# Assessment of Appalachian Basin Oil and Gas Resources: Utica-Lower Paleozoic Total Petroleum System

By Robert T. Ryder

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### Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |
| acre | 0.4047 | square hectometer ($hm^2$) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square foot ($ft^2$) | 929.0 | square centimeter ($cm^2$) |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| square inch ($in^2$) | 6.452 | square centimeter ($cm^2$) |
| section (640 acres or 1 square mile) | 259.0 | square hectometer ($hm^2$) |

| | | |
|---|---|---|
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| barrel (bbl), (petroleum, 1 barrel=42 gal) | 0.1590 | cubic meter ($m^3$) |
| gallon (gal) | 3.785 | liter (L) |
| gallon (gal) | 0.003785 | cubic meter ($m^3$) |
| cubic inch ($in^3$) | 16.39 | cubic centimeter ($cm^3$) |
| cubic inch ($in^3$) | 0.01639 | cubic decimeter ($dm^3$) |
| cubic inch ($in^3$) | 0.01639 | liter (L) |
| cubic foot ($ft^3$) | 28.32 | cubic decimeter ($dm^3$) |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| | Pressure | |
| atmosphere, standard (atm) | 101.3 | kilopascal (kPa) |
| bar | 100 | kilopascal (kPa) |
| inch of mercury at 60ºF (in Hg) | 3.377 | kilopascal (kPa) |
| pound-force per square inch ($lbf/in^2$) | 6.895 | kilopascal (kPa) |
| pound per square foot ($lb/ft^2$) | 0.04788 | kilopascal (kPa) |
| pound per square inch ($lb/in^2$) | 6.895 | kilopascal (kPa) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Area | |
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |
| square hectometer ($hm^2$) | 2.471 | acre |
| square kilometer ($km^2$) | 247.1 | acre |
| square centimeter ($cm^2$) | 0.001076 | square foot ($ft^2$) |
| square meter ($m^2$) | 10.76 | square foot ($ft^2$) |

| | | |
|---|---|---|
| square centimeter (cm$^2$) | 0.1550 | square inch (ft$^2$) |
| square hectometer (hm$^2$) | 0.003861 | section (640 acres or 1 square mile) |
| hectare (ha) | 0.003861 | square mile (mi$^2$) |
| square kilometer (km$^2$) | 0.3861 | square mile (mi$^2$) |
| | Volume | |
| cubic meter (m$^3$) | 6.290 | barrel (petroleum, 1 barrel = 42 gal) |
| liter (L) | 0.2642 | gallon (gal) |
| cubic meter (m$^3$) | 264.2 | gallon (gal) |
| cubic centimeter (cm$^3$) | 0.06102 | cubic inch (in$^3$) |
| cubic decimeter (dm$^3$) | 61.02 | cubic inch (in$^3$) |
| liter (L) | 61.02 | cubic inch (in$^3$) |
| cubic decimeter (dm$^3$) | 0.03531 | cubic foot (ft$^3$) |
| cubic meter (m$^3$) | 35.31 | cubic foot (ft$^3$) |
| | Pressure | |
| kilopascal (kPa) | 0.009869 | atmosphere, standard (atm) |
| kilopascal (kPa) | 0.01 | bar |
| kilopascal (kPa) | 0.2961 | inch of mercury at 60°F (in Hg) |
| kilopascal (kPa) | 0.1450 | pound-force per inch (lbf/in) |
| kilopascal (kPa) | 20.88 | pound per square foot (lb/ft$^2$) |
| kilopascal (kPa) | 0.1450 | pound per square inch (lb/ft$^2$) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

# Assessment of Appalachian Basin Oil and Gas Resources: Utica-Lower Paleozoic Total Petroleum System

By Robert T. Ryder

## Introduction

The Utica–Lower Paleozoic Total Petroleum System (TPS) is an important TPS identified in the 2002 U.S. Geological Survey (USGS) assessment of undiscovered, technically recoverable oil and gas resources in the Appalachian basin province (Milici and others, 2003). The TPS is named for the Upper Ordovician Utica Shale, which is the primary source rock, and for multiple lower Paleozoic sandstone and carbonate units that are the important reservoirs (fig. 1). Upper Cambrian through Upper Silurian petroleum-bearing strata that constitute the Utica–Lower Paleozoic TPS thicken eastward from about 2,700 ft at the western margin of the Appalachian basin to about 12,000 ft at the thrust-faulted eastern margin of the Appalachian basin (fig. 2). The Utica–Lower Paleozoic TPS covers approximately 170,000 $mi^2$ of the Appalachian basin from northeastern Tennessee to southeastern New York and from central Ohio to eastern West Virginia (fig. 3). The boundary of the TPS is defined by the following geologic features: (1) the northern boundary (from central Ontario to northeastern New York) extends along the outcrop limit of the Utica Shale-Trenton Limestone; (2) the northeastern boundary (from southeastern New York, through southeastern Pennsylvania-western Maryland-easternmost West Virginia, to northern Virginia) extends along the eastern limit of the Utica Shale-Trenton Limestone in the thrust-faulted eastern margin of the Appalachian basin; (3) the southeastern boundary (from west-central and southwestern Virginia to eastern Tennessee) extends along the eastern limit of the Trenton Limestone in the thrust-faulted eastern margin of the Appalachian basin; (4) the southwestern boundary (from eastern Tennessee, through eastern Kentucky, to southwestern Ohio) extends along the approximate facies change from the Trenton Limestone with thin black shale interbeds (on the east) to the equivalent Lexington Limestone without black shale interbeds (on the west); (5) the northern part of the boundary in southwestern Ohio to the Indiana border extends along an arbitrary boundary between the Utica Shale of the Appalachian basin and the Utica Shale of the Sebree trough (Kolata and others, 2001); and (6) the northwestern boundary (from east-central Indiana, through northwesternmost Ohio and southeasternmost Michigan, to central Ontario) extends along the approximate southeastern boundary of the Michigan Basin (fig. 3).

Although the Utica–Lower Paleozoic TPS extends into northwestern Ohio, southeastern Michigan, and northeastern Indiana (fig. 3), these areas have been assigned to the Michigan Basin (Swezey and others, 2005) and are outside the scope of this paper. Furthermore, although the northern part of the Utica–Lower Paleozoic TPS extends across the Great Lakes (Lake Erie and Lake Ontario) into southern Ontario, Canada (fig. 3*)*, only the undiscovered oil and gas resources in the U.S. waters of the Great Lakes have been included in the USGS assessment of the Utica–Lower Paleozoic TPS. This TPS is similar to the Point Pleasant-Brassfield (!) petroleum system previously identified by Drozd and Cole (1994) in the Ohio part of the Appalachian basin.

## Key Elements of the Total Petroleum System

### Petroleum Occurrence

Oil and gas in the Utica–Lower Paleozoic TPS were first discovered in the late 1880s in central Ohio (see for example, DeBrosse and Vohwinkel, 1974) and, through 2002, cumulative production + remaining reserves in the Utica–Lower Paleozoic TPS represent an estimated 15 to 20 percent (1.8 to 2.4 billion barrels of oil equivalent, BBOE) of the discovered oil and gas resources in the basin (unpublished estimate by R.T. Ryder, 2006). The majority of the petroleum discovered to date in the TPS is located on the east-dipping, western flank of the Appalachian basin in central and eastern Ohio, northwestern Pennsylvania, and western New York (figs. 4, 5, 6, and 7). Generally, the oil and (or) gas fields in the TPS produce from a variety of lower Paleozoic reservoirs at depths of less than 6,000 ft. However, scattered gas fields in the TPS, discovered from 1980 to the present, also occur in the deeper parts of the Appalachian basin in south-central New York, central Pennsylvania, and central West Virginia at depths between about 7,000 and 12,000 ft. Only a few small oil and (or) gas fields have been discovered in the thrust belt in the southeastern part of the TSP (figs. 4, 5). These fields in the thrust belt consist of two small oil fields in southwestern Virginia (discovered in 1943 and 1963) and a small gas field with associated oil in nearby eastern Tennessee (discovered in the early 1980s). Based on their geochemical character (Dennen and others, in press), an Ordovician source rock in the Utica–Lower Paleozoic TPS (upper part of the Trenton Limestone with thin interbedded black shale equivalent to the Utica Shale) is favored in this report for the for the oils in the thrust belt fields. Other possible source rocks for the thrust belt fields, the Ordovician Paperville and Sevier Shales located in easternmost thrust sheets of the Appalachian basin, are considered to be less plausible because the faulted anticlines that trapped the oils in the thrust belt fields probably formed after oil generation and migration had occurred from the Paperville-Sevier Shales. The most active petroleum exploration in the Utica–Lower Paleozoic TPS during the late 1990s and the first decade of the 21st century has targeted gas accumulations in hydrothermal and (or) fractured dolomite in the Upper Ordovician Trenton and Black River Limestones of south-central New York (New York Division of Mineral Resources, 2005; Smith, 2006), central West Virginia (Avary, 2006), and north-central Pennsylvania (Laughrey and Kostelnik, 2006b).

### Source Rocks

The Utica Shale (black shale of Late Ordovician age) is the primary source rock in the Utica-Lower Paleozoic TPS and is distributed across much of New York, Ohio, Pennsylvania, and West Virginia (fig. 8). Although the Utica Shale is not recognized in central and southern West Virginia and southwestern Virginia, this area has equivalent units of thin black shale in the uppermost part of the Trenton Limestone (Group) that are included as source rocks in the Utica-Lower Paleozoic TPS (fig. 8). Typical thicknesses for the Utica Shale range from 180 to 230 ft in eastern Ohio, from 175 to 250 ft in northern West Virginia, from 320 to 350 ft in central Pennsylvania (known here as the Antes Shale), from 150 to 250 ft in western New York, and from 350 to 700 ft in southeastern New York. Although some differences exit, the range in thickness values for the Utica Shale cited here are reasonably consistent with the thickness values for the Utica Shale presented by Riley and others (2006).

Total organic carbon (TOC) values (in wt percent) for the Utica Shale are usually greater than 1 percent, and TOC values in the 2 to 3 percent range outline a broad, northeast-trending area that extends across western and southern Pennsylvania, eastern Ohio, northern West Virginia, and southeastern New York (Wallace and Roen, 1989; Ryder and others, 1998) (fig. 8). The Utica Shale is characterized by

Type II kerogen (Ryder and others, 1998), a variety of kerogen that is typically prone to oil generation (Tissot and Welte, 1984; Peters and Cassa, 1994). Conodont color alteration index (CAI) isograds, based on samples from the Upper Ordovician Trenton Limestone (Group) (Repetski and others, in press), indicate that a pod of mature Utica source rocks occupies most of the TPS (figs. 3, 8).

Oil-source rock correlations in the U.S. part of the TPS are limited to several oil extracts from the Utica Shale in eastern Ohio and a group of oils from Cambrian and Ordovician reservoirs in central and eastern Ohio (Ryder and others, 1998). Comparisons of gas chromatograms and gas chromatogram-mass spectroscopy fragmentograms from these localities have suggested a positive oil-source rock correlation. In particular, alkane distributions of the extracts and oils are characterized by a moderate preference for odd-numbered n-alkanes between $nC_{11}$ and $nC_{19}$ and by observable isoprenoids (Cole and others, 1987; Ryder and others, 1998). Similar oil-source rock correlation studies by Obermajer and others (1999) in southern Ontario suggested to them that the Trenton Limestone was the most likely source for the oils in Cambrian and Ordovician reservoirs in Ontario. Although the Trenton Limestone is a credible source rock where it contains thin beds of black shale that are similar in character to the Utica Shale, on a regional basis the Utica Shale is considered in this report to be the primary source rock. As previously mentioned, the Trenton Limestone with thin black interbeds is the likely source rock for the oils in the thrust belt fields in southwestern Virginia and eastern Tennessee.

The Silurian part of the Utica-Lower Paleozoic TPS may have received local contributions of oil and gas from Middle and Upper Devonian black shale source rocks (Cole and others, 1987) and (or) from Silurian black shale and carbonate source rocks (Ryder and others, 2007). However, any significant contribution from these source rocks to the Utica-Lower Paleozoic TPS is considered to be unlikely. For one reason, the Devonian black shale source rocks are separated from the Utica-Lower Paleozoic TPS by a 2,000- to 2,500-ft-thick sequence of Upper Silurian through Middle Devonian rocks that includes a 400- to 1,000-ft-thick, widespread unit of Silurian evaporites (fig. 2). This Silurian evaporite unit should be largely impervious to oil and gas migration, thus preventing any significant mixing of oils and gases between the Devonian Shale-Middle and Upper Paleozoic TPS (see Milici and others, 2003) and the Utica-Lower Paleozoic TPS. However, based on geochemical evidence in the Michigan basin, some oils generated from Ordovician source rocks appear to have migrated vertically through thick, widespread Silurian evaporite beds (Hatch and others, 2005).

## Burial History, Thermal History, and Hydrocarbon Migration

Burial history and thermal history models by Rowan (2006) indicated that the Utica Shale in eastern Ohio and northern West Virginia entered the oil-generation window approximately between Late Devonian and Late Pennsylvanian time, and the Utica Shale entered the gas-generation window between Middle Mississippian and Early Permian time. For example, in the Humble No. 1 Minesinger well (Utica top=8,650 ft) and the Exxon No. Gainer-Lee well (Utica top=10,600 ft) in northern West Virginia (figs. 3, 9, and 10), the Utica Shale entered the oil window in Late Devonian time (≈ 375 Ma) and the shale entered the gas window in Early Permian time (≈ 280 Ma). In the Occidental No. 1 Burley well (Utica top=12,650 ft) in northern West Virginia (figs. 3, 11), the Utica Shale also entered the oil window in Late Devonian time (≈ 385 Ma), but entered the gas window in Middle Mississippian time (≈ 330 Ma). By comparison, the Amerada No. 1 Ullman well (Utica top=8,200 ft) and the Great Lakes No. 1 Drake well (Utica top=4,700 ft) in eastern Ohio (figs. 3, 10, and 11), the Utica Shale entered the oil window in Late Devonian (≈ 360 Ma) and Late Pennsylvanian time (≈ 300 Ma), respectively, but the Utica Shale in neither well achieved sufficient burial to enter the gas window. The burial and thermal history model of the Pan American No. 1 Windbigler well (Utica top=3,010 ft) in central Ohio suggested that little or no oil and gas was generated from the Utica Shale at this location (figs. 3, 10).

Hydrocarbon migration occurred both vertically and laterally (updip toward the northwest) soon after initial oil generation from the Utica Shale and probably lasted at least until the early phases of post- Paleozoic uplift and erosion. Also, migration probably followed multiple pathways that included bedding-parallel zones of secondary porosity, dissolution zones along the regional Knox unconformity (fig. 1), and regionally pervasive to local tectonic fractures (fig. 12). Pervasive fracturing of the Cambrian and Ordovician strata, caused by recurrent tectonism, may have been a convenient mechanism to transport Utica Shale-derived oil and gas from a basinal, downdip location, across underlying strata, into older reservoirs (fig. 12). Secondary migration may have occurred in places, particularly where initially trapped oil was converted to gas during episodes of deeper burial and tectonic readjustment.

## Reservoir Rocks

The following reservoir rocks (in ascending stratigraphic order) were evaluated in the Utica-Lower Paleozoic TPS for undiscovered oil and gas resources in the 2002 USGS Appalachian basin assessment (Milici and others, 2003): the Upper Cambrian Copper Ridge Dolomite (figs. 1, 4), the Upper Cambrian Rose Run Sandstone (figs. 1, 4), the Lower Ordovician Beekmantown Dolomite (figs. 1, 4), the Upper Ordovician Black River/Trenton Limestone (figs. 1, 5), the Lower Silurian Clinton/Medina/Tuscarora Sandstone (sandstone) (figs. 1, 6), and the Lower and Upper Silurian Lockport Dolomite (Newburg zone) (figs. 1, 7). Sandstone reservoirs in the Upper Ordovician Queenston Shale (figs. 1, 6) also were evaluated in the 2002 USGS assessment, but their undiscovered gas resources were included in the assessment of the Lower Silurian sandstones. Additional reservoirs of secondary importance in the Utica-Lower Paleozoic TPS include the Upper Ordovician Bald Eagle Sandstone (fig. 2) (Laughrey and Harper, 1996) and the Upper Silurian Williamsport Sandstone (Newburg sandstone) (figs. 2, 7) (Patchen, 1996). These secondary reservoirs were not assessed for undiscovered oil and gas in the 2002 USGS Appalachian basin assessment because their resources were considered to be negligible. The amount of accumulated gas in the Bald Eagle Sandstone probably was never very large, whereas most of the accumulated gas in the Newburg sandstone has already been found. Shale gas from the Upper Ordovician Utica Shale (fig. 1) was not identified or assessed as a viable resource in the 2002 USGS Appalachian basin assessment largely because there was no commercial gas production from the shale in the United States at the time. Although there is still no commercial production from the Utica Shale in the United States as of April 2008, the unit deserves some discussion in this report because of the recent interest it has generated as a potential gas reservoir (Martin, 2005; Nyahay and others, 2007). Recently, gas discoveries have been reported from the Utica Shale in the St. Lawrence Lowlands of Quebec (fig. 3) (Park, 2008).

### Copper Ridge Dolomite, Rose Run Sandstone, and Beekmantown Dolomite

Oil and gas accumulations in the Copper Ridge Dolomite, Rose Run Sandstone, and Beekmantown Dolomite reservoirs are commonly associated with the overlying Knox unconformity (figs. 1, 13). In Ohio, the Copper Ridge dolomite, Rose Run sandstone, and Beekmantown dolomite are informal units in the Knox Dolomite (fig. 1). The prominent lithology of the Copper Ridge Dolomite and the Beekmantown Dolomite is microcrystalline to medium crystalline dolomite. The Rose Run Sandstone is a quartz arenite to subarkose with dolomite cement.

Reservoirs in the Copper Ridge Dolomite and Beekmantown Dolomite are characterized by secondary vuggy porosity that is controlled in part by the leaching of algal stromatolites during subaerial exposure that accompanied the formation of the Knox unconformity (Dolly and Busch, 1972; Riley and others, 1993; Ryder, 1994). Intercrystalline porosity in the medium-crystalline dolomite of the Copper Ridge and Beekmantown Dolomites provides an additional porosity type (Riley and others, 1993; Ryder, 1994). Many of the rhomb-shaped crystals that constitute the medium-crystalline dolomite show dissolution features along their edges (Riley and others, 1993).

The dominant porosity type in the Rose Run Sandstone is secondary porosity characterized by oversized pores, moldic pores, and enlarged intergranular pores (Riley and others, 1993; Riley and others, 2002). The enlarged pores are interpreted as dissolution features that formed when the Rose Run Sandstone interacted with deep basin brines (Riley and others, 1993). Porosity values for the Rose Run Sandstone range from near zero to 11 percent, and average 5.9 percent (Riley and others, 1993). Fractures are rarely observed in the Rose Run Sandstone, but they are suspected to be present on the basis of production characteristics (Riley and others, 2002).

### Black River and Trenton Limestones

The Black River Limestone consists of carbonate mudstone and wackestone and the overlying Trenton Limestone consists of fossiliferous limestone (wackestone, packstone, and grainstone). The majority of the high-yield oil and (or) gas reservoirs in the Black River and Trenton Limestones of south-central New York, northwest Ohio, and northeast Ohio consist of medium- to coarsely crystalline hydrothermal dolomite. The hydrothermal dolomite reservoirs in the Black River and Trenton Limestones are commonly narrow and linear in plan view (fig. 5) because hot ascending fluids that altered the limestone host rock to dolomite were confined largely to subvertical fault zones that originated in the Proterozoic basement (New York Division of Mineral Resources, 2005; Smith, 2006). Although the Black River and Trenton reservoirs in West Virginia are controlled by northeast-trending fault zones in the Rome trough, hydrothermal dolomite is absent there and the dominant porosity is controlled by fractures (Patchen and Mroz, 2006). Fractured limestone also characterizes the reservoirs in the upper part of the Trenton Limestone in north-central New York (New York Division of Mineral Resources, 1987; Avary, 2006).

The hydrothermal dolomite reservoirs are characterized by vuggy, intercrystalline, and fracture porosity (Smith, 2006; Wickstrom and Gray, 1988; Sagan and Hart, 2006; Laughrey and Kostelnik, 2006a). Typical porosity values in the dolomitized Black River and Trenton reservoirs in south-central New York range from 5 to 16 percent (Nyahay and others, 2006). Moreover, initial reservoir pressures of the Black River and Trenton reservoirs in New York are abnormally low, with values typically less than 0.43 psi/ft (Nyahay and others, 2006).

### Clinton sandstone, Medina sandstone, Medina Group sandstones and Tuscarora Sandstone

The Clinton-Medina-Tuscarora sandstone reservoirs are predominantly very-fine- to fine-grained quartz arenites, sublitharenites, and subarkoses with silica and calcite cement (Castle, 1998; Ryder and Zagorski, 2003). The Clinton/Medina sandstone interval in Ohio and the Medina Group interval in Pennsylvania and New York range in thickness from about 100 to 200 ft, whereas the Tuscarora Sandstone interval in Pennsylvania and West Virginia ranges in thickness from about 500 to 700 ft (figs. 3, 14). Moreover, the Tuscarora Sandstone has a greater percentage of net sandstone and is typically coarser grained than the Clinton sandstone, Medina sandstone, and Medina Group sandstones.

Oil and gas trapped in the Clinton sandstone, Medina sandstone, Medina Group sandstones, and the Tuscarora Sandstone constitute a regional hydrocarbon accumulation that was named the Lower Silurian regional accumulation by Ryder and Zagorski (2003). Following Ryder and Zagorski (2003), the Lower Silurian regional accumulation is divided into a basin-center part which occupies eastern Ohio, central Pennsylvania, and central West Virginia and a hybrid-conventional part that occupies the updip part of the accumulation in central Ohio, northwestern Pennsylvania, and western New York (fig. 14).

The sandstone reservoirs in the basin-center part of the regional accumulation have relatively low permeability (less than or equal to 0.1 millidarcys) and porosity (3 to 10 percent) values, whereas the sandstone reservoirs in the hybrid-conventional part of the accumulation have higher permeability (greater than 0.1 millidarcys) and porosity (5-15 percent) values (Ryder and Zagorski, 2003). Although fracture porosity plays a major role in the improvement of Tuscarora Sandstone reservoir performance (Avary, 1996), its role in the improvement of Clinton-Medina reservoir performance is debatable. However, there are a growing number of examples where open fractures have improved production in Clinton-Medina sandstone reservoirs in the basin-center part of the regional accumulation. All the Clinton-Medina-Tuscarora sandstones have been altered to some degree by burial diagenesis. The primary porosity type is secondary intergranular owing to the dissolution of feldspar and unstable lithic fragments (Zagorski, 1999; Ryder and Zagorski, 2003). Primary intergranular porosity is present locally in the Clinton-Medina-Tuscarora sandstones because of incomplete silica cementation (Ryder and Zagorski, 2003).

Most of the Clinton sandstone-Medina sandstone-Medina Group sandstone reservoirs are underpressured with values ranging from about 0.25 to 0.42 psi/ft (Ryder and Zagorski, 2003). However, the Tuscarora Sandstone reservoir pressures are variable and range from normal (hydrostatic), to underpressured, to slightly overpressured (Avary, 1996; Ryder and Zagorski, 2003).

## Queenston Shale

The Queenston Shale is a red bed unit that consists predominantly of shale with smaller amounts of siltstone and sandstone. Sandstone reservoirs in the upper part of the Queenston Shale in western New York contain gas that is either produced exclusively from these reservoirs or is co-produced with gas in the Medina Group sandstone reservoirs. These gas accumulations in the Queenston Shale and overlying Medina Group sandstones are located in the hybrid-conventional part of the regional accumulation. Sandstone beds within the Queenston Shale are typically fine-grained quartz arenites with permeability values that average 0.20 millidarcys and porosity values that average 3 to 4 percent (Saroff, 1987; Ward, 1988).

## Lockport Dolomite (Newberg zone)

The predominant lithology of the Lockport Dolomite is microcrystalline to finely crystalline dolomite. The reservoirs are typically 5- to 40-ft thick and are associated with bioherm buildups, however, commonly the reservoirs cap the bioherms rather that being part of them (Santini and Coogan, 1983; Noger and others, 1996). This observation is consistent with the interpretation by Laughrey (1987) that the reservoir zones consist of rubble derived from nearby bioherms. In contrast, many of the gas fields in the Upper Silurian Guelph Formation of the Lockport Group in southern Ontario, Canada, appear to produce directly from biohermal reservoirs that are interpreted as main or barrier reefs (Bailey, 1986). Similar reservoir conditions also may occur in the upper part of the Lockport Dolomite (Group) in the United States that is equivalent to the Guelph Formation.

Reservoir porosity in the Lockport Dolomite commonly consists of widespread zones of vuggy, moldic, and intercrystalline porosity (Multer, 1963; Santini and Coogan, 1983; Laughrey, 1987). Vuggy and moldic porosity in the Lockport Dolomite in western Pennsylvania averages about 9.6 percent and intercrystalline porosity averages about 3.4 percent (Laughrey, 1987). The thickest of the porous zones generally occurs in the upper part of the Lockport Dolomite in Ohio and is referred to informally as the Newburg zone (Multer, 1963; Santini and Coogan, 1983). Reservoir pressures in the Newburg zone are abnormally low (Noger and others, 1996).

### Utica Shale

The Utica Shale consists of thinly laminated black shale that is rich in organic matter. Commonly, the Utica Shale is calcareous. Based on black shale reservoirs in the Utica Shale of the St. Lawrence Lowlands of Quebec (Aguilera, 1978), a hypothetical Utica Shale reservoir is proposed in this report for the United States part of the Appalachian basin. The Utica Shale reservoirs in Quebec are self-sourced, fractured, have porous zones that range in thickness from 50-90 feet, and have water saturations that approach zero. Furthermore, fracture porosity for the Utica Shale reservoir in Quebec averages 1.4 percent and the reservoir pressure is generally normal (Aguilera, 1978). Natural fractures have been observed in outcrop and in core for the Utica Shale in New York State (Martin, 2005).

### Traps

Stratigraphic traps and combination structural–stratigraphic traps provide the majority of the traps in the Utica-Lower Paleozoic TPS and most of them are very subtle. Stratigraphic traps include unconformity traps (Copper Ridge Dolomite, Rose Run Sandstone, Beekmantown Dolomite), paleotopographic or buried hills traps (Copper Ridge Dolomite, Rose Run Sandstone, Beekmantown Dolomite), carbonate bioherm traps (Newburg zone), sedimentary-facies pinchouts (Clinton sandstone), and diagenetic-facies traps (Trenton-Black River hydrothermal dolomite, Clinton-Medina sandstones). Structural traps in the TPS are characterized largely by low-amplitude anticlines, structural terraces, faulted anticlines, and faults. Commonly, the anticlinal traps in the Tuscarora Sandstone are associated with natural fractures. Most combination structural-stratigraphic traps are sedimentary-facies pinchouts against low-amplitude anticlines.

An unusual type of trapping condition, perhaps caused by high mobile-water saturation, may be the primary mode of entrapment for the basin-center part of the Lower Silurian regional gas accumulation (Ryder and Zagorski, 2003). A similar zone of high mobile-water saturation appears to have trapped gas in the deep basin gas accumulation in the Alberta Basin of western Canada (Masters, 1979).

### Seals

The 400- to 1,000-ft-thick Upper Silurian Salina Group that contains halite, anhydrite, anhydritic dolomite mudstone, and dolomite mudstone is the regional seal for the Utica-Lower Paleozoic TPS (fig. 2). Secondary seal rocks include the Upper Ordovician Utica Shale, Reedsville Shale, Queenston Shale and Juniata Formation, and the Lower Silurian Rochester Shale and Rose Hill Formation (fig. 2).

## Assessment Units

An assessment unit (AU) is a mappable volume of rock within the TPS that encompasses discovered and undiscovered fields which share similar geologic traits and socio-economic factors (Klett and others, 2000). As used in this report, an AU is analogous to a play in the 1995 National Assessment of United States Oil and Gas Resources (Gautier and others, 1995) and in the Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996).

The Utica-Lower Paleozoic TPS contains both conventional oil and gas resources and continuous (unconventional) gas resources. A conventional resource (accumulation) has a discrete field outline with a well-defined downdip hydrocarbon-water contact, whereas a continuous resource (accumulation) is widely distributed with a poorly defined boundary, is not localized by a single trap, and is not associated with a downdip hydrocarbon-water contact (Schmoker, 1997). A different methodology has been applied to each of these resource types. For the assessment of conventional resources, a field-size methodology is used where estimated sizes and numbers of undiscovered fields are based on the size distribution and discovery history of known fields in a given AU (play) (Houghton and others, 1993; Gautier and Dolton, 1995). Also, the conventional resources methodology considers a "growth factor" to account for resources expected to be added to reserves as a consequence of the extension of known fields, the revision of reserve estimates, and the addition of new pools to discovered fields (U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1995; Attanasi and others, 1999). In contrast, for the assessment of continuous resources, a cell-based methodology is used where the total resource is estimated from the number of undrilled cells within and adjoining a designated continuous accumulation, the size of each undrilled cell (the optimum drainage area for a single well), and the estimated ultimate recovery (EUR) of hydrocarbon resource (usually natural gas) by a single well that drains each cell (Schmoker, 1996, 1999; Klett and Charpentier, 2003). All input parameters and estimated conventional and continuous (unconventional) resources are expressed probabilistically as ranges of values.

## Assessment Units of Conventional Oil and Gas Resources

### Lower Paleozoic Carbonates in Thrust Belt AU

#### Description

The Lower Paleozoic Carbonates in Thrust Belt AU is located along the folded and thrust faulted southeastern margin of the Utica-Lower Paleozoic TPS (fig. 15). Gas trapped in faulted anticlines constitutes the primary resource. Reservoir units are carbonate rocks in the Knox Dolomite (Group) and the Trenton Limestone (Group). Several small oil and gas fields are present in the AU in southwestern Virginia and adjoining eastern Tennessee (figs. 4, 5). A Geologic Events Chart summarizing the key events for the Lower Paleozoic Carbonates in Thrust Belt AU is shown in figure 16.

#### Sizes and Numbers of Fields

Three fields have been discovered to date in this AU. The ultimate size of the two oil fields in southwest Virginia that produce from the Trenton Limestone is about 0.30 million barrels of oil (MMBO) each with negligible amounts of gas, whereas the ultimate size of the gas field with associated oil in nearby eastern Tennessee that produces primarily from the Knox Group is about 35.5 billion cubic feet of gas (BCFG) and about 0.319 MMBO (Hatcher and others, 2001). Based on the sizes of analogous gas fields in the thrust belt of the western United States, the estimated size distribution of undiscovered gas fields in the Lower Paleozoic Carbonates in Thrust Belt AU ranges from an estimated minimum of 3 BCFG to a maximum of 500 BCFG. The analogous gas fields were degraded appropriately to approximate the expected sizes, porosity preservation, and post-entrapment history of Lower Paleozoic carbonate rocks in the Appalachian basin. The median size of undiscovered gas fields is 15 BCFG (mean=28 BCFG). The number of estimated undiscovered gas fields ranges from a minimum of 5 to a maximum of 15. The median number of undiscovered gas fields is 10.

#### Resource

The undiscovered, technically recoverable gas resource in the Lower Paleozoic Carbonates in Thrust Belt AU is estimated (at a mean value) to be 301.90 BCFG (table 1). Natural gas liquids associated with the gas resource are estimated (at a mean value) to be 3.02 million barrels (MMBNGL) (table 1).

## Knox Unconformity AU

### Description

The Knox Unconformity AU covers most of the Utica-Lower Paleozoic TPS including the area where the Utica Shale source rock is immature with respect to oil and gas generation (fig. 15). Oil and gas trapped in buried hills, truncation traps, and stratigraphic pinchouts beneath the Knox unconformity constitute the primary resource. Reservoir units are the Copper Ridge Dolomite, the Beekmantown Dolomite, and the Rose Run Sandstone. Previously discovered oil and gas fields in the AU are located largely in central and eastern Ohio, but several small gas fields are located in northwestern Pennsylvania and western New York (figs. 4, 15). A Geologic Events Chart summarizing the key events for the Knox Unconformity AU is shown in figure 17.

### Sizes and Numbers of Fields

Approximately 51 oil fields (39 in Copper Ridge-Knox reservoirs and 12 in Beekmantown-Rose Run reservoirs) have been discovered to date in the Ohio part of the AU. These fields range in ultimate size from less than 0.2 MMBO to about 18.6 MMBO (unpublished data from Mark E. Wolfe, 1995; unpublished estimates from R.T. Ryder, 2000, based on Janssens (1993; 1998—unpublished data)). An additional 11 oil fields have been discovered in Cambrian sandstone reservoirs in southern Ontario, Canada, and these fields range in ultimate size from less than 0.1 MMBO to about 1.65 MMBO (Ontario Ministry of Natural Resources, 2001). Based on these oil field sizes, the estimated size distribution of undiscovered oil fields in the Knox Unconformity AU ranges from a minimum of 0.5 MMBO to a maximum of 10 MMBO. The median size of undiscovered oil fields is 1.2 MMBO. The number of estimated undiscovered oil fields ranges from a minimum of 3 to a maximum of 40. The median number of undiscovered oil fields is 20.

By comparison, approximately 24 gas fields (2 in Copper Ridge-Knox reservoirs and 22 in Beekmantown-Rose Run reservoirs) have been discovered to date in the Ohio part of the Knox Unconformity AU. These fields range in ultimate size from less than 1 BCFG to about 50 BCFG (Baranoski and others, 1996, and unpublished estimates from R.T. Ryder, 2000, based on Janssens (1993; 1998—unpublished data)). An additional 13 gas fields have been discovered in New York (3), Pennsylvania (4), and Ontario, Canada (6), and these additional fields range in ultimate size from less than 1 BCFG to about 21.5 BCFG (field located in southern Ontario) (Ontario Ministry of Natural Resources, 2001). Based on the sizes of these gas fields, the estimated size distribution of undiscovered gas fields in the Knox Unconformity AU ranges from a minimum of 3 BCFG to a maximum of 250 BCFG. The median size of undiscovered gas fields is 8 BCFG. The number of estimated undiscovered gas fields range from a minimum of 5 to a maximum of 60. The median number of undiscovered gas fields is 30.

### Resource

The undiscovered, technically recoverable oil resource in the Knox Unconformity AU is estimated (at a mean value) to be 30.44 MMBO (table 1). Furthermore, the gas resources associated with the oil resources are estimated (at a mean value) to be 152.33 BCFG, whereas the nonassociated gas resources are estimated (at a mean value) to be 421.61 BCFG (table 1). Natural gas liquids associated with the oil resources and nonassociated gas resources are estimated (at a mean value) to be

1.53 MMBNGL and 4.21 MMBNGL, respectively (table 1). According to Coleman and others (2006), approximately 10 percent or less of the oil and gas resources are estimated to be in the Great Lakes (Lakes Erie and Ontario).

## Black River-Trenton Hydrothermal Dolomite AU

### Description

The Black River-Trenton Hydrothermal Dolomite AU covers most of the Utica-Lower Paleozoic TPS, including the area where the Utica Shale source rock is immature with respect to oil and gas generation (fig. 15). Oil and gas trapped in dolomitized and (or) fractured limestone reservoirs aligned with basement fault zones constitute the primary resource. The main reservoir unit is the Black River Limestone (Group). Discovered gas fields in the Black River-Trenton Hydrothermal Dolomite AU are located largely in south-central and north-central New York (figs. 5, 15). Other discoveries in the AU include several small oil and gas fields in Ohio and small gas fields in West Virginia (figs. 5, 15). This AU also includes the giant Lima-Indiana oil and gas field (figs. 5, 15) that is located on the Findlay arch (fig. 1) in northwestern Ohio. A Geologic Events Chart summarizing the key events for the Black River-Trenton Hydrothermal Dolomite AU is shown in figure 17.

### Sizes and Numbers of Fields

Three small oil fields (with ultimate sizes less than 0.25 MMBO) have been discovered to date in the Black River-Trenton Hydrothermal Dolomite AU in central and eastern Ohio (Avary, 2006). These Ohio oil fields do not include the small fields in the Trenton Limestone on the Findlay arch or the giant Lima-Indiana field on the Findlay arch, with an ultimate size of approximately 514 MMBO (Moody and others, 1970). Except for the Lima-Indiana oil field, most oil fields discovered to date in Black River and Trenton reservoirs are located in southern Ontario, Canada (24 fields and 20 pools) and in southeastern Michigan (4 fields). The 12 largest Black River-Trenton oil fields in Ontario, Canada, have ultimate sizes that range from less than 0.2 MMBO to 6 MMBO (Ontario Ministry of Natural Resources, 2001; Trevail and others, 2004), whereas the 4 oil fields in Michigan have ultimate sizes that range from less than 0.1 MMBO to about 124 MMBO (Albion-Scipio field, Hurley and Budros, 1990). Based on these oil-field sizes, the estimated size distribution of undiscovered oil fields in the Black River-Trenton Hydrothermal Dolomite AU ranges from a minimum of 0.5 MMBO to a maximum of 30 MMBO. The median size of undiscovered oil fields is 1 MMBO. The number of estimated undiscovered oil fields ranges from a minimum of 1 to a maximum of 25. The median number of undiscovered oil fields is 9.

By comparison, approximately 26 gas fields have been discovered (through 2004) in south-central New York in hydrothermal dolomite reservoirs that are primarily within the Black River Group (Avary, 2006; Smith, 2006). An additional 20 gas fields have been discovered (through 2004) in north-central New York in fractured limestone reservoirs that are primarily within the Trenton Group (New York Division of Mineral Resources, 1987; Avary, 2006). The New York gas fields with hydrothermal dolomite reservoirs have ultimate sizes that range from less than 0.5 BCFG to at least 50 BCFG (estimates by R.T. Ryder, 2007, based on cumulative production data from Avary, 2006); however, all of the gas fields in northeastern New York with fractured limestone reservoirs have ultimate sizes that are probably less than 0.5 BCFG (Avary, 2006). Several small gas fields produce from hydrothermal dolomite reservoirs in central and eastern Ohio, and these gas fields range in ultimate size from about 0.5 BCFG to about 6 BCFG (estimates by R.T. Ryder, 2007, based on cumulative production data from Avary, 2006). An additional 20 gas fields (plus 10 pools) have been discovered in hydrothermal dolomite reservoirs in Ontario, Canada, and these gas fields range in ultimate size from less than 0.1 BCFG to about 13.5 BCFG (Ontario Ministry of Natural Resources, 2001; Trevail and others, 2004). The four oil fields that produce from hydrothermal dolomite reservoirs in Michigan have associated gas volumes that range from negligible to about 212 BCFG (Albion-Scipio field, Hurley and Budros, 1990). The single gas field in West Virginia produces from a fractured limestone reservoir in the Trenton Limestone and has an ultimate size of about 10 BCFG (estimate by R.T. Ryder, 2007, based on cumulative production data from Avary, 2006). Based on these sizes of gas fields, the estimated size distribution of undiscovered gas fields in the Black River-Trenton Hydrothermal Dolomite AU (including the fractured limestone reservoirs) ranges from a minimum of 3 BCFG to a maximum of 750 BCFG. The median size of undiscovered gas fields is 18 BCFG. The number of estimated undiscovered gas fields ranges from a minimum of 5 to a maximum of 110. The median number of undiscovered gas fields is 50.

### Resource

The undiscovered, technically recoverable oil resource in the Black River-Trenton Hydrothermal Dolomite AU is estimated (at a mean value) to be 16.29 MMBO (table 1). Furthermore, the gas resources associated with the oil resources are estimated (at a mean value) to be 81.48 BCFG, whereas the nonassociated gas resources are estimated (at a mean value) to be 1,837.22 BCFG (table 1). Natural gas liquids associated with the oil resources and nonassociated gas resources are estimated (at a mean value) to be 0.82 MMBNGL and 18.33 MMBNGL, respectively (table 1). According to Coleman and others (2006), approximately 40 percent of the oil resource is estimated to be in the Great Lakes (Lake Erie) and approximately 16 percent of the gas resource is estimated to be in the Great Lakes (Lakes Erie and Ontario).

## Lockport Dolomite AU

### Description

The Lockport Dolomite AU is located in the north-central part of the Utica-Lower Paleozoic TPS that covers most of Ohio, northwestern Pennsylvania, and western New York (fig. 18). About one-half of the AU area in Ohio is located where the Utica Shale source rock is immature with respect to oil and gas generation (fig. 18). Gas trapped on the flanks of biohermal buildups, and in compaction anticlines that overlie the biohermal buildups, constitutes the primary resource. Reservoir units are zones of vuggy and moldic porosity in the Lockport Dolomite, the largest of which is the Newburg zone. Known gas fields (several with local associated oil) in the AU are located primarily in central Ohio, but several small gas fields are located in northwestern Pennsylvania and western New York (figs. 7, 18). A Geologic Events Chart summarizing the key events for the Lockport Dolomite AU is shown in figure 19.

### Sizes and Numbers of Fields

Approximately 29 gas fields have been discovered to date in the Ohio part of the AU, and these fields range in ultimate size from less than 0.1 BCFG to about 20.2 BCFG (Janssens, 1977; Santini and Coogan, 1983; Noger and others, 1996). The larger of two gas fields in Pennsylvania that produce from the Lockport Dolomite has an ultimate size of about 5.8 BCFG (Noger and others, 1996) and the one gas field in New York has an ultimate size of less than 0.1 BCFG (Noger and others, 1996). An additional 34 gas fields have been discovered in Lockport Group (Dolomite) reservoirs in southern Ontario, Canada, and these additional gas fields range in ultimate size from less than 0.1 BCFG to about

63 BCFG (Ontario Ministry of Natural Resources, 2001). Also, about 20 small oil fields have been discovered in the Lockport Group in southern Ontario, Canada, but the ultimate size of each of these fields is less the 1 MMBO (Ontario Ministry of Natural Resources, 2001). Based on these sizes of gas fields, the estimated size distribution of undiscovered gas fields in the Lockport Dolomite AU ranges from a minimum of 3 BCFG to a maximum of 100 BCFG. The median size of undiscovered gas fields is 7 BCFG. The number of estimated undiscovered gas fields ranges from a minimum of 2 to a maximum of 50. The median number of undiscovered gas fields is 20.

#### Resource

The undiscovered, technically recoverable gas resource in the Lockport Dolomite AU is estimated (at a mean value) to be 207.49 BCFG (table 1). Natural gas liquids associated with the gas resource are estimated (at a mean value) to be 2.08 MMBNGL (table 1). According to Coleman and others (2006), approximately 90 percent of the gas resource is estimated to be in the Great Lakes (Lake Erie).

## Assessment Units of Continuous Gas Resources

All four of the defined assessment units with continuous gas resources in the Utica-Lower Paleozoic TPS are associated with the Lower Silurian regional accumulation. Basin-center gas in the Lower Silurian regional accumulation is divided between the Clinton-Medina Basin Center AU and the Tuscarora Basin Center AU, whereas the hybrid-conventional part of the regional accumulation is divided between the Clinton-Medina Transitional AU and the Clinton-Medina Transitional Northeast AU (fig. 20). For the 2002 assessment, the term transitional was preferred by the USGS assessment committee instead of the term hybrid-conventional originally used by Ryder and Zagorski (2003). The Clinton-Medina Transitional Northeast AU also includes gas resources from sandstone reservoirs in the Queenston Shale as well as from sandstone reservoirs in the Medina Group. Although natural gas is the dominant hydrocarbon resource in these four assessment units, a substantial amount of oil is also present in the Clinton-Medina Basin Center AU and the Clinton-Medina Transitional AU.

### Clinton-Medina Basin Center AU

#### Description

The Clinton-Medina Basin Center AU is located in the western part of the Utica-Lower Paleozoic TPS that covers most of eastern Ohio, northwestern Pennsylvania, and small parts of western West Virginia and western New York (fig. 20). Most of the AU is located where the Utica Shale source rock is at or above the threshold of dominant thermal gas generation (CAI 2-3) (fig. 8). The eastern margin of the Clinton-Medina Basin Center AU is largely facies-controlled, and marks the approximate boundary between sandstone reservoirs of the Clinton sandstone-Medina sandstone-Medina Group and sandstone reservoirs of the Tuscarora Sandstone (Tuscarora Basin Center AU). The western margin of the Clinton-Medina Basin Center AU is a transitional boundary between an updip, regional zone of higher water saturation (possibly a “water block” trap) toward the west (Clinton-Medina Transitional AU) and a basinward zone of more pervasive gas saturation toward the east. Also, the reservoir pressures change gradually across the western margin of the Clinton-Medina Basin Center AU from abnormally low pressures toward the east to pressures approaching hydrostatic toward the west. Numerous gas wells (approximately 25,000) are located in the western part of the AU, where drilling depths to the Clinton-Medina reservoirs range from about 4,000 to 6,000 ft. However, fewer gas wells are located in the eastern downdip part of the AU, where drilling depths to the Clinton-Medina reservoirs range from about 6,500 to 8,500 ft. Judging from the presence of a small number of widely distributed gas wells and wells with gas shows, very likely, large areas in the largely undrilled eastern part of the Clinton-Medina Basin Center AU should produce gas during the next 30 years. A Geologic Events Chart summarizing the key events for the Clinton-Medina Basin Center AU is shown in figure 21.

### Sizes of Undrilled Cells (the Optimum Drainage Area for a Single Well)

The estimated sizes of the undrilled cells in the AU range from a minimum of 10 acres to a maximum of 110 acres. The median size of undrilled cells is 40 acres.

### Untested Area that has Potential for Additions to Reserves During the Next 30 Years

The untested area with potential additions to reserves in the AU ranges from a minimum of about 754,480 acres to a maximum of about 8,125,075 acres. The median untested area with potential additions to reserves is 4,160,200 acres. Based on previous drilling results, the expected success ratio for new wells may be as high as 91 percent.

### Distribution of Estimated Ultimate Recovery (EUR) per Well Values

Based on decline-curve plots for approximately 1,000 wells, organized into thirds according to their year of discovery, the EUR distribution per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Clinton-Medina Basin Center AU ranges from a minimum of 0.010 BCFG to a maximum of 1.2 BCFG. The median EUR value is 0.080 BCFG.

### Resource

The undiscovered, technically recoverable gas resource in the Clinton-Medina Basin Center AU is estimated (at a mean value) to be 10,832.70 BCFG (table 2). Associated oil was assessed in the AU by applying a mean coproduct ratio for untested cells of 10 barrels of liquid/MMCFG (or a gas-oil ratio of 100,000 MCFG/BO). This oil, which is expressed as natural gas liquids associated with the gas resource and is estimated (at a mean value) to be 108.33 MMBNGL (table 2).

## Tuscarora Basin Center AU

### Description

The Tuscarora Basin Center AU is located in the central part of the Utica-Lower Paleozoic TPS that covers most of West Virginia, southwestern through northeastern Pennsylvania, and small parts of south-central New York, easternmost Kentucky, and southwestern Virginia (fig. 20). Most of the AU is located where the Utica Shale source rock has exceeded the threshold for dominant thermal gas generation (CAI 3-5) (fig. 8). The eastern margin of the Tuscarora Basin Center AU coincides with the western limit of the fold and thrust belt (Allegheny structural front) along the southeastern margin of the Utica-Lower Paleozoic TPS (fig. 3), whereas the western margin of the Tuscarora Basin Center AU coincides with the approximate boundary that marks the facies change between sandstone reservoirs of the Clinton sandstone-Medina Group and sandstone reservoirs of the Tuscarora Sandstone. Fewer than 50 gas wells (commonly associated with large percentages of noncombustible gas) are present in the Tuscarora Basin Center AU, where drilling depths to the Tuscarora Sandstone reservoir range from about 6,500 to about 12,000 ft. These gas wells are located on faulted anticlines where the Tuscarora Sandstone reservoir is cut by numerous open fractures that increase the permeability of an otherwise tightly cemented, nonreservoir sandstone. Consequently, only those areas in the Tuscarora Basin Center AU with fractured anticlinal folds are expected to produce gas during the next 30 years. A Geologic Events Chart summarizing the key events for the Tuscarora Sandstone Basin Center AU is shown in figure 21.

### Sizes of Undrilled Cells (the Optimum Drainage Area for a Single Well)

The estimated sizes of the undrilled cells in the AU range from a minimum of 40 acres to a maximum of 160 acres. The median size of undrilled cells is 80 acres.

### Untested Area that has Potential for Additions to Reserves During the Next 30 Years

The untested area with potential additions to reserves in the AU ranges from a minimum of about 25,578 acres to a maximum of about 735,057 acres. The median untested area with potential additions to reserves is 242,325 acres. Based on previous drilling results, the expected success ratio for new wells drilled along the fractured anticlines is 60 percent.

### Distribution of Estimated Ultimate Recovery (EUR) per Well Values

Based on decline-curve plots for approximately 40 wells, the EUR distribution per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Tuscarora Sandstone Basin Center AU ranges from a minimum of 0.010 BCFG to a maximum of 4.0 BCFG. The median EUR value is 0.070 BCFG.

### Resource

The undiscovered, technically recoverable gas resource in the Tuscarora Sandstone Basin Center AU is estimated (at a mean value) to be 2,619.59 BCFG (table 2). Natural gas liquids associated with the gas resource are estimated (at a mean value) to be 10.48 MMBNGL (table 2).

## Clinton-Medina Transitional AU

### Description

The Clinton-Medina Transitional AU is located in the western part of the Utica-Lower Paleozoic TPS that extends across central Ohio, northwestern Pennsylvania, western New York and small parts of western West Virginia and eastern Kentucky (fig. 20). The Clinton-Medina Transitional AU also includes a large part of Lake Erie (fig. 20). Most of the AU is located where the Utica Shale source rock is within the thermal region of dominant oil generation (CAI 1.5-2) (fig. 8). The eastern margin of the Clinton-Medina Transitional AU is a transitional boundary between an updip, regional zone of higher water saturation (possibly a “water block” trap) toward the west and a basinward zone of more pervasive gas saturation toward the (Clinton-Medina Basin Center AU). The western margin of the Clinton-Medina Transitional AU is marked by the westernward pinchout limit of the Clinton sandstone into stratigraphically equivalent Lower Silurian shale and carbonate strata. Also, the reservoir pressures change gradually across the Clinton-Medina Transitional AU from abnormally low pressures near the eastern margin to hydrostatic pressures near the western margin. Drilling depths to the Clinton-Medina reservoirs in the AU range from about 1,500 to 4,000 ft. Except for U.S. portions of Lake Erie, most of the Clinton-Medina Transitional AU has been densely drilled by oil and gas wells (approximately 55,250 wells), some of which were drilled more than 100 years ago. Although the AU is densely drilled, there are still many small undrilled areas that likely will produce oil and gas during the next 30 years.  A Geologic Events Chart summarizing the key events for the Clinton-Medina Transitional AU is shown in figure 21.

### Sizes of Undrilled Cells (the Optimum Drainage Area for a Single Well)

The estimated sizes of the undrilled cells in the AU range from a minimum of 10 acres to a maximum of 110 acres.  The median size of undrilled cells is 40 acres.

### Untested Area that has Potential for Additions to Reserves During the Next 30 Years

The untested area with potential additions to reserves in the AU ranges from a minimum of about 3,177,984 acres to a maximum of about 9,402,231 acres.  The median untested area with potential additions to reserves is 5,821,348 acres.  Based on previous drilling results, the expected success ratio for new wells may be as high as 77 percent.

### Distribution of Estimated Ultimate Recovery (EUR) per Well Values

Based on decline-curve plots for several thousand wells, organized into thirds according to their year of discovery, the EUR distribution per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Clinton-Medina Transitional AU ranges from a minimum of 0.010 BCFG to a maximum of 1.0 BCFG.  The median EUR value is 0.060 BCFG.

### Resource

The undiscovered, technically recoverable gas resource in the Clinton-Medina Transitional AU is estimated (at a mean value) to be 11,770.64 BCFG (table 2).  Associated oil was assessed in the AU by using a mean coproduct ratio for untested cells of 12 barrels of liquid/MMCFG (or a gas-oil ratio of 83,000 MCFG/BO).  This oil is expressed as natural gas liquids associated with the gas resource, and is estimated (at a mean value) to be 141.25 MMBNGL (table 2).  According to Coleman and others (2006), approximately 20 percent of the gas resource is estimated to be in the Great Lakes (Lake Erie).

## Clinton-Medina Transitional Northeast AU

### Description

The Clinton-Medina Transitional Northeast AU is located in the northern part of the Utica-Lower Paleozoic TPS and represents the northeastern extension of the Clinton-Medina Transitional AU into central New York (fig. 20).  Most of the AU is located where the Utica Shale source rock is at or above the threshold of dominant thermal gas generation (CAI 2-3) (fig. 8).   The southern margin of the Clinton-Medina Transitional Northeast AU is largely facies-controlled, and marks the approximate boundary between sandstone reservoirs of the Medina Group and sandstone reservoirs of the Tuscarora Sandstone (Tuscarora Basin Center AU).  The northern margin of the Clinton-Medina Transitional Northeast AU is marked by the outcrop limit of the Medina Group.  The eastern and western margins of the Clinton-Medina Transitional Northeast AU define the approximate limits of sandstone units in the Queenston Shale.  These sandstone units, along with eastward-thinning sandstone units of the Medina Group, form the major reservoirs in the AU.  Drilling depths to the Medina Group and Queenston Shale sandstone reservoirs in the AU range from about 1,000 to 5,000 ft.  Most of the known gas wells to date (approximately 250 wells) are located in the northern and western parts of the AU.  Judging from the presence of a small number of widely distributed gas wells and small gas fields, very likely, parts of the largely undrilled southern part of the Clinton-Medina Transitional Northeast AU should produce gas during the next 30 years. A Geologic Events Chart summarizing the key events for the Clinton-Medina Transitional Northeast AU is shown in figure 21.

### Sizes of Undrilled Cells (the Optimum Drainage Area for a Single Well)

The estimated sizes of the undrilled cells in the AU range from a minimum of 10 acres to a maximum of 110 acres. The median size of undrilled cells is 40 acres.

### Untested Area that has Potential for Additions to Reserves During the Next 30 Years

The untested area with potential additions to reserves in the AU ranges from a minimum of about 82,625 acres to a maximum of about 2,306,500 acres. The median untested area with potential additions to reserves is 739,341 acres. Based on previous drilling results, the success ratio for new wells is 75 percent.

### Distribution of Estimated Ultimate Recovery (EUR) per Well Values

Based on decline-curve plots for several thousand wells, organized into thirds according to their year of discovery, the EUR distribution per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Clinton-Medina Transitional Northeast AU ranges from a minimum of 0.010 BCFG to a maximum of 0.90 BCFG. The median EUR value is 0.060 BCFG.

### Resource

The undiscovered, technically recoverable gas resource in the Clinton-Medina Transitional Northeast AU is estimated (at a mean value) to be 1,618.85 BCFG (table 2). Natural gas liquids associated with the gas resource are estimated (at a mean value) to be 16.19 MMBNGL (table 2).

## Utica Shale AU

### Description

Because the Utica Shale was not identified as a potential gas reservoir in the 2002 USGS assessment of the Appalachian basin, there are no Utica Shale AU boundaries defined in this report. If a hypothetical Utica Shale AU had been defined, then its most optimum location probably would have been defined in the northeastern part of the Utica-Lower Paleozoic TPS in southeastern New York and northeastern Pennsylvania. In this area, the Utica Shale is several hundred feet thick, has TOC values between 1 and 3, and has thermal maturity values above the threshold for dominant thermal gas generation.

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