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

By Robert T. Ryder

Chapter G.10 of

Coal and Petroleum Resources in the Appalachian Basin: Distribution, Geologic Framework, and Geochemical Character

Edited by Leslie F. Ruppert and Robert T. Ryder

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Pressure	
pound per square inch (lb/in^2) (psi)	6.895	kilopascal (kPa)
	Permeability	
millidarcy (mD)	9.86923×10^{-16}	square meter (m^2)

The pressure gradient in a well commonly is derived by dividing the pressure (in pounds per square inch, or psi) at a given stratigraphic interval by the depth of the interval (in feet, or ft). The calculated or measured pressure gradient can be compared with a hydrostatic (or normal) gradient of 0.43–0.45 psi/ft (9.7–10.1 kilopascals per meter, or kPa/m). A pressure of greater than 0.45 psi/ft (10.1 kPa/m) is referred to as overpressured, whereas a pressure of less than 0.45 psi/ft (10.1 kPa/m) is referred to as underpressured.

Letter Symbols for Units of Measure

BBOE	billion barrels of oil equivalent
BCFG	billion cubic feet of gas
CFG	cubic feet of gas
MMBNGL	million barrels of natural gas liquids
MMBO	million barrels of oil
MMCFG	million cubic feet of gas
TCFG	trillion cubic feet of gas

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

By Robert T. Ryder[1]

Abstract

The Utica-Lower Paleozoic Total Petroleum System (TPS) in the Appalachian Basin Province is named for the Upper Ordovician Utica Shale, which is the source rock, and for multiple lower Paleozoic sandstone and carbonate units that are the important reservoirs. The total organic carbon (TOC) values for the Utica Shale are usually greater than 1 weight percent. TOC values ranging from 2 to 3 weight percent outline a broad, northeast-trending area that extends across western and southern Pennsylvania, eastern Ohio, northern West Virginia, and southeastern New York. The Utica Shale is characterized by type II kerogen, which is a variety of kerogen that is typically prone to oil generation. Conondont color-alteration index (CAI) isograds, which are based on samples from the Upper Ordovician Trenton Limestone (or Group), indicate that a pod of mature Utica Shale source rocks occupies most of the TPS.

The following strata (in ascending stratigraphic order) are the most important reservoir rocks for oil and gas in the Utica-Lower Paleozoic TPS: (1) the Upper Cambrian Copper Ridge dolomite in Ohio; (2) the Upper Cambrian Rose Run sandstone in Ohio; (3) the Upper Ordovician Black River Limestone (or Group) and Trenton Limestone in New York, West Virginia, and Ohio; (4) the Lower Silurian "Clinton" sandstone, Medina sandstone, Medina Group sandstones, and Tuscarora Sandstone in Ohio, Pennsylvania, New York, and West Virginia; and (5) the Lower and Upper Silurian Lockport Dolomite (also known as the Newburg zone) in Ohio. Strata containing oil and gas reservoirs of secondary importance are sandstone reservoirs in the Upper Ordovician Queenston Shale in New York, the Upper Ordovician Bald Eagle Sandstone in Pennsylvania, and the Upper Silurian Williamsport Sandstone (also known as the Newburg sandstone) in West Virginia. The Upper Ordovician Utica Shale may be an important gas and oil(?) reservoir in the future. In about 2011, after this report was written, commercial natural gas and oil was discovered in the Utica Shale in eastern Ohio.

Both conventional oil and gas resources and continuous (unconventional) gas resources are present in the Utica-Lower Paleozoic TPS. Conventional oil and gas resources in the Utica-Lower Paleozoic TPS were assessed by the U.S. Geological Survey (USGS) in 2002 in the following assessment units (AU): (1) the Lower Paleozoic Carbonates in Thrust Belt AU, (2) the Knox Unconformity AU, (3) the Black River-Trenton Hydrothermal Dolomite AU, and (4) the Lockport Dolomite AU. The total estimated undiscovered oil and gas resources for these four AUs, at a mean value, was about 46 million barrels of oil (MMBO) and about 3 trillion cubic feet of gas (TCFG), respectively. In contrast, continuous (unconventional) gas resources in the TPS were assessed by the USGS in 2002 in four AUs associated with the "Clinton" sandstone, Medina sandstone, Medina Group sandstones, Tuscarora Sandstone, and sandstones in the Queenston Shale. The total estimated undiscovered gas for these four AUs, at a mean value, was about 26.8 TCFG. A hypothetical Utica Shale AU for oil(?) and continuous gas is identified in this report. In 2012, the Utica Shale was recognized by the USGS as a continuous AU and was assessed by Kirschbaum and others (2012).

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 feet (ft) at the western margin of the Appalachian basin to about 12,000 ft at the thrust-faulted eastern margin of the Appalachian basin (in the Valley and Ridge province) (fig. 2). The Utica-Lower Paleozoic TPS covers approximately 170,000 square miles (mi^2) of the Appalachian basin from northeastern Tennessee to central New York and from western Ohio to eastern West Virginia (figs. 2, 3). The boundary of the TPS is defined by the following geologic features: (1) the northern boundary (from central Ontario to southeastern New York) extends along the outcrop limit of the Utica Shale or Trenton

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Limestone; (2) the northeastern boundary (from southeastern New York, through southeastern Pennsylvania, western Maryland, easternmost West Virginia, and northern Virginia) extends along the eastern limit of the Utica Shale or 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 western 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, Canada) 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 east-central Indiana (fig. 3), these areas have been assigned to the Michigan Basin (Swezey and others, 2005) and are outside the scope of this report. 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 beneath the U.S. waters of the Great Lakes have been included in the USGS assessment of the Utica-Lower Paleozoic TPS.

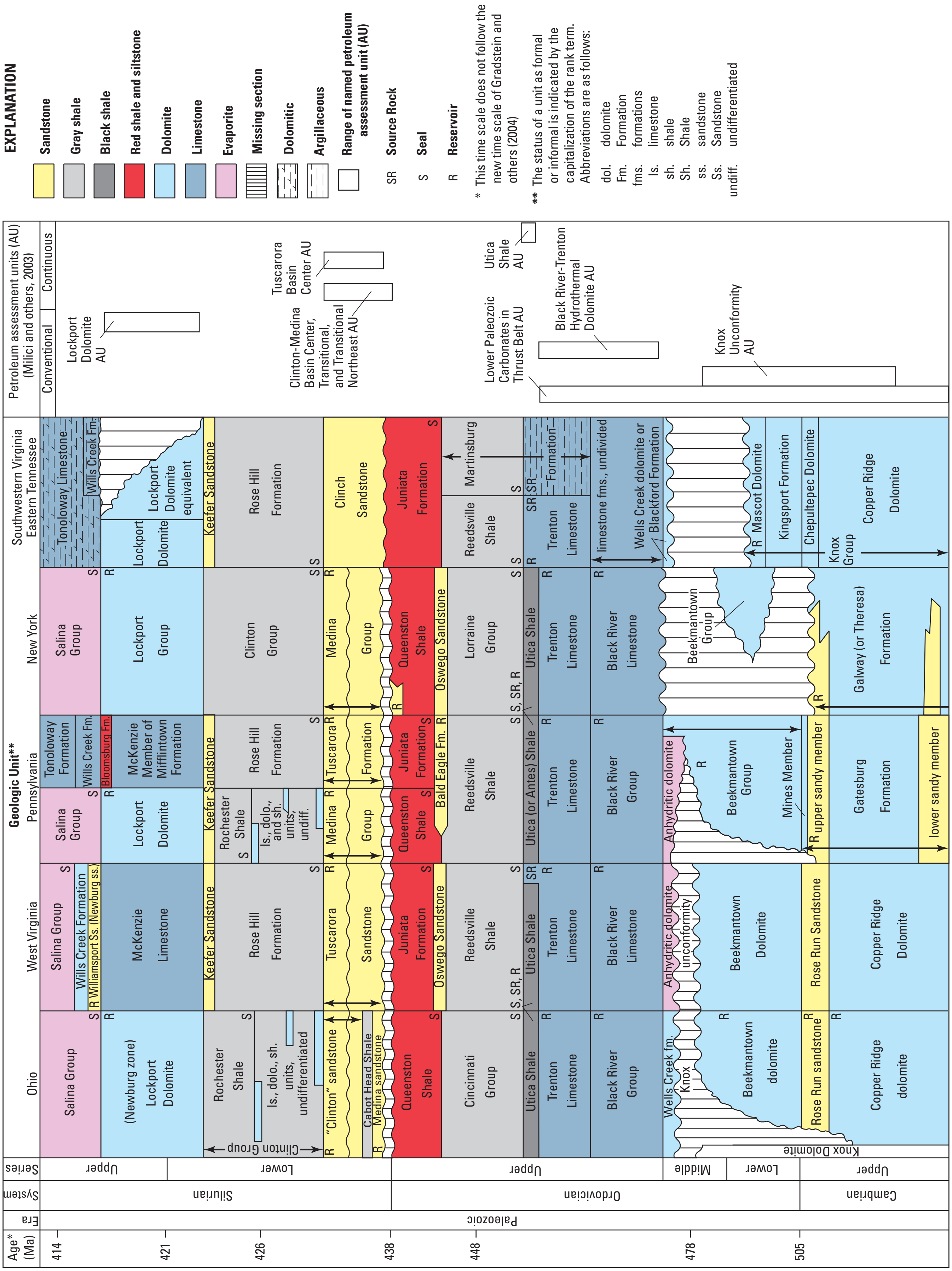
The Utica-Lower Paleozoic TPS is similar to the Point Pleasant-Brassfield(!) petroleum system identified by Drozd and Cole (1994) in the Ohio part of the Appalachian basin except for differences in stratigraphic nomenclature assigned to the same source rock-reservoir rock pairs. For example, Drozd and Cole (1994) assigned the term “Point Pleasant Formation” (Findlay arch and Cincinnati arch nomenclature) to the Ordovician black shale source rock, whereas this report assigns the term “Utica Shale” (Appalachian basin nomenclature) to the same rocks. Furthermore, Drozd and Cole (1994) assigned the term “Brassfield Formation” (equivalent to the “Clinton” sandstone) to the major reservoir unit, whereas this report assigns the more inclusive term “lower Paleozoic” to the reservoir unit. In addition to the Brassfield Formation, Drozd and Cole (1994) also included the Knox Dolomite and Lockport Group as important reservoirs in the Point Pleasant-Brassfield(!) petroleum system. Therefore, except for the Black River and Trenton Limestone reservoir (which is excluded), the Point Pleasant-Brassfield(!) petroleum system includes the same major reservoirs as the Utica-Lower Paleozoic TPS. Another difference between the petroleum systems is that the Utica-Lower Paleozoic TPS has a regional focus, whereas the Point Pleasant-Brassfield(!) has a more local focus.

Key Elements of the Total Petroleum System

Petroleum Occurrence

Oil and gas in the Utica-Lower Paleozoic TPS were discovered in the late 1880s in central Ohio (see for example, DeBrosse and Vohwinkel, 1974). Through 2002, cumulative production plus 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, or 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, 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 TPS (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). Geochemical character studies by Dennen and others (this volume, chap. G.12) indicate that the upper part of the Trenton Limestone (which contains thin, interbedded black shale equivalent to the Utica Shale), most likely is the source rock 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 the 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 and 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 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, 2004; Smith, 2006), central West Virginia (Avary, 2006), and north-central Pennsylvania (Laughrey and Kostelnik, 2006b).

Figure 1 (facing page). Correlation chart showing the stratigraphic units and assessment units in the Utica-Lower Paleozoic Total Petroleum System and source rocks, reservoirs, and seals. Ma, million years ago.



EXPLANATION
Sandstone
Gray shale
Black shale
Red shale and siltstone
Dolomite
Limestone
Evaporite
Missing section
Dolomitic
Argillaceous
Range of named petroleum assessment unit (AU)
SR Source Rock
S Seal
R Reservoir
* This time scale does not follow the new time scale of Gradstein and others (2004)
** The status of a unit as formal or informal is indicated by the capitalization of the rank term. Abbreviations are as follows:
dol. dolomite
Fm. Formation
fms. formations
ls. limestone
sh. shale
Sh. Shale
ss. sandstone
Ss. Sandstone
undiff. undifferentiated
Age* (Ma)
Era
System
Series
Geologic Unit**
Ohio
West Virginia
Pennsylvania
New York
Southwestern Virginia Eastern Tennessee
Petroleum assessment units (AU) (Milici and others, 2003)
Conventional
Continuous
414
421
426
438
448
478
505
Paleozoic
Silurian
Ordovician
Cambrian
Upper
Lower
Middle
Salina Group
(Newburg zone) Lockport Dolomite
Rochester Shale
ls., dolo., sh. units, undifferentiated
Clinton Group
"Clinton" sandstone
Cabot Head Shale
Medina sandstone
Queenston Shale
Cincinnati Group
Utica Shale
Trenton Limestone
Black River Group
Wells Creek fm.
Knox
Beekmantown dolomite
Rose Run sandstone
Copper Ridge dolomite
Knox Dolomite
Wills Creek Formation
Williamsport Ss. (Newburg ss.)
McKenzie Limestone
Keefer Sandstone
Rose Hill Formation
Tuscarora Sandstone
Juniata Formation
Oswego Sandstone
Reedsville Shale
Black River Limestone
Anhydritic dolomite
unconformity
Beekmantown Dolomite
Rose Run Sandstone
Copper Ridge Dolomite
Tonoloway Formation
Bloomsburg Fm.
McKenzie Member of Mifflintown Formation
Lockport Dolomite
Rochester Shale
ls., dolo., and sh. units, undiff.
Medina Group
Tuscarora Formation
Bald Eagle Fm.
Utica (or Antes) Shale
Beekmantown Group
Mines Member
upper sandy member
Gatesburg Formation
lower sandy member
Salina Group
Lockport Group
Clinton Group
Medina Group
Queenston Shale
Lorraine Group
Black River Limestone
Galway (or Theresa) Formation
Tonoloway Limestone
Wills Creek Fm.
Lockport Dolomite equivalent
Clinch Sandstone
Martinsburg Formation
limestone fms., undivided
Wells Creek dolomite or Blackford Formation
Mascot Dolomite
Kingsport Formation
Chepultepec Dolomite
Knox Group
Lockport Dolomite AU
Clinton-Medina Basin Center, Transitional, and Transitional Northeast AU
Tuscarora Basin Center AU
Lower Paleozoic Carbonates in Thrust Belt AU
Utica Shale AU
Black River-Trenton Hydrothermal Dolomite AU
Knox Unconformity AU

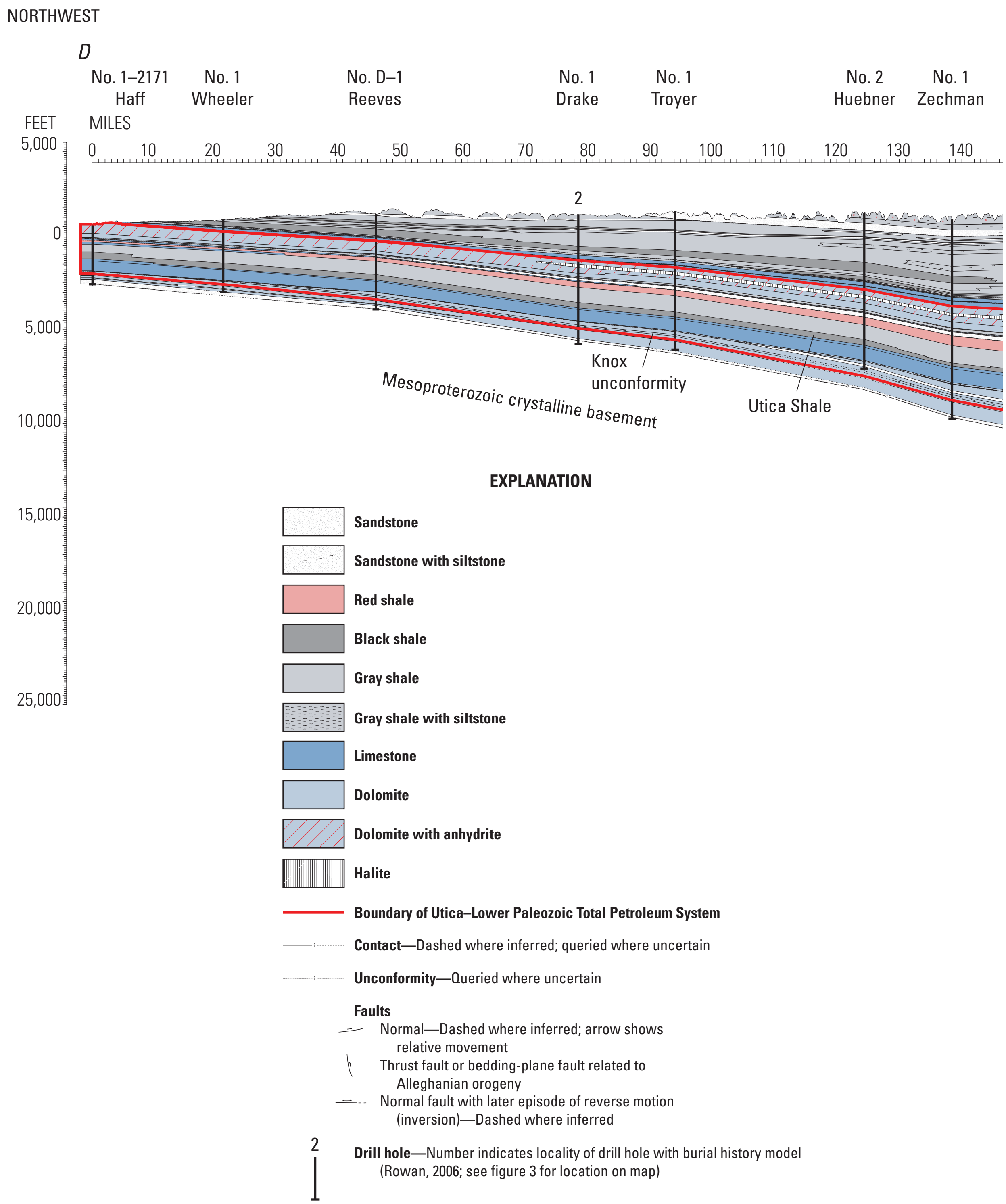


Figure 2. Geologic cross section *D–D′* through the Appalachian basin showing Upper Cambrian, Ordovician, and Silurian rocks that constitute the Utica-Lower Paleozoic Total Petroleum System (Ryder and others, 2009). See figure 3 for the line of section. This cross section is part of a series of previously published and lettered regional cross sections through the Appalachian basin (Ryder and others, 2008, 2009, 2012; and chap. E.4.1, this volume).

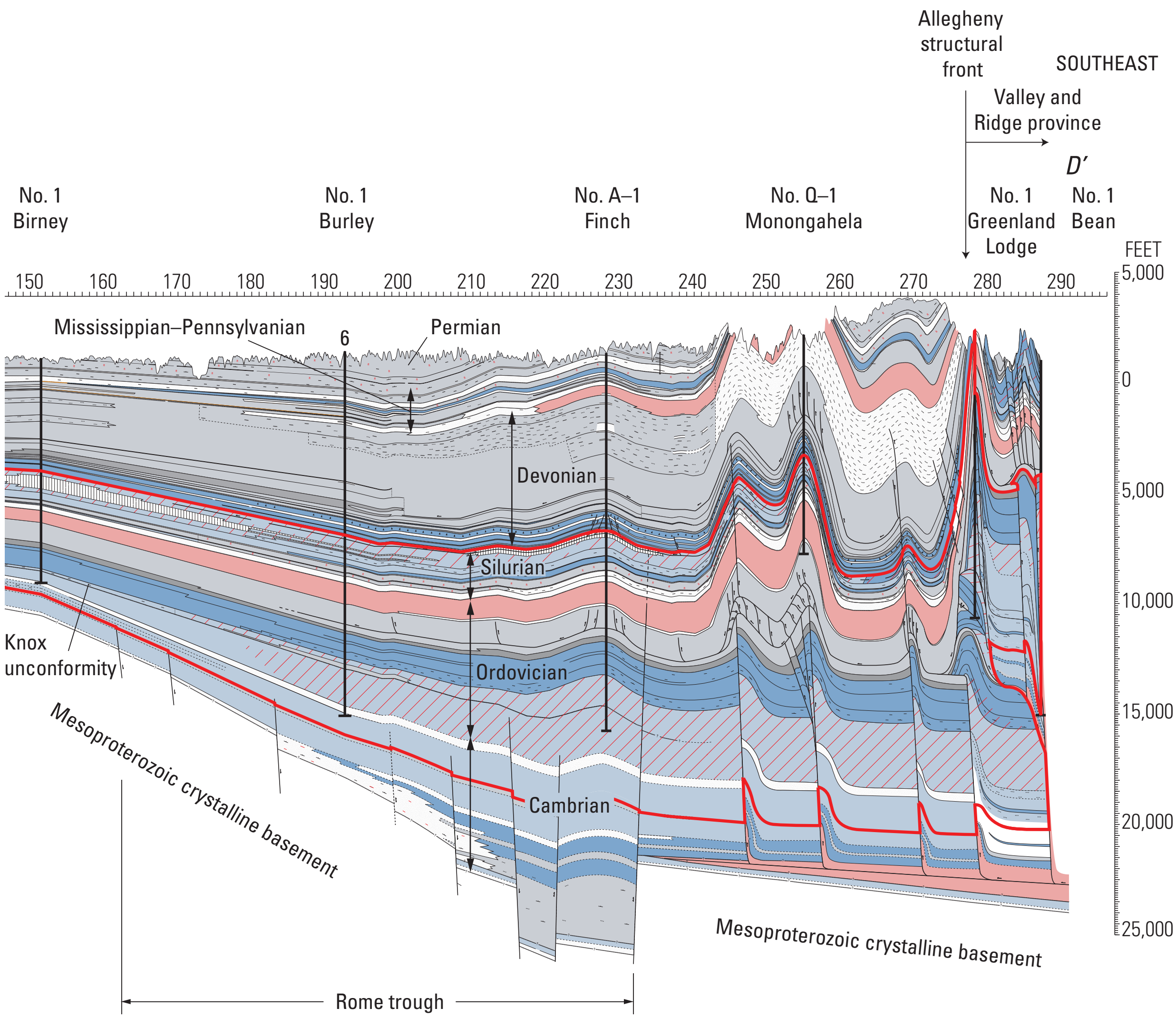
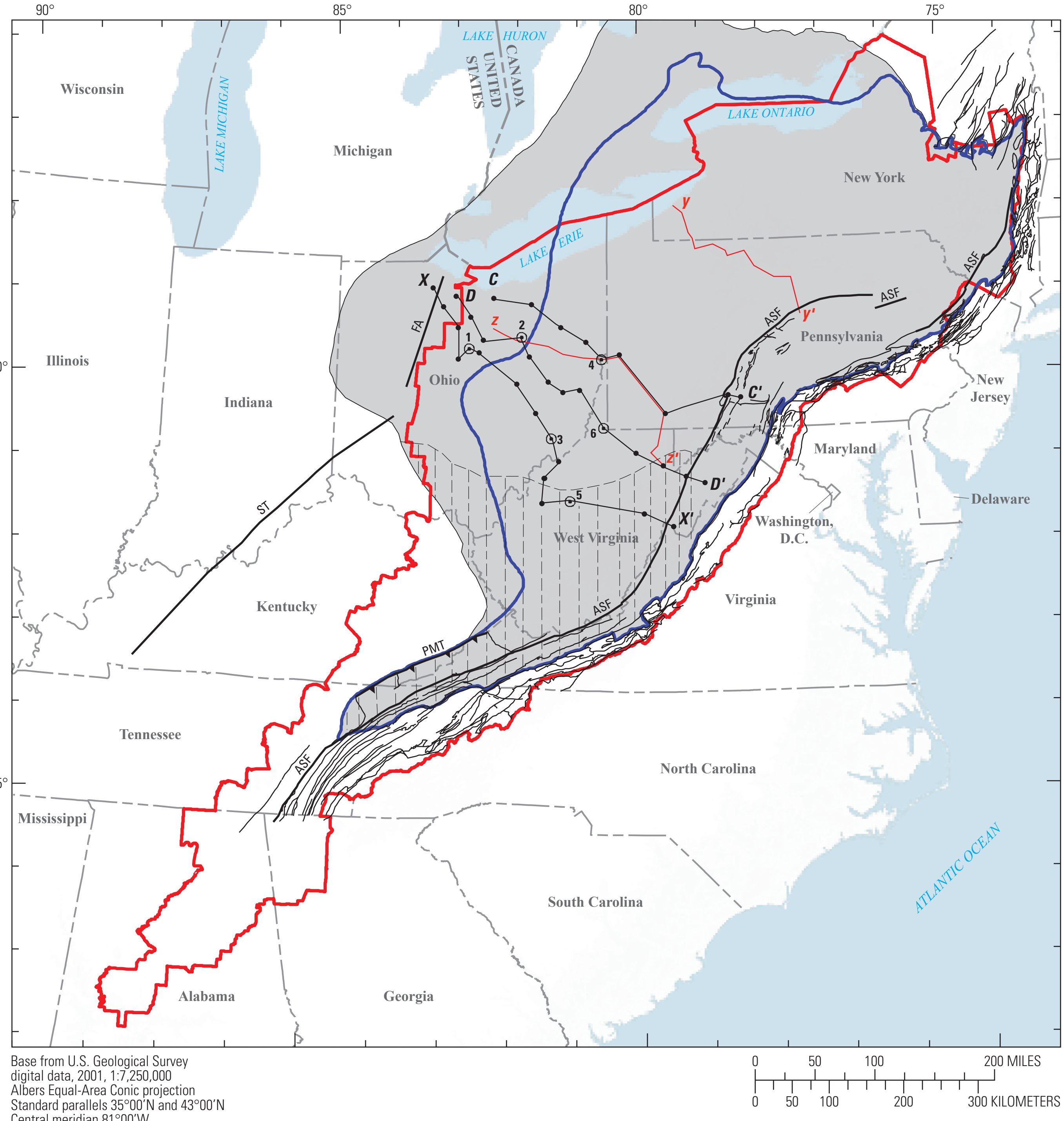


Figure 2. Continued.



EXPLANATION

- Utica-Lower Paleozoic Total Petroleum System
- Trenton Limestone Ordovician with black shale
- Boundary of Appalachian Basin Province
- Fault
- Mature Utica Shale source rock
- Major structual feature—ASF, Allegheny structural front; FA, Findlay order; PMT, Pine Mountain thrust fault; ST, Sebree trough

- *X*—*X'* Restored stratigraphic cross section showing Upper Cambrian, Ordovician, and Silurian rocks (figure 13) and location of wells
- *C*—*C'* Geologic cross section showing Cambrian, Ordovician, and Silurian rocks and location of wells
- *D*—*D'* Geologic cross section showing Upper Cambrian, Ordovician, and Silurian rocks in Utica-Lower Paleozoic TPS (figure 2) and location of wells
- *y*—*y'* Restored stratigraphic cross section showing Lower Silurian rocks (figure 14)
- *z*—*z'* Restored stratigraphic cross section showing Lower Silurian rocks (figure 14)

Drill hole with burial history model
1 No. 1 Windbigler
2 No. 1 Drake
3 No. 1 Ullman
4 No. 1 Minesinger
5 No. 1 Gainer-Lee
6 No. 1 Burley

Figure 3. Index map showing the location of the Appalachian basin, the Utica-Lower Paleozoic Total Petroleum System, and key features.

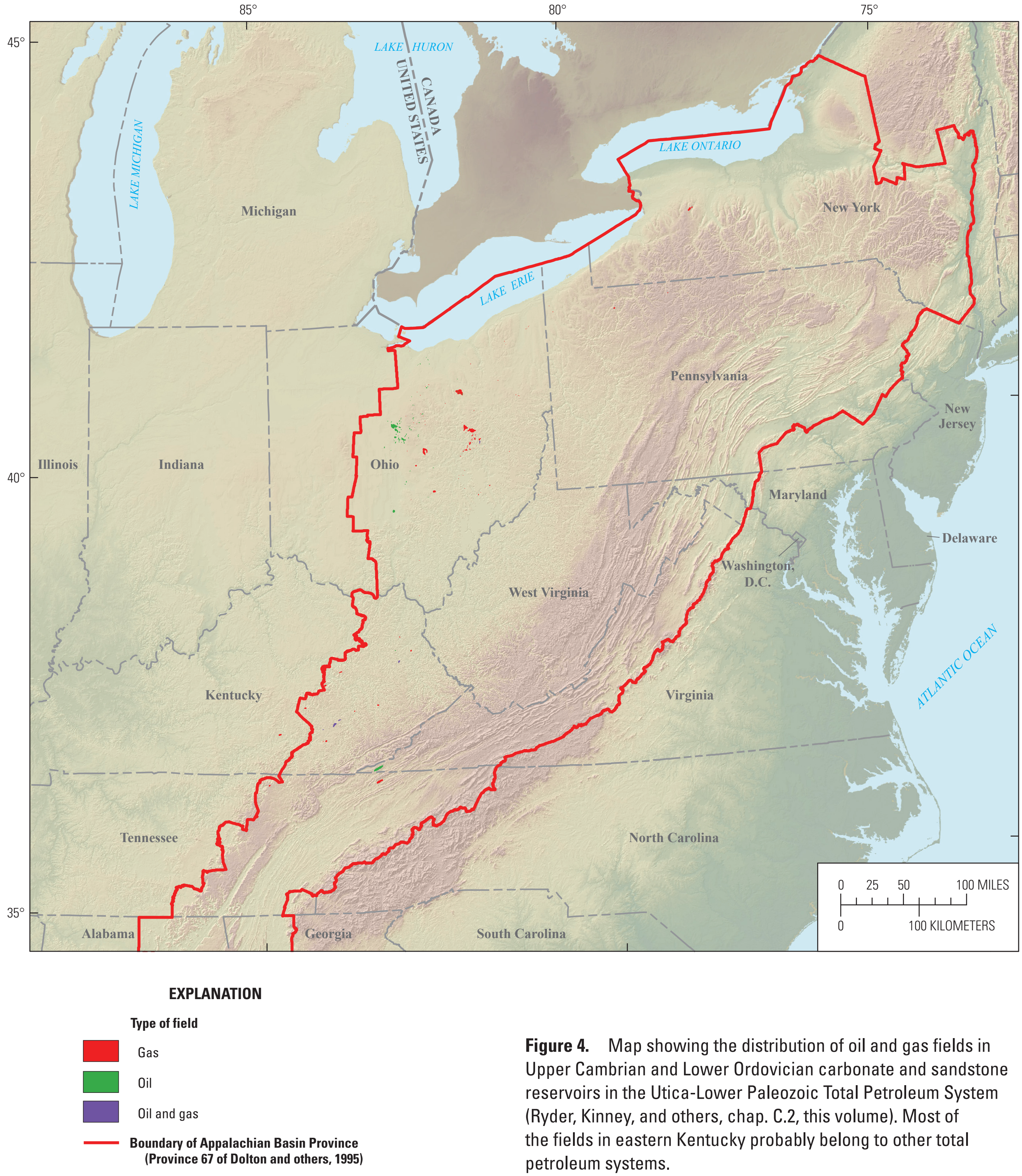


Figure 4. Map showing the distribution of oil and gas fields in Upper Cambrian and Lower Ordovician carbonate and sandstone reservoirs in the Utica-Lower Paleozoic Total Petroleum System (Ryder, Kinney, and others, chap. C.2, this volume). Most of the fields in eastern Kentucky probably belong to other total petroleum systems.

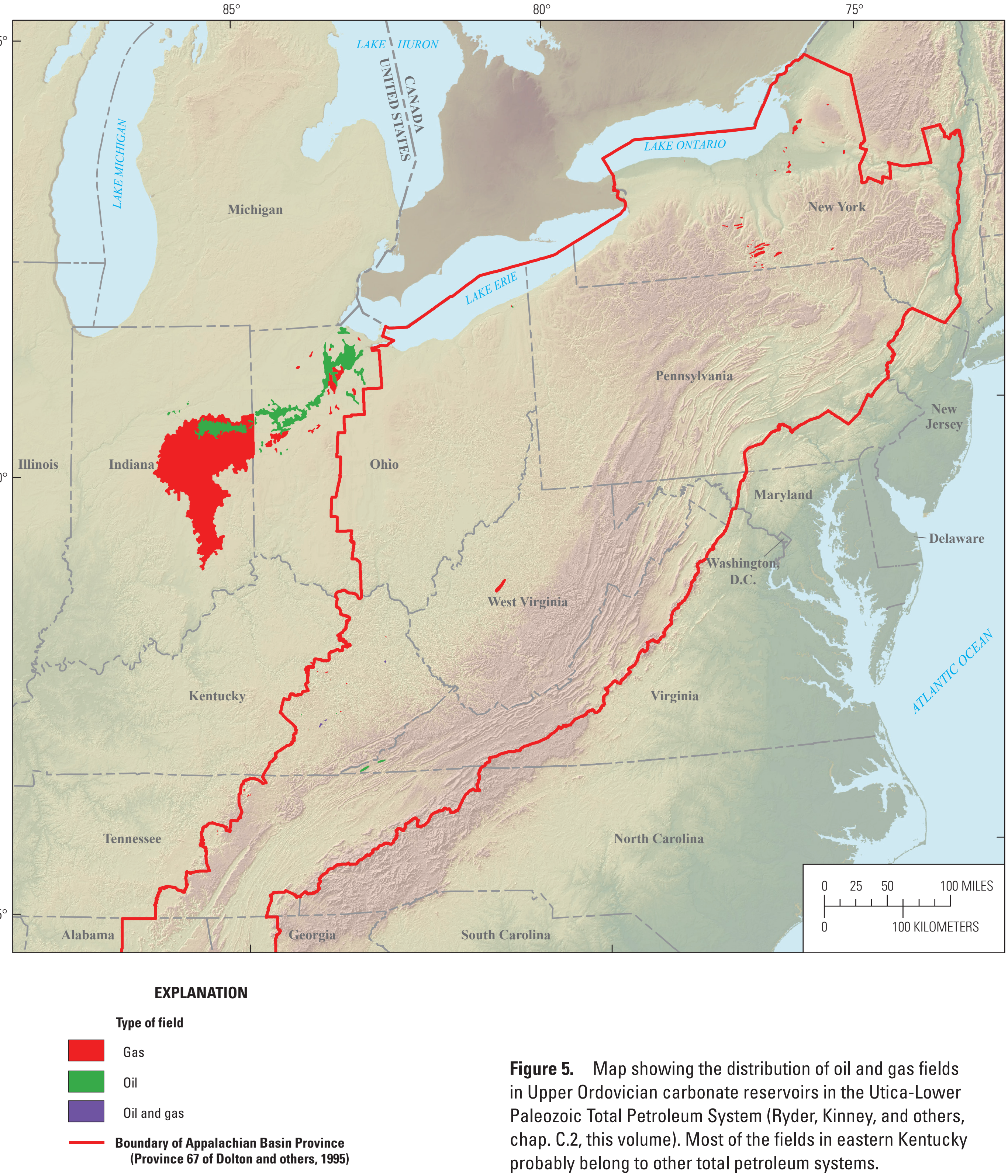


Figure 5. Map showing the distribution of oil and gas fields in Upper Ordovician carbonate reservoirs in the Utica-Lower Paleozoic Total Petroleum System (Ryder, Kinney, and others, chap. C.2, this volume). Most of the fields in eastern Kentucky probably belong to other total petroleum systems.

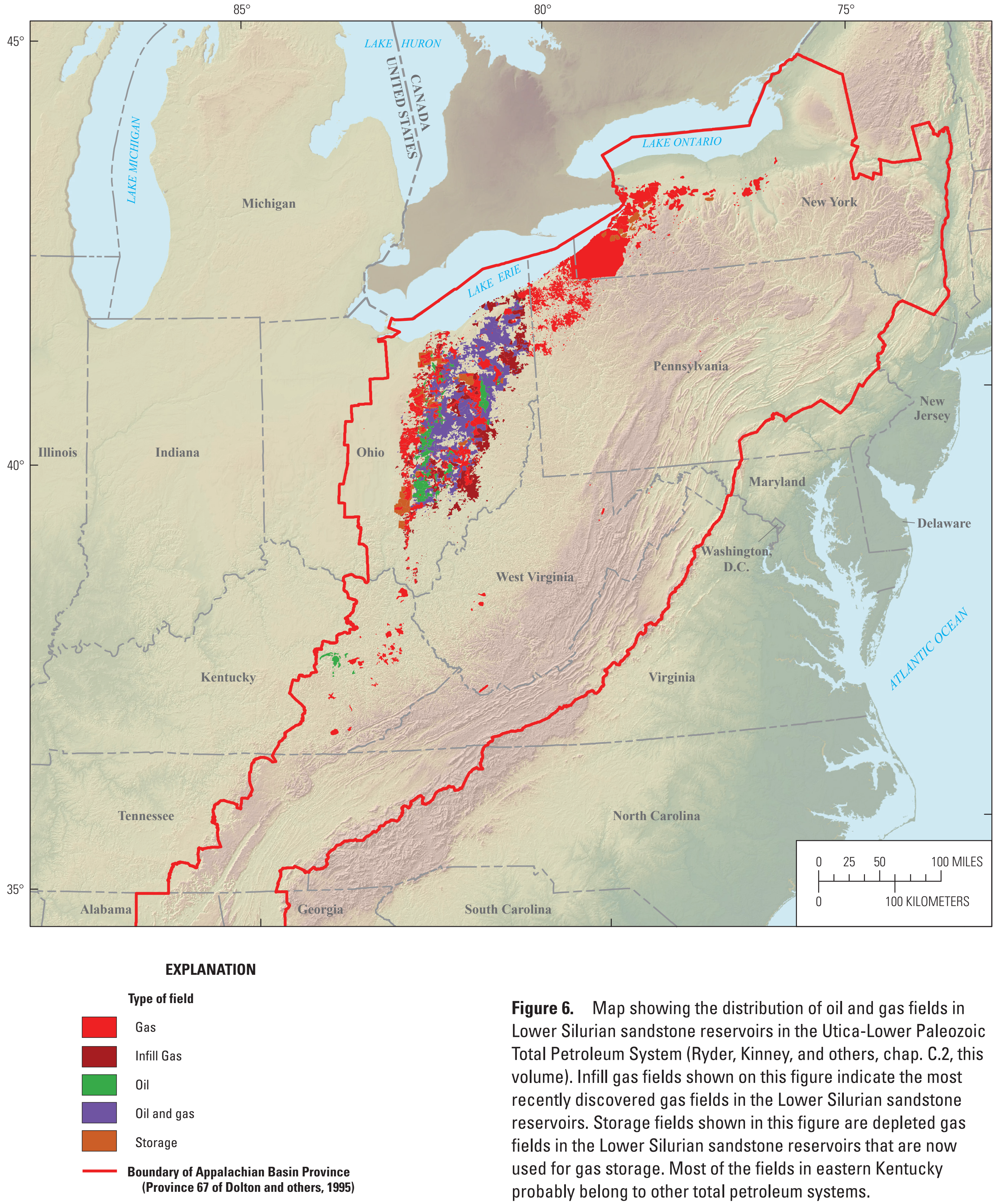


Figure 6. Map showing the distribution of oil and gas fields in Lower Silurian sandstone reservoirs in the Utica-Lower Paleozoic Total Petroleum System (Ryder, Kinney, and others, chap. C.2, this volume). Infill gas fields shown on this figure indicate the most recently discovered gas fields in the Lower Silurian sandstone reservoirs. Storage fields shown in this figure are depleted gas fields in the Lower Silurian sandstone reservoirs that are now used for gas storage. Most of the fields in eastern Kentucky probably belong to other total petroleum systems.

EXPLANATION

Type of field

- Gas
- Oil
- Storage
- **Boundary of Appalachian Basin Province (Province 67 of Dolton and others, 1995)**

Figure 7. Map showing the distribution of oil and gas fields in Lower and Upper Silurian carbonate and sandstone reservoirs in the Utica-Lower Paleozoic Total Petroleum System (Ryder, Kinney, and others, chap. C.2, this volume). Storage fields shown on this figure are depleted gas fields in Lower and Upper carbonate and sandstone reservoirs that are now used for gas storage. Most of the fields in eastern Kentucky probably belong to other total petroleum systems.

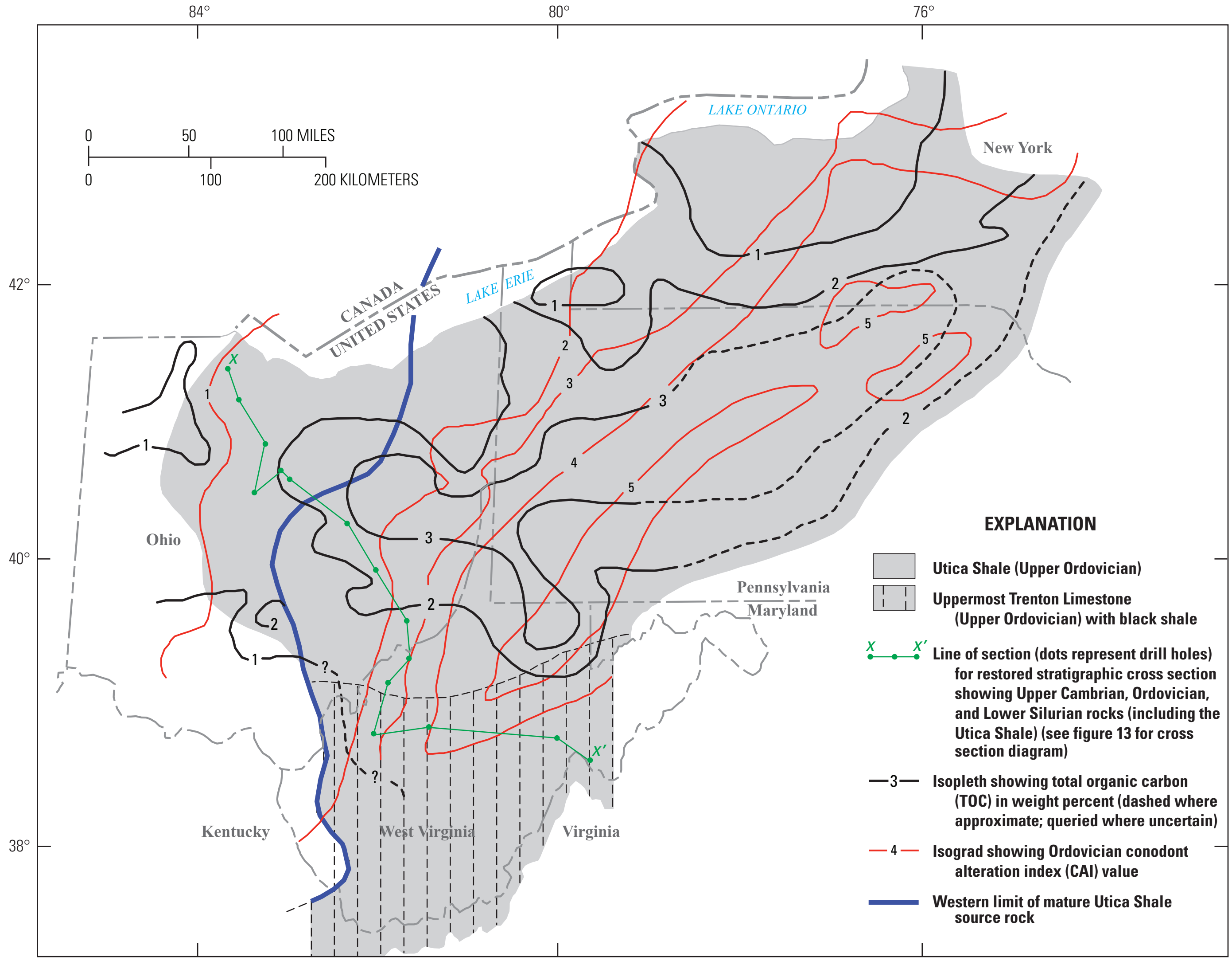


Figure 8. Map showing the distribution of the Utica Shale and equivalent thin black shale beds in the uppermost Trenton Limestone. Also shown are the distribution of total organic carbon (TOC) content (in weight percent) in the Utica Shale (Ryder and others, 1998) and the Ordovician conodont color-alteration index (CAI) isograds (Repetski and others, 2008).

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, West Virginia, and westernmost Maryland (fig. 8). Although the Utica Shale is not recognized in central and southern West Virginia and southwestern Virginia, these areas have 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 (where the unit is known 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 exist, the ranges in thickness 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 for the Utica Shale are usually greater than 1 weight percent. TOC values ranging from 2 to 3 weight percent 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 (organic facies B and BC of Jones, 1987) (Ryder and others, 1998), which is 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, which are based on samples from the Upper Ordovician Trenton Limestone (or Group) (Repetski and others, 2008), indicate that a pod of mature Utica Shale 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 studies of 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 suggest 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 n-C_{11} and n-C_{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 that the Trenton Limestone was the most likely source rock for the oils in Cambrian and Ordovician reservoirs in Ontario. On a regional basis, the Utica Shale is considered in this report to be the primary source rock, 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. 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, this volume, chap. G.11); however, any significant contribution from these source rocks to the Utica-Lower Paleozoic TPS is considered to be unlikely because 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 Silurian evaporite unit (fig. 2). This 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. Geochemical evidence in the Michigan basin, however, indicates that 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 entered the gas-generation window between Middle Mississippian and Early Permian time. For example, in northern West Virginia in the Humble No. 1 Minesinger well, where the top of the Utica Shale is at 8,650 ft, and in the Exxon No. 1 Gainer-Lee well, where the top of the Utica is at 10,600 ft (figs. 3, 9, 10), the Utica Shale entered the oil-generation window in Late Devonian time (approximately 375 million years ago (Ma)) and entered the gas-generation window in Early Permian time (approximately 280 Ma). Also in northern West Virginia, in the Occidental No. 1 Burley well, where the top of the Utica is at 12,650 ft (figs. 3, 11), the Utica entered the oil-generation window in Late Devonian time (approximately 385 Ma), but entered the gas-generation window in Middle Mississippian time (approximately 330 Ma). By comparison in eastern Ohio, in the Amerada No. 1 Ullman well, where the top of the Utica is at 8,200 ft, and in the Great Lakes No. 1 Drake well, where the top of the Utica is at 4,700 ft, (figs. 3, 10, 11), the Utica entered the oil-generation window in Late Devonian time (approximately 360 Ma) and Late Pennsylvanian time (approximately 300 Ma), respectively; however, in both wells, the Utica was not sufficiently buried to enter the gas-generation window. In central Ohio, the burial and thermal history model of the Pan American No. 1 Windbigler well, where the top of the Utica is at 3,010 ft, suggested that little or no oil and gas was generated from the Utica 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 (caused by recurrent tectonism) of the Cambrian and Ordovician strata may have been a convenient mechanism to transport Utica Shale-derived oil and gas from a downdip location in the basin, across underlying strata, and into older reservoirs (fig. 12). Secondary migration may have occurred in places, particularly where the initially trapped oil was converted to gas during episodes of deeper burial and tectonic readjustment.

In northwestern Ohio and parts of central Ohio, the Utica Shale source rock is probably immature with respect to oil and gas generation (fig. 3). Thus, oil and gas fields located in lower Paleozoic reservoirs in these areas (for example, the Lima-Indiana field, fig. 12) probably migrated there from a region of higher thermal maturity where oil and (or) gas was generated from the Utica Shale.

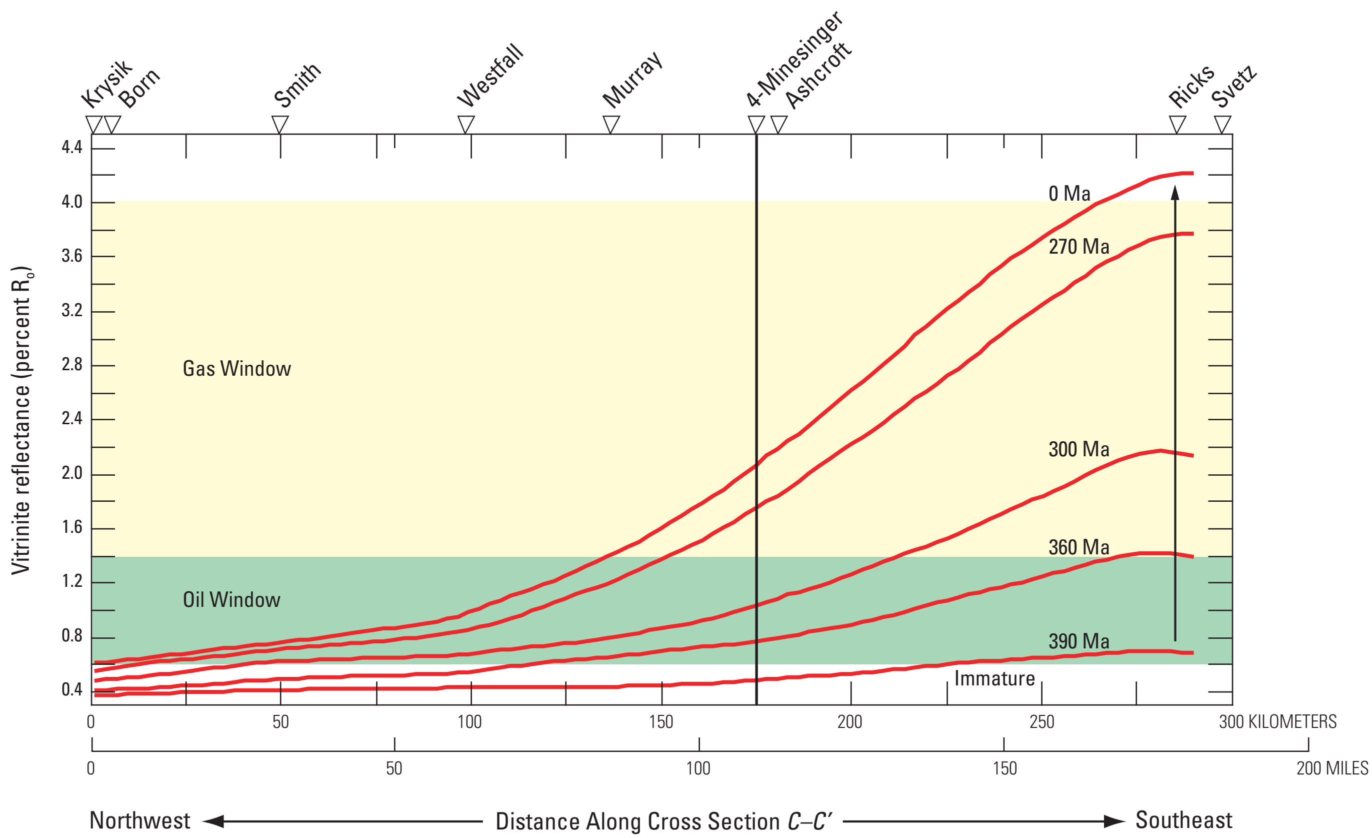


Figure 9. Chart showing the calculated thermal maturity (vitrinite reflectance, R_o, in percent) profiles for the Ordovician Utica Shale (Rowan, 2006) along geologic cross section *C–C′* (Ryder and others, 2012). The profiles were calculated for specific times (including the present (0 million years ago (Ma)), maximum burial (270 Ma), and earlier times) to show the evolution of thermal maturation through time. The approximate top of the gas window is indicated by the bottom of the yellow shaded region (R_o is 1.4 percent). The names and locations of the wells are shown along the top of the profile. See figure 3 for the location of the No. 1 Minesinger well (solid vertical line).

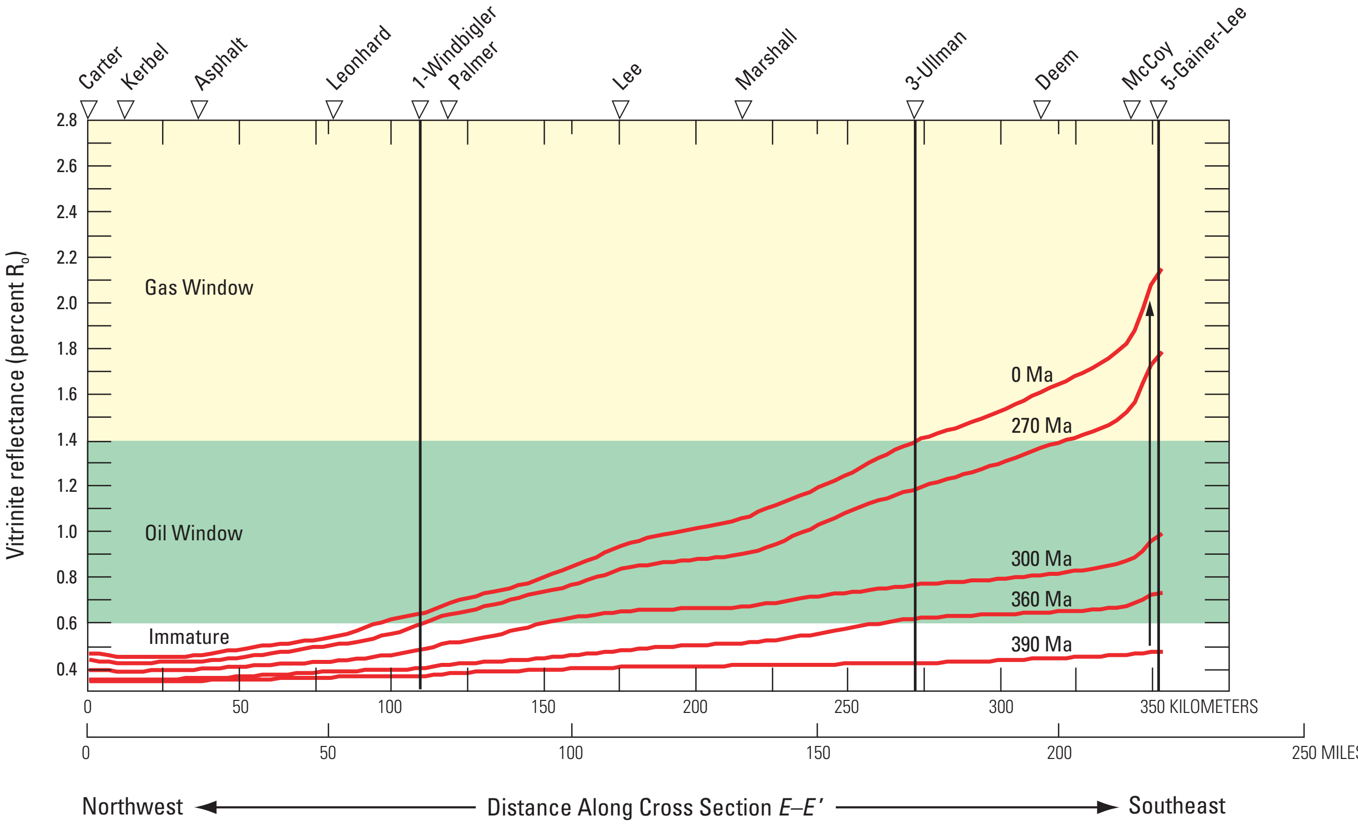


Figure 10. Chart showing the calculated thermal maturity (vitrinite reflectance, R_o, in percent) profiles for the Ordovician Utica Shale (Rowan, 2006) along geologic cross section *E–E′* (Ryder and others, 2008). The profiles were calculated for specific times (including the present (0 million years ago (Ma)), maximum burial (270 Ma), and earlier times) to show the evolution of thermal maturation through time. The approximate top of the gas window is indicated by the bottom of the yellow shaded region (R_o is 1.4 percent). Geologic cross section *E–E′* follows the same line of section as the restored stratigraphic cross section through Upper Cambrian, Ordovician, and Lower Silurian rocks shown on figures 3 and 13. The names and locations of the wells are shown along the top of the profile. See figure 3 for the locations of the No. 1 Windbigler, No. 1 Ullman, and the No. 1 Gainer-Lee wells (solid vertical lines).

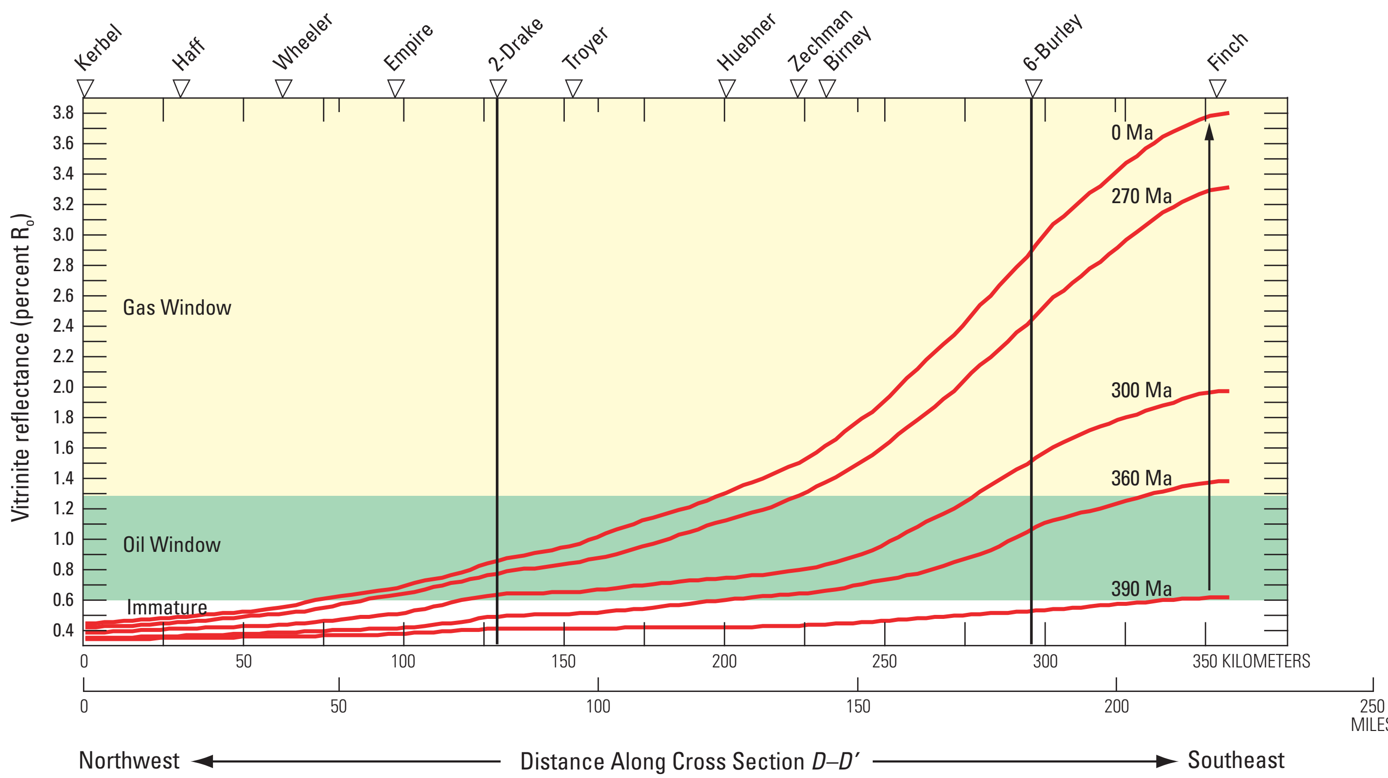


Figure 11. Chart showing the calculated thermal maturity (vitrinite reflectance, R_o, in percent) profiles for the Ordovician Utica Shale (Rowan, 2006) along geologic cross section *D–D′* (Ryder and others, 2009). The profiles were calculated for specific times (including the present (0 million years ago (Ma)), maximum burial (270 Ma), and earlier times) to show the evolution of thermal maturation through time. The approximate top of the gas window is indicated by the bottom of the yellow shaded region (R_o is 1.4 percent). The names and locations of the wells are shown along the top of the profile. See figure 3 for the location of geologic cross section *D–D′* and the No. 1 Drake and No. 1 Burley wells (solid vertical lines).

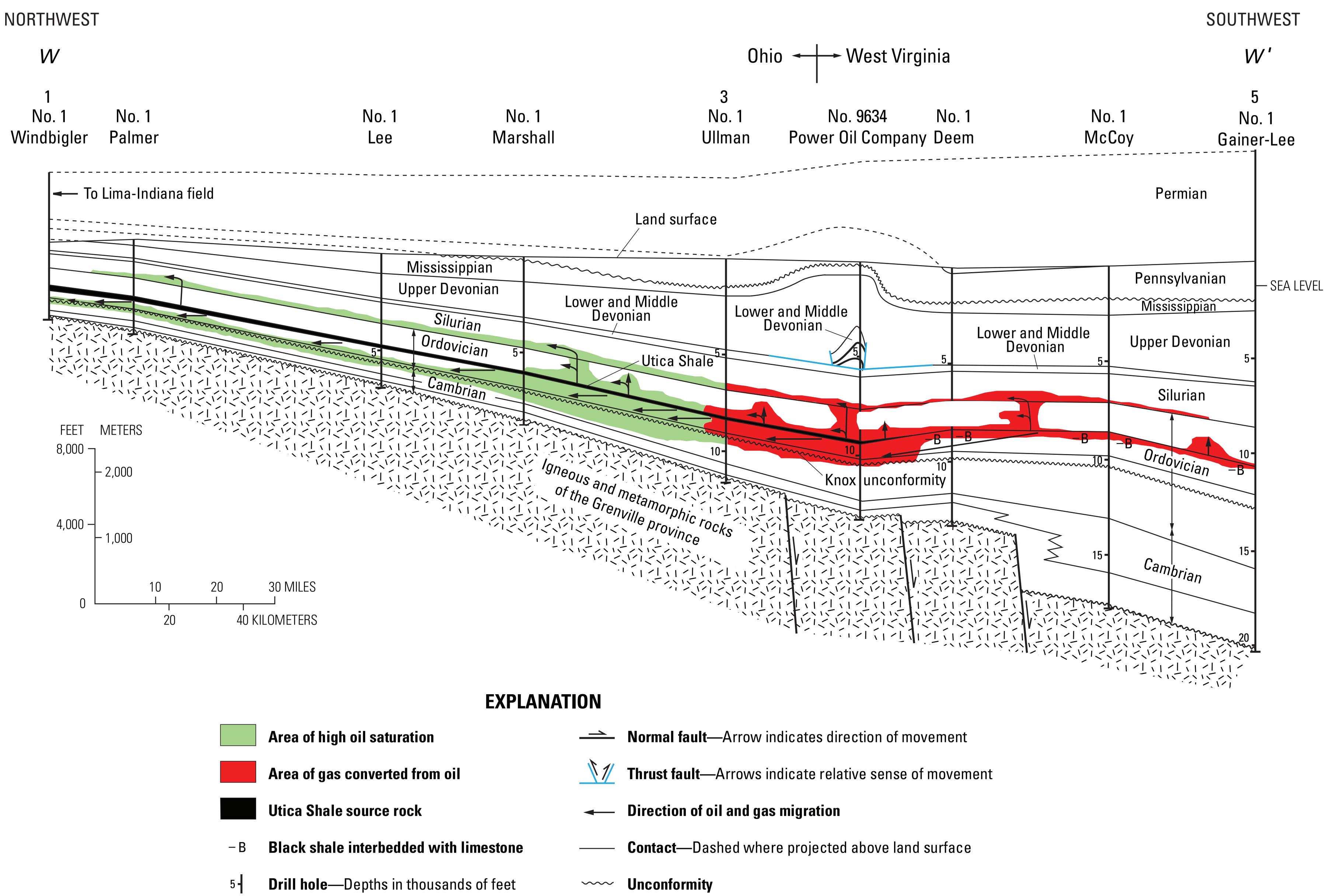


Figure 12. Generalized geologic cross section *W–W′* through the Appalachian basin from central Ohio to western West Virginia showing suggested locations of oil and gas generated from the Ordovician Utica Shale (modified from Ryder and others, 1998). This geologic cross section follows the middle part of the restored stratigraphic cross section *X–X′* through Upper Cambrian, Ordovician, and Lower Silurian rocks shown on figure 3. Cross section *W–W′* also closely follows cross section *E–E′* noted in figure 10. Drill-hole numbers refer to those shown on figure 3.

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 informally named Copper Ridge dolomite in Ohio (figs. 1, 4); the Upper Cambrian informally named Rose Run sandstone in Ohio, the informally named upper sandy member of the Gatesburg Formation in Pennsylvania, and the upper part of the formally named Galway (or Theresa) Formation in New York (figs. 1, 4); the Lower Ordovician informally named Beekmantown dolomite in Ohio, the formally named Beekmantown Group in Pennsylvania, and the upper part of the formally named Knox Group in southwestern Virginia and eastern Tennessee (figs. 1, 4); the Upper Ordovician Black River Group (or Limestone) and Trenton Limestone in Ohio, New York, Pennsylvania, West Virginia, and southwestern Virginia (figs. 1, 5); the Lower Silurian Tuscarora Sandstone (or Formation) in Pennsylvania and West Virginia, the informally named "Clinton" sandstone[2] and Medina sandstone in Ohio, and the Medina Group in New York (figs. 1, 6); and the Lower and Upper Silurian Lockport Dolomite (also known as the Newburg zone) in Ohio and Pennsylvania and the Lockport Group in New York (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 of Pennsylvania (fig. 1) (Laughrey and Harper, 1996) and the Upper Silurian Williamsport Sandstone (also known as the informal Newburg sandstone) of West Virginia (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 only identified as a hypothetical reservoir and was not 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 of the Knox Dolomite in Ohio

Oil and gas accumulations in the Copper Ridge dolomite, Rose Run sandstone, and Beekmantown dolomite reservoirs in Ohio commonly are associated with the overlying Knox unconformity (figs. 1, 13). 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 0 to 11 percent and average 5.9 percent (Riley and others, 1993). Fractures are observed rarely in the Rose Run sandstone, but they are suspected to be present on the basis of production characteristics (Riley and others, 2002).

Black River Limestone (or Group) and Trenton Limestone

The Black River Limestone in West Virginia and the Black River Group in Ohio, Pennsylvania, and New York consist of carbonate mudstone and wackestone. 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 Limestone (or Group) and Trenton Limestone of south-central New York, northwestern Ohio, and northeastern Ohio consists of medium to coarsely crystalline hydrothermal dolomite. The hydrothermal dolomite reservoirs in the Black River Limestone (or Group) and Trenton Limestone commonly are narrow and linear in plan view (fig. 5) because hot ascending

[2]The "Clinton" sandstone in Ohio was miscorrelated by drillers with strata in the type Clinton Group of New York when in fact it is equivalent to the underlying type Medina Group of New York. Although this miscorrelation has caused confusion in nomenclature, the term continues to be widely used in the literature and by the oil and gas industry. Early drillers correctly identified the Medina sandstone in Ohio as a partial equivalent of the type Medina Group of New York.

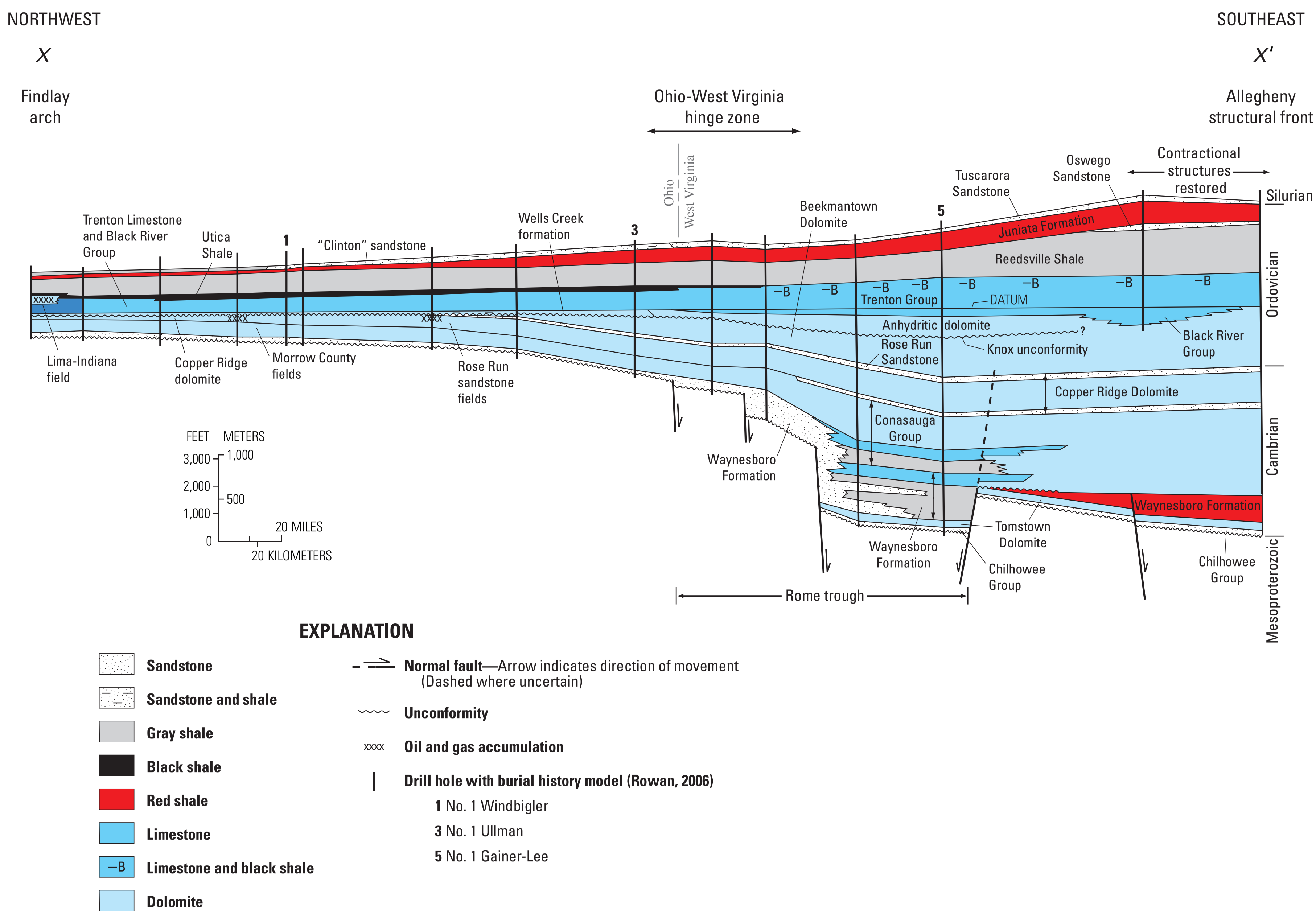


Figure 13. Restored stratigraphic cross section from northwestern Ohio to eastern West Virginia, showing Upper Cambrian, Ordovician, and Lower Silurian rocks (modified from Ryder and others, 1998). Also shown are the stratigraphic positions of selected oil and gas fields and the Ordovician Utica Shale source rock. The line of section is located on figures 3 and 8.

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, 2004; 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) and in the Trenton Limestone in the thrust belt in southwestern Virginia (Bartlett, 1988).

The hydrothermal dolomite reservoirs are characterized by vuggy, intercrystalline, and fracture porosity (Wickstrom and Gray, 1988; Laughrey and Kostelnik, 2006a; Sagan and Hart, 2006; Smith, 2006). 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 pressure gradients of the Black River and Trenton reservoirs in New York are abnormally low, with values typically less than 0.43 pounds per square inch per foot (psi/ft) (Nyahay and others, 2006).

“Clinton” Sandstone, Medina Sandstone, Medina Group Sandstones, and Tuscarora Sandstone

The sandstone reservoirs in the “Clinton” sandstone, Medina sandstone, Medina Group, and Tuscarora Sandstone 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” through Medina sandstone interval in Ohio and the Medina Group interval in Pennsylvania and New York range in thickness from about 100 to 200 ft and contain some siltstone and shale interbeds, whereas the Tuscarora Sandstone interval in Pennsylvania and West Virginia ranges in thickness from about 500 to 700 ft (fig. 14). Moreover, the Tuscarora Sandstone has a greater percentage of 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 (which 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 millidarcies) and porosity (3 to 10 percent), whereas the sandstone reservoirs in the hybrid-conventional part of the accumulation have higher permeability (greater than 0.1 millidarcies) and porosity (5 to 15 percent) (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. There are a growing number of examples, however, 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, which is the result of 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).

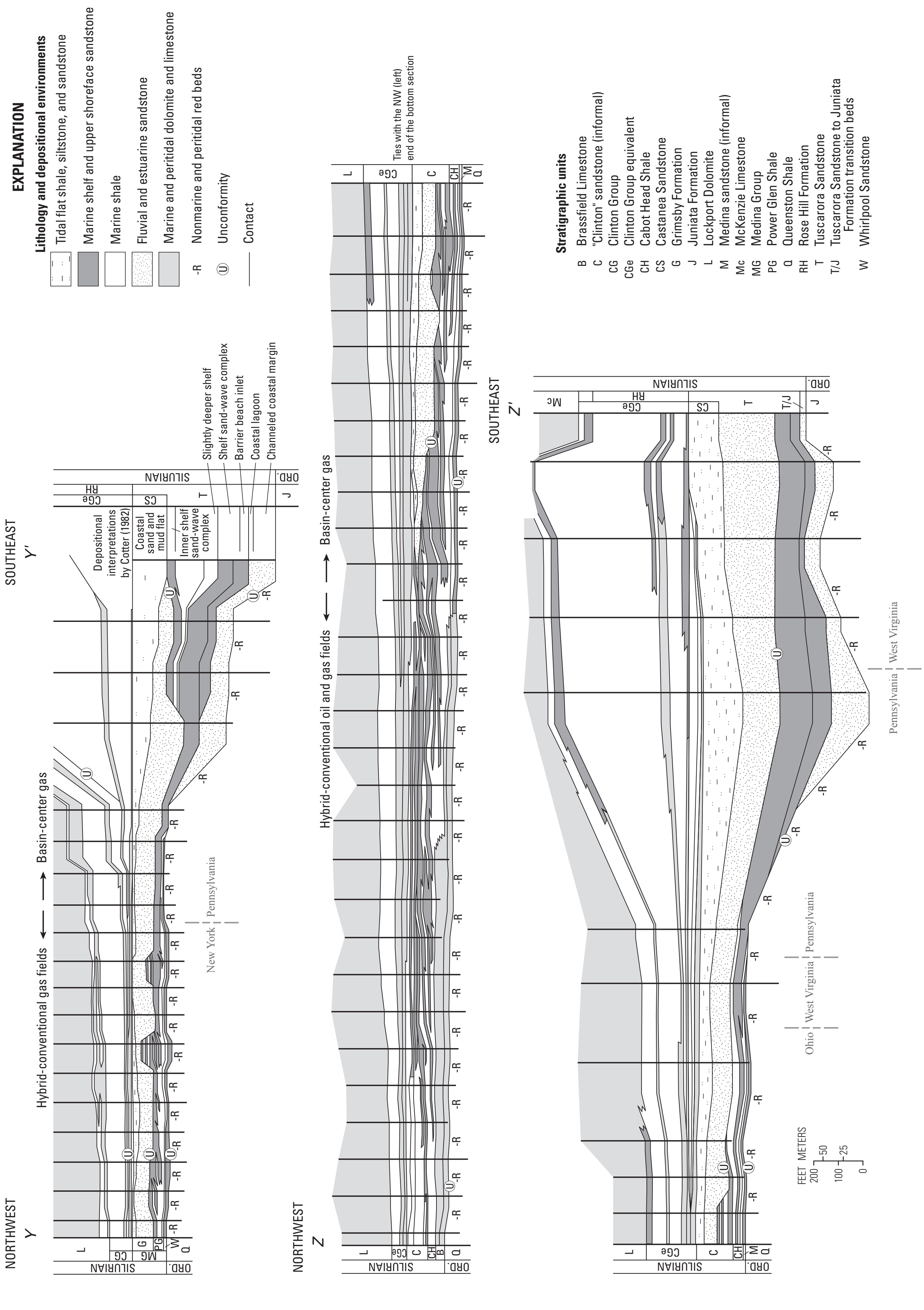
Most of the “Clinton” sandstone-Medina sandstone-Medina Group sandstone reservoirs are underpressured with pressure gradients ranging from about 0.25 to 0.42 psi/ft (Ryder and Zagorski, 2003). The Tuscarora Sandstone reservoir pressure gradients, however, are variable and range from normal (hydrostatic), 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 coproduced 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 typically are fine-grained quartz arenites with permeability that averages 0.20 millidarcies and porosity that averages 3 to 4 percent (Saroff, 1987; Ward, 1988).

Lockport Dolomite (Newburg zone) or Lockport Group

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; commonly, however, the reservoirs cap the bioherms rather than 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. By contrast, many of the gas fields in the Upper Silurian Guelph Formation


EXPLANATION
Lithology and depositional environments
Tidal flat shale, siltstone, and sandstone
Marine shelf and upper shoreface sandstone
Marine shale
Fluvial and estuarine sandstone
Marine and peritidal dolomite and limestone
-R Nonmarine and peritidal red beds
U Unconformity
Contact
Stratigraphic units
B Brassfield Limestone
C "Clinton" sandstone (informal)
CG Clinton Group
CGe Clinton Group equivalent
CH Cabot Head Shale
CS Castanea Sandstone
G Grimsby Formation
J Juniata Formation
L Lockport Dolomite
M Medina sandstone (informal)
Mc McKenzie Limestone
MG Medina Group
PG Power Glen Shale
Q Queenston Shale
RH Rose Hill Formation
T Tuscarora Sandstone
T/J Tuscarora Sandstone to Juniata Formation transition beds
W Whirlpool Sandstone
NORTHWEST
Y
SOUTHEAST
Y′
Hybrid-conventional gas fields
Basin-center gas
New York
Pennsylvania
Depositional interpretations by Cotter (1982)
Coastal sand and mud flat
Inner shelf sand-wave complex
Slightly deeper shelf
Shelf sand-wave complex
Barrier beach inlet
Coastal lagoon
Channeled coastal margin
SILURIAN
ORD.
NORTHWEST
Z
Hybrid-conventional oil and gas fields
Basin-center gas
Ties with the NW (left) end of the bottom section
SOUTHEAST
Z′
Ohio
West Virginia
Pennsylvania
FEET METERS
200 50
100 25
0

of the Lockport Group in southern Ontario, Canada, appear to produce directly from biohermal reservoirs whose depositional origin is interpreted as main or barrier reefs (Bailey, 1986). Similar reservoir conditions also may occur in the upper part of the Lockport Dolomite (or Group) in the United States, which is equivalent to the Guelph Formation.

The Lockport Dolomite reservoir commonly is characterized by 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 pressure gradients in the Newburg zone are abnormally low (Noger and others, 1996).

Utica Shale

The Utica Shale consists of black, thinly laminated, commonly calcareous shale that is rich in organic matter. The Utica Shale of the St. Lawrence Lowlands of Quebec, Canada, contains black shale reservoirs (Aguilera, 1978); therefore, a hypothetical Utica Shale reservoir is proposed in this report for the U.S. part of the Appalachian basin. The Utica Shale reservoirs in Quebec are self-sourced and fractured, have porous zones that range in thickness from 50 to 90 ft, and have water saturations that approach 0. Furthermore, fracture porosity for the Utica Shale reservoir in Quebec averages 1.4 percent, and the reservoir pressure gradient is generally normal (Aguilera, 1978). Natural fractures have been observed in outcrops and in cores 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, and Beekmantown dolomite in Ohio), paleotopographic or buried hills traps (Copper Ridge dolomite, Rose Run sandstone, and Beekmantown dolomite in Ohio), carbonate bioherm traps (Newburg zone in Ohio or Lockport Group in New York), sedimentary-facies pinchouts ("Clinton" sandstone in Ohio), and diagenetic-facies traps (hydrothermal dolomite of the Trenton Limestone and Black River Limestone (or Group) in West Virginia, New York, and Ohio; and the "Clinton" and Medina sandstones in Ohio). Structural traps in the TPS are characterized by low-amplitude anticlines such as in southwestern Virginia (Bartlett, 1988); they also may include structural terraces, faulted anticlines, and faults in other parts of the basin. Commonly, the anticlinal traps in the Tuscarora Sandstone are associated with natural fractures (Avary, 1996). 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).

Figure 14 (facing page). Stratigraphic framework and depositional sequences in Lower Silurian and adjoining strata in parts of New York, Ohio, Pennsylvania, and West Virginia (Ryder and Zagorski, 2003). See figure 3 for the locations of the sections (shown as red lines). The New York-Pennsylvania section (top) is from Hettinger (2001) and the Ohio-Pennsylvania-West Virginia section (middle and bottom) is from Ryder (2004). ORD., Ordovician.

Seals

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

Assessment Units

An assessment unit (AU) is a mappable volume of rock within the TPS that encompasses discovered and undiscovered fields that share similar geologic traits and socioeconomic factors (Klett and others, 2000). As used in this report, an AU is analogous to the term "play" as used 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 assessment methodology has been applied to each of these resource types. For the assessment of conventional resources, a field-size methodology is used, whereby estimated sizes and numbers of undiscovered fields are based on the distribution of sizes and the discovery history of known fields in a given AU (play) (Houghton and others, 1993; Gautier and Dolton, 1995). Also, the conventional-resource 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). By contrast, for the assessment of continuous resources, a cell-based methodology is used, whereby the total resource is estimated from (1) the number of undrilled cells within and adjoining a designated continuous accumulation, (2) the size of each undrilled cell (the optimum drainage area for a single well), and (3) the estimated ultimate recovery (EUR) of a 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 That Contain Conventional Oil and Gas Resources

Lower Paleozoic Carbonates in Thrust Belt Assessment Unit

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 upper part of the Knox Group and the Trenton Limestone in southwestern Virginia and western Tennessee and equivalent strata in the thrust belt of central and northern Virginia, West Virginia, and Pennsylvania. Several small oil and gas fields are present in the assessment unit 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 southwestern Virginia that produce from the Trenton Limestone is about 0.30 million barrels of oil (MMBO); each oil field produces negligible amounts of gas. In nearby eastern Tennessee, however, the ultimate size of the gas field with associated oil 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). The distribution of estimated sizes of undiscovered gas fields in the Lower Paleozoic Carbonates in Thrust Belt AU is based on the sizes of similar gas fields in the analogous thrust belt of the western United States and ranges from a 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 is 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

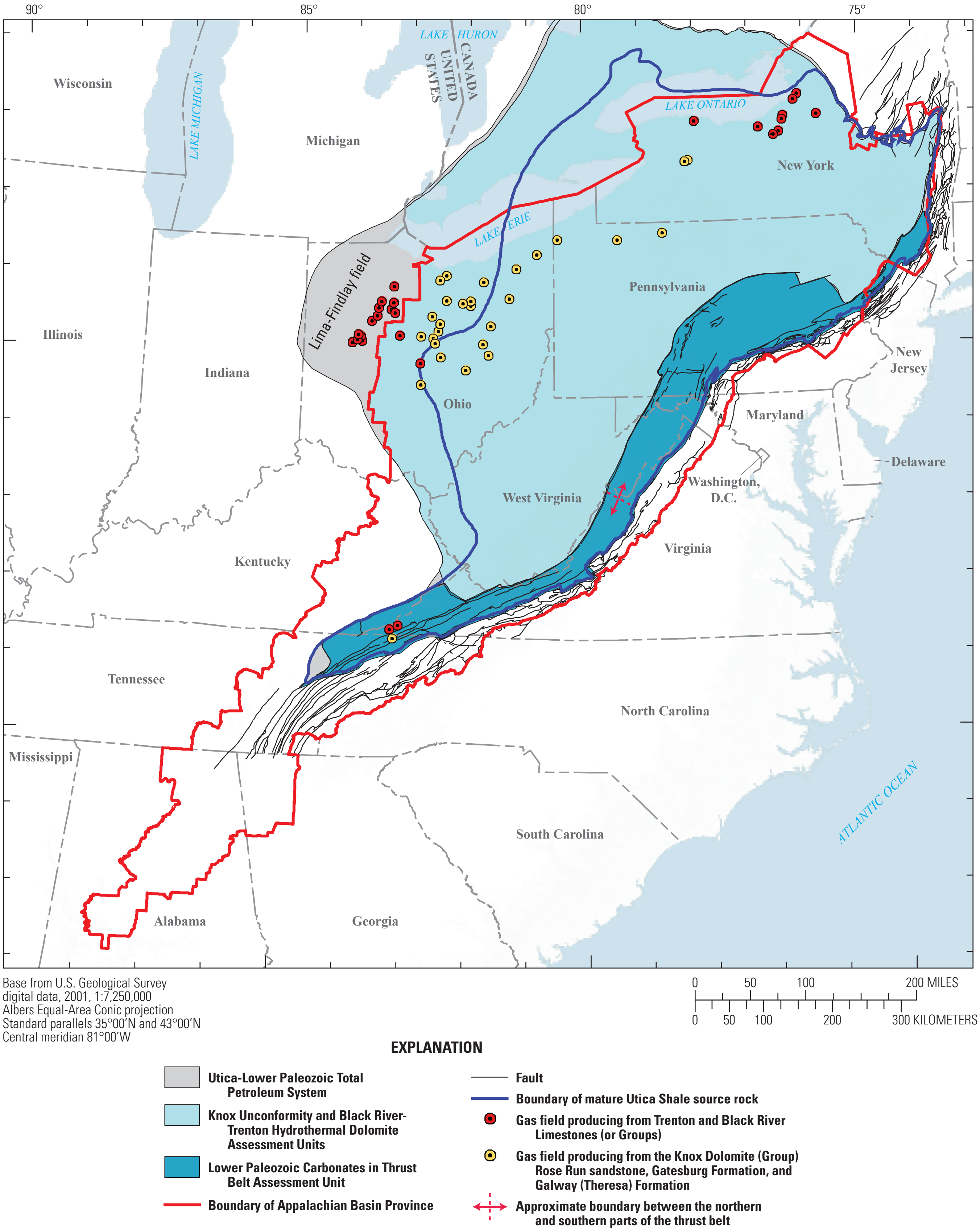
The undiscovered, technically recoverable gas resource in the Lower Paleozoic Carbonates in Thrust Belt AU is estimated (at a mean value) to be 301.90 BCFG (table 1). Natural gas liquids associated with the gas resource are estimated (at a mean value) to be 3.02 million barrels of natural gas liquids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

Knox Unconformity Assessment Unit

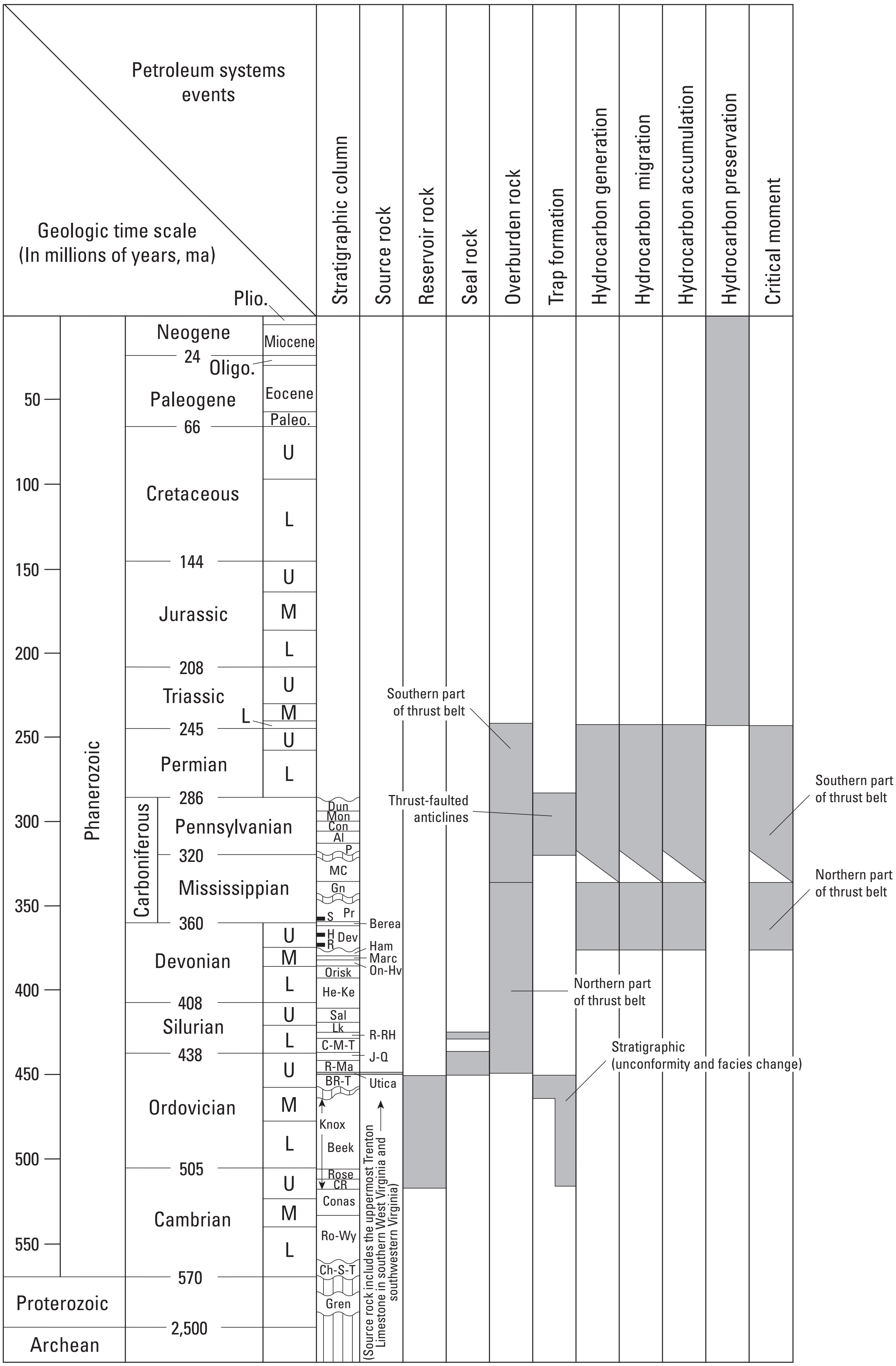
Description

The Knox Unconformity AU covers most of the Utica-Lower Paleozoic TPS, including the area where the Utica Shale source rock probably is immature with respect to oil and (or) gas generation (fig. 15). Oil and gas trapped in buried hills, truncation traps, and stratigraphic pinchouts beneath the Knox unconformity constitute the primary resource. The major reservoir units in this assessment unit are the Copper Ridge dolomite, the Beekmantown dolomite, and the Rose Run sandstone in central and eastern Ohio; however, this assessment unit also includes several small gas fields in the upper sandy member of the Gatesburg Formation in northwestern Pennsylvania and the upper part of the Galway (or Theresa) Formation in western New York (figs. 4, 15). A geologic events chart summarizing the key events for the Knox Unconformity AU is shown in figure 17.

Figure 15 (facing page). Map of the Appalachian Basin Province showing the Utica-Lower Paleozoic Total Petroleum System and the accompanying Lower Paleozoic Carbonates in Thrust Belt, Knox Unconformity, and Black River-Trenton Hydrothermal Dolomite Assessment Units (Milici and others, 2004). Also shown are selected gas fields that produce from the Knox Dolomite (Group), Rose Run sandstone in Ohio, upper sandy member of the Gatebsurg Formation in Pennsylvania, Galway (Theresa) Formation in New York, and the Black River and Trenton Limestones (or Groups) (Roen and Walker, 1996).



90°
85°
80°
75°
40°
35°
LAKE HURON
CANADA
UNITED STATES
LAKE MICHIGAN
LAKE ONTARIO
LAKE ERIE
Wisconsin
Michigan
New York
Lima-Findlay field
Pennsylvania
Illinois
Indiana
Ohio
New Jersey
Maryland
Delaware
Washington, D.C.
West Virginia
Virginia
Kentucky
Tennessee
North Carolina
Mississippi
South Carolina
ATLANTIC OCEAN
Alabama
Georgia
Base from U.S. Geological Survey
digital data, 2001, 1:7,250,000
Albers Equal-Area Conic projection
Standard parallels 35°00′N and 43°00′N
Central meridian 81°00′W
0 50 100 200 MILES
0 50 100 200 300 KILOMETERS
EXPLANATION
Utica-Lower Paleozoic Total Petroleum System
Knox Unconformity and Black River-Trenton Hydrothermal Dolomite Assessment Units
Lower Paleozoic Carbonates in Thrust Belt Assessment Unit
Boundary of Appalachian Basin Province
Fault
Boundary of mature Utica Shale source rock
Gas field producing from Trenton and Black River Limestones (or Groups)
Gas field producing from the Knox Dolomite (Group) Rose Run sandstone, Gatesburg Formation, and Galway (Theresa) Formation
Approximate boundary between the northern and southern parts of the thrust belt



Petroleum systems events
Geologic time scale (In millions of years, ma)
Stratigraphic column
Source rock
Reservoir rock
Seal rock
Overburden rock
Trap formation
Hydrocarbon generation
Hydrocarbon migration
Hydrocarbon accumulation
Hydrocarbon preservation
Critical moment
50
100
150
200
250
300
350
400
450
500
550
Phanerozoic
Proterozoic
Archean
Neogene
24
Paleogene
66
Cretaceous
144
Jurassic
208
Triassic
245
Permian
286
Carboniferous
Pennsylvanian
320
Mississippian
360
Devonian
408
Silurian
438
Ordovician
505
Cambrian
570
2,500
Plio.
Miocene
Oligo.
Eocene
Paleo.
U
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Dun
Mon
Con
Al
P
MC
Gn
S
Pr
H
R
Dev
Orisk
He-Ke
Sal
Lk
C-M-T
R-Ma
BR-T
Knox
Beek
Rose
CR
Conas
Ro-Wy
Ch-S-T
Gren
Berea
Ham
Marc
On-Hv
R-RH
J-Q
Utica
(Source rock includes the uppermost Trenton Limestone in southern West Virginia and southwestern Virginia)
Southern part of thrust belt
Thrust-faulted anticlines
Northern part of thrust belt
Stratigraphic (unconformity and facies change)
Southern part of thrust belt
Northern part of thrust belt

Sizes and Numbers of Fields

Approximately 51 oil fields (39 in Copper Ridge dolomite reservoirs and 12 in Beekmantown and Rose Run sandstone 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 (Mark E. Wolfe, Ohio Department of Natural Resources, Division of Geology, unpub. data, 1995; unpublished estimates from R.T. Ryder, 2000, based on Arie Janssens, consulting geologist, unpub. data, 1993, 1998). An additional 11 oil fields have been discovered in Cambrian sandstone reservoirs in southern Ontario, Canada; these fields range in ultimate size from less than 0.1 MMBO to about 1.65 MMBO (Ontario Ministry of Natural Resources, 2001). The estimated distribution of sizes of undiscovered oil fields in the Knox Unconformity AU is based on these oil-field sizes and 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.

Figure 16 (facing page). Events chart for the Lower Paleozoic Carbonates in Thrust Belt Assessment Unit. Abbreviations for rock unit names are as follows (in approximate stratigraphic order): Gren, Grenville province basement rocks; Ch-S-T, Chilhowee Group and Shady Dolomite or Tomstown Dolomite; Ro-Wy, Rome Formation or Waynesboro Formation; Conas, Conasauga Group; CR, Copper Ridge dolomite (or Dolomite); Rose, Rose Run sandstone (or Sandstone) or upper sandy member of the Gatesburg Formation or Galway (or Theresa) Formation; Beek, Beekmantown dolomite (or Dolomite, Group); Knox, Knox Dolomite (or Group); BR-T, Black River Limestone (or Group) and Trenton Limestone; Utica, Utica Shale; R-Ma, Reedsville Shale or Martinsburg Formation; J-Q, Juniata Formation or Queenston Shale; C-M-T, "Clinton" sandstone, Medina sandstone, Medina Group, or Tuscarora Sandstone; R-RH, Rochester Shale or Rose Hill Formation; Lk, Lockport Dolomite (or Group); Sal, Salina Group; He-Ke, Helderberg Limestone and Keyser Limestone; Orisk, Oriskany Sandstone; On-Hv, Onondaga Limestone or Huntersville Chert; Marc, Marcellus Shale of the Hamilton Group; Ham, upper part of the Hamilton Group; Dev, Upper Devonian shale and sandstone; R, Rhinestreet Shale Member of the West Falls Formation; H, Huron Member of the Ohio Shale; Berea, Berea Sandstone; S, Sunbury Shale; Pr, Price Group; Gn, Greenbrier Limestone; MC, Mauch Chunk Formation; P, Pottsville Group; Al, Allegheny Group; Con, Conemaugh Group; Mon, Monongahela Group; Dun, Dunkard Group. Other abbreviations are as follows: L, Lower; M, Middle; Oligo., Oligocene; Paleo., Paleocene; Plio., Pliocene; U, Upper. The approximate location of the boundary between the southern and northern parts of the thrust belt is shown in figure 15. The time scale is modified after Magoon and Dow (1994).

By contrast, approximately 24 gas fields (2 in Copper Ridge dolomite reservoirs and 22 in Beekmantown dolomite and Rose Run sandstone 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; unpublished estimates from R.T. Ryder, 2000, based on Arie Janssens, consulting geologist, unpub. data, 1993, 1998). An additional 13 gas fields have been discovered in equivalent reservoirs in New York (3), Pennsylvania (4), and Ontario, Canada (6); these additional fields range in ultimate size from less than 1 BCFG to about 21.5 BCFG (specifically, a field located in southern Ontario) (Ontario Ministry of Natural Resources, 2001). The estimated distribution of sizes of undiscovered gas fields in the Knox Unconformity AU is based on the sizes of these gas fields and 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 ranges 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 underlie the Great Lakes (Lakes Erie and Ontario).

Black River-Trenton Hydrothermal Dolomite Assessment Unit

Description

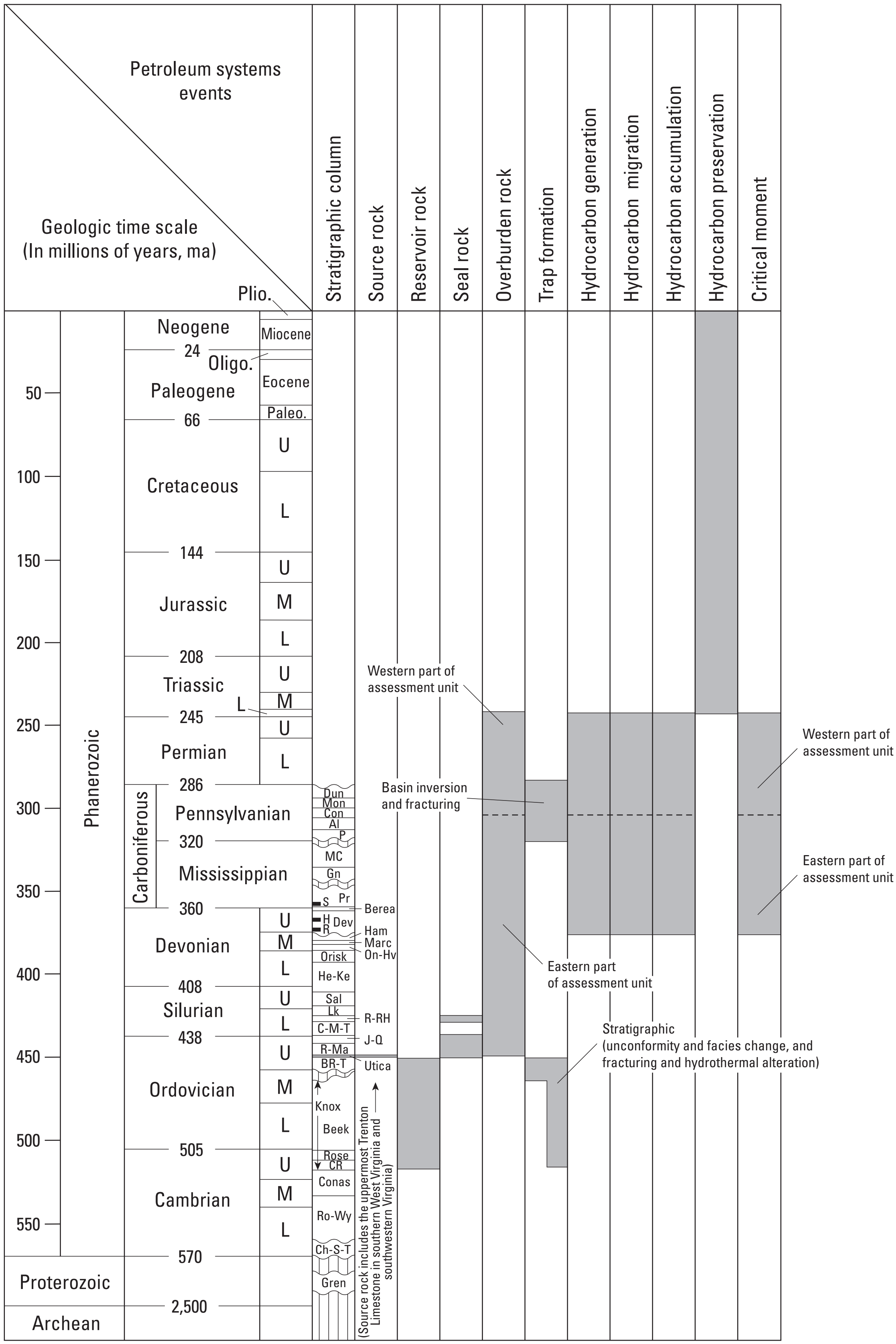
The Black River-Trenton Hydrothermal Dolomite AU covers most of the Utica-Lower Paleozoic TPS, including the area where the Utica Shale source rock is immature with respect to oil and gas generation (fig. 15). Oil and gas trapped in dolomitized and (or) fractured limestone reservoirs aligned with basement fault zones constitute the primary resource. The main reservoir in the assessment unit is the dolomitized and fractured Black River Group and Trenton Limestone. Oil and gas was produced from this reservoir in the late 1800s and early 1900s in the giant Lima-Indiana field (figs. 5, 15), which is located on the Findlay arch (fig. 1) in northwestern Ohio (Wickstrom and Gray, 1988; Wickstrom and others, 1992). More recently (late 1990s), gas was discovered in the dolomite and fractured Black River Group and Trenton Limestone reservoir in south-central New York (fig. 5) (Smith, 2006), and through 2008, about 30 to 40 fields are distributed across a six-county area (New York Division of Mineral Resources, 2008). Other discoveries in the dolomitized and fractured Black River Group and Trenton Limestone reservoirs include several small oil and gas fields in Ohio and small gas fields in West Virginia (figs. 5, 15). This assessment unit also includes fractured limestone reservoirs in the Trenton Limestone in New York where gas is produced from a group of small fields. 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 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, which has 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 (specifically, the Albion-Scipio field; Hurley and Budros, 1990). The estimated distribution of sizes of undiscovered oil fields in the Black River-Trenton Hydrothermal Dolomite AU is based on the sizes of these oil fields and 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 contrast, 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, which are 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, which are 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 (specifically, the 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, which is based on cumulative production data from Avary, 2006). The estimated distribution of sizes of undiscovered gas fields in the Black River-Trenton Hydrothermal Dolomite AU (including the fractured limestone reservoirs) is based on the sizes of these gas fields and ranges from a minimum of 3 BCFG to a maximum of 750 BCFG.

Figure 17 (facing page). Events chart for the Knox Unconformity and Black River-Trenton Hydrothermal Dolomite Assessment Units. Abbreviations for rock unit names are as follows (in approximate stratigraphic order): Gren, Grenville province basement rocks; Ch-S-T, Chilhowee Group and Shady Dolomite or Tomstown Dolomite; Ro-Wy, Rome Formation or Waynesboro Formation; Conas, Conasauga Group; CR, Copper Ridge dolomite (or Dolomite); Rose, Rose Run sandstone (or Sandstone) or upper sandy member of the Gatesburg Formation or Galway (or Theresa) Formation; Beek, Beekmantown dolomite (or Dolomite, Group); Knox, Knox Dolomite (or Group); BR-T, Black River Limestone (or Group) and Trenton Limestone; Utica, Utica Shale; R-Ma, Reedsville Shale or Martinsburg Formation; J-Q, Juniata Formation or Queenston Shale; C-M-T, "Clinton" sandstone, Medina sandstone, Medina Group, or Tuscarora Sandstone; R-RH, Rochester Shale or Rose Hill Formation; Lk, Lockport Dolomite (or Group); Sal, Salina Group; He-Ke, Helderberg Limestone and Keyser Limestone; Orisk, Oriskany Sandstone; On-Hv, Onondaga Limestone or Huntersville Chert; Marc, Marcellus Shale of the Hamilton Group; Ham, upper part of the Hamilton Group; Dev, Upper Devonian shale and sandstone; R, Rhinestreet Shale Member of the West Falls Formation; H, Huron Member of the Ohio Shale; Berea, Berea Sandstone; S, Sunbury Shale; Pr, Price Group; Gn, Greenbrier Limestone; MC, Mauch Chunk Formation; P, Pottsville Group; Al, Allegheny Group; Con, Conemaugh Group; Mon, Monongahela Group; Dun, Dunkard Group. Other abbreviations are as follows: L, Lower; M, Middle; Oligo., Oligocene; Paleo., Paleocene; Plio., Pliocene; U, Upper. The western parts of the assessment units include eastern and central Ohio, western New York, and northwestern Pennsylvania, whereas the eastern parts of the assessment units include the remainder of the area in New York, Pennsylvania, Maryland, West Virginia, and southwestern Virginia as far east as the thrust belt (fig. 16). The time scale is modified after Magoon and Dow (1994).



Petroleum systems events
Geologic time scale (In millions of years, ma)
Stratigraphic column
Source rock
Reservoir rock
Seal rock
Overburden rock
Trap formation
Hydrocarbon generation
Hydrocarbon migration
Hydrocarbon accumulation
Hydrocarbon preservation
Critical moment
Plio.
Neogene
Miocene
24
Oligo.
Paleogene
Eocene
Paleo.
66
Cretaceous
144
Jurassic
208
Triassic
245
Permian
286
Pennsylvanian
320
Mississippian
360
Carboniferous
Devonian
408
Silurian
438
Ordovician
505
Cambrian
570
Proterozoic
2,500
Archean
Phanerozoic
50
100
150
200
250
300
350
400
450
500
550
Dun
Mon
Con
Al
P
MC
Gn
S
Pr
H
R
Dev
Orisk
He-Ke
Sal
Lk
C-M-T
R-Ma
BR-T
Knox
Beek
Rose
CR
Conas
Ro-Wy
Ch-S-T
Gren
Berea
Ham
Marc
On-Hv
R-RH
J-Q
Utica
(Source rock includes the uppermost Trenton Limestone in southern West Virginia and southwestern Virginia)
Western part of assessment unit
Basin inversion and fracturing
Eastern part of assessment unit
Stratigraphic (unconformity and facies change, and fracturing and hydrothermal alteration)
Western part of assessment unit
Eastern part of assessment unit

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 underlie the Great Lakes (Lake Erie), and approximately 16 percent of the gas resource is estimated to underlie the Great Lakes (Lakes Erie and Ontario).

Lockport Dolomite Assessment Unit

Description

The Lockport Dolomite AU is located in the north-central part of the Utica-Lower Paleozoic TPS and covers much of central and eastern Ohio, northwestern Pennsylvania, and western New York, including the area in north-central Ohio where the Utica Shale source rock probably is immature with respect to oil and (or) 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 31 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, 1975, 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 (or 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 than 1 MMBO (Ontario Ministry of Natural Resources, 2001). The estimated distribution of sizes of undiscovered gas fields in the Lockport Dolomite AU is based on the sizes of these gas fields and 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. Because the Lockport Dolomite AU was assessed as a gas-producing region with negligible associated oil, the sizes of the 20 oil fields in Ontario, Canada, were omitted from the assessment process.

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 underlie the Great Lakes (Lake Erie).

Assessment Units That Contain 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 team instead of the term “hybrid-conventional,” which was 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 also is present in the Clinton-Medina Basin Center AU and the Clinton-Medina Transitional AU.

Clinton-Medina Basin Center Assessment Unit

Description

The Clinton-Medina Basin Center AU is located in the central part of the Utica-Lower Paleozoic TPS that covers most of eastern Ohio, northwestern Pennsylvania, and small

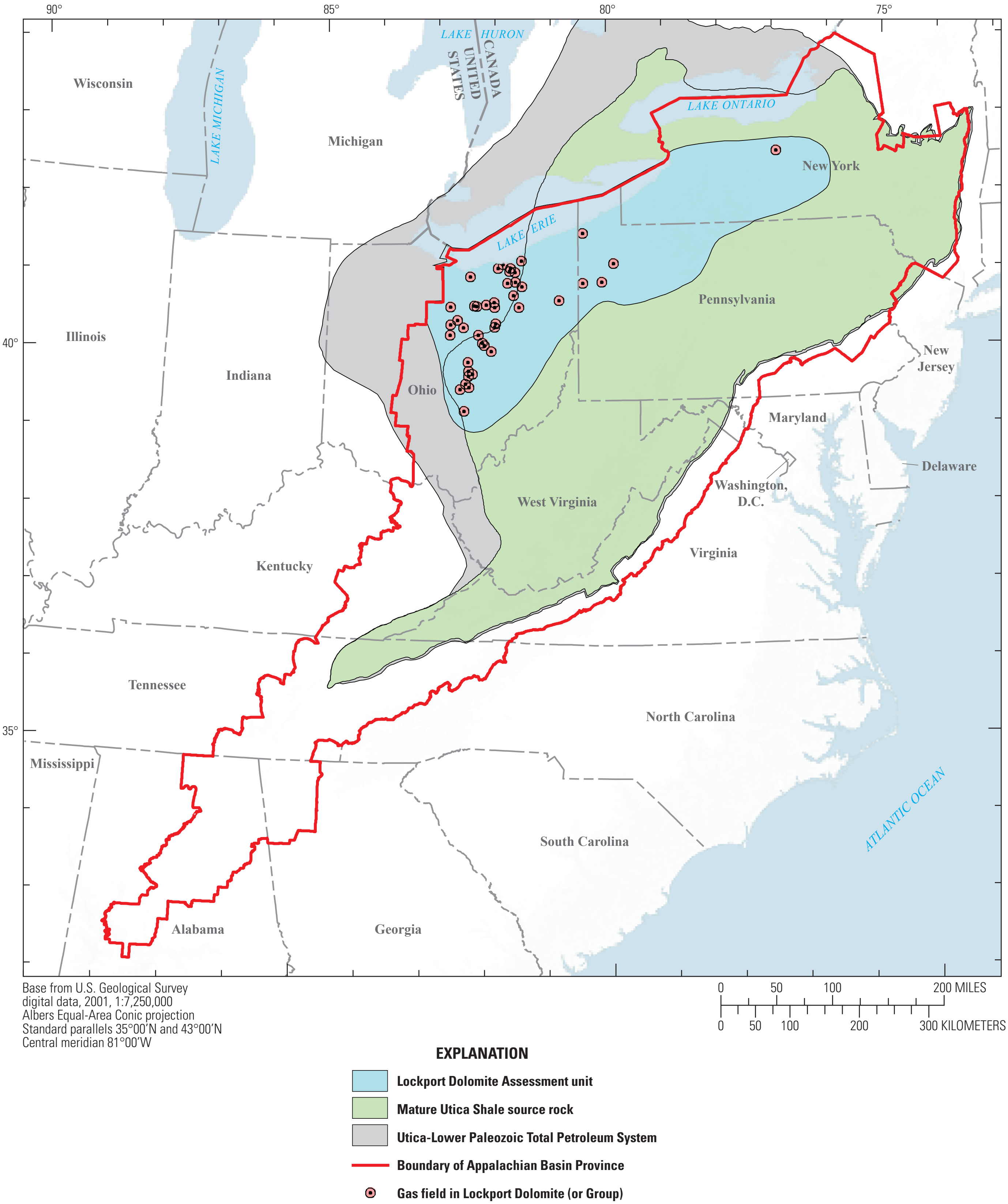
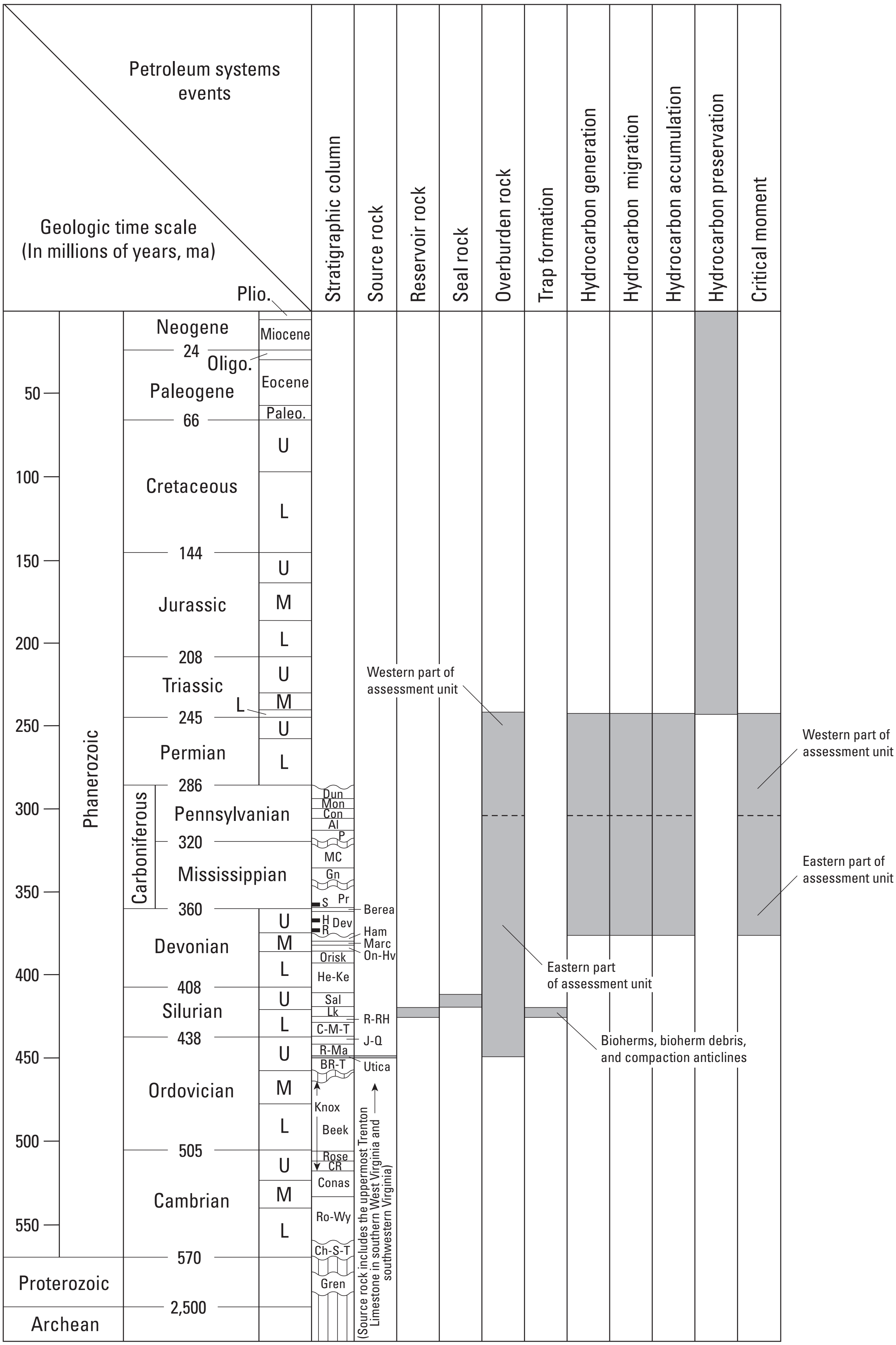


Figure 18. Map of the Appalachian Basin Province showing the Utica-Lower Paleozoic Total Petroleum System and the accompanying Lockport Dolomite Assessment Unit (Milici and others, 2004). Also shown are selected gas fields that produce from the Lockport Dolomite (or Group) (Roen and Walker, 1996).



Petroleum systems events
Geologic time scale (In millions of years, ma)
Stratigraphic column
Source rock
Reservoir rock
Seal rock
Overburden rock
Trap formation
Hydrocarbon generation
Hydrocarbon migration
Hydrocarbon accumulation
Hydrocarbon preservation
Critical moment
Plio.
Neogene
Miocene
24
Oligo.
Paleogene
Eocene
66
Paleo.
Cretaceous
U
L
144
Jurassic
U
M
L
208
Triassic
U
M
L
245
Permian
U
L
286
Carboniferous
Pennsylvanian
320
Mississippian
360
Devonian
U
M
L
408
Silurian
U
L
438
Ordovician
U
M
L
505
Cambrian
U
M
L
570
Phanerozoic
Proterozoic
2,500
Archean
50
100
150
200
250
300
350
400
450
500
550
Dun
Mon
Con
Al
P
MC
Gn
S
Pr
H
R
Dev
Orisk
He-Ke
Sal
Lk
C-M-T
R-Ma
BR-T
Knox
Beek
Rose
CR
Conas
Ro-Wy
Ch-S-T
Gren
Berea
Ham
Marc
On-Hv
R-RH
J-Q
Utica
(Source rock includes the uppermost Trenton Limestone in southern West Virginia and southwestern Virginia)
Western part of assessment unit
Eastern part of assessment unit
Bioherms, bioherm debris, and compaction anticlines
Western part of assessment unit
Eastern part of assessment unit

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 controlled largely by a change in facies that marks the approximate boundary between sandstone reservoirs of the informally named “Clinton” and Medina sandstones or the 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 pressure gradients 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” and 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” and Medina reservoirs range from about 6,500 to 8,500 ft. The presence of a small number of widely distributed gas wells and wells with gas shows indicates that large areas in the mostly undrilled eastern part of the Clinton-Medina Basin Center AU very likely could 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.

Figure 19 (facing page). Events chart for the Lockport Dolomite Assessment Unit. Abbreviations for rock unit names are as follows (in approximate stratigraphic order): Gren, Grenville province basement rocks; Ch-S-T, Chilhowee Group and Shady Dolomite or Tomstown Dolomite; Ro-Wy, Rome Formation or Waynesboro Formation; Conas, Conasauga Group; CR, Copper Ridge dolomite (or Dolomite); Rose, Rose Run sandstone (or Sandstone) or upper sandy member of the Gatesburg Formation or Galway (or Theresa) Formation; Beek, Beekmantown dolomite (or Dolomite, Group); Knox, Knox Dolomite (or Group); BR-T, Black River Limestone (or Group) and Trenton Limestone; Utica, Utica Shale; R-Ma, Reedsville Shale or Martinsburg Formation; J-Q, Juniata Formation or Queenston Shale; C-M-T, “Clinton” sandstone, Medina sandstone, Medina Group, or Tuscarora Sandstone; R-RH, Rochester Shale or Rose Hill Formation; Lk, Lockport Dolomite (or Group); Sal, Salina Group; He-Ke, Helderberg Limestone and Keyser Limestone; Orisk, Oriskany Sandstone; On-Hv, Onondaga Limestone or Huntersville Chert; Marc, Marcellus Shale of the Hamilton Group; Ham, upper part of the Hamilton Group; Dev, Upper Devonian shale and sandstone; R, Rhinestreet Shale Member of the West Falls Formation; H, Huron Member of the Ohio Shale; Berea, Berea Sandstone; S, Sunbury Shale; Pr, Price Group; Gn, Greenbrier Limestone; MC, Mauch Chunk Formation; P, Pottsville Group; Al, Allegheny Group; Con, Conemaugh Group; Mon, Monongahela Group; Dun, Dunkard Group. Other abbreviations are as follows: L, Lower; M, Middle; Oligo., Oligocene; Paleo., Paleocene; Plio., Pliocene; U, Upper. The western part of the assessment unit includes eastern and central Ohio, western New York, and northwestern Pennsylvania, whereas the eastern part of the unit includes central New York and north-central Pennsylvania (fig. 18). The time scale is modified after Magoon and Dow (1994).

Sizes of Undrilled Cells

The estimated sizes of the undrilled cells (the optimum drainage area for a single well) in the AU range from a minimum of 10 acres to a maximum of 110 acres. The median size of the 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 during the next 30 years 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. Previous drilling results indicate that the expected success ratio for new wells may be as high as 91 percent.

Estimated Ultimate Recovery Per Well

Based on decline-curve plots (Troy Cook, USGS, oral commun., 2002) for approximately 1,000 wells, organized into thirds according to their year of discovery, the values for the estimated ultimate recovery (EUR) per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Clinton-Medina Basin Center AU range 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 per MMCFG (or a gas-to-oil ratio of 100,000 cubic feet of gas (CFG) per barrel of oil (BO)). This oil, which is expressed as natural gas liquids associated with the gas resource, is estimated (at a mean value) to be 108.33 MMBNGL (table 2).

Tuscarora Basin Center Assessment Unit

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). 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 sandstone, and Medina Group and the 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 estimated sizes of the undrilled cells (the optimum drainage area for a single well) in the AU range from a minimum of 40 acres to a maximum of 160 acres. The median size of the 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 during the next 30 years 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. Previous drilling results indicate that the expected success ratio for new wells drilled along the fractured anticlines is 60 percent.

Estimated Ultimate Recovery Per Well

Based on decline-curve plots (Troy Cook, USGS, oral commun., 2002) for approximately 40 wells, the values for the estimated recovery (EUR) per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Tuscarora Sandstone Basin Center AU range 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 Assessment Unit

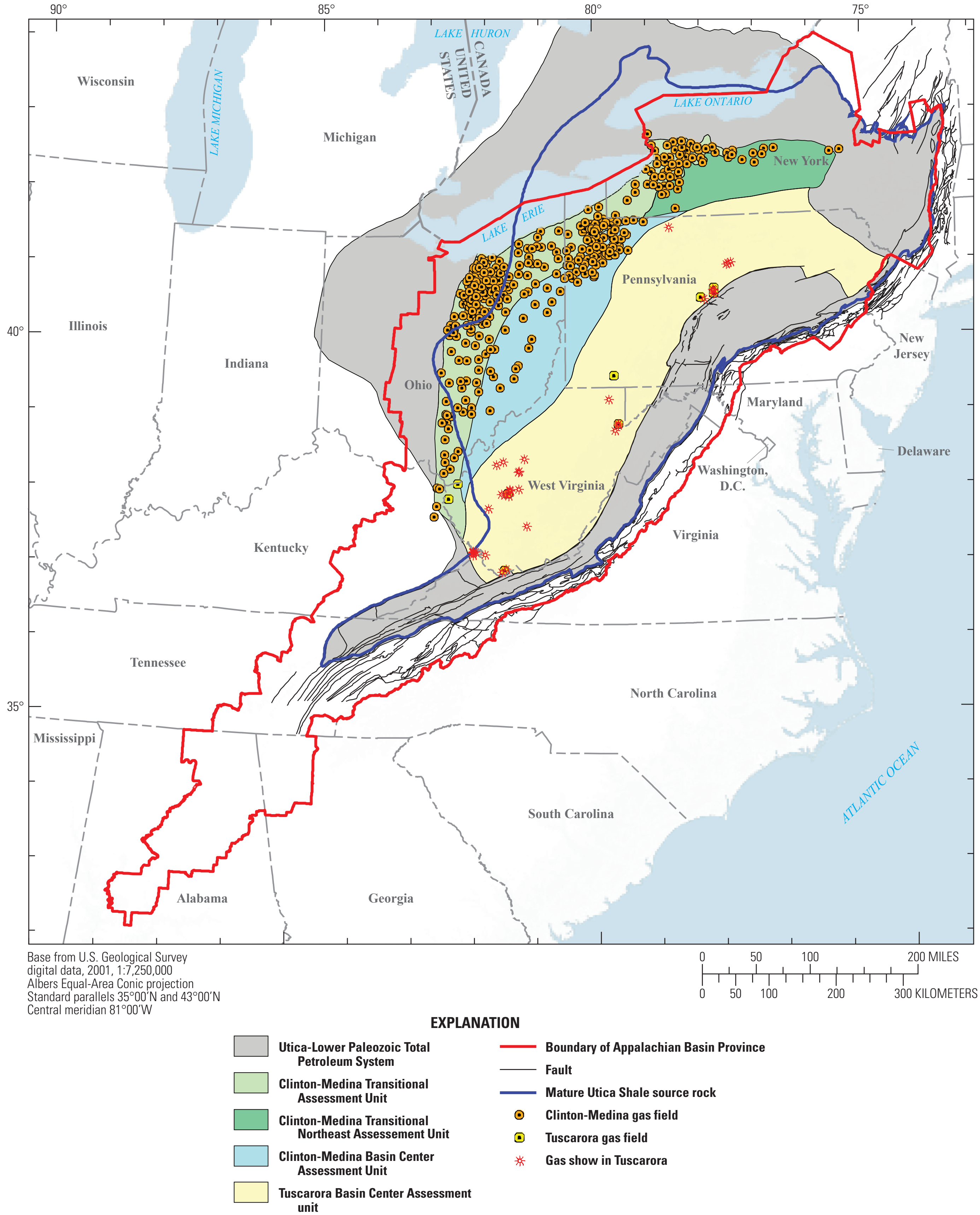
Description

The Clinton-Medina Transitional AU is located in the west-central 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 area underlying 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 east. The western margin of the Clinton-Medina Transitional AU is marked by the westward pinchout limit of the "Clinton" and Medina sandstones 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" and Medina reservoirs in the AU range from about 1,500 to 4,000 ft. Except for the U.S. portions underlying 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 estimated sizes of the undrilled cells (the optimum drainage area for a single well) in the AU range from a minimum of 10 acres to a maximum of 110 acres. The median size of the undrilled cells is 40 acres.

Figure 20 (facing page). Map of the Appalachian Basin Province showing the Utica-Lower Paleozoic Total Petroleum System and the accompanying Clinton-Medina Basin Center, Tuscarora Basin Center, Clinton-Medina Transitional, and Clinton-Medina Transitional Northeast Assessment Units (Milici and others, 2004). Also shown are selected gas fields that produce from the "Clinton" sandstone, Medina sandstone, Medina Group, and Tuscarora Sandstone (Roen and Walker, 1996).



90°
85°
80°
75°
40°
35°
LAKE HURON
CANADA
UNITED STATES
LAKE MICHIGAN
LAKE ONTARIO
LAKE ERIE
ATLANTIC OCEAN
Wisconsin
Michigan
Illinois
Indiana
Ohio
New York
Pennsylvania
New Jersey
Maryland
Delaware
Washington, D.C.
West Virginia
Virginia
Kentucky
Tennessee
North Carolina
Mississippi
South Carolina
Alabama
Georgia
Base from U.S. Geological Survey
digital data, 2001, 1:7,250,000
Albers Equal-Area Conic projection
Standard parallels 35°00'N and 43°00'N
Central meridian 81°00'W
0 50 100 200 MILES
0 50 100 200 300 KILOMETERS
EXPLANATION
Utica-Lower Paleozoic Total Petroleum System
Clinton-Medina Transitional Assessment Unit
Clinton-Medina Transitional Northeast Assessment Unit
Clinton-Medina Basin Center Assessment Unit
Tuscarora Basin Center Assessment unit
Boundary of Appalachian Basin Province
Fault
Mature Utica Shale source rock
Clinton-Medina gas field
Tuscarora gas field
Gas show in Tuscarora

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 during the next 30 years 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. Previous drilling results indicate that the expected success ratio for new wells may be as high as 77 percent.

Estimated Ultimate Recovery Per Well

Based on decline-curve plots (Troy Cook, USGS, oral commun., 2002) for several thousand wells, organized into thirds according to their year of discovery, the values for the estimated ultimate recovery (EUR) per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Clinton-Medina Transitional AU range 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-to-oil ratio of 83,000 CFG/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 underlie the Great Lakes (Lake Erie).

Clinton-Medina Transitional Northeast Assessment Unit

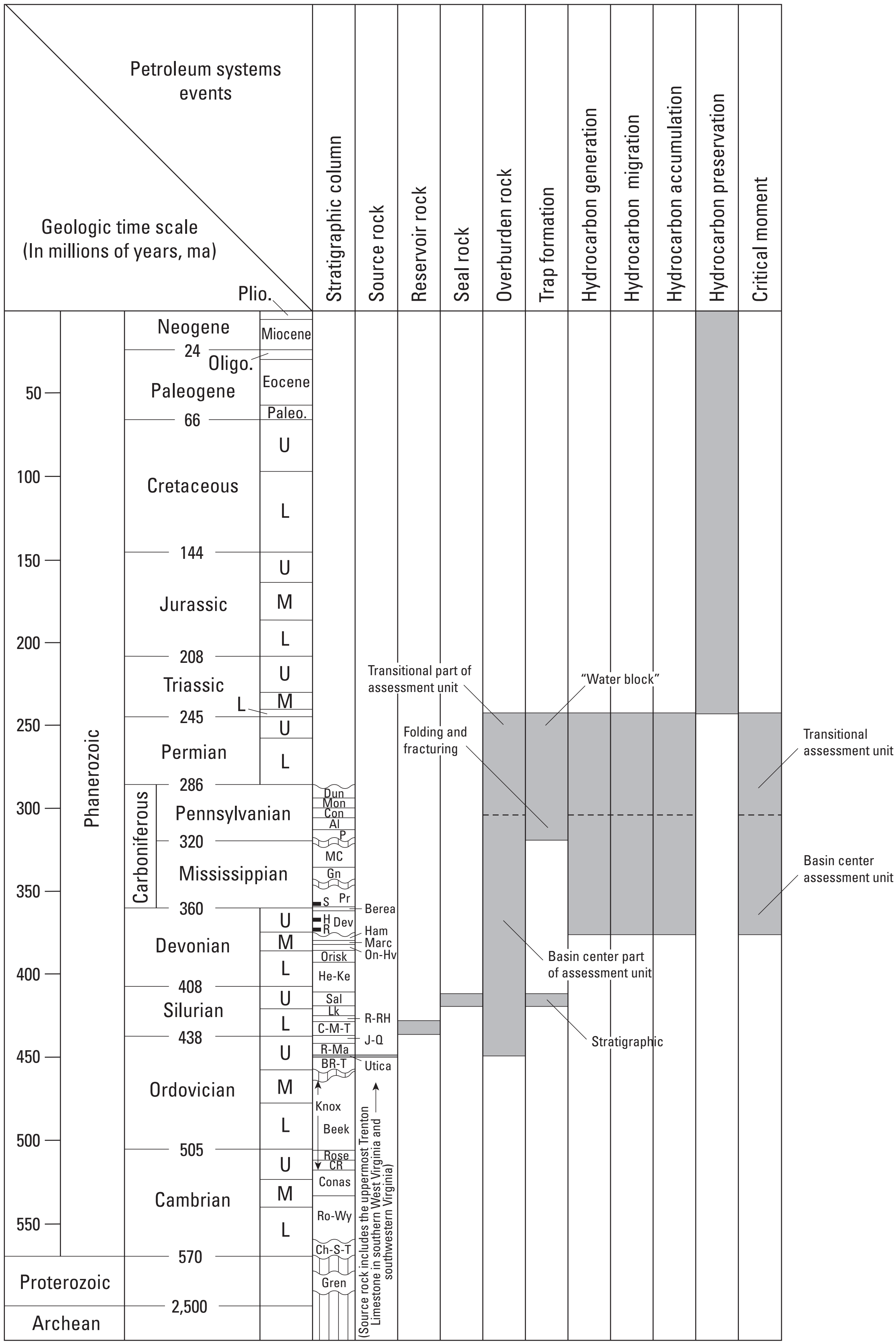
Description

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 controlled largely by a change in the facies that 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 are defined by 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. The presence of a small number of widely distributed gas wells and small gas fields indicates that parts of the largely undrilled southern part of the Clinton-Medina Transitional Northeast AU very likely could 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 estimated sizes of the undrilled cells (the optimum drainage area for a single well) in the AU range from a minimum of 10 acres to a maximum of 110 acres. The median size of the undrilled cells is 40 acres.

Figure 21 (facing page). Events chart for the Clinton-Medina Basin Center, Tuscarora Basin Center, Clinton-Medina Transitional, and Clinton-Medina Transitional Northeast Assessment Units. Abbreviations for rock unit names are as follows (in approximate stratigraphic order): Gren, Grenville province basement rocks; Ch-S-T, Chilhowee Group and Shady Dolomite or Tomstown Dolomite; Ro-Wy, Rome Formation or Waynesboro Formation; Conas, Conasauga Group; CR, Copper Ridge dolomite (or Dolomite); Rose, Rose Run sandstone (or Sandstone) or upper sandy member of the Gatesburg Formation or Galway (or Theresa) Formation; Beek, Beekmantown dolomite (or Group); Knox, Knox Dolomite (or Dolomite, Group); BR-T, Black River Limestone (or Group) and Trenton Limestone; Utica, Utica Shale; R-Ma, Reedsville Shale or Martinsburg Formation; J-Q, Juniata Formation or Queenston Shale; C-M-T, “Clinton” sandstone, Medina sandstone, Medina Group, or Tuscarora Sandstone; R-RH, Rochester Shale or Rose Hill Formation; Lk, Lockport Dolomite (or Group); Sal, Salina Group; He-Ke, Helderberg Limestone and Keyser Limestone; Orisk, Oriskany Sandstone; On-Hv, Onondaga Limestone or Huntersville Chert; Marc, Marcellus Shale of the Hamilton Group; Ham, upper part of the Hamilton Group; Dev, Upper Devonian shale and sandstone; R, Rhinestreet Shale Member of the West Falls Formation; H, Huron Member of the Ohio Shale; Berea, Berea Sandstone; S, Sunbury Shale; Pr, Price Group; Gn, Greenbrier Limestone; MC, Mauch Chunk Formation; P, Pottsville Group; Al, Allegheny Group; Con, Conemaugh Group; Mon, Monongahela Group; Dun, Dunkard Group. Other abbreviations are as follows: L, Lower; M, Middle; Oligo., Oligocene; Paleo., Paleocene; Plio., Pliocene; U, Upper. The boundary between the transitional and basin center assessment units is shown in figure 20. The time scale is modified after Magoon and Dow (1994).



Petroleum systems events
Geologic time scale (In millions of years, ma)
Stratigraphic column
Source rock
Reservoir rock
Seal rock
Overburden rock
Trap formation
Hydrocarbon generation
Hydrocarbon migration
Hydrocarbon accumulation
Hydrocarbon preservation
Critical moment
Phanerozoic
Proterozoic
Archean
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Plio.
Miocene
Oligo.
Eocene
Paleo.
24
66
144
208
245
286
320
360
408
438
505
570
2,500
50
100
150
200
250
300
350
400
450
500
550
Dun
Mon
Con
Al
P
MC
Gn
S
Pr
H
R
Dev
Orisk
He-Ke
Sal
Lk
C-M-T
R-Ma
BR-T
Knox
Beek
Rose
CR
Conas
Ro-Wy
Ch-S-T
Gren
Berea
Ham
Marc
On-Hv
R-RH
J-Q
Utica
(Source rock includes the uppermost Trenton Limestone in southern West Virginia and southwestern Virginia)
Transitional part of assessment unit
Folding and fracturing
"Water block"
Basin center part of assessment unit
Stratigraphic
Transitional assessment unit
Basin center assessment unit

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 during the next 30 years 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. Previous drilling results indicate that the success ratio for new wells is 75 percent.

Estimated Ultimate Recovery Per Well

Based on decline-curve plots (Troy Cook, USGS, oral commun., 2002) for several thousand wells, organized into thirds according to their year of discovery, the values for the estimated ultimate recovery (EUR) per well (or per untested cell) used to estimate the recoverable gas from undrilled cells in the Clinton-Medina Transitional Northeast AU range 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).

Utica Shale Assessment Unit

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, it probably would have been located from eastern Ohio, through most of Pennsylvania, to southeastern New York. 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. Also, eastern Ohio has potential for oil associated with the natural gas.

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References Cited

Aguilera, R., 1978, Log analysis of gas-bearing fracture shales in the Saint Lawrence lowlands of Quebec, *in* Annual Technical Conference and Exhibition of the Society of Petroleum Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), Dallas, Tex., October 1–3, 1978: Society of Petroleum Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers Paper SPE 7445, 16 p.

Attanasi, E.D., Mast, R.F., and Root, D.H., 1999, Oil, gas field growth projections; wishful thinking or reality?: Oil and Gas Journal, v. 97, no. 14, p. 79–81.

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

Avary, K.L., 2006, Trenton-Black River production history and analysis, chap. 6 *of* Patchen, D.G., Hickman, J.B., Harris, D.C., Drahovzal, J.A., Lake, P.D., Smith, L.B., Nyahay, Richard, Schulze, Rose, Riley, R.A., Baranoski, M.T., Wickstrom, L.H., Laughrey, C.D., Kostelnik, Jaime, Harper, J.A., Avary, K.L., Bocan, John, Hohn, M.E., and McDowell, Ronald, A geologic play book for Trenton-Black River Appalachian basin exploration: Morgantown, W. Va., National Technical Laboratory, U.S. Department of Energy Report, p. 211–227, 1 CD-ROM disc. [Prepared by a consortium under DOE award DE–FC26–03NT41856. Final report of work performed from October 1, 2003, to March 30, 2006.]

Bailey, S.M.B., 1986, A new look at the development, configuration and trapping mechanisms of the Silurian Guelph reefs of southwestern Ontario, *in* McLean, D.D., ed., Proceedings of the 25th Annual Conference of the Ontario Petroleum Institute Inc., London, Ontario, Canada, October 19–21, 1986: Ontario Petroleum Institute Technical Volume, v. 25, no. 16, 28 p.

Baranoski, M.T., Riley, R.A., and Wolfe, M.E., 1996, Play COk; Cambrian-Ordovician Knox Group unconformity play, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 181–187.

Bartlett, C.S., 1988, Trenton Limestone fracture reservoirs in Lee County, southwestern Virginia, *in* Keith, B.D., ed., The Trenton Group (Upper Ordovician series) of eastern North America; deposition, diagenesis, and petroleum: American Association of Petroleum Geologists Studies in Geology 29, p. 27–35.

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

Cole, G.A., Drozd, R.J., Sedivy, R.A., and Halpern, H.I., 1987, Organic geochemistry and oil-source correlations, Paleozoic of Ohio: American Association of Petroleum Geologists Bulletin, v. 71, no. 7, p. 788–809.

Coleman, J.L., Swezey, C.S., Ryder, R.T., and Charpentier, R.R., 2006, Undiscovered oil and gas resources underlying the U.S. portions of the Great Lakes, 2005: U.S. Geological Survey Fact Sheet 2006–3049, 4 p.

Cook, Troy, and Charpentier, R.R., 2010, Assembling probabilistic performance parameters of shale-gas wells: U.S. Geological Survey Open-File Report 2010–1138, 17 p., accessed June 21, 2011, at http://pubs.usgs.gov/of/2010/1138/.

DeBrosse, T.A., and Vohwinkel, J.C., 1974, Oil and gas fields of Ohio (including underground storage areas): Columbus, Ohio, Ohio Division of Geological Survey in cooperation with Ohio Division of Oil and Gas, 1 sheet, scale 1:500,000.

Dolly, E.D. and Busch, D.A., 1972, Stratigraphic, structural, and geomorphologic factors controlling oil accumulation in Upper Cambrian strata of central Ohio: American Association of Petroleum Geologists Bulletin, v. 56, no. 12, p. 2335–2368.

Dolton, G.L., Varnes, K.L., Gautier, D.L., and Barnet, D.L., 1995, Oil and gas resource assessment areas 1995, lower 48 States: U.S. Geological Survey Open-File Report 95–75–I, 1 sheet.

Drozd, R.J., and Cole, G.A., 1994, Point Pleasant-Brassfield(!) petroleum system, Appalachian basin, U.S.A., *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system—From source to trap: American Association of Petroleum Geologists Memoir 60, p. 387–398. (Also available at http://search.datapages.com/data/specpubs/methodo2/data/a077/a077/0001/0350/0387.htm.)

Gautier, D.L. and Dolton, G.L., 1995, Methodology for assessment of undiscovered conventional accumulations, *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 national assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, 1 CD-ROM disc.

Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995, 1995 national assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, 1 CD-ROM disc.

Gradstein, F.M., Ogg, J.G., and Smith, A.G., 2004, A geologic time scale 2004: Cambridge, United Kingdom, Cambridge University Press, 610 p.

Hatch, J.R., Swezey, C.S., Hayba, D.O., Harrison, W.B., Wylie, A.S., Repetski, J.E., East, J.A., and Modroo, A., 2005, Evidence for vertical petroleum leakage across Silurian evaporites in the Michigan Basin of North America [abs.]: American Association of Petroleum Geologists Annual Convention Abstracts, v. 14, p. A60.

Hatcher, R.D., Jr., Williams, R.T., and McCown, M.W., 2001, Swan Creek field; Isolated success or tip of the iceberg?: Oil and Gas Journal, v. 99, no. 40, p. 38–44.

Hettinger, R.D., 2001, Subsurface correlations and sequence stratigraphic interpretations of Lower Silurian strata in the Appalachian basin of northeast Ohio, southwest New York, and northwest Pennsylvania: U.S. Geological Survey Geologic Investigations Series Map I–2741, 1 sheet, 1 pamphlet.

Houghton, J.C., Dolton, G.L., Mast, R.F., Masters, C.D., and Root, D.H., 1993, U.S. Geological Survey estimation procedure for accumulation size distributions by play: American Association of Petroleum Geologists Bulletin, v. 77, no. 3, p. 454–466.

Hurley, N.F., and Budros, Ron, 1990, Albion-Scipio and Stoney Point fields—U.S.A. Michigan Basin, *in* Beaumont, E.A., and Foster, N.H., compilers, Stratigraphic traps, v. I: American Association of Petroleum Geologists Treatise of Petroleum Geology, Atlas of Oil and Gas Fields, v. A–018, p. 1–37.

Janssens, Adriaan, 1975, Catalog of oil and gas wells in “Newburg” (Silurian) of Ohio: Ohio Division of Geological Survey Information Circular 42, 19 p.

Janssens, Adriaan, 1977, Oil and gas in Ohio—Past, present, and future, *in* Proceedings, Eighth Annual Appalachian Petroleum Geology Symposium, Morgantown, W. Va., March 8–11, 1977: Morgantown, W. Va. [National Energy Technical Laboratory], p. 1–39, 2 plates.

Janssens, Arie, 1993, 1992 oil and gas production from Rose Run, Beekmantown, and selected Trempealeau wells in Ohio, *in* An update on Ohio’s subsurface geology, Proceedings from the Ohio Geological Society Special Meeting, First Annual Technical Symposium, Canton, Ohio, October 20, 1993: Columbus, Ohio, Ohio Geological Society, 8 p.

Jones, R.W., 1987, Organic facies, *in* Brooks, James, and Welte, Dietrich, eds., Advances in petroleum geochemistry, v. 2: London, United Kingdom, Academic Press, p. 1–90.

Kirschbaum, M.A., Schenk, C.J., Cook, T.A., Ryder, R.T., Charpentier, R.R., Klett, T.R., Gaswirth, S.B., Tennyson, M.E., and Whidden, K.J., 2012, Assessment of undiscovered oil and gas resources of the Ordovician Utica Shale of the Appalachian Basin Province, 2012: U.S. Geological Survey Fact Sheet 2012–3116, 6 p. Available at http://pubs.usgs.gov/fs/2012/3116/ (accessed 12/23/2014).

Klett, T.R., and Charpentier, R.R., 2003, FORSPAN model users guide: U.S. Geological Survey Open-File

Report 03–354, 37 p., appendices. (Also available at http://pubs.er.usgs.gov/publication/ofr03354.)

Klett, T.R., Schmoker, J.W., Charpentier, R.R., Ahlbrandt, T.S., and Ulmishek, G.F., 2000, Glossary, *in* U.S. Geological Survey world petroleum assessment 2000—Description and results: U.S. Geological Survey Digital Data Series DDS–60, 4 CD-ROM discs.

Kolata, D.R., Huff, W.D., and Bergström, S.M., 2001, The Ordovician Sebree Trough; an oceanic passage to the Midcontinent United States: Geological Society of America Bulletin, v. 113, no. 8, p. 1067–1078.

Laughrey, C.D., 1987, Evaluating the Lockport Dolomite—Problems, pores, and possibilities, *in* The Eighteenth Annual Appalachian Petroleum Geology Symposium; Rifts, ramps, reefs, and royalties: West Virginia Geological and Economic Survey Circular C–40, p. 56–58.

Laughrey, C.D., and Harper, R.M., 1996, Play Obe; Upper Ordovician Bald Eagle Formation fractured anticlinal play, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 164–167.

Laughrey, C.D., and Kostelnik, Jaime, 2006a, Petrography of the Trenton Limestone and Black River Group carbonate rocks in the Appalachian Basin, chap. 3 *of* Patchen, D.G., Hickman, J.B., Harris, D.C., Drahovzal, J.A., Lake, P.D., Smith, L.B., Nyahay, Richard, Schulze, Rose, Riley, R.A., Baranoski, M.T., Wickstrom, L.H., Laughrey, C.D., Kostelnik, Jaime, Harper, J.A., Avary, K.L., Bocan, John, Hohn, M.E., and McDowell, Ronald, A geologic play book for Trenton-Black River Appalachian basin exploration: Morgantown, W. Va., National Technical Laboratory, U.S. Department of Energy Report, p. 64–100, 1 CD-ROM disc. [Prepared by a consortium under DOE award number DE–FC26–03NT41856. Final report of work done from October 1, 2003, to March 30, 2006.]

Laughrey, C.D., and Kostelnik, Jaime, 2006b, Geochemistry of natural gases from Trenton and Black River Formation carbonate reservoirs, Appalachian Basin, chap. 5 *of* Patchen, D.G., Hickman, J.B., Harris, D.C., Drahovzal, J.A., Lake, P.D., Smith, L.B., Nyahay, Richard, Schulze, Rose, Riley, R.A., Baranoski, M.T., Wickstrom, L.H., Laughrey, C.D., Kostelnik, Jaime, Harper, J.A., Avary, K.L., Bocan, John, Hohn, M.E., and McDowell, Ronald, A geologic play book for Trenton-Black River Appalachian basin exploration: Morgantown, W. Va., National Technical Laboratory, U.S. Department of Energy Report, p. 161–210, 1 CD-ROM disc. [Prepared by a consortium under DOE award number DE–FC26–03NT41856. Final report of work done from October 1, 2003, to March 30, 2006.]

Magoon, L.B., and Dow, W.G., eds., 1994, The petroleum system—From source to trap: American Association of Petroleum Geologists Memoir 60, 655 p.

Martin, J.P., 2005, The Utica and Hamilton Shales—The next fractured shale play, *in* Proceedings, Fourth Annual Gas Shales Summit, Production and potential, Denver, Colo., December 1–2, 2005: New York, N.Y., Strategic Research Institute, 35 p.

Masters, J.A., 1979, Deep basin gas trap, western Canada: American Association of Petroleum Geologists Bulletin, v. 63, no. 2, p. 151–181.

Milici, R.C., Ryder, R.T., and Swezey, C.S., 2004, Estimated recovery of oil and natural gas from the central and northern parts of the Appalachian basin, eastern U.S.A. [abs.], *in* Proceedings, Thirty-Second International Geological Congress, Topical symposia T09.01—Fossil fuels, abstract 256-38, Florence, Italy, August 20–28, 2004: Florence, Italy, Thirty-Second International Geological Congress, 1 CD-ROM disc.

Milici, R.C., Ryder, R.T., Swezey, C.S., Charpentier, R.R., Cook, T.A., Crovelli, R.A., Klett, T.R., Pollastro, R.M., and Schenk, C.J., 2003, Assessment of undiscovered oil and gas resources of the Appalachian Basin Province, 2002: U.S. Geological Survey Fact Sheet 009–03, 2 p. (Also available at http://pubs.usgs.gov/fs/fs-009-03/.)

Moody, J.P., Mooney, J.W., and Spivak, J., 1970, Giant oil fields of North America, *in* Halbouty, M.T., ed., Geology of giant petroleum fields: American Association of Petroleum Geologists Memoir 14, p. 8–16.

Multer, H.G., 1963, Geology of the Silurian producing zones in the Moreland oil pool, Wayne County, northeastern Ohio: Ohio Division of Geological Survey Report of Investigations 46, 48 p.

New York Division of Mineral Resources, 1987, Historical digest; Trenton and Black River Formations, *in* New York State oil, gas, and mineral resources 1987; annual report: Albany, N.Y., New York Department of Environmental Conservation, New York Division of Mineral Resources, p. 27–31.

New York Division of Mineral Resources, 2004, Map 3—Trenton-Black River fields, central New York, 2004, *in* New York State oil, gas, and mineral resources 2004; twenty-first annual report: Albany, N.Y., New York Department of Environmental Conservation, New York Division of Mineral Resources, p. 14.

New York Division of Mineral Resources, 2008, Map 3—Trenton-Black River fields, central New York, 2008, *in* New York State oil, gas, and mineral resources 2008; twenty-fifth annual report: Albany, N.Y., New York Department of Environmental Conservation, New York Division of Mineral Resources, p. 15.

Noger, M.C., Meglen, J.F., Humphreys, Matthew, and Baranoski, M.T., 1996, Play Sld; Upper Silurian Lockport

Dolomite-Keefer (Big Six) Sandstone, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 145–150.

Nyahay, R., Schultz, R., Smith, L.B., Riley, R., and Patchen, D.G., 2006, Trenton-Black River key field and play descriptions, chap. 8 *of* Patchen, D.G., Hickman, J.B., Harris, D.C., Drahovzal, J.A., Lake, P.D., Smith, L.B., Nyahay, Richard, Schulze, Rose, Riley, R.A., Baranoski, M.T., Wickstrom, L.H., Laughrey, C.D., Kostelnik, Jaime, Harper, J.A., Avary, K.L., Bocan, John, Hohn, M.E., and McDowell, Ronald, A geologic play book for Trenton-Black River Appalachian basin exploration: Morgantown, W. Va., National Technical Laboratory, U.S. Department of Energy Report, p. 254–336, 1 CD-ROM disc. [Prepared by a consortium under DOE award number DE–FC26–03NT41856. Final report of work done from October 1, 2003, to March 30, 2006.]

Nyahay, Richard, Leone, James, Smith, L.B., Martin, J.P., and Jarvie, D.J., 2007, Update on regional assessment of gas potential in the Devonian Marcellus and Utica Shales of New York [abs.], *in* Programs and abstracts, 2007 Eastern Section American Association of Petroleum Geologists, Thirty-sixth annual meeting, Lexington, Ky., September 16–18, 2007: [Lexington, Ky., Kentucky Geological Survey], p. 46. (Also available at http://karl.nrcce.wvu.edu/esaapg/ESAAPG_Meetings/2007/2007_Abstracts.pdf.)

Obermajer, M., Fowler, M.G., and Snowdon, L.R., 1999, Depositional environment and oil generation in Ordovician source rocks from southwestern Ontario, Canada; organic geochemical and petrological approach: American Association of Petroleum Geologists Bulletin, v. 83, no. 9, p. 1426–1453.

Ontario Ministry of Natural Resources, 2001, Oil and gas pools and pipelines of southern Ontario: London, Ontario, Canada, Ontario Ministry of Natural Resources and Ontario Oil, Gas and Salt Resources Library, 1 sheet, scale 1:360,000.

Park, Gary, 2008, Forest announces big-time shale gas play: Petroleum News, v. 13, no. 14, p. 4.

Patchen, D.G., 1996, Play Sns; The Upper Silurian Newburg sandstone play, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 139–144.

Patchen, D.G., and Mroz, T.H., 2006, Consortium produces geologic play book: GasTIPS, v. 12, no. 2, p. 7–9.

Peters, K.E., and Cassa, M.R., 1994, Applied source rock geochemistry, *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system—From source to trap: American Association of Petroleum Geologists Memoir 60, p. 93–120.

Repetski, J.E., Ryder, R.T., Weary, D.J., Harris, A.G., and Trippi, M.H., 2008, Thermal maturity patterns (CAI and %R_o) in Upper Ordovician and Devonian rocks of the Appalachian basin; a major revision of USGS Map I–917–E using new subsurface collections: U.S. Geological Survey Scientific Investigations Map SIM–3006, 1 CD-ROM disc.

Riley, R.A., Baranoski, M.T., and Wickstrom, L.H., 2006, Regional stratigraphy of the Trenton-Black River, chap. 1 *of* Patchen, D.G., Hickman, J.B., Harris, D.C., Drahovzal, J.A., Lake, P.D., Smith, L.B., Nyahay, Richard, Schulze, Rose, Riley, R.A., Baranoski, M.T., Wickstrom, L.H., Laughrey, C.D., Kostelnik, Jaime, Harper, J.A., Avary, K.L., Bocan, John, Hohn, M.E., and McDowell, Ronald, A geologic play book for Trenton-Black River Appalachian basin exploration: Morgantown, W. Va., National Technical Laboratory, U.S. Department of Energy Report, p. 4–38, 30 plates, 1 CD-ROM disc. [Prepared by a consortium under DOE award number DE–FC26–03NT41856. Final report of work done from October 1, 2003, to March 30, 2006.]

Riley, R.A., Harper, J.A., Baranoski, M.T., Laughrey, C.D., and Carlton, R.W., 1993, Measuring and predicting reservoir heterogeneity in complex depocenters; the Late Cambrian Rose Run Sandstone of eastern Ohio and western Pennsylvania: Columbus, Ohio, Ohio Department of Natural Resources, Division of Geological Survey, 257 p. [Prepared by the Appalachian Oil and Natural Gas Consortium under U.S. Department of Energy contract no. DE–AC22–90BC14657.]

Riley, R.A., Wicks, John, and Thomas, John, 2002, Cambrian-Ordovician Knox production in Ohio; Three case studies of structural-stratigraphic traps: American Association of Petroleum Geologists Bulletin, v. 86, no. 4, p. 539–555.

Roen, J.B., and Walker, B.J., eds., 1996, The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 201 p.

Rowan, E.L., 2006, Burial and thermal history of the central Appalachian basin, based on three 2-D models of Ohio, Pennsylvania, and West Virginia: U.S. Geological Survey Open-File Report 2006–1019, 35 p., available only online at http://pubs.usgs.gov/of/2006/1019/.

Ryder, R.T., 1994, The Knox unconformity and adjoining strata, western Morrow County, Ohio, *in* Shafer, W.E., ed., The Ohio Geological Society anthology on the Morrow County, Ohio "oil boom," 1961-1967 and the Cambro-Ordovician reservoir of central Ohio: Columbus, Ohio, Ohio Geological Society, p. 249–271.

Ryder, R.T., 2004, Stratigraphic framework and depositional sequences in the Lower Silurian regional oil and gas accumulation, Appalachian basin; from Ashland County, Ohio, through southwestern Pennsylvania, to Preston County, West Virginia: U.S. Geological Survey Geologic Investigations Series Map 2810, 2 sheets, 1 pamphlet.

Ryder, R.T., 2008, Assessment of Appalachian basin oil and gas resources; Utica-Lower Paleozoic Total Petroleum System: U.S. Geological Survey Open-File Report 2008–1287, 29 p., accessed June 21, 2011, at http://pubs.usgs.gov/of/2008/1287/.

Ryder, R.T., Burruss, R.C., and Hatch, J.R., 1998, Black shale source rocks and oil generation in the Cambrian and Ordovician of the central Appalachian basin, USA: American Association of Petroleum Geologists Bulletin, v. 82, no. 3, p. 412–441. (Also available online at http://archives.datapages.com/data/bulletns/1998/03mar/0412/0412.htm.)

Ryder, R.T., Crangle, R.D., Jr., Trippi, M.H., Swezey, C.S., Lentz, E.E., Rowan, E.L., and Hope, R.S., 2009, Geologic cross section *D–D′* through the Appalachian basin from the Findlay arch, Sandusky County, Ohio, to the Valley and Ridge province, Hardy County, West Virginia: U.S. Geological Survey Scientific Investigations Map 3067, 2 sheets, 1 pamphlet, 52 p. (Also available at http://pubs.usgs.gov/sim/3067/.)

Ryder, R.T., Swezey, C.S., Crangle, R.D., Jr., and Trippi, M.H., 2008, Geologic cross section *E–E′* through the Appalachian basin from the Findlay arch, Wood County, Ohio, to the Valley and Ridge province, Pendleton County, West Virginia: U.S. Geological Survey Scientific Investigations Map 2985, 2 sheets, 1 pamphlet, 48 p. (Also available at http://pubs.usgs.gov/sim/2985/.)

Ryder, R.T., Trippi, M.H., Swezey, C.S., Crangle, R.D., Jr., Hope, R.S., Rowan, E.L., and Lentz, E.E., 2012, Geologic cross section *C–C′* through the Appalachian basin from Erie County, north-central Ohio, to the Valley and Ridge province, Bedford County, south-central Pennsylvania: U.S. Geological Survey Scientific Investigations Map 3172, 2 sheets, 1 pamphlet (Also available at http://pubs.usgs.gov/sim/3172/).

Ryder, R.T., and Zagorski, W.A., 2003, Nature, origin, and production characteristics of the Lower Silurian regional oil and gas accumulation, central Appalachian basin, United States: American Association of Petroleum Geologists Bulletin, v. 87, no. 5, p. 847–872.

Sagan, J.A., and Hart, B.S., 2006, Three-dimensional seismic-based definition of fault-related porosity development; Trenton-Black River interval, Saybrook, Ohio: American Association of Petroleum Geologists Bulletin, v. 90, no. 11, p. 1763–1785.

Santini, R.J., and Coogan, A.H., 1983, The Silurian Newburg (Lockport) gas pools in Summit County, Ohio; complex structural-stratigraphic petroleum accumulations: Northeastern Geology, v. 5, no. 3–4, p. 181–191.

Saroff, S.T., 1987, Subsurface structure and nature of gas production of the Upper Ordovician Queenston Formation, Auburn gas field, Cayuga County, New York, *in* Shumaker, R.C., compiler, Appalachian Basin Industrial Associates, Program, fall meeting, Morgantown, W. Va.: Morgantown, W. Va., Appalachian Basin Industrial Associates [through West Virginia University], v. 13, p. 38–58.

Schmoker, J.W., 1996, Method for assessing continuous-type (unconventional) hydrocarbon accumulations, *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 national assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, release 2, 1 CD-ROM disc.

Schmoker, J.W., 1997, Continuous hydrocarbon reservoirs: U.S. Geological Survey Fact Sheet 024–97, 3 p.

Schmoker, J.W., 1999, U.S. Geological Survey assessment model for continuous (unconventional) oil and gas accumulations—the “FORSPAN” model: U.S. Geological Survey Bulletin 2168, 9 p., available only online at http://pubs.usgs.gov/bul/b2168/.

Smith, L.B., Jr., 2006, Origin and reservoir characteristics of Upper Ordovician Trenton-Black River hydrothermal dolomite reservoirs in New York: American Association of Petroleum Geologists Bulletin, v. 90, no. 11, p. 1691–1718.

Swezey, C.S., Hatch, J.R., Hayba, D.O., Repetski, J.E., Charpentier, R.R., Cook, T.A., Klett, T.R., Pollastro, R.M., and Schenk, C.J., 2005, Assessment of undiscovered oil and gas resources of the U.S. portion of the Michigan Basin province, 2004: U.S. Geological Survey Fact Sheet 2005–3070, 2 p.

Tissot, B.P., and Welte, D.H., 1984, Petroleum formation and occurrence [second edition]: Berlin, Germany, Springer-Verlag, 699 p.

Trevail, R.A., Carter, T.R., and McFarland, S., 2004, Trenton-Black River hydrothermal dolomite reservoirs in Ontario; an assessment of remaining potential after 100 years of production, *in* Ontario-New York Oil and Gas Conference and Forty-Third Annual Conference of the Ontario Petroleum Institute, Niagara Falls, Ontario, Canada, November 8–10, 2004: London, Ontario, Canada, Ontario Petroleum Institute, v. 43, 36 p.

U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1995, 1995 national assessment of United States oil and gas resources: U.S. Geological Survey Circular 1118, 20 p.

Wallace, L.G., and Roen, J.B., 1989, Petroleum source rock potential of the Upper Ordovician black shale sequence, northern Appalachian basin: U.S. Geological Survey Open-File Report 89–488, 66 p.

Ward, T.L., 1988, Natural gas production from Ordovician Queenston Formation in West Auburn field, Cayuga County, New York [abs.]: American Association of Petroleum Geologists Bulletin, v. 72, no. 8, p. 974.

Wickstrom, L.H., and Gray, J.D., 1988, Geology of the Trenton Limestone in northwestern Ohio, *in* Keith, B.D., ed., The Trenton Group (Upper Ordovician series) of eastern North America; deposition, diagenesis, and petroleum: American Association of Petroleum Geologists Studies in Geology 29, p. 159–172.

Wickstrom, L.H., Gray, J.D., and Steiglitz, R.D., 1992, Stratigraphy, structure, and production history of the Trenton Limestone (Ordovician) and adjacent strata in northwestern Ohio: Ohio Division of Geological Survey Report of Investigations 143, 78 p., 1 plate.

Zagorski, W.A., 1999, Regional trapping styles in the “Clinton” Medina Sandstone Group, Appalachian basin, *in* Ontario Petroleum Institute, Thirty-eighth annual conference, Niagara Falls, Ontario, Canada, November 3–5, 1999: London, Ontario, Canada, Ontario Petroleum Institute, v. 38, 34 p.

Tables 1–2

Table 1. Results of assessed undiscovered, technically recoverable oil and gas resources for conventional assessment units (AU) in the Utica-Lower Paleozoic Total Petroleum System.

[F95 denotes the 95th fractile; the probability of more than F95 is 95 percent. F50 and F5 are defined similarly. Abbreviations: BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; MMBO, million barrels of oil; —, not applicable. Data are from Milici and others (2003)]

Assessment unit (AU) in the Utica-Lower Paleozoic Total Petroleum System	Field type	Total undiscovered resources											
		Oil (MMBO)				Gas (BCFG)				Natural gas liquids (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Lower Paleozoic Carbonates in Thrust Belt AU	Gas	—	—	—	—	38.61	253.95	725.60	301.90	0.37	2.46	7.55	3.02
Knox Unconformity AU	Oil	11.70	29.55	51.65	30.44	53.49	143.31	279.60	152.33	0.50	1.40	2.99	1.53
	Gas	—	—	—	—	150.76	404.67	749.87	421.61	1.39	3.92	8.04	4.21
Black River-Trenton Hydrothermal Dolomite AU	Oil	3.14	13.96	37.19	16.29	14.55	67.73	195.06	81.48	0.14	0.66	2.03	0.82
	Gas	—	—	—	—	575.13	1,740.48	3,388.28	1,837.22	5.37	16.92	36.10	18.33
Lockport Dolomite AU	Gas	—	—	—	—	60.23	191.77	403.71	207.49	0.56	1.86	4.30	2.08

Table 2. Results of assessed undiscovered, technically recoverable gas resources for continuous assessment units (AU) in the Utica-Lower Paleozoic Total Petroleum System.

[F95 denotes the 95th fractile; the probability of more than F95 is 95 percent. F50 and F5 are defined similarly. Abbreviations: BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; MMBO, million barrels of oil; —, not applicable. Data are from Milici and others (2003)]

Assessment unit (AU) in the Utica-Lower Paleozoic Total Petroleum System	Field type	Total undiscovered resources											
		Oil (MMBO)				Gas (BCFG)				Natural gas liquids (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Clinton-Medina Basin Center AU	Gas	—	—	—	—	6,149.33	10,310.89	17,288.78	10,832.70	54.65	101.03	186.77	108.33
Clinton-Medina Transitional AU	Gas	—	—	—	—	8,986.25	11,627.12	15,044.10	11,770.64	89.78	136.71	208.17	141.25
Clinton-Medina Transitional Northeast AU	Gas	—	—	—	—	573.25	1,397.79	3,408.33	1,618.85	5.29	13.70	35.46	16.19
Tuscarora Basin Center AU	Gas	—	—	—	—	949.07	2,274.63	5,451.60	2,619.59	3.50	8.91	22.71	10.48
Utica Shale AU*	Gas	—	—	—	—	Hypothetical; did not assess quantitatively				—	—	—	—

*Added to the Utica-Lower Paleozoic Total Petroleum System by the author (R.T. Ryder) since the 2002 U.S. Geological Survey Appalachian basin assessment (Milici and others, 2003).