservoirs in regions of high initial gas flow, equal to or exceeding 1,000 MCFG per day, show no obvious relation to interpreted depositional facies or systems tracts. However, these data do suggest that high reservoir performance of the Whirlpool Sandstone/Medina sandstone in the lower transgressive systems tract may be important for higher gas yields. Whether the regions of higher yield wells represent production "sweet spots" in the regional accumulation is yet to be established.

ACKNOWLEDGMENTS

Geophysical logs were obtained from the Ohio Division of Geologic Survey (ODGS), Pennsylvania Topographic and Geological Survey (PTGS), New York State Department of Environmental Conservation (NYSDEC), and Riley Electric Log Inc. Initial production flow of natural gas from wells on section A–A′ was compiled from completion reports filed with the ODGS, PTGS, and NYSDEC and from the Petroleum Information/Dwights LLC Well History Control System database. Garry Yates (ODGS), John Harper (PTGS), Don Drazan (NYSDEC), and Craig Wandrey (USGS) were particularly cooperative in obtaining these data. Discussions with Robert D. Hettinger and Peter J. McCabe, USGS, Denver, improved the sequence stratigraphic interpretations of this investigation.

REFERENCES CITED

Avary, K.L., 1996, Play Sts; The Lower Silurian Tuscarora Sandstone fractured anticlinal play, in Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 151–155.

Berg, T.M., McInerney, M.K., Way, J.H., and MacLachlan, D.B., 1983, Stratigraphic correlation chart of Pennsylvania: Pennsylvania Topographic and Geologic Survey General Geology Report 75, 1 sheet.

Boswell, R.M., Pool, Susan, Pratt, Skip, and Matchen, D.L., 1993, Appalachian basin low-permeability sandstone reservoir characteristics; Final contractor's report: EG & G Washington Analytical Services, Inc., Report 94CC–R91–003, 73 p. (Prepared under U.S. Department of Energy contract no. DE–AC21–90MC26328; available from U.S. Department of Energy, Morgantown Energy Technology Center, Morgantown, W. Va.).

Brett, C.E., Goodman, W.M., and LoDuca, S.T., 1990, Sequence, cycles, and basin dynamics in the Silurian of the Appalachian foreland basin: Sedimentary Geology, v. 69, no. 3/4, p. 191–244.

Brett, C.E., Tepper, D.H., Goodman, W.M., LoDuca, S.T., and Eckert, Bea-Yeh, 1995, Revised stratigraphy and correlations of the Niagaran provincial series (Medina, Clinton, and Lockport Groups) in the type area of western New York: U.S. Geological Survey Bulletin 2086, 66 p.

Castle, J.W., 1998, Regional sedimentology and stratal surfaces of a Lower Silurian clastic wedge in the Appalachian foreland basin: Journal of Sedimentary Research, v. 68, no. 6, p. 1201–1211.

Cotter, Edward, 1982, Tuscarora Formation of Pennsylvania:

Society of Economic Paleontologists and Mineralogists, Guidebook for Eastern Section field trip, 105 p.

Davis, T.B., 1984, Subsurface pressure profiles in gas-saturated basins, in Masters, J.A., ed., Elmworth; Case study of a deep basin gas field: American Association of Petroleum Geologists Memoir 38, p. 189–203.

DeBrosse, T.A., and Vohwinkel, J.C., comps., 1974, Oil and gas fields of Ohio: Columbus, Ohio Division of Geological Survey and Ohio Division of Oil and Gas, 1 sheet, scale about 1:500,000.

Dennison, J.M., and Head, J.W., 1975, Sealevel variations interpreted from the Appalachian basin Silurian and Devonian: American Journal of Science, v. 275, no. 10, p. 1089–1120.

de Witt, Wallace, Jr., 1993, Principal oil and gas plays in the Appalachian basin (province 131): U.S. Geological Survey Bulletin 1839–I, 37 p.

Drake, A.A., Jr., Sinha, A.K., Laird, Jo, and Guy, R.E., 1989, The Taconic orogen, in Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States, v. F–2 of The geology of North America: Boulder, Colo., Geological Society of America, p. 101–177.

Duke, W.L., Fawcett, P.J., and Brusse, W.C., 1991, Prograding shoreline deposits in the Lower Silurian Medina Group, Ontario and New York; Storm- and tide-influenced sedimentation in a shallow epicontinental sea, and the origin of enigmatic shore-normal channels encapsulated by open shallow-marine deposits, in Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., eds., Shelf sand and sandstone bodies; Geometry, facies, and sequence stratigraphy: International Association of Sedimentologists Special Publication 14, p. 339–375.

Fisher, D.W., 1959, Correlation of the Silurian rocks in New York State: New York State Museum and Science Service Map and Chart Series, 1 sheet.

Heyman, Louis, 1977, Tully (Middle Devonian) to Queenston (Upper Ordovician) correlations in the subsurface of western Pennsylvania: Pennsylvania Bureau of Topographic and Geologic Survey Mineral Resource Report 73, 16 p., 3 pls.

Hill, R.E., Kukal, G.C., Middlebrook, M., and Peterson, R.E., 1992, Geological, petrophysical and engineering analysis of the Clinton Sandstone; Belden & Blake Corporation Central Waste No. 12, Mahoning County, Ohio: Chicago, Gas Research Institute, GRI contract no. 5091–212–2242, 43 p.

Horvath, A.L., 1970, Relationships of Lower Silurian strata in Ohio, West Virginia, and northern Kentucky: The Ohio Journal of Science, v. 67, no. 6, p. 341–359.

Horvath, A.L., O'Brien, M.H., and Pryce, R.A., 1970, Generalized cross section, stratigraphic correlations, Silurian strata from Highland County, Ohio to Montgomery County, Virginia, in Silurian stratigraphy, central Appalachian basin: Charleston, W. Va., Appalachian Geological Society, 1 pl.

Keighin, C.W., 1998, Depositional dip-oriented cross section through the Lower Silurian “Clinton” sands and Medina Group in northeastern Ohio and western Pennsylvania: U.S. Geological Survey Open-File Report 98–500, 1 pl.

Keighin, C.W., and Hettinger, R.D., 1997, Depositional dip-oriented cross-section through the Lower Silurian “Clinton”sands and Medina Group in northeastern Ohio and western Pennsylvania [abs.]: American Association of Petroleum Geologists Bulletin, v. 81, no. 9, p. 1555.

Keltch, B.W., Wilson, D.A., and Potter, P.E., 1990, Deltaic depositional controls on Clinton Sandstone reservoirs, Senecaville gas field, Guernsey County, Ohio, in Barwis, J.H., McPherson, J.G., and Studlick, J.R.J., eds., Sandstone petroleum reservoirs: New York, Springer-Verlag, p. 263–280.

Kleffner, M.A., 1985, Conodont biostratigraphy of the stray “Clinton” and “Packer Shell” (Silurian, Ohio subsurface) and its bearing on correlation, in The new Clinton collection; 1985: Columbus, Ohio Geological Society, p. 221–230.

Knight, W.V., 1969, Historical and economic geology of Lower Silurian Clinton sandstone of northeastern Ohio: American Association of Petroleum Geologists Bulletin, v. 53, no. 7, p. 1421–1452.

Laughrey, C.D., 1984, Petrology and reservoir characteristics of the Lower Silurian Medina Group sandstones, Athens and Geneva fields, Crawford County, Pennsylvania: Pennsylvania Bureau of Topographic and Geologic Survey Mineral Resource Report 85, 126 p.

Law, B.E., and Spencer, C.W., 1993, Gas in tight reservoirs; An emerging major source of energy, in Howell, D.G., ed., The future of energy gases: U.S. Geological Survey Professional Paper 1570, p. 233–252.

McCormac, M.P., Mychkovsky, G.O., Opritza, S.T., Riley, R.A., Wolfe, M.E., Larsen, G.E., and Baranoski, M.T., 1996, Play Scm; Lower Silurian Cataract/Medina Group (“Clinton”) Sandstone play, in Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 156–163.

McDowell, R.C., 1983, Stratigraphy of the Silurian outcrop belt on the east side of the Cincinnati arch in Kentucky, with revisions in nomenclature: U.S. Geological Survey Professional Paper 1151–F, 27 p., 2 pls.

Metzger, S.L., 1981, A subsurface study and paleo-environmental analysis of the Medina Group, Chautauqua County, New York: Fredonia, The State University of New York, College at Fredonia, M.S. thesis, 102 p.

Middleton, G.V., Rutka, M., and Salas, C.J., 1987, Depositional environments in the Whirlpool Sandstone Member of the Medina Group, in Duke, W.L., ed., Sedimentology, stratigraphy, and ichnology of the Lower Silurian Medina Formation in New York and Ontario: Society of Economic Paleontologists and Mineralogists, Eastern Section, 1987 annual field trip guidebook, p. 1–15.

Miller, B.M., 1975, A summary of oil and gas production and reserve histories of the Appalachian basin, 1859–1972: U.S. Geological Survey Bulletin 1409, 36 p.

New York State Department of Environmental Conservation, 1986, New York oil and gas fields: New York State Department of Environmental Conservation, Division of Mineral Resources Map, 1 sheet, scale 1:250,000.

———1998, New York State oil, gas, and mineral resources 1997: New York State Department of Environmental Conservation, Division of Mineral Resources Annual Report, 48 p.

Osten, M.A., 1982, The subsurface stratigraphy, paleoenvironmental interpretation and petroleum geology of the Albion Group (Lower Silurian), southeast Ohio: Kent, Ohio, Kent State University, M.S. thesis, 166 p., 13 pls.

Overbey, W.K., Jr., and Henniger, B.R., 1971, History, development, and geology of oil fields in Hocking and Perry Counties, Ohio: American Association of Petroleum Geologists Bulletin, v. 55, no. 2, p. 183–203.

Palmer, A.R., comp., 1983, The Decade of North American Geology 1983 geologic time scale: Geology, v. 11, no. 9, p. 503–504.

Pees, S.T., 1983, Model area describes NW Pennsylvania's Medina play (pt. 1): Oil and Gas Journal, v. 81, no. 21, p. 55–60.

———1994, Silurian Medina gas revitalizing Pennsylvania's historic Oil Creek: Oil and Gas Journal, v. 92, no. 42, p. 116–121.

Pennsylvania Bureau of Topographic and Geologic Survey, 1994, Deep well oil and gas exploration and development in Pennsylvania: Pennsylvania Bureau of Topographic and Geologic Survey Open-File Report 94–01, 2 sheets, scale 1:250,000.

Pepper, J.F., de Witt, Wallace, Jr., and Everhart, G.M., 1953, The "Clinton" sands in Canton, Dover, Massillon, and Navarre quadrangles, Ohio: U.S. Geological Survey Bulletin 1003–A, 15 p., 7 pls.

Petroleum Information Corporation, 1994, Atlas completes 500th well in Pennsylvania's Mercer County: Petroleum Information Corporation, (Denver), Appalachian Basin Report, v. 33, no. 13, p. 1.

Piotrowski, R.G., 1981, Geology and natural gas production of the Lower Silurian Medina Group and equivalent rock units in Pennsylvania: Pennsylvania Bureau of Topographic and Geologic Survey Mineral Resource Report 82, 21 p., 11 pls.

Reinson, G.E., 1992, Transgressive barrier island and estuarine systems, in Walker, R.G., and James, N.P., eds., Facies models; Response to sea level change: St. Johns, Newfoundland, Geological Association of Canada, p. 179–194.

Rickard, L.V., 1975, Correlation of Silurian and Devonian rocks in New York State: New York State Museum and Science Service Map and Chart Series 24, 16 p., 4 pls.

Rodgers, John, 1970, The tectonics of the Appalachians: New York, Wiley-Interscience, 271 p.

Ross, C.A., and Ross, J.R.P., 1996, Silurian sea-level fluctuations, in Witzke, B.J., Ludvigson, G.A., and Day, Jed, eds., Paleozoic sequence stratigraphy; Views from the North American craton: Geological Society of America Special Paper 306, p. 187–192.

Ryder, R.T., 1998, Characteristics of discrete and basin-centered parts of the regional oil and gas accumulation in Lower Silurian sandstone reservoirs of the Appalachian basin; Preliminary results from a data set of 25 oil and gas fields: U.S. Geological Survey Open-File Report 98–216, 71 p.

Ryder, R.T., Aggen, K.L., Hettinger, R.D., Law, B.E., Miller, J.J., Nuccio, V.F., Perry, W.J., Jr., Prensky, S.E., San Filipo, J.R., and Wandrey, C.J., 1996, Possible continuous-type (unconventional) gas accumulation in the Lower Silurian "Clinton" sands, Medina Group, and Tuscarora Sandstone in the Appalachian basin; A progress report of 1995 project activities: U.S. Geological Survey Open-File Report 96–42, 82 p.

Seibert, J.L., 1987, Analysis of the "Clinton" sandstone and its hydrocarbon potential in south-central Mahoning County, Ohio: Akron, Ohio, University of Akron, M.S. thesis, 124 p.

Shanley, K.W., McCabe, P.J., and Hettinger, R.D., 1992, Tidal influence in Cretaceous fluvial strata from Utah, USA; A key to sequence stratigraphic interpretations: Sedimentology, v. 39, p. 905–930.

Smosna, Richard, and Patchen, Douglas, 1980, Niagaran bioherms and interbioherm deposits of western West Virginia: American Association of Petroleum Geologists Bulletin, v. 64, no. 5, p. 629–637.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: American Association of Petroleum Geologists Methods in Exploration Series No. 7, 55 p.

Walker, R.G., 1992, Facies, facies models, and modern stratigraphic concepts, in Walker, R.G., and James, N.P., eds, Facies models; Response to sea level change: St. Johns, Newfoundland, Geological Association of Canada, p. 1–14.

Yeakel, L.S., Jr., 1962, Tuscarora, Juniata, and Bald Eagle paleocurrents and paleogeography in the central Appalachians: Geological Society of America Bulletin, v. 73, p. 1515–1539.

Zagorski, W.A., 1988, Exploration concepts and methodology for deep Medina Sandstone reservoirs in northwestern Pennsylvania [abs.]: American Association of Petroleum Geologists Bulletin, v. 72, no. 8, p. 976.

———1991, Model of local and regional hydrocarbon traps in the Lower Silurian Medina Sandstone Group, Cooperstown gas field, Crawford and Venango Counties, Pennsylvania: Pittsburgh, University of Pittsburgh, M.S. thesis, 132 p.

———1996, Structural vs. stratigraphic controls on production in "Clinton"/Medina sandstone fields, Ohio and Pennsylvania: Presented at the Ohio Chapter of the Society of Professional Well Log Analysts luncheon, November 21, 1996, Canton, Ohio.