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SUBSURFACE CORRELATIONS AND SEQUENCE STRATIGRAPHIC INTERPRETATIONS OF LOWER SILURIAN STRATA IN THE APPALACHIAN BASIN OF NORTHEAST OHIO, SOUTHWEST NEW YORK, AND NORTHWEST PENNSYLVANIA

By

R.D. Hettinger

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INTRODUCTION

Significant quantities of recoverable natural gas resources are estimated to be in the regionally extensive Lower Silurian Medina Group and “Clinton” sandstone of the Appalachian Basin (Gautier and others, 1995; Ryder and others, 1996; Ryder, 1998). In order to assess these accumulations of natural gas more accurately, the U.S. Geological Survey (USGS) has investigated the Silurian stratigraphy along six lines of cross section located in New York, Pennsylvania, Ohio, and West Virginia (fig. 1). Cross section A–A' extends about 375 mi from northeast to southwest and is oriented approximately parallel to the nearby paleoshoreline of the Silurian epeiric sea. The remaining cross sections extend about 100–200 mi from northwest to southeast and are oriented nearly perpendicular to the paleoshoreline. Stratigraphic investigations along A–A' were reported by Ryder (2000), correlations along D–D' were reported by Keighin (1998), and investigations along E–E' and F–F' were in progress at the time of this publication. This report provides correlations for Silurian strata along cross sections B–B' and C–C', which are located in the northern part of the Appalachian Basin (figs. 1 and 2). Cross section B–B' extends about 140 mi from Chautauqua County, N.Y., to Clinton County, Pa., and C–C' extends about 200 mi from Lake County, Ohio, to Clinton County, Pa. Correlations are made along B–B' and C–C' for the Lower Silurian Medina and Clinton Groups, Lower Silurian Tuscarora and Rose Hill Formations, and Lower and Upper Silurian Lockport Group and Mifflintown Formation (lower part). Emphasis is placed on the Medina Group because it is the principal natural gas reservoir in the Silurian deposit.

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STRATIGRAPHIC NOMENCLATURE AND PREVIOUS INTERPRETATIONS

During the Silurian Period (439–408.5 Ma, time scale of Harland and others, 1990), the northern Appalachian Basin was at a latitude of 20°–25° S., and it was largely covered by an epeiric sea (Van der Voo, 1988; Brett and others, 1990). Early Silurian sedimentation in the northern Appalachian Basin was influenced by tectonism as well as glacially induced sea-level fluctuations (Cotter, 1982, 1983; Johnson and McKerrow, 1991; Middleton, 1987; Ross and Ross, 1996). At least seven sea-level fluctuations on the order of 150 ft occurred during the Silurian, several of which were during the Llandoverian (Johnson and McKerrow, 1991; Ross and Ross, 1996; and references included within). Siliciclastic sediment was sourced from the Taconic Highlands and accumulated in the adjoining foreland basin and on a passive carbonate-dominated ramp located immediately westward of the foreland basin (Brett and others, 1990) (fig. 2*A*).

Silurian rocks are exposed in the Niagara region of New York and along the folded and thrust-faulted eastern margin of the Appalachian Basin in New York and Pennsylvania (fig. 2*B*). Cross sections B–B' and C–C' are located 50–200 mi south of the Niagara region, and they terminate in the Silurian exposures of central Pennsylvania (fig. 2*B*). Silurian strata were drilled at depths ranging from 2,000 to 11,500 ft along the cross sections. In the Niagara region, Silurian strata are assigned to the Niagaran Provincial Series and overlying Vernon Shale. The Niagaran Provincial Series is about 400 ft thick, and it includes (in ascending order) the Medina, Clinton, and Lockport Groups (figs. 3, 4). Coeval strata are about 2,400 ft thick near the town of Williamsport, Pa. (fig. 2*B*), where they are assigned (in ascending order) to the Tuscarora, Rose Hill, Mifflintown, and Bloomsburg Formations (fig. 3) (Cotter, 1988).

Numerous outcrop and subsurface investigations have been conducted in Silurian strata throughout the northern part of the Appalachian Basin. Significant to this study are outcrop investigations and stratigraphic summaries by Brett and others (1990, 1991, 1995), Cotter (1982, 1983), and Duke and others (1991), and subsurface investigations by Castle (1998) and Laughrey (1984). An overview of their publications is provided in order to better understand the stratigraphy of Silurian strata along cross sections B–B' and C–C'. The reader is referred to their publications for a comprehensive bibliography. Brett and others (1990) summarized depositional interpretations for Silurian strata in the northern Appalachian Basin, and they divided the rocks into six unconformity-bounded sequences. The sequence stratigraphic and chronostratigraphic correlations of Brett and others (1990) are shown in figure 3. The stratigraphic nomenclature in the Niagara region was subsequently revised by Brett and others (1995); their revised nomenclature is shown in figure 3, and is used in this report. Dual references to Brett and others (1990, 1995) indicate that the stratigraphic nomenclature used in depositional interpretations by Brett and others (1990) was changed to match revisions by Brett and others (1995).

MEDINA GROUP

The Medina Group is about 80–155 ft thick in the Niagara region of New York where it consists of siliciclastic sediment deposited in fluvial, tidal, and marine environments (fig. 4). In the Niagara region, the Medina includes (in ascending order) the Whirlpool Sandstone, Power Glen Shale, Devils Hole Sandstone, Grimsby Formation, Thorold Sandstone, Cambria Shale, and Kodak Sandstone (figs. 3, 4). Brett and others (1995) showed the distribution of these formations along a dip-oriented profile (fig. 5*A*). The Whirlpool, Power Glen, and Devils Hole are lower Llandoverian (Rhuddanian), the Grimsby is lower Llandoverian (uppermost Rhuddanian to lowermost Aeronian), and the Thorold and Cambria are probably Aeronian (Brett and others, 1995). The Kodak was shown to be Aeronian, B_2–B_3 by Brett and others (1990) (fig. 3) but was revised as being probably B_3 by Brett and others (1995). The entire Power Glen to Thorold succession passes laterally into the Cabot Head Shale in central Ohio (Knight, 1969). In the subsurface of eastern Ohio, the Whirlpool Sandstone is informally referred to as the Medina sandstone; the Power Glen Shale is called the Cabot Head Shale (lower); and the remaining part of the Medina Group is informally referred to as the “Clinton” sandstone (fig. 3). In western Pennsylvania, the Medina Group is divided into (in ascending order) the Whirlpool Sandstone, Cabot Head Shale, and Grimsby Sandstone. The entire Medina Group passes laterally into the Tuscarora Formation of central Pennsylvania. The Thorold, Cambria, and Kodak of New York are considered to be correlative with the Castanea Member of the Tuscarora in Pennsylvania.

The Medina Group was considered by Brett and others (1990) to represent an unconformity-bound sequence with lowstand fluvial and transgressive marine deposits in its lower part, and progradational marine and coastal plain deposits in its upper part. Sediment was derived from an eastern source (Yeakel, 1962) and possibly a northeastern source (Brett and others, 1991), and it was distributed along a relatively straight to slightly arcuate shoreline that extended from north-northeast to south-southwest across New York and Pennsylvania (Cotter, 1982, 1983; Duke and others, 1991). Duke and others (1991) cited the German Bay of the North Sea as a modern analog for the Medina shorelines.

The Whirlpool Sandstone overlies the regional Cherokee discontinuity (fig. 5*A*) that truncates the Upper Ordovician Queenston Shale. Although the Queenston has commonly been considered to be nonmarine, Middleton (1987, p. 2) cited evidence that it is a supratidal deposit with interbeds of marine mud. The lower part of the Whirlpool consists of trough cross-stratified sandstone that has been interpreted as a braided stream deposit (Middleton and others, 1987) on the shelf margin (Brett and others, 1990). Hummocky cross-bedded sandstone in the upper part of the Whirlpool, fossiliferous mudrock in the Power Glen, and horizontally laminated to hummocky cross-bedded sandstone in the Devils Hole have been described as shallow shelf sands and deeper shelf muds associated with an overall marine transgression (Brett and others, 1990, 1991, 1995).

Burrowed shale and hummocky cross-bedded sandstone in the lower part of the Grimsby as well as planar and trough cross-bedded and bioturbated sandstone in the upper part of the Grimsby have been described within coarsening-upward stratal successions (Brett and others, 1990, 1995; Duke and others, 1991; Martini, 1971). Each succession has been interpreted to represent the progradation of shoreface and marine tidal flat sand over marine mud (Brett and others, 1990; Duke and others, 1991) within shallow shelf and tidal flat environments (Brett and others, 1991). Duke and others (1991) described channel-form deposits in the Grimsby and interpreted that they accumulated in tidally influenced creeks and estuaries. Coarsening-upward and progradational deposition are also described for the overlying

Thorold-Kodak succession (Brett and others, 1990). The Thorold is a massive to locally cross-bedded channel sandstone that contains brachiopod fragments; the Cambria is an interbedded shale, siltstone, and sandstone characterized by ostracodes, caliche horizons, and desiccation cracks; and the Kodak is a rhythmically interbedded sandstone and shale that contains abundant trace fossils (Brett and others, 1995).

Subsurface investigations in Pennsylvania by Piotrowski (1981) and Laughrey (1984) resulted in interpretations for the Medina that were generally consistent with those made for the Niagara region. Piotrowski (1981) considered the Medina Group to have been deposited in a large delta complex that was dominated by channels near the shoreline and dominated by bars farther seaward. Laughrey (1984) interpreted the Whirlpool and lower part of the Cabot Head as a sublittoral and offshore deposit associated with a marine transgression that stabilized along a line that extended from Warren to Beaver Counties (fig. 1). He considered the Grimsby to have been deposited during a subsequent marine regression; the lower part of the Grimsby contained shoreface deposits, and the upper part of the Grimsby contained braided river and tidal deposits within a coastal sand/mud complex. More recently, Castle (1998) concluded that the Whirlpool, lower Power Glen/Cabot Head, and lowermost estuarine interval in the Tuscarora were deposited within a transgressive systems tract over a regional sequence boundary unconformity that correlated to the Cherokee discontinuity. He further interpreted that the Grimsby was deposited within a highstand systems tract along a wave-dominated shelf, a wave- and tide-influenced inner shelf, and a tide-dominated shoreline. Castle also recognized two regionally extensive flooding surfaces that allowed for precise correlations between the Medina and Tuscarora; the lower flooding surface is at the base of Cambria Shale-equivalent strata, and the upper is at the base of Neahga Shale-equivalent strata in the overlying Clinton Group. Strata located between the flooding surfaces were interpreted to represent a landward shift in facies that was also recognized in the Tuscarora. As a result, Castle postulated that shoreline deposits in the Grimsby were laterally equivalent with fluvial and estuarine strata in the Tuscarora, and intertidal and subtidal facies in the upper part of the Medina were correlative with the coastal plain strata of the Tuscarora's Castanea Member.

CLINTON GROUP

The Clinton Group is divided into lower, middle, and upper parts that are dominated by marine mudrock and carbonates (figs. 3, 4). Brett and others (1990) interpreted that the lower and middle parts each represented unconformity-bound sequences, and the upper part represented two additional unconformity-bound sequences. The lower part of the Clinton onlapped a regional unconformity that beveled the underlying Medina Group (Brett and others, 1990, 1995) (fig. 3). The lower and middle parts of the Clinton were also beveled in a westward direction by the unconformity at the base of the upper Clinton (Brett and others, 1990) (fig. 3); therefore, the middle Clinton is not found in rocks exposed in the Niagara region of New York.

In the Niagara region, the lower Clinton is less than 10 ft thick, and it is represented by inner shelf mudrock of the Neahga Shale and offshore carbonate of the overlying Reynales Limestone. The Neahga was shown as Aeronian, B_3 to C_1 by Brett and others (1990) (fig. 3), and it was revised to Aeronian, B_2 to C_1 by Brett and others (1995). In west-central New York, the lower Clinton is about 90 ft thick and consists of (in ascending order) the Maplewood Shale, Furnaceville Member, Bear Creek Shale, Sodus Shale, and Wolcott Limestone. The Maplewood is laterally equivalent to the Neahga Shale, and the Furnaceville and Bear Creek are laterally equivalent to the Reynales Limestone; the overlying Sodus Shale (Aeronian, C_3 to Telychian, C_4) and Wolcott Limestone (Telychian, C_4) are offshore deposits. The Reynales-Wolcott succession is equivalent to the basal 100 ft of the lower Rose Hill Formation in central Pennsylvania (Brett and others, 1990). In Ohio, the lower Clinton appears to pass into (in ascending order) the upper Cabot Head (Plum Creek) Shale, Oldham Limestone, and Lulbegrud Shale. Although Brett and others (1990, p. 209) considered the Plum Creek–Lulbegrud succession to be approximately equivalent to the Neahga-Sodus succession, correlations by Ryder (2000) suggested that the Plum Creek–Lulbegrud is slightly older than the Neahga-Sodus.

The middle part of the Clinton Group is represented in central New York by the 45- to 120-ft-thick Sauquoit Formation (upper Llandoverian, Telychian, C_5) and laterally equivalent Otsquago Sandstone (Brett and others, 1990).

The Sauquoit comprises primarily shale with interbeds of siltstone and sandstone, and the Otsquago consists of interbedded mudrock, sandstone, and conglomerate. The middle Clinton is equivalent to at least 300–360 ft of the middle shaly member of the Rose Hill Formation in central Pennsylvania (Brett and others, 1990).

The upper Clinton was divided into two unconformity-bound sequences by Brett and others (1990). In the Niagara region, the lower sequence contains relatively deep-water marine shale and carbonates in the Merritton Limestone and Williamson Shale (uppermost Llandoverian, upper Telychian, C_6), and overlying Rockway Dolomite (lowermost Wenlockian) (Brett and others, 1990, 1995). The lower sequence also includes the Dayton Limestone and overlying Estill Shale in Ohio (Telychian, C_6), as well as the Center Sandstone Member and superposed upper shaly member of the Rose Hill Formation in central Pennsylvania (Brett and others, 1990). In the Niagara region, the upper sequence contains shallow-water crinoidal grainstones in the Irondequoit Limestone (lowermost Wenlockian, lower Sheinwoodian), marine mudrock in the Rochester Shale (lower to middle Wenlockian), and argillaceous to sandy carbonate in the DeCew Dolomite (middle Wenlockian) (Brett and others, 1990, 1995). Shallow-water deposits of the Irondequoit represent a basinward facies shift over deeper-water mudrock. The Rochester and DeCew were interpreted to have stratal successions arranged in retrogradational, aggradational, and progradational stacking patterns (Brett and others, 1990).

LOCKPORT GROUP

The Lockport Group consists of argillaceous dolomite and minor amounts of dolomitic limestone and shale (Brett and others, 1995). Coeval rocks in central Pennsylvania are within the McKenzie Member of the Mifflintown Formation. In the Niagara region of New York, the Lockport is 160–175 ft thick and includes (in ascending order) the Gasport Dolomite, Goat Island Dolomite, Eramosa Dolomite, and Guelph Dolomite. The Gasport is uppermost Wenlockian; it is about 20–37 ft thick and contains biohermal and biostromal grainstone, dolomite, and shaly dolomite. The Goat Island was shown to be Ludlovian by Brett and others (1990, 1995, figs. 14 and 15, respectively); however Brett and others (1995, p. 53) stated that the Goat Island is probably uppermost Wenlockian to lowermost Ludlovian. The Goat Island is about 26–56 ft thick and comprises thick- to massive-bedded dolomite overlain by argillaceous dolomite with shale partings. The Eramosa is Ludlovian; it is about 38–50 ft thick and consists of medium- to massive-bedded, biostromal dolomite. The Guelph is upper Ludlovian; it is about 36 ft thick and consists of laminated, fine-grained, oolitic dolomite that grades upward to shale. The Gasport and lower part of the Goat Island were interpreted as shallow shelf deposits. The upper part of the Goat Island was interpreted as a deep-water deposit, and the Eramosa and Guelph were interpreted as shoaling-upward successions of marine strata (Brett and others, 1990, 1995).

TUSCARORA FORMATION

The Tuscarora Formation is considered to be Lower Silurian, extending from the base of the Llandoverian to the Llandoverian, C_2–C_3 stage (Berry and Boucot, 1970; Cotter, 1983, 1988). However, the Tuscarora does not contain age-diagnostic fossils, and its age is inferred from its stratigraphic position between the Upper Ordovician Juniata Formation and Lower Silurian Rose Hill Formation (Cotter, 1982). Brett and others (1990) indicated that the Tuscarora is no younger than Llandoverian, C_1 (fig. 3) based on its inferred correlation to the Medina Group. The Tuscarora overlies strata of terrestrial origin in the Juniata Formation (Cotter, 1983). Facies variations in the Tuscarora are shown in a dip-oriented diagram by Cotter (1982) (fig. 5*B*). According to Cotter, the lower part of the Tuscarora was deposited along beaches and estuaries during a major marine transgression that stabilized in central Pennsylvania, near the city of Harrisburg (fig. 2*B*). The main body of the Tuscarora was deposited during a series of minor shoreline fluctuations; sediment accumulated on the marine shelf northwest of the shoreline, and in braided river systems southeast of the shoreline. Cotter contended that the upper part of the Tuscarora accumulated along a coastal sand and mud flat as the shoreline advanced to the northwest.

The Tuscarora is about 600 ft thick where it is exposed near the town of Mill Hall, Pa. (fig. 2*B*). Tuscarora successions at the Mill Hall exposure were described and interpreted by Cotter (1982), and they are shown at the southeast ends of cross sections B–B' and C–C'. According to Cotter, the Tuscarora at Mill Hall consists (in ascending order) of the following facies: (1) channeled coast, (2) lagoonal, (3) barrier beach inlets, (4) marine shelf, and (5) coastal sand and mud flat. The following descriptions are based on Cotter (1982):

Channeled coastal facies are about 90 ft thick and contain fine- to medium-grained, cross-bedded sandstone and thin interbeds of mudrock. Trace fossils of *Monocraterion* and *Rusophycus* indicate a marine influence, and landward-directed foresets suggest estuarine flow.

Lagoonal facies are about 18 ft thick and contain dark fissile shale and thin interbeds of fine-grained, ripple-laminated sandstone with mud drapes. Trace fossils of *Monocraterion* and *Rusophycus* are common.

Barrier beach inlet facies are about 28 ft thick. They overlie an erosional surface and contain white, medium-grained, moderately sorted to well-sorted sandstone with flood- and ebb-oriented cross-beds.

Marine shelf facies (western cross-laminated facies of Cotter, 1982, 1983). The marine shelf facies are about 300 ft thick. Subfacies include (in ascending order): (1) a beach-attached shelf sand wave complex, (2) a slightly deeper shelf complex, and (3) an inner shelf sand wave complex. Each subfacies is heterolithic; sandstone dominates the lower and upper subfacies, but the deeper shelf complex has nearly equal amounts of sandstone and shale. Sandstone is medium to coarse grained in the basal sand wave complex, and grain size generally decreases in the overlying subfacies. Sandstone bodies have flat bases and wavy tops that may be capped by granules. Beds are trough and planar cross-stratified and transport directions are predominantly seaward, although shoreline parallel and uncommon landward directions are also reported. *Arthrophycus* trace fossils are common throughout, and *Rusophycus* is also found in the slightly deeper shelf deposits. Sedimentary features are interpreted by Cotter to have been derived by storm-driven currents although he stated that tidal currents might also be possible.

Coastal sand and mud flat facies are about 140 ft thick and form the Castanea Member of the Tuscarora. They consist of very fine grained to fine-grained, bioturbated sandstone with *Skolithos*, *Arthrophycus*, and *Chondrites* trace fossils. Foresets in two channel-form sandstone bodies indicate a seaward transport direction. Marine interbeds are more common in the upper part of the member.

ROSE HILL FORMATION

The Rose Hill Formation occupies the stratigraphic interval between the Tuscarora Formation and the Keefer Sandstone Member of the Mifflintown Formation. The Rose Hill consists of about 500 ft of marine mudrock and minor amounts of marine limestone where it has been drilled near the eastern ends of cross sections B–B' and C–C'. The Rose Hill is divided (in ascending order) into lower shaly member, Cabin Hill Sandstone Member, middle shaly member, Center Sandstone Member, and upper shaly member. Only the lower, middle, and upper shaly members are present near the eastern ends of cross sections B–B' and C–C'. Brett and others (1990) correlated the basal 180–300 ft of Rose Hill to the lower Clinton Group of west-central New York, and they correlated the 300- to 360-ft-thick middle shaly member to the middle part of the Clinton Group in west-central New York (fig. 3). The upper shaly member was correlated to the Merritton Limestone and Williamson Shale of New York, and the Dayton Limestone and Estill Shale of Ohio.

STRATIGRAPHIC CORRELATIONS ALONG CROSS SECTIONS B–B' AND C–C'

Correlations of the Medina, Clinton, and Lockport Groups and the Tuscarora and Rose Hill Formations are shown along cross sections B–B' and C–C'. Stratigraphic correlations were made using geophysical logs from 113 drill holes; the drill holes are identified in table 1 and their locations are shown in figure 2*C*. The holes are spaced about 1 mi apart in Ohio and New York, and about 2–52 mi apart in Pennsylvania. Lithologies are interpreted from a combination of natural gamma and density logs responses as described in figure 6. Selected natural gamma logs are shown on each cross section; the base of the Reynales Limestone was used as a datum for display purposes. The southeast ends of both cross sections are at the exposure of the Tuscarora Formation at Mill Hall, which was described by Cotter (1982).

Group and formational boundaries shown on the cross sections are based, in part, on comparisons to geophysical logs shown in Brett and others (1990, 1995), Castle (1998), and Laughrey (1984). Most importantly, cross section A–A' (Ryder, 2000) provided correlations from the Niagara region to cross sections B–B' and C–C'. Cross section A–A' intersects B–B' and C–C' at drill holes 18 and 50, respectively (table 1). The Medina Group was divided into the Whirlpool Sandstone, Power Glen Shale, and Grimsby Formation along the New York part of cross section B–B', and coeval units along the Pennsylvania part of B–B' include the Whirlpool Sandstone, Cabot Head Shale, and Grimsby Sandstone, respectively. The Clinton Group was divided into the Neahga Shale, Reynales Limestone, Williamson Shale, Irondequoit Limestone, and Rochester Shale along the New York part of cross section B–B', and the Clinton also contains the Dayton Limestone, an unnamed shale, and an unnamed limestone along parts of cross section C–C'. The unnamed shale and unnamed limestone were tentatively correlated to the Lulbegrud Shale and underlying Oldham Limestone, respectively, based on correlations made by Ryder (2000). Ryder's correlations also suggest that the unnamed shale is equivalent to the Neahga Shale. In the subsurface of Pennsylvania, the Irondequoit, Dayton, and Reynales are composed of hard dense dolomite and are therefore labeled as the Irondequoit, Dayton, and Reynales Dolomites, following the nomenclature used by the Pennsylvania Geological Survey. Other formations that might also be present on the cross sections are not shown because they are difficult to identify on geophysical logs and their presence is not certain. For example, the Grimsby might contain strata equivalent to the Devils Hole, Thorold, Cambria, Kodak, and Neahga. Additionally, the lower part of the Irondequoit might be laterally equivalent to the Rockway Dolomite, and the DeCew Dolomite might be within the undivided strata of the Lockport Group.

Both cross sections show southeastern transitions of the Medina Group to the Tuscarora Formation, and southeastern transitions of the Clinton Group to the Rose Hill and Mifflintown (lower part) Formations. The Medina–Tuscarora and Clinton–Rose Hill intervals thicken dramatically southeast of Elk and Potter Counties, Pa. The thicker stratigraphic intervals are attributed to increased subsidence and preservation of strata within the main depositional trough of the Appalachian foreland basin. Correlations of the Medina-Tuscarora transition are described in the section of this report regarding sequence stratigraphy. Correlations showing Clinton–Rose Hill–Mifflintown transitions are based on descriptions and diagrams by Brett and others (1990) and Heyman (1977). At the northwest end of the cross sections, the lower part of the Clinton Group is represented either by the Neahga Shale and Reynales Limestone, or the unnamed limestone and unnamed shale. The Reynales splits into two parts that diverge to the southeast. In this report, the upper split of the Reynales is tentatively correlated to the Wolcott Limestone, and strata between the upper and lower splits are tentatively correlated to the Sodus Shale based on diagrams and descriptions by Brett and others (1990, p. 206, 207, 235–237). The interval between the base of the lower Reynales and top of the upper Reynales (Wolcott-equivalent) is correlated to the lower shaly member of the Rose Hill based on descriptions by Brett and others (1990, p. 207) that equate the lower Clinton to the lower 180–300 ft of the Rose Hill. The middle part of the Clinton Group is represented by a 0- to 250-ft-thick wedge of Sauquoit-equivalent strata located above the Wolcott-equivalent strata. Brett and others (1990, p. 210, 211) considered the Sauquoit to be equivalent with the 300- to 360-ft-thick middle shaly member of the Rose Hill Formation. The upper part of the Clinton Group is represented by the interval containing the Dayton Limestone/Dayton Dolomite, Williamson Shale, Irondequoit Limestone/Irondequoit Dolomite, and Rochester Shale. Southeastern transitions shown on the cross sections for the Irondequoit and underlying Williamson are based on diagrams by Brett and others (1990, their fig. 26) that correlate the Irondequoit to the Keefer Sandstone Member, and the underlying 40- to 60-ft-thick Williamson Shale to the upper part of the Rose Hill Formation. The Keefer-Irondequoit interval was identified between the depths of 9,460 ft and 9,518 ft in drill hole 51 (cross section B–B') by Heyman (1977, his drill hole 34).

Several unconformable relations are indicated by the correlations shown for the Clinton Group on cross sections B–B' and C–C'. The most notable unconformity is at the base of the upper part of the Clinton Group; it underlies the Williamson Shale on cross section B–B', and the Dayton Limestone/Dayton Dolomite and Williamson Shale-equivalent on cross section C–C'. The unconformity truncates Sauquoit Formation-equivalent strata (middle Clinton) on both cross sections, and appears to truncate the Reynales between drill holes 14 and 16 on cross section C–C'. Further evidence for the unconformity is provided along the northwest end of cross section B–B' where the Williamson Shale (Telychian, C_6) overlies the Reynales Limestone (Aeronian, C_2). Other apparent stratal truncations suggest additional unconformities; these include: (1) an apparent truncation of Sodus Shale-equivalent strata along the base of the upper split of the Reynales in both cross sections; the truncation appears to extend through the lower Reynales between drill holes 42 and 47 on cross section C–C', and (2) a possible truncation of the Dayton at the base of the Irondequoit between drill holes 4 and 6 on cross section C–C'. Although these unconformities are also supported by the chronostratigraphic correlations by Brett and others (1990) (fig. 3) they were not shown on the cross sections because the apparent truncations were local in extent, and they could simply represent areas where the underlying strata thin and pinch out.

SEQUENCE STRATIGRAPHY OF THE MEDINA AND CLINTON (LOWER PART) GROUPS

Recognition of sequence boundary unconformities and systems tracts might be critical for understanding the variability of reservoir performance for the Medina Group. Sequence stratigraphic interpretations of the Medina Group and lower part of the Clinton Group along cross sections B–B' and C–C' are based on the superposition and interpretations of informally designated units A through E that are shown in figure 7. References to coarsening- and fining-upward stratal successions are based on criteria described in figure 6. Units A, C, and E are dominated by fining-upward successions and are interpreted to be retrogradational based on their deepening-upward succession of facies. Units B and D are dominated by coarsening-upward successions and are interpreted to be progradational based on their shallowing-upward and forward-stepping stratal successions. Unconformities at the bases of units A, C, and E are interpreted from regionally extensive surfaces that scour underlying strata. Maximum marine flooding surfaces are placed along regionally extensive boundaries that divide retrogradational strata from superposed progradational strata. Brief descriptions of each unit are provided below. References to fluvial, tidal, estuarine, shoreface, or offshore facies in the units are based on published descriptions and interpretations of coeval rocks described in previous sections of this report.

Unit A contains retrogradational successions of fluvial and nearshore marine sandstone in the Whirlpool Sandstone/Medina sandstone, and shelf mudrock in the lower part of the Power Glen Shale/Cabot Head/Cabot Head (lower) Shales. Unit A overlies the Cherokee discontinuity and its top is at a maximum marine flooding surface in the Power Glen Shale/Cabot Head/Cabot Head (lower) Shales.

Unit B contains progradational deposits of shelf mudrock and sandstone in the upper part of the Power Glen Shale/Cabot Head/Cabot Head (lower) Shales, as well as progradational deposits of shelf/shoreface sandstone in the lower part of the Grimsby Formation/Grimsby Sandstone. Unit B conformably overlies unit A.

Unit C contains retrogradational deposits of interbedded sandstones and mudrock. The strata are interpreted as tidal channels, and the upper part of the unit might contain a thin deposit of marine mudrock. Unit C is encased in shelf mudrock of the Cabot Head Shale (lower) along the northwest part of cross section C–C'. The sharp undulating base of unit C scours unit B; it has as much as 50 ft of relief and is interpreted to be unconformable.

Unit D contains progradational shelf and shoreface mudrock and sandstone in the upper part of the Cabot Head Shale (lower), lower part of the "Clinton" sandstone, and lower part of the Grimsby Formation/Grimsby Sandstone. The unit is located along the northwest part of cross section C–C', and it is also found locally along B–B' in drill holes 21 (4,140–4,178 ft) and 32 (4,483–4,496 ft). Unit D conformably overlies unit C in cross section C–C', but its contact over unit B in cross section B–B' is interpreted to be disconformable.

Unit E contains retrogradational deposits in the upper part of the Medina Group, unnamed limestone, Neahga Shale (and its laterally equivalent unnamed shale), and Reynales Limestone/Reynales Dolomite. The sandstone-dominated lower part of unit E is probably equivalent to tidal- and estuarine-channel deposits in the Grimsby. The mudrock-dominated upper part of the unit is probably equivalent to tidal-flat deposits in the upper Grimsby, Thorold, Cambria, and Kodak Formations, and it might also include inner shelf deposits of the Neahga Shale. The top of unit E is represented by offshore carbonates of the Reynales Limestone/Reynales Dolomite or the unnamed shale where the Reynales is not present. The sharp undulating base of unit E has as much as 60 ft of relief; it scours units B, C, and D and is interpreted to be unconformable.

Stratal successions within units A through E indicate that the Medina Group and lower part of the Clinton Group can be divided into three unconformity-bound sequences along cross sections B–B' and C–C'. The sequences and their respective basal sequence boundary unconformities are referred to by the numbers 1, 2, and 3 on the cross sections. Following the sequence stratigraphic terminology and concepts of Van Wagoner and others (1988, 1990), each sequence boundary unconformity is recognized by truncation of underlying strata and a basinward shift in overlying strata. Incision is attributed to a loss of accommodation space associated with a fall in relative base level. Each overlying sequence was deposited during a subsequent rise in relative base level. The sequences are divided into transgressive and highstand systems tracts; the transgressive systems tract developed when accommodation exceeded sediment supply, and the highstand systems tract developed when accommodation was equal to, or less than, sediment supply. Each transgressive systems tract overlies the basal sequence boundary unconformity and contains deepening-upward successions of strata that are capped by a maximum marine flooding surface. Ravinement surfaces are transgressive surfaces of erosion within transgressive systems tracts (Dalrymple and others, 1992; Walker, 1992); they are situated between shoreface deposits and underlying fluvial, tidal, or estuarine strata. The ravinement surfaces within units A and C are not shown on the cross sections because contacts between the various facies could not be differentiated on the geophysical logs. Each highstand systems tract overlies a maximum flooding surface and contains aggradational or progradational successions of strata that are truncated by an unconformity of disconformity.

Sequences 1, 2, and 3 within the Medina Group and lower part of the Clinton Group are described below. Tentative correlations of each sequence southeast to the Tuscarora and Rose Hill Formations are provided in the following section of this report.

Sequence 1

Sequence 1 includes the Whirlpool Sandstone/Medina sandstone, Power Glen/Cabot Head/Cabot Head (lower) Shales, and lower part of the Grimsby Formation/Grimsby Sandstone. It comprises retrogradational and progradational strata in units A and B. The underlying sequence boundary (sequence boundary 1) is equivalent to the regional Cherokee discontinuity, and it separates supratidal mudrock in the Ordovician Queenston Shale from braided fluvial deposits in the basal part of the Lower Silurian Whirlpool Sandstone/Medina sandstone. The juxtaposition of braided fluvial strata over supratidal mudrock is interpreted to represent a significant basinward shift of facies. Castle (1998) attributed thickness variations of the lower Whirlpool to irregular topography on the basal Silurian unconformity. The transgressive systems tract is represented by unit A. Its deepening-upward successions have been interpreted as retrogradational, whereby shallow incised valleys were backfilled with fluvial strata during the initial rise in sea level, and overlying nearshore and offshore strata were deposited during the subsequent marine transgression. The highstand systems tract of sequence 1 is represented by progradational deposits of shoreface and shelf parasequences in unit B.

Sequence 2

Sequence 2 includes the upper part of the Cabot Head Shale (lower) and lower part of the "Clinton" sandstone along the western part of cross section C–C'. Sequence 2 is also found in the Grimsby Formation at drill holes 21 and 32 along cross section B–B'. The sequence comprises units C and D, and the sharp undulating contact at the base of unit C is the basal sequence boundary (sequence boundary 2). The sequence boundary extends 60 mi along C–C' and scours as much as 50 ft into unit B. Variations in the thickness of unit C are attributed to irregular topography along the sequence boundary. The sequence boundary separates shelf and shoreface deposits in unit B from overlying tidal channel deposits in unit C, and these juxtapositions are interpreted to represent a minor basinward shift in facies.

The transgressive and highstand systems tracts in sequence 2 are represented by units C and D, respectively, and they comprise tidal channel deposits that are overlain by marine mudrock. In this interpretation, incised valleys were backfilled with tidally influenced strata during the initial rise in sea level, and the overlying offshore-marine strata were deposited during the subsequent marine transgression. The highstand systems tract is represented by progradational parasequences in unit D.

Unit D conformably overlies unit C along the western part of C–C', and it disconformably overlies unit B in drill hole 49 on C–C' and drill holes 21 and 32 on B–B'. The disconformable contact between units B and D is labeled R/2 on the cross section, and it is interpreted as a transgressive surface of erosion (ravinement surface) that was cut as the shoreline retreated to areas located southeast of the valley-fill deposits of unit C. The ravinement surface is interpreted to merge northwest with the basal sequence boundary and maximum flooding surface of sequence 2.

Sequence 3

The lower part of sequence 3 is represented by the upper part of the Medina Group and the lower part of the Clinton Group. The basal sequence boundary unconformity (sequence boundary 3) truncates sequences 1 and 2 along much of both cross sections. The sequence boundary is interpreted to represent broad and gentle topography of a regionally extensive valley system that was incised during a fall in relative base level.

The transgressive systems tract in sequence 3 is represented by unit E. Tidally influenced strata in unit E overlie over shelf and shoreface deposits in units B and D, and these juxtapositions are interpreted to represent a basinward shift in facies associated with the fall in relative base level. During the initial phase of the subsequent rise in base level, the topography is interpreted to have been backfilled by tidal- and estuarine-channel deposits that form the lower part of unit E. As base level continued to rise, the topography was covered by finer grained tidal-flat deposits described in the upper part of unit E. The tidal flat was then scoured by a transgressive surface of erosion (ravinement surface) as the shoreline moved southeast across the area. The ravinement surface is interpreted to be the same unconformable surface that truncated the Thorold, Cambria, and Kodak Formations in the Niagara region (fig. 5*A*). A conglomerate located at the base of the Neahga Shale in the Niagara region (identified as the Densmore Creek Phosphate Bed in figure 4) might represent a lag deposit associated with the ravinement. Inner shelf mudrock of the Neahga Shale and offshore carbonate of the Reynales Limestone/Reynales Dolomite were subsequently deposited after the shoreline had retreated southeast of the cross sections, and the top of the Reynales Limestone/Reynales Dolomite is tentatively interpreted as the top of the transgressive systems tract.

The highstand systems tract in sequence 3 might be represented along the southeast parts of each cross section by the Sodus (?) Shale equivalent and lower shaly member of the Rose Hill Formation. However to the northwest, these presumed highstand deposits have been removed by erosion along the unconformity between the Reynales Limestone (Aeronian, C_{1-2}) and Williamson Shale (Telychian, C_6). An alternative interpretation by Ryder (2000) places the top of the transgressive systems tract at a maximum flooding surface that he described in the unnamed shale in the basal Clinton Group of Ohio. According to Ryder, the highstand systems tract of sequence 3 would include strata in the Neahga Shale and unnamed shale, as well as the Reynales Limestone/Reynales Dolomite.

CORRELATIONS FROM THE MEDINA GROUP TO THE TUSCARORA FORMATION

The Tuscarora Formation and Medina Group have been described as a siliciclastic wedge whereby proximal facies of the Tuscarora grade northwest to distal facies of the Medina. Deposition of the wedge has been attributed to a single, overall transgressive-regressive marine cycle. Transgressive deposition has been interpreted for the Whirlpool Sandstone, Power Glen Shale, and Devils Hole Sandstone (Brett and others, 1990; Duke and others, 1991; Middleton and others, 1987); Whirlpool and lower part of the Cabot Head Shale (Laughrey, 1984; Piotrowski, 1981); and lower and main part of the Tuscarora Formation (Cotter, 1983). Regressive deposition has been interpreted for the Grimsby-Kodak succession (Brett and others, 1990; Duke and others, 1991), upper part of the Cabot Head and Grimsby (Laughrey, 1984; Piotrowski, 1981), and Castanea Member (Cotter, 1983). However, facies transitions between the Medina and Tuscarora are not straightforward because accommodation has been affected by variations in sea level and tectonic subsidence in the foreland basin. Descriptions of erosional-based estuarine channel-fill deposits in the Grimsby-Thorold succession (Duke and Brusse, 1987; Duke and others, 1991), and descriptions of marine beds in the upper part of the Castanea (Cotter, 1983), provide evidence that these formations were partially transgressive. Castle (1998) contended that the Cambria Shale (New York), upper Grimsby (eastern Ohio and western Pennsylvania), and Castanea Member were transgressive deposits rather than regressive deposits as previously thought.

Sequence stratigraphic interpretations made in this report indicate the Medina Group was deposited during several transgressive and regressive marine cycles, and an analysis of facies at Mill Hall, as described by Cotter (1982), suggests that Tuscarora deposition was influenced by the same transgressive-regressive cycles. In this report, the Tuscarora Formation is divided into three sequences at Mill Hall. The sequences are described below, and they are tentatively correlated northwest to the Medina Group in cross sections B–B' and C–C'.

Sequence 1 is represented by the basal 240 ft of the Tuscarora at the Mill Hall section. Its inferred basal sequence boundary divides fluvial deposits of the Juniata Formation from superposed fluvial and estuarine deposits of the Tuscarora. The inference of the sequence boundary is based on the recognition of: (1) a sea-level lowstand at the end of the Ordovician (Middleton, 1987), (2) an Ordovician-Silurian age sequence boundary unconformity throughout much of the northern Appalachian Basin (Castle, 1998), and (3) channeled coastal deposits in the basal Tuscarora (Cotter, 1982, 1983). The transgressive systems tract overlies the sequence boundary and includes about 175 ft of rock that passes upward through deposits of a channeled coast, lagoon, barrier beach inlet, and basal part of a shelf sand-wave complex. The maximum flooding surface was placed at a horizon in the shelf sand-wave complex that was overlain by an increased amount of marine mudrock. These deepening-upward stratal successions are interpreted to correlate with unit A, which contains the Whirlpool Sandstone/Medina sandstone and lower part of the Power Glen/Cabot Head Shale. The highstand systems tract is represented by about 65 ft of the shelf sand-wave complex that overlies the maximum flooding surface. In this report, the upward increase of sandstone within the complex is attributed to progradation of the shoreline. The shelf sand-wave complex is interpreted to grade northwest into shelf mudrock and hummocky cross-bedded sandstone of unit B. Similar facies transitions have been described by Driese and others (1991) for deposits in the Clinch Sandstone (Tuscarora-equivalent strata) and Rockwood Formation of east Tennessee. The Clinch is dominated by a cross-stratified sandstone facies that is similar to the sand-wave complex of the Tuscarora (Driese and others, 1991). Driese and others interpreted the cross-stratified sandstone facies as megaripples and shelf sand waves that were deposited in a progradational, storm-dominated, shoreface setting. The megaripples and sand waves were interpreted to grade into hummocky cross-stratified beds of the Rockwood Formation that were situated on the inner shelf.

Sequence 2 occupies the stratigraphic interval located 240–450 ft above the base of the Tuscarora at Mill Hall. Its base is represented by the contact between the shelf sand-wave complex and overlying strata deposited on a slightly deeper shelf. The contact is interpreted as a ravinement surface that converges in a seaward direction (northwest) toward the basal sequence boundary unconformity and maximum flooding surface described for unit C within sequence 2. The ravinement surface is labeled R/2 on the cross sections and it has been correlated northwest through drill holes 53, 51, 32, and 21 on B–B', and 60 and 49 on C–C'. At Mill Hall, the ravinement surface is overlain by about 50 ft of slightly deeper shelf deposits that form the upper part of the transgressive systems tract; the lower part of the transgressive systems tract is represented by unit C along the northwest part of cross section C–C'. The maximum flooding surface and top of the transgressive systems tract is inferred by an increase in mudrock about 295 ft above the base of the Tuscarora. The overlying highstand systems tract is about 150 ft thick and consists of shallowing-upward successions that pass upward through slightly deeper shelf, and inner shelf facies. In this report, the highstand deposits are interpreted to prograde westward and correlate with shoreface deposits described in unit D of the Medina Group.

Sequence 3 is represented by the 140-ft-thick Castanea Member at Mill Hall and it might also include strata in the overlying Rose Hill Formation. The Castanea comprises tidally influenced coastal strata that contain channel-form deposits associated with through-flowing fluvial systems; marine interbeds are more common in the upper part of the member (Cotter, 1983). These deepening-upward successions are interpreted to represent retrogradational deposition associated with a rise in relative base level. The deepening-upward successions are correlated to the finer grained upper part of the Grimsby and "Clinton" sandstone that are within the transgressive systems tract of sequence 3 along the northwest part of the cross sections. Castle (1998) also correlated the Castanea to the finer grained upper part of the Grimsby Sandstone in western Pennsylvania and interpreted the strata as retrogradational. The highstand systems tract of sequence 3 might be represented by marine deposits in the overlying lower shaly member of the Rose Hill Formation.

OIL AND GAS

Initial production data from the Medina Group and Tuscarora Formation are provided, where available, for drill holes displayed on cross sections B–B' and C–C'. Forty-four holes have initial production values that range from 20 to 7,000 thousand ft^3 of gas (MCFG) per day, and the mean value is about 650 MCFG per day. Additionally, most of those holes located along the Ohio part of cross section C–C' also yielded an initial production of less than 20 barrels of oil. Fourteen drill holes shown on the cross sections are either dry and abandoned or lack initial production data; most of these holes are located in central Pennsylvania where reservoir porosity and permeability of the Medina Group and Tuscarora Formation are reduced due to depth of burial. However, the Amoco/UGI Texas-Gulf #1 well (drill hole 60, cross section C–C'), located in the Devils Elbow field, Centre County, Pa., had an initial production of 7,000 MCFG per day from depths between 10,759 and 10,974 ft in the Tuscarora Formation. Harper and others (1999) related the large yield in the Amoco/UGI Texas-Gulf #1 well to fracture porosity and bedding-plane partings.

Perforated zones in the Medina Group and Tuscarora Formation are also shown for holes displayed on cross sections B–B' and C–C'. Although all of the sequences and associated systems tracts defined in this report have been perforated in various holes, the initial production data do not specify which strata are productive. However, a tally of the perforated zones suggest which intervals the operators considered most productive on a regional basis. The transgressive systems tract of sequence 3 is the most frequently perforated interval, having been perforated in about 90 percent of the holes tested for initial production. The highstand systems tracts of sequences 1 and 2 were targeted by operators in about 50 percent of the holes tested. The least targeted intervals were the transgressive systems tracts of sequences 1 and 2, which were perforated in less than 25 percent of the holes tested.

SUMMARY AND CONCLUSIONS

Previous investigators have interpreted that Lower Silurian rocks in the northern Appalachian Basin accumulated in marine shelf, nearshore marine, and terrestrial environments within a foreland basin. Sedimentation was affected by various rates of subsidence, accommodation space, and sediment supply owing to sea-level fluctuations and tectonic activity. Most investigators have considered deposition of the Lower Silurian Medina Group and Tuscarora Formation to have been associated with a single transgressive-regressive marine cycle.

Subsurface sequence stratigraphic investigations in this report provide alternate interpretations whereby the Medina and Tuscarora were deposited during two transgressive-regressive marine cycles and the transgressive phase of a third marine cycle. Strata in the lower part of the Clinton Group might have been deposited in the transgressive phase of the third cycle as well. The depositional cycles spanned a 6- to 7-million year period that extended from the earliest Rhuddanian to the latest Aeronian, C_1 or C_2 Stages of the Llandoverian Series. Three sea level lowstands existed during Rhuddanian Stage, and each lowstand was followed by a sea level rise that culminated in a sea level highstand. Unconformities associated with the sea level lowstand are represented by sequence boundaries 1, 2, and 3, as defined in this report. The development of transgressive and highstand systems tracts in each unconformity-bounded sequence are summarized in figure 8.

Initial production data indicate that nearly all formations in the Medina Group have been explored for natural gas along the northwest parts of cross sections B–B' and C–C'. The mean initial gas production is about 650 MCFG per day based on values reported for 44 producing drill holes located along the cross sections. One well (drill hole 60, cross section C–C') had an initial production of 7,000 MCFG per day. Fourteen additional drill holes were either dry and abandoned or lacked initial production data. Perforated zones in the producing drill holes indicate that transgressive deposits of sequence 3 and highstand deposits of sequences 1 and 2 were the most frequently targeted strata for initial production tests.

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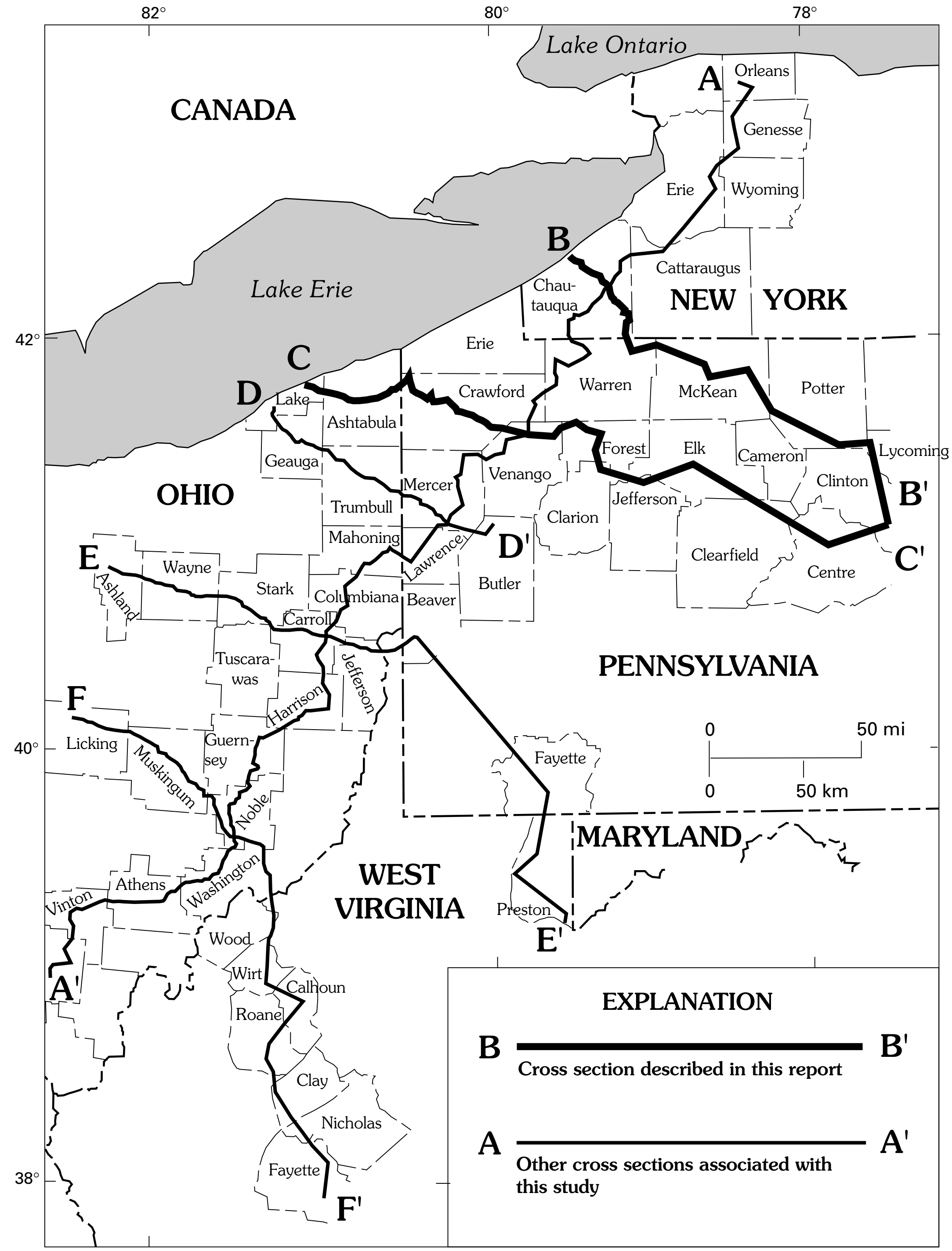

Figure 1. Locations of cross sections constructed by the U.S. Geological Survey to assess continuous gas accumulations in Lower Silurian strata of the Appalachian Basin. A–A' trends approximately parallel to the paleoshoreline of an epicontinental sea that covered much of North America during the Silurian Period. Correlations along cross-sections B–B' and C–C' are shown in this report. Correlations along A–A' were reported by Ryder (2000), and correlations along D–D' were reported by Keighin (1998). Investigations by R.T. Ryder along cross sections E–E' and F–F' were in progress at the time of this publication and were expected to be published at a later date.

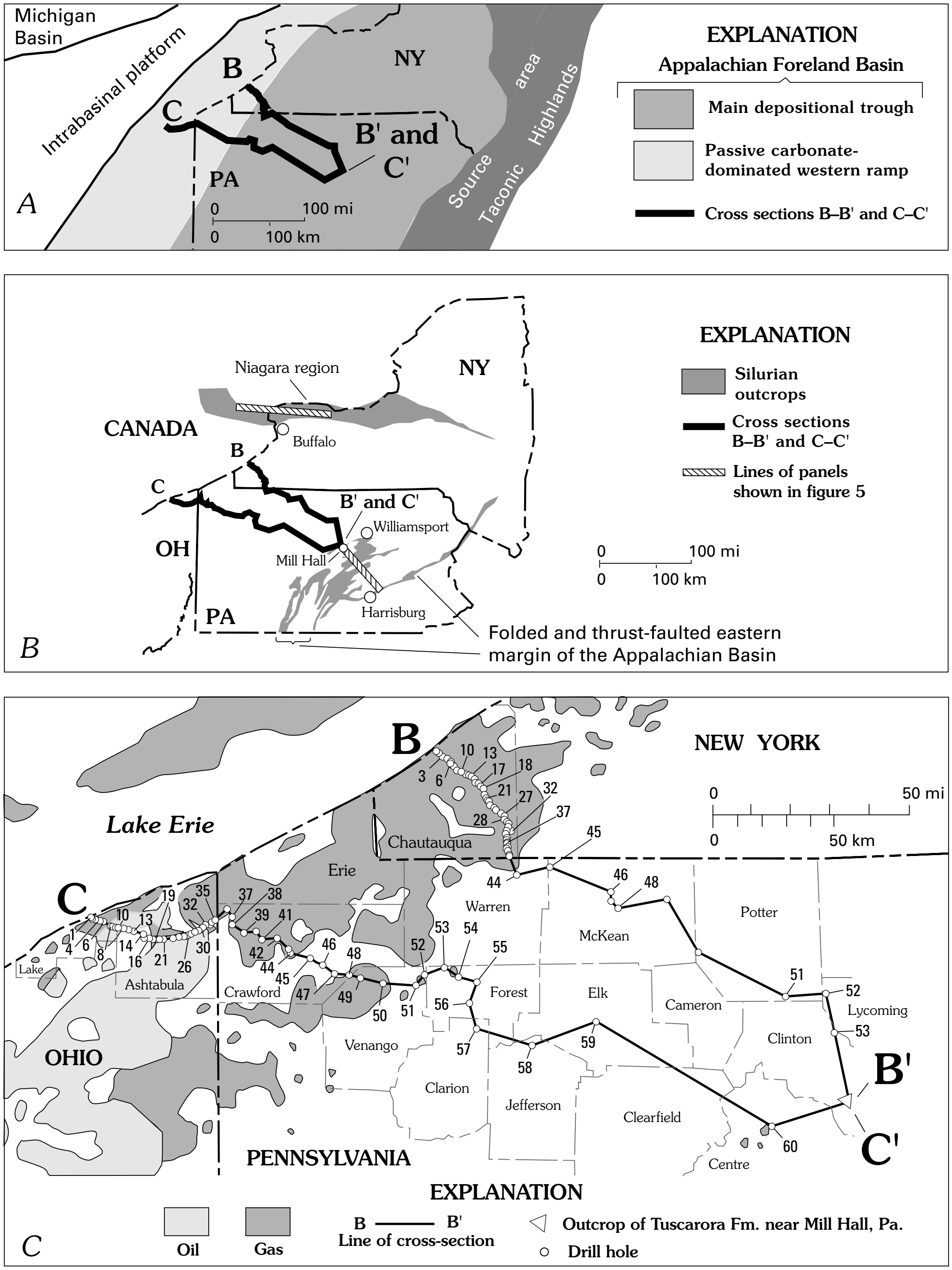

Figure 2. Locations of cross sections B–B' and C–C'. *A*, Cross sections located with respect to paleogeography during the medial Silurian; modified from Brett and others (1990). *B*, Cross sections located with respect to Silurian outcrops in the northern Appalachian Basin. The Niagaran Provincial Series is exposed in the Niagara region, and coeval strata near the town of Williamsport, Pa., are assigned to the Tuscarora, Rose Hill, Mifflintown, and Bloomsburg Formations. *C*, Location of drill holes and measured section along B–B' and C–C', and areas with oil and gas accumulations in the Lower Silurian Medina Group and Tuscarora Formation. Areas with oil and gas accumulations are based on Ryder (1998). The southeastern end of both cross sections is at an outcrop of the Tuscarora Formation near the town of Mill Hall, Pa. (fig. 2*B*); the outcrop was described by Cotter (1982, 1983). Drill holes are numbered consecutively from left to right on each cross section, and selected drill hole numbers are shown. All drill holes are identified in table 1.

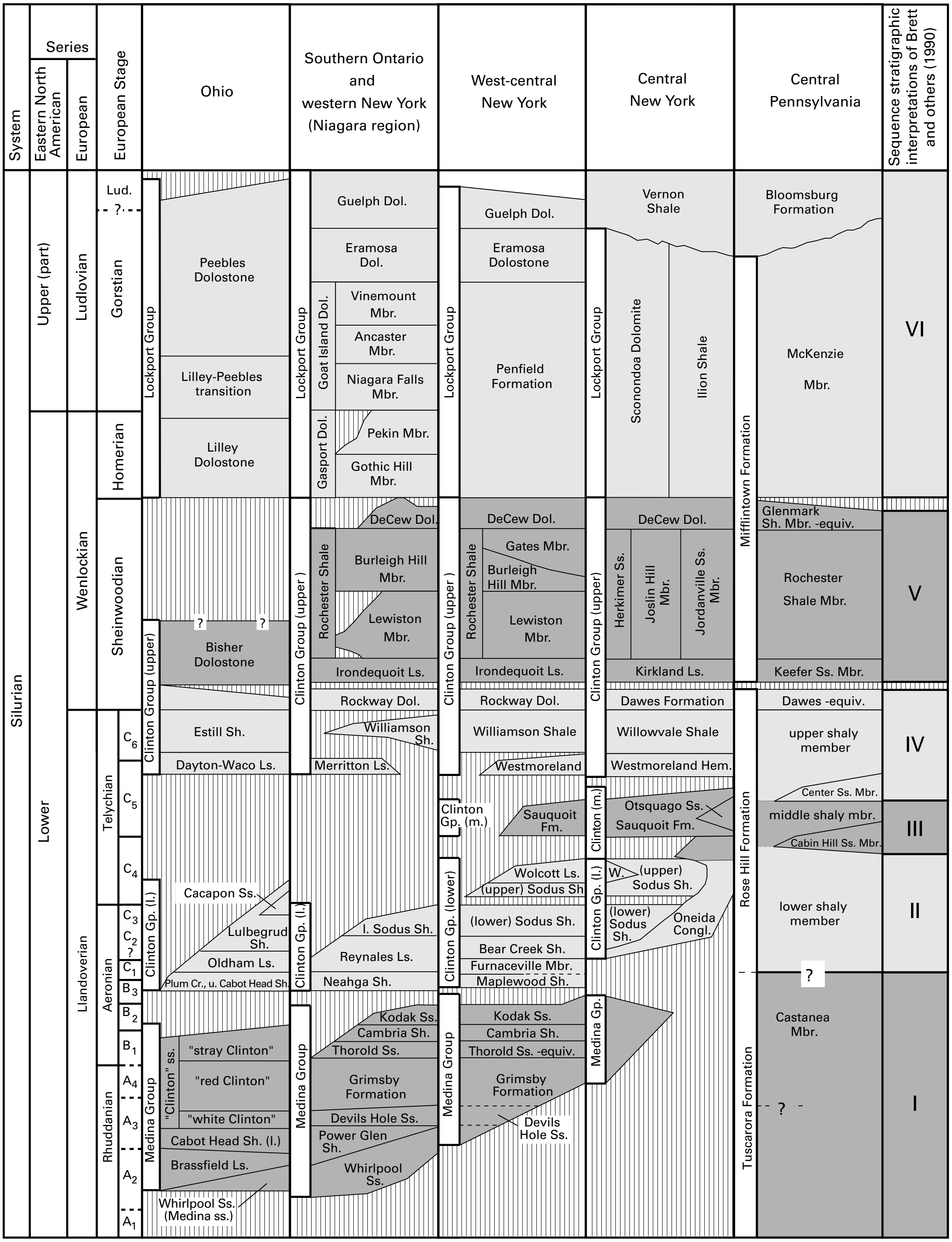

Figure 3. Chronostratigraphic correlations of Silurian strata in Ohio, southern Ontario and western New York (Niagara region), west-central New York, central New York, and central Pennsylvania. Diagram is compiled and modified from Brett and others (1990, their figs. 7B and 14). Many units in the Medina Group and Tuscarora Formation are not precisely dated. Vertical ruling represents unconformities. Gray areas represent unconformity-bound sequences, labeled I through VI, of Brett and others (1990). Nomenclature in southern Ontario and New York has been modified to match revisions by Brett and others (1995, their figs. 9 and 15). The lower part of the Clinton Group was extended into Ohio based on descriptions by Brett and others (1990, p. 209). Abbreviations: Group (Gp.), lower (l.), middle (m.), upper (u.), Formation (Fm.), Member (Mbr., mbr.), Conglomerate (Congl.), Sandstone (Ss., ss.), Shale (Sh.), Dolomite (Dol.), Hematite (Hem.), Limestone (Ls.), Ludfordian (Lud.), Creek (Cr.), Wolcott Limestone (W.), equivalent (equiv.).

Series	Group	Formation	Thickness (ft)	Lithologic description	Depositional summary
Niagaran Provincial Series	Lockport	Guelph Dol.	< 40 ?	Fine-grained oolitic dolomite, shaly in upper part. Contains sparse fossils and stromatolites.	Progradational marine
		Eramosa Dol.	38–50	Thick- to thin-bedded, bituminous, fossiliferous dolomite with chert horizons. Some units lack fossils.	
		Goat Island Dol.	26–56	Vinemount Member is a thin- to medium-bedded, fossiliferous, shaly dolomite; Ancaster Member is a thin-bedded, cherty, fossiliferous dolomite; Niagara Falls Member is a biohermal grainstone.	Deeper marine (Vinemount Mbr.)
		Gasport Dol.	20–37	Pekin Member grades laterally from argillaceous dolomicrite to bioherms and dolorudites; Gothic Hill Member is a fossiliferous dolograinstone to dolopackstone.	Shallow marine shelf
	Clinton, upper	DeCew Dol.	5–12	Argillaceous to sandy dolomite with thin shale partings. Unit has sparse fossils and is characterized by contorted bedding.	Deep water offshore marine
		Rochester Sh.	2–120	The Burleigh Hill Member is calcareous to dolomitic mudstone; its upper part has abundant laminated pelletal grainstones and is increasingly calcareous upwards, grading to limestone. The underlying Lewiston Member is calcareous mudstone that is fossiliferous in its lower and upper parts.	
		Irondequoit Ls.	12–22	Thick- to massive-bedded, fossiliferous, dolomitic packstone and grainstone with medium- to massive-bedded, fossiliferous limestone and thin shale interbeds in upper part.	Shallow water high energy
		Rockway Dol.	7–12	Thin- to medium-bedded, burrowed, dolomitic wackestones with thin interbeds of dolomitic shale. Base contains Salmon Creek Phosphate Bed, which comprises bioturbated dolomicrite with quartz and phosphate pebbles.	Deep shelf
		Williamson Sh.	< 1–79	Fissile shale containing graptolite fossils. Base contains Second Creek Phosphate Bed, which comprises quartz and phosphate pebbles.	
		Merritton Ls.	< 3.5	Dolomitic to argillaceous limestone with shale partings. Limestone contains brachiopod fossils and glauconite. Lower beds are bioturbated. Basal part has phosphate nodules and chert pebbles.	
	Clinton, lower	Reynales Ls.	0–12	Represented by Hickory Corners Member, which consists of thin- to medium-bedded limestone with shale partings, fossils, and some chert.	Offshore carbonates
		Neahga Sh.	< 2–6	Fissile shale with sparse fossils. Basal Densmore Creek Phosphate Bed contains nodules, pebbles, and cobbles of quartzite and phosphate in a sandstone matrix.	Inner shelf muds
	Medina	Kodak Ss.	< 1–11	Rhythmically interbedded sandstone and shale. Contains abundant trace fossils, locally.	Shoreface , shallow shelf, tidal flat, and tidal channels
		Cambria Sh.	< 1–14	Interbedded fine-grained sandstone, siltstone, and shale with sparse fossils. Caliche horizons and desiccation cracks are in some western sections.	
		Thorold Ss.	5–10	Mottled, cross-bedded, channel sandstone that grades laterally to a massive pelletal sandstone.	
		Grimsby Fm.	29–72	Interbedded sandstone, conglomerate, and shale. Sandstone is fine to medium grained. Sandstone beds in upper part of Grimsby are trough cross-stratified; sandstone beds in lower part of Grimsby are planar laminated and hummocky cross-stratified. Basal 10–15 ft of Grimsby is fossiliferous and bioturbated, and includes a phosphatic dolomite and pebble lag in the Artpark Phosphate Bed.	Condensed interval (Artpark Phosphate Bed)
		Devils Hole Ss.	13–15	Sandstone with shale interbeds; sandstone is fine to medium grained, horizontally to hummocky cross laminated, and well sorted.	Shallow shelf
		Power Glen Sh.	11–28	Shale containing hummocky cross-stratified and bioturbated sandstone, dolomite, siltstone, limestone, and sparse fossils.	Deeper shelf
		Whirlpool Ss.	18–28	Upper part is finer grained and hummocky cross-stratified sandstone. Lower part is fine- to medium-grained trough cross-stratified sandstone and contains large channel fills.	Nearshore marine, shallow shelf superposed over braided fluvial

Figure 4. Summary of the Niagaran Provincial Series in the Niagara region. Nomenclature, descriptions, depositional summaries, and unconformities are from Brett and others (1990, 1991, 1995, and references included therein). Their interpretations of major unconformities are shown by thick dashed lines, and their interpretations of minor unconformities are shown by thin dashed lines. Abbreviations: Dolomite (Dol.), Formation (Fm.), Limestone (Ls.), Member (Mbr.), Sandstone (Ss.), Shale (Sh.).

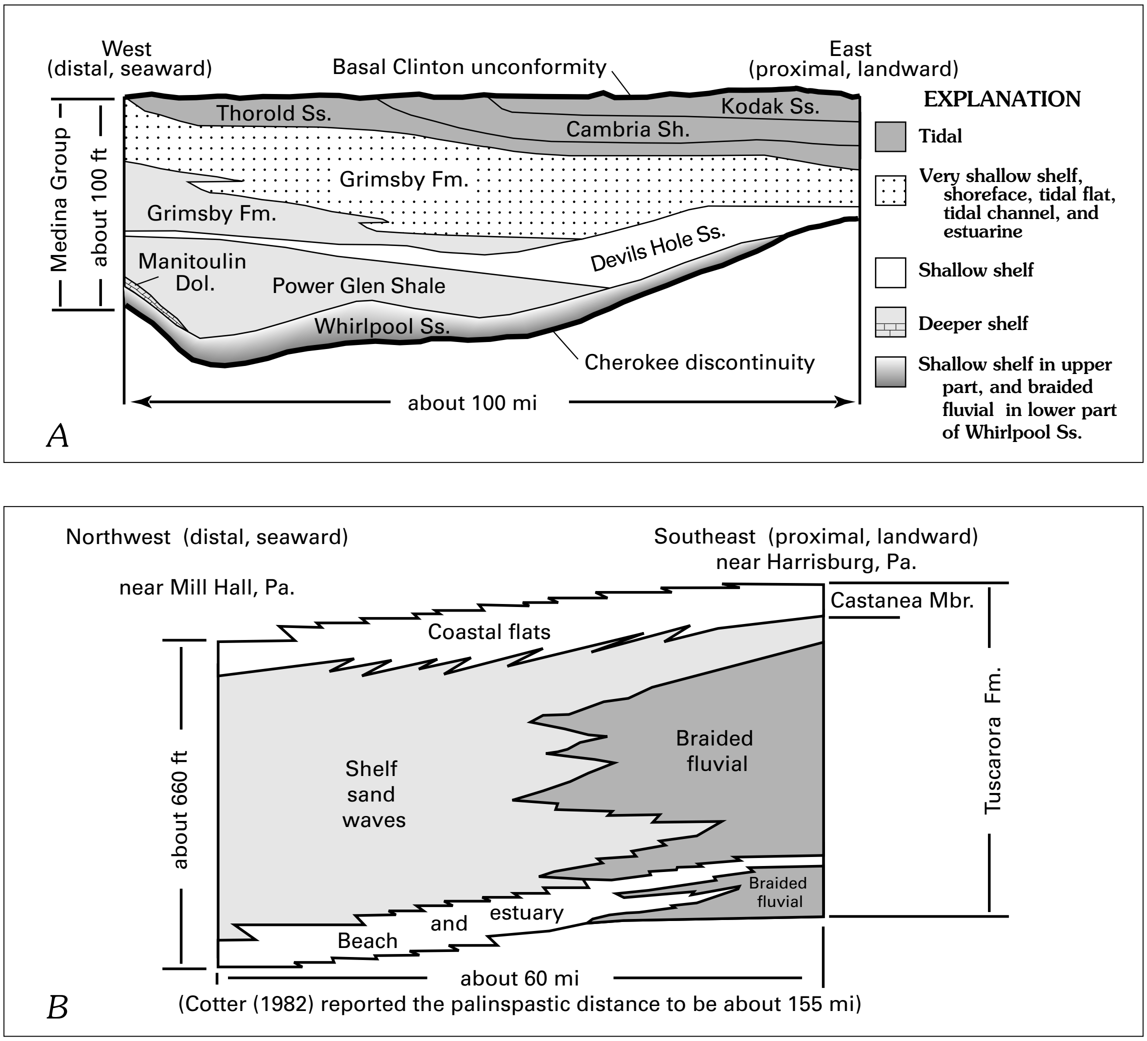

Figure 5. Previous depositional interpretations made from exposures of the Medina Group and Tuscarora Formation. Both panels show facies distributions along depositional dip; panel locations are shown in figure 2*B*. *A*, Depositional interpretations for Medina Group in the Niagara region; modified from Brett and others (1995). Interpretations are based on Brett and others (1990, 1991, 1995, and references included therein) and Duke and others (1991); tidal interpretations in the upper part of the Medina Group are based on Castle (1998) and Laughrey (1984). *B*, Depositional interpretations for the Tuscarora Formation along the folded and thrust-faulted eastern margin of the Appalachian Basin; modified from Cotter (1982). Abbreviations: Formation (Fm.), Member (Mbr.), Sandstone (Ss.), Shale (Sh.), Dolomite (Dol.).

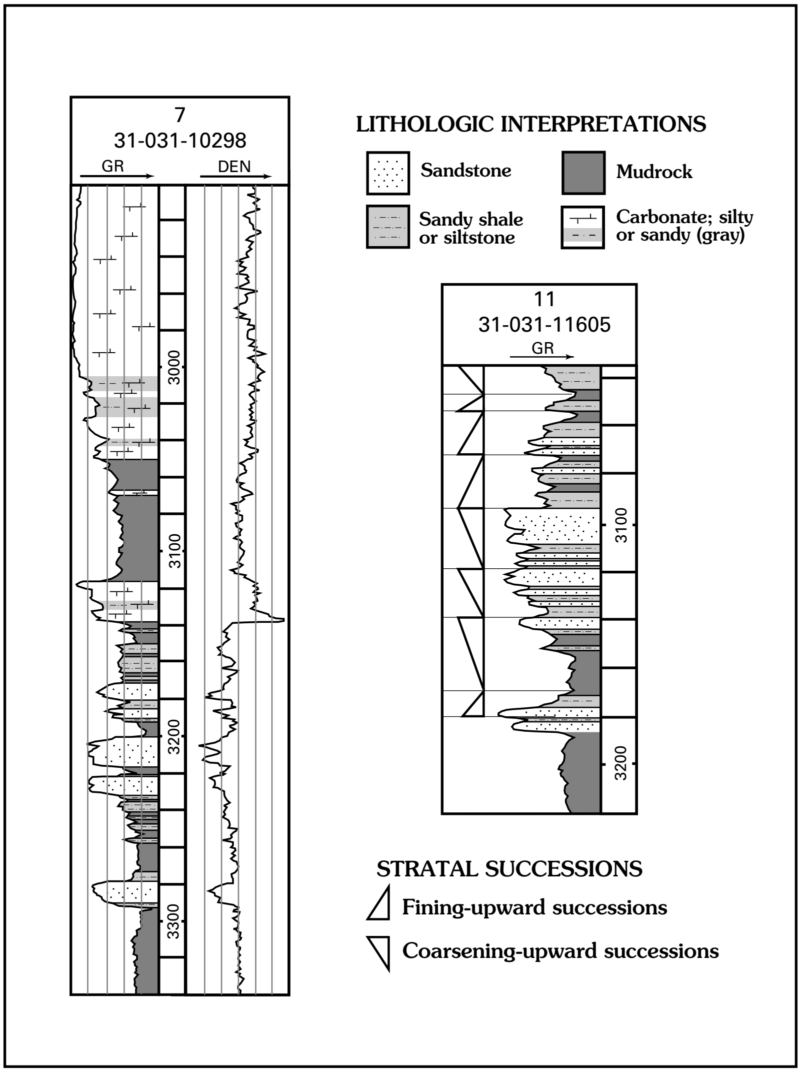

Figure 6. Criteria used for lithologic interpretations in drill holes located along cross sections B–B' and C–C'. Examples from drill holes 7 and 11 (table 1, cross section B–B'). Down-hole depths are labeled at 100-ft intervals. Lithologies are interpreted from combined responses of natural gamma (GR) and density (DEN) logs; values increase to the right as indicated by arrows. Sandstone has low to moderate GR and DEN values; siltstone has moderate GR and DEN values; mudrock has high GR and moderate DEN values; carbonates have low GR and moderate to high DEN values. Coarsening-upward siliciclastic successions have upwardly decreasing GR values, and fining-upward siliciclastic successions have upwardly increasing GR values.