APPALACHIAN BASIN PROVINCE (067)

by R. T. Ryder

INTRODUCTION

The Appalachian Basin is a foreland basin containing Paleozoic sedimentary rocks of Early Cambrian through Early Permian age. From north to south, the Appalachian Basin Province crosses New York, Pennsylvania, eastern Ohio, West Virginia, western Maryland, eastern Kentucky, western Virginia, eastern Tennessee, northwestern Georgia, and northeastern Alabama.

In a clockwise direction, starting in northern New York, the Appalachian Basin is bounded by the following provinces: Adirondack Uplift (071), Blue Ridge Thrust Belt (068), Louisiana–Mississippi Salt Basins (049), Black Warrior Basin (065), and Cincinnati Arch (066). The northern end of the Appalachian Basin extends offshore into Lakes Erie and Ontario as far as the United States–Canada border. The northwestern flank of the basin is a broad homocline that dips gently southeastward off the Cincinnati Arch. A complexly thrust faulted and folded terrane (Appalachian Fold and Thrust Belt or Eastern Overthrust Belt), formed at the end of the Paleozoic by the Alleghenian orogeny, characterizes the eastern flank of the basin. Allochthonous metamorphic and igneous rocks of the Blue Ridge Thrust Belt that bounds the eastern part of the Appalachian Basin Province were thrust westward more than 150 mi over lower Paleozoic sedimentary rocks.

The Appalachian Basin province covers an area of about 185,500 sq mi. The province is 1,075 mi long from northeast to southwest and between 20 to 310 mi wide from northwest to southeast.

The Appalachian Basin has had a long history of oil and gas production, and much of it has not been systematically recorded; thus, there are no commercial data bases for field size and production history. An ad hoc field file consisting of about 1,100 fields was used in this assessment. It was compiled from published production records from the States of Pennsylvania, West Virginia, New York, and Tennessee which have been kept from the early 1960's; proprietary oil and gas, Energy Information Administration (EIA), U.S. Department of Energy Integrated Field File (OGIFF); published scientific articles and reports; and unpublished industry reports and records.

Discovery of oil in 1859 in the Drake well, Venango County, northwestern Pennsylvania, marked the beginning of the oil and gas industry in the Appalachian Basin. Oil in the Drake well was produced from an Upper Devonian stray sandstone at a depth of about 70 ft. This discovery well opened a prolific trend of oil and gas fields, producing from Upper Devonian, Mississippian, and Pennsylvanian sandstone reservoirs, that extends from southern New York, across western Pennsylvania, central West Virginia, and eastern Ohio, to eastern Kentucky. From 1859 through 1993, approximately 2.3 BBO and 31 TCFG have been produced from the trend. Primary annual oil production in the trend peaked at about 36.3 MMBO in 1900, whereas oil production from secondary recovery peaked at about 37.6 MMBO in 1937. Exploration in the trend presently is for gas in low-permeability sandstone reservoirs at depths between 4,500 and 6,000 ft.

A second major trend of oil and gas production in the Appalachian Basin began with the discovery in 1885 of oil and gas in Lower Silurian "Clinton" sandstone reservoirs in Knox County, Ohio. By the late 1880's and early 1900's, the trend extended both north and south across east-central Ohio and included several counties in western New York where gas was discovered in Lower Silurian Medina Group sandstones. Hydrofrac techniques introduced in the early 1950's greatly improved oil and gas recovery from "Clinton" and Medina sandstones and thus encouraged exploration to depths greater than 4,000 ft. The Lower Silurian "Clinton" and Medina sandstone trend now extends across most of central and eastern Ohio, northwestern Pennsylvania, western New York, and a small part of northeastern Kentucky. From 1885 through 1993 approximately 345 MMBO and 7.5 TCFG have been produced from the trend. Current exploration in the trend is for gas in low-permeability sandstone reservoirs at depths between 5,500 and 7,000 ft.

About 1900, large oil reserves were discovered in Silurian and Devonian carbonate reservoirs in east-central Kentucky. Truncation traps beneath a widespread pre-Upper Devonian unconformity and low-amplitude anticlines control most of the accumulations. The high-quality limestone and dolomite reservoirs resulted from extensive subaerial exposure and karst processes. Drilling depths to the reservoirs range from about 800 to 2,500 ft. This trend is confined to east-central Kentucky where, between 1900 and the end of 1993, approximately 162.5 MMBO and 205 BCF of associated gas were produced. Now the trend is almost exhausted.

Important gas discoveries from the Lower Devonian Oriskany Sandstone in Cambridge County, Ohio, in 1924, Schuyler County, New York, in 1930, and Kanawha County, West Virginia, in 1936 opened a major gas-producing trend across parts of New York, Pennsylvania, Maryland, Ohio, West Virginia, Kentucky, and Virginia. Early gas exploration was concentrated in the western part of the trend where the gas was trapped in high-porosity sandstone by updip pinchouts, broad anticlines, and combination traps. By the 1950's, exploration for Oriskany gas moved eastward into deeper and structurally more complex parts of the basin where highly compressed, thrust-faulted anticlines are the traps, and fracture porosity has improved the quality of the tightly cemented reservoirs. Fractured Middle Devonian Huntersville Chert, which overlies the Oriskany Sandstone, is an important reservoir in the Oriskany Sandstone gas-producing trend in Pennsylvania, West Virginia, and Maryland. Approximately 2.9 TCFG have been produced from this trend through 1993. Exploration is still active in the trend for gas trapped in faulted anticlines at depths between 6,000 and 9,000 ft.

The most recent drilling boom in the Appalachian Basin occurred in the 1960's in Morrow County, Ohio, where oil was discovered at about 3,000 ft in the Upper Cambrian part of the Knox Dolomite. Paleotopographic highs beneath the widespread Middle Ordovician Knox unconformity provide the traps. The reservoirs consist of vuggy dolomite formed by prolonged subaerial exposure and karst processes. About 60 MMBO and 30 BCF of associated gas have been produced from Morrow County and several adjoining counties through 1993. Exploration continues in Ohio for fields beneath the Knox unconformity, but the activity has shifted eastward where the objective is gas and condensate in the Late Cambrian(?) Rose Run Sandstone and Lower Ordovician part of the Knox Dolomite (Beekmantown Dolomite).

The Appalachian Basin has produced about 3 BBO and 42 TCFG through 1993. Among the largest oil fields in the basin are Bradford (McKean Co., Pa., and Allegheny Co., N.Y.), discovery date 1871, reservoir Upper Devonian Bradford sandstones, ultimate recovery 680 MMBO; East Canton (Stark Co., Ohio), discovery date 1966, reservoir Lower Silurian "Clinton" sandstone, ultimate recovery 100 MMBO; Big Sinking (Estill and Lee Counties, Ky.), discovery date 1918, reservoir Upper Silurian and Middle Devonian "Corniferous" limestone, ultimate recovery 80 MMBO; Fairview-Statler Run-Mt. Morris, (Monongalia County, W.Va.), discovery date 1890, reservoir Lower Mississippian Big Injun sandstone, ultimate recovery 32 MMBO. The largest gas fields include Big Sandy area, eastern Kentucky and adjoining West Virginia, discovery date 1892 (major development of shale gas began in 1920's), reservoir(s) Upper Devonian black shale and Mississippian and Pennsylvanian sandstone, ultimate recovery >3 TCFG; Elk-Poca, Kanawha County, W. Va., discovery date 1936, reservoir Lower Devonian Oriskany Sandstone, ultimate recovery 1 TCFG; Lakeshore, Chautauqua County, N.Y., discovery date 1904, reservoir Lower Silurian Medina Group sandstones, ultimate recovery 650 BCFG; Driftwood, Cameron County, Pa., discovery date 1951, reservoir Lower Devonian Oriskany Sandstone, ultimate recovery 260 BCFG.

Deep drilling in the late 1970's and early 1980's for gas in the Appalachian Fold and Thrust Belt east of the Allegheny structural front has been unsuccessful. Potential reservoirs in the Upper Cambrian and Lower Ordovician Knox Group (dolomite), Middle Ordovician Trenton Group (limestone), and Tuscarora Sandstone were primary objectives. In addition to two small oil fields discovered in southwesternmost Virginia in 1949 and 1963, this part of the Appalachian Basin has yielded only five or six small gas fields.

Equally disappointing were the results of deep drilling in the 1970's for gas in the Rome Trough of Pennsylvania, West Virginia, and Kentucky. This Middle Cambrian rift basin, with prospective Middle Cambrian sandstone and carbonate reservoirs, has been tested by about 20 drill holes that end in Middle Proterozoic basement rock. Several of these drill holes in west-central West Virginia exceed depths of 19,000 ft. Discoveries in the Rome Trough have been limited to one small oil field and several good gas shows.

Exploration in the last 10 years has focused primarily on the following objectives: gas in low-permeability sandstone reservoirs of the Lower Silurian "Clinton" sandstone and Medina Group in eastern Ohio, northwestern Pennsylvania, and western New York; gas in low-permeability sandstone reservoirs of the Upper Devonian sequence in central Pennsylvania and east-central West Virginia; gas in the Lower Devonian Oriskany Sandstone and overlying Middle Devonian Huntersville Chert trapped by thrust-faulted anticlines (New York, Pennsylvania, and West Virginia); gas in fractured Middle and Upper Devonian black shale in New York, Pennsylvania, Ohio, West Virginia, Kentucky, and Virginia; and gas in the Upper Cambrian(?) Rose Run Sandstone and Lower Ordovician part of the Knox Dolomite (Beekmantown Dolomite) trapped beneath the Knox unconformity in eastern Ohio.

Nineteen conventional plays and 16 unconventional plays are recognized in this province for this assessment. Of the 16 unconventional plays, 12 are in continuous-type accumulations and 4 are coalbed gas plays. R.C. Milici has described those continuous-type plays in the Devonian black shale. Dudley D. Rice and Thomas M. Finn have described the coalbed gas plays; further discussion of and references for coalbed gas plays may be found in Rice's chapter "Geologic framework and description of coalbed gas plays" elsewhere in this CD-ROM.

The plays are listed below numerically; unconventional plays are shown in italics. In the text, the conventional plays will be described and followed, in general, by the unconventional plays. One exception is the Tuscarora Sandstone and Clinton/Medina Sandstone group of plays 6727 through 6732 which are discussed together; this group includes both conventional and unconventional plays; the narrative for the group begins with the conventional Tuscarora Sandstone Gas Play (6727). A similar exception is the group of Upper Devonian sandstone plays 6733 through 6737 which are also discussed together, beginning with unconventional play 6733, Upper Devonian Sandstone Gas High Potential Play, and also includes both conventional and unconventional plays.

6701 Rome Trough

6702 Upper Cambrian, Ordovician, and Lower/Middle Silurian Thrust Belt

6703 Beekmantown/Knox Carbonate Oil/Gas

6704 Rose Run/Gatesburg/Theresa Sandstone Gas

6706 Trenton/Black River Carbonate Oil/Gas

6708 Queenston/Bald Eagle Sandstone Gas

6714 Keefer/Big Six Sandstone Gas

6715 "Corniferous Limestone" /Big Six Sandstone Oil/Gas

6716 Upper Silurian Sandstone Gas

6717 Silurian Carbonate Gas

6718 Silurian and Devonian Carbonate Thrust Belt

6719 Devonian Carbonate Gas

6720 Oriskany Sandstone Gas/Faulted Anticlines

6721 Oriskany Sandstone Gas

6725 Mississippian and Pennsylvanian Sandstone/Carbonate

6727 Tuscarora Sandstone Gas

6728 *Clinton/Medina Sandstone Gas High Potential*

6729 *Clinton/Medina Sandstone Gas Medium Potential*

6730 *Clinton/Medina Sandstone Gas Medium-Low Potential*

6731 *Clinton/Medina Sandstone Gas Low Potential*

6732 Clinton/Medina Sandstone Oil/Gas

6733 *Upper Devonian Sandstone Gas High Potential*
6734 *Upper Devonian Sandstone Gas Medium Potential*
6735 *Upper Devonian Sandstone Gas Medium-Low Potential*
6736 *Upper Devonian Sandstone Gas Low Potential*
6737 Upper Devonian Sandstone Oil/Gas
6740 *Devonian Black Shale-Greater Big Sandy*
6741 *Devonian Black Shale -Greater Siltstone Content*
6742 *Devonian Black Shale-Lower Thermal Maturity*
6743 *Devonian Black Shale-Undeveloped NE Ohio and Western Pennsylvania*
6750 *Northern Appalachian Basin–Anticline*
6751 *Northern Appalachian Basin–Syncline*
6752 *Central Appalachian Basin–Central Basin*
6753 *Cahaba Coal Field*

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CONVENTIONAL AND UNCONVENTIONAL PLAYS

6701. ROME TROUGH PLAY (HYPOTHETICAL)

The Rome Trough is a narrow northeast-trending rift basin that underlies the Appalachian Basin in Pennsylvania, West Virginia, and Kentucky. Approximately 6,000 – 9,000 ft of Lower and Middle Cambrian shallow-marine to peritidal carbonate, sandstone, and shale fill the rift. The Rome Trough Play is defined by gas trapped in sandstone and carbonate reservoirs within the rift by basement-controlled fault blocks and anticlines. Stratigraphically, the play involves the Lower and Middle Cambrian Rome Formation and the Middle and Upper Cambrian Conasauga Group. The play is hypothetical and is confined mostly to the Kentucky and West Virginia part of the Rome Trough. The sandstone and carbonate reservoirs are classified as conventional.

Reservoirs: Sandstone in axial and basin-margin locations with respect to the rift system are important reservoirs in the play. Axial sandstone deposits generally are more quartzose in composition and better sorted than the basin margin sandstones, and they contain abundant carbonate grains. Locally, the axial sandstone deposits are so calcareous that they are more appropriately identified as sandy limestone. Both the axial and basin-margin sandstone facies contain feldspar, but the latter facies generally contains the most because of its closer proximity to granitic terranes. Deep burial diagenesis has occluded much of the primary porosity in the axial and basin-margin sandstones with silica and calcite cement. Most intergranular porosity that remains is secondary in nature, having resulted from the dissolution of feldspar and carbonate grains and carbonate cement.

Vuggy limestone and dolomite, created by brief subaerial exposure and karst processes, are potential reservoirs. Limestone reservoirs having oomoldic and biomoldic porosity and secondary intergranular porosity may be present.

Very likely, tectonic fractures are required to improve the quality of the sandstone and limestone reservoirs. In some cases, fractures may be the sole cause of a reservoir's porosity and permeability. Fractures are abundant in the rift-fill sequence as a result of multiple periods of reactivation along fault-bounded basement blocks, but there is some question as to whether or not they are still open at depths greater than 10,000 ft.

Source rocks: Dark-gray to black shale and argillaceous limestone in the Conasauga Group and upper part of the Rome Formation are the likely sources of gas and local oil in the play. Individual shale beds are no thicker than about 1 ft, but their cumulative thickness may be several tens of feet. Argillaceous limestone sequences may be as thick as 150 – 200 ft. TOC values of the dark-gray to black shale and limestone in the Conasauga Group and Rome Formation range from 0.05 to 0.59 percent (avg 0.27, n=22). Because of their high level of thermal maturation, the type of organic matter in the shale and limestone could not be determined.

Scattered CAI and T_{max} values indicate that the rift-fill sequence in the northern West Virginia and Pennsylvania parts of the Rome Trough is overmature with respect to the generation of oil and gas. In central and southern West Virginia the Rome Trough is in the late stages of the gas generation zone, whereas in eastern Kentucky the Rome Trough is in the late stages of the oil generation zone. Dry thermal gas is the expected hydrocarbon type in most of the Rome Trough. In the Kentucky part of the Rome Trough local oil is expected to be associated with the dry gas.

Timing and migration: Oil and gas generation from the Conasauga Group and Rome Formation in the Rome Trough probably occurred from latest Ordovician to Late Devonian time, depending on local thermal and burial conditions. Most of the oil and gas generated at this time was trapped in nearby structures formed by extensional and(or) transtensional tectonics. Many of the original traps were modified by later compressional events such as the late Paleozoic Alleghenian orogeny, and, thus, oil and gas might have been redistributed to younger traps or lost.

Traps: Faulted rollover anticlines, tilted fault blocks, and positive flower structures are the major traps expected in the play. Closure on these structural traps may cover an area as large as 10,000 acres. The traps are most likely to be present between the depths of 8,000 and 15,000 ft. Seals for the structural traps are micrite and argillaceous micrite of the Conasauga Group and shale and siltstone of the Rome Formation. Abnormally high formation pressure measured in parts of the Rome Trough indicates that the seals are very efficient.

Exploration status: No more than 50 holes have been drilled through all or part of the rift-sequence in the Rome Trough. Several good gas and oil shows have been reported, the best of which was an initial potential flow of between 5 and 9 MMCFGPD from the Exxon No. 1 McCoy well in Jackson County, West Virginia. The well produced briefly before it was abandoned in 1975. The Mavity oil field, discovered in 1967 in Boyd County, Kentucky, produced about 10,000 BO in 1-1/2 years from a sandstone in the upper part of the Conasauga Group.

Resource potential: This play has potential for several undiscovered gas fields greater than 6 BCFG. A small oil field and good gas and oil shows indicate that hydrocarbons are present in the rift sequence. Moreover, numerous structures in the Rome Trough have not been tested. Several factors may limit the potential of the play: (1) reservoirs may be widely scattered and of low quality, (2) source beds may be very local and lean, and (3) numerous episodes of basement-fault reactivation may have permitted much of the gas to escape.

6702. UPPER CAMBRIAN, ORDOVICIAN, AND LOWER/MIDDLE SILURIAN THRUST BELT PLAY

The Upper Cambrian, Ordovician, and Lower/Middle Silurian Thrust Belt Play is defined by gas trapped in anticlines of the Appalachian Fold and Thrust Belt between, approximately, the Allegheny structural front on the west and the Blue Ridge structural front and thrust fault on the east. Dolomite, limestone, and sandstone reservoirs are prospective. Stratigraphically, the play involves the Upper Cambrian and Lower Ordovician Knox Group, Upper Cambrian Gatesburg Formation, Lower Ordovician and lower Middle Ordovician Beekmantown Group, Middle Ordovician Black River, Trenton, and Chickamauga Limestones, Upper Ordovician Bald Eagle (Oswego) Sandstone, Lower Silurian Tuscarora (Clinch) Sandstone, and Middle Silurian Keefer Sandstone. The play is confirmed and extends from New York to Alabama. The prospective reservoirs are classified as conventional.

Reservoirs: Platform dolomite and limestone that have vuggy porosity are important reservoirs in the play. The vuggy porosity was caused largely by karst processes and (or) by migrating deep basin fluids. Although these zones of vuggy porosity are capable of producing high-quality reservoirs in general, they probably are very discontinuous and heterogeneous in the play area. Among the most extensive zones of vuggy porosity are those formed beneath the Middle Ordovician Knox unconformity as a result of widespread subaerial exposure and karst activity. Limestone containing zones of oomoldic and biomoldic porosity, formed by one or more dissolution mechanisms, represents reservoirs of secondary importance.

Sandstone of shallow-marine, fluvial, and deltaic origin constitute a second group of important reservoirs. The composition of the sandstones range from quartzarenite to litharenite, and their feldspar content ranges from several percent to as much as 10 percent. Burial diagenesis has plugged much of the primary porosity in the sandstones with silica and calcite cement. Secondary intergranular porosity caused by the dissolution of feldspar, rock fragments, and cement is the dominant porosity type in the sandstone reservoirs. Locally, primary intergranular porosity has been preserved by unusual circumstances such as grain coatings of iron-rich cement.

Tectonic fractures greatly improve the quality of the carbonate and sandstone reservoirs and, in some cases, may be the sole cause of the reservoir. Fractures are commonly associated with faulted ramp anticlines, imbricate fault slices, and decollement zones, but many of them are cemented by syn- and post-tectonic episodes of burial and fluid flow.

Source rocks: Black shale and argillaceous limestone in the Middle Ordovician Utica Shale, Antes Shale, Dolly Ridge Formation of the Trenton Group, Trenton Limestone, Martinsburg Formation (lower part), and Chickamauga Limestone are the most likely sources of gas and local oil in the play. The thickness of the black shale and limestone sequences ranges from 200 to 400 ft. Gas and oil generated from these source beds are required to migrate approximately 1,000 – 1,500 ft downsection to reach dolomite reservoirs in the Cambrian and Lower Ordovician sequence. In contrast, between 4,000 and 5,000 ft of upward vertical migration is required for oil and gas from Middle Ordovician source beds to reach Lower and Middle Silurian sandstone reservoirs.

Black shale and argillaceous limestone in the Middle Ordovician Jacksonburg Limestone, Liberty Hall Formation, Paperville Shale, Blockhouse Shale, Sevier Formation, and Athens Shale--now located in far-traveled thrust sheets along the eastern margin of the play area--may be source beds of secondary importance. These shale and limestone sequences are generally thicker and of deeper water origin than those in the western part of play, but hydrocarbons generated from them would have migrated a long distance to charge available reservoirs. Upper Devonian black shale may be a local source rock in southern Virginia and eastern Tennessee where it is overridden by frontal thrust slices of lower Paleozoic carbonate rocks.

TOC values in the Middle Ordovician black shale and argillaceous limestone sequences range from about 0.5 to 3 percent. Organic matter mostly consists of type II kerogen. Based on CAI and T_{max} values, the source beds in the Pennsylvania part of the play are overmature with respect to the generation of oil and gas. This region of overmature Middle Ordovician source beds continues northward into adjoining southeast New York and southward into adjoining western Maryland and eastern West Virginia. From northern Virginia and adjoining West Virginia the overmature region begins to narrow southward and follow the eastern limit of the play through southwestern Virginia, eastern Tennessee, northeastern Georgia, and eastern Alabama. The remainder of the play area, from northeastern West Virginia to east-central Alabama, is mainly in the gas generation zone. A narrow region along the western side of the play area in southwestern Virginia, east-central Tennessee, northwesternmost Georgia, and northeastern Alabama is in the oil generation zone. Dry thermal gas and local oil are the expected hydrocarbon types. Because of the generally high thermal maturity of the strata in the play area, high amounts of noncombustible gas may be mixed with the methane gas.

Timing and migration: Peak oil and gas generation from Middle Ordovician shale and argillaceous limestone source beds probably occurred between Late Pennsylvanian and Early Triassic time when these rocks were deeply buried under an eastward-thickening wedge of orogenic sediments and thrust sheets. Ramp anticlines formed during the Alleghenian orogeny (Pennsylvanian-Permian) were available to trap the hydrocarbons. Abnormally high formation pressures achieved in the source beds may have assisted the vertical migration of oil and (or) gas. Middle Ordovician source beds in the interior parts of the fold and thrust belt may have reached maturity at a slightly earlier time when fewer compressional structures were available to trap the oil and gas. Some of these hydrocarbons may have migrated up the adjoining northwest flank of the basin.

Traps: Faulted ramp anticlines and imbricate fault slices formed above zones of bedding plane detachment in Cambrian and (or) Ordovician shale are the major traps. Some of the traps are very complex with structural closure and(or) fracturing commonly occurring at several structural and stratigraphic levels and in different geographic locations. Closure on the traps may cover an area as large as 5,000 acres. The depth range to unexplored structural traps is between 10,000 and 15,000 ft.

Important shale and micrite seals are present in the Middle Ordovician part of the Beekmantown Group; Middle Ordovician Loysburg Formation, Blackford Formation, Lenoir Limestone, Chickamauga Limestone and Antes Shale; Upper Ordovician Reedsville Shale, Martinsburg Formation, Juniata Formation, and Sequatchie Formation; and the Middle Silurian Rose Hill Formation, Rochester Shale, and Mifflintown Formation.

Exploration status: Approximately 100 holes have been drilled to one or more of the objective reservoirs in the play, resulting in the discovery of several small oil and gas fields. The largest oil fields, Rose Hill and Ben Hur, located in Lee County, Virginia, produce oil from fractured limestone in the Middle Ordovician sequence. From 1946 through 1993, about 600,000 BO have been produced from the Rose Hill field. Possibly the production in this field will exceed 1 MMBO. One well in the field produces from fractured dolomite in the Knox Group. Another 1-well oil field was found in 1980 in the Middle Ordovician Stones River Group in Cumberland County, Tennessee.

The largest gas fields found to date produce from the Tuscarora Sandstone in Centre County, Pennsylvania, (discovery dates 1977 – 1982), and in Tucker and Preston Counties, West Virginia, (discovery date 1963). The Devils Elbow field (Centre Co., Pa.) and the Leadmine field (Tucker and Preston Cos., W. Va.,) will each ultimately produce at least 6 BCFG. Additional known gas fields in the play are an unnamed 1-well Knox field in Grainger County, Tennessee, and a 2-well Keefer Sandstone pool in the North Headsville field, Mineral County, West Virginia.

Resource potential: This play has potential for several undiscovered gas fields greater than 6 BCFG. Small oil and gas fields indicate that hydrocarbons are present in all the prospective reservoirs. Several factors may limit the potential of the play: (1) reservoirs may be widely scattered and low in quality, (2) although good source beds are present, they are in less than optimum positions to have charged prospective reservoirs, (3) 10 – 20 dry holes drilled in the 1980's have tested some of the most attractive structures in the play, and (4) post-Triassic uplift and erosion of the fold and thrust belt may have permitted most of the oil and gas to escape

6703. BEEKMANTOWN/KNOX CARBONATE OIL/GAS PLAY

The Beekmantown/Knox Carbonate Oil and Gas Play is defined by oil and gas trapped in Cambrian and Lower to lower Middle Ordovician platform dolomite reservoirs by truncation traps, paleotopographic highs, and low-amplitude basement-controlled anticlines. The play involves Cambrian and Lower Ordovician dolomite approximately between the Allegheny structural front and the western limit of the Appalachian Basin. This play area is northwest of the Valley and Ridge part of the Appalachian Fold and Thrust Belt and contains few, if any, bedding-plane detachment structures in pre-Upper Ordovician rocks. Stratigraphically, the play involves the Upper Cambrian and Lower Ordovician Knox Group and the Lower Ordovician and lower Middle Ordovician Beekmantown Group. Commonly, the Cambrian part of the Knox Dolomite in central Ohio is referred to as the Trempealeau Dolomite. Also included in the central Ohio part of the play are thin quartzose sandstones (for example, Krysik sandstone) intercalated with the Upper Cambrian dolomite.

The play is confirmed and extends across parts of New York, Pennsylvania, Ohio, West Virginia, Kentucky, Virginia, Tennessee, and Alabama. Prospective reservoirs in the play are classified as conventional.

Reservoirs: Dolomite that has vuggy and (or) fracture porosity is the most important reservoir in the play. The vuggy porosity formed by subaerial exposure and karst processes. Commonly, tectonic fracturing is required to improve the quality of the dolomite reservoirs. Most likely, the fracturing resulted from recurrent movement of fault-bounded basement blocks. Some of the fractures may have originated by the undermining and collapse of karst terranes.

The most porous and continuous zones of vuggy porosity are either directly beneath or within several hundred feet of the widespread Middle Ordovician Knox unconformity. Intercrystalline porosity in coarsely crystalline sparry dolomite supplements the vuggy porosity in these reservoirs. Periods of subaerial exposure of shorter duration have formed karst-related porous zones in dolomite far below the Knox unconformity. These zones may be suitable for oil and gas reservoirs, particularly if tectonic fractures and selective dissolution of unstable cement and intraclasts by circulating basin fluids have improved their porosity.

Source rocks: Black shale and argillaceous limestone in the Middle Ordovician Utica Shale, Antes Shale, Trenton Limestone, and Dolly Ridge Formation of the Trenton Group are the most likely sources of oil and gas in the New York, Pennsylvania, Ohio, and West Virginia parts of the play. The thickness of the black shale and limestone sequences ranges from 200 to 400 ft. Oil and gas are required to migrate approximately 1,000–1,500 ft downsection to reach dolomite reservoirs in the Cambrian and Lower Ordovician sequence. In Kentucky and adjoining western West Virginia, shale and argillaceous limestone in the Middle and Upper Cambrian Conasauga Group in the Rome Trough may be the source of oil and gas.

Black shale and argillaceous limestone is the Middle Ordovician Jacksonburg Limestone, Liberty Hall Formation, Paperville Shale, Blockhouse Shale, Sevier Formation, and Athens Shale--outside the play area in far-traveled thrust sheets along the eastern margin of the Valley and Ridge--may be source beds of secondary importance. These shale and limestone sequences are generally thicker and of deeper water origin than those sequences in the play area, but hydrocarbons generated from them would have migrated a long distance to charge available reservoirs. Oil and gas in the Virginia, Tennessee, and Alabama parts of the play probably depend on these source rocks.

TOC values in the Middle Ordovician black shale and argillaceous limestone sequences range from about 0.5 to 3 percent. Organic matter mostly consists of type II kerogen. Based on CAI and T_{max} values, Middle Ordovician source beds in the New York, Pennsylvania, eastern Ohio, and West Virginia parts of the play are in the gas generation zone. The gas generation zone continues into Kentucky where Cambrian shale and limestone in the Rome Trough, rather than Middle Ordovician shale and limestone, are probable source beds for the play. Middle Ordovician source beds in a narrow zone that adjoins the Allegheny structural front in Pennsylvania and New York are overmature with respect to oil and gas generation. In most of central and eastern Ohio, Middle Ordovician source beds are in the oil generation zone. Although Middle Ordovician rocks in southern Ohio, Kentucky, Tennessee, and Alabama are in the oil generation zone, they contain no known source rocks. Oil and thermal gas are the expected hydrocarbon types in the play.

Timing and migration: Peak oil and gas generation from Middle Ordovician shale and argillaceous limestone source beds probably occurred between Late Pennsylvanian and Early Triassic time when these rocks were deeply buried under an eastward-thickening wedge of orogenic sediments and thrust sheets. Much of the oil and gas that was generated from Middle Ordovician source beds migrated up the gently dipping northwest flank of the basin along porous carbonate horizons beneath the Knox unconformity. Numerous stratigraphic traps and a modest number of anticlinal traps were available to entrap the migrating hydrocarbons. As the zone of oil and gas generation expanded northward and westward with increasing burial, traps on the homoclinal northwest flank of the basin became charged with locally derived hydrocarbons.

Cambrian source beds in the Rome Trough of Kentucky and adjoining West Virginia probably reached the oil and gas generation zone in latest Ordovician to Late Devonian time. Some of this oil and gas may have migrated vertically upward into Cambrian and Lower Ordovician reservoirs and become trapped in basement-involved fault blocks and anticlines.

Traps: Truncation traps and paleotopographic hills beneath the Knox unconformity are principal traps in the play. Commonly, these traps are combined with small anticlines, anticlinal noses, and faults. These stratigraphic traps cover an area as large as 2,000 acres. Low-amplitude anticlines controlled by basement tectonics also may be important traps in the play. In general, these structural traps are larger than the stratigraphic traps and, because of their history of recurrent growth, may be associated with fracture-enhanced reservoirs.

Important seals in the play are green shale and argillaceous dolomite in the Middle Ordovician Wells Creek Formation (Dolomite), Shadow Lake Formation, and Pamelia Formation and anhydritic dolomicrite and local shale in the lower Middle Ordovician part of the Beekmantown Group. These units directly overlie the Knox unconformity throughout much of the play area. Also, thick dolomicrite units separating karst-related porous zones in the Knox and Beekmantown Group are good seals.

Exploration status: The Morrow County, Ohio, oil boom in the early 1960's led to the discovery of 50 – 75 oil fields trapped in Cambrian dolomite beneath the Knox unconformity. Drilling depths to the reservoir range from 3,000 to 4,000 ft. About 29 of the fields are equal to or greater than 1 MMBO in size, the largest of which has an ultimate recovery of approximately 15 MMBO. Through 1993, about 60 MMBO and 30 BCF of associated gas have been produced from Morrow County and adjoining counties. The largest fields in the trend are Cardington East, ultimate recovery ~15 MMBO; Denmark, ultimate recovery ~7.5 MMBO; and Woodbury South, ultimate recovery ~6.2 MMBO.

Gas and minor oil accumulations were discovered in the Lower Ordovician Beekmantown Group (Dolomite) of eastern Ohio and northwestern Pennsylvania in the late 1960's through the early 1980's. Most of the gas is in 1-well fields at depths between 8,000 and 10,000 ft. Several gas wells in Columbiana County, Ohio, produced briefly at a rate of 10 – 14.5 MMCFGPD. Bakersville, the largest Beekmantown field, is in Coshocton County, Ohio. Discovered in 1980 along the Upper Cambrian(?) Rose Run Sandstone producing trend, this field produces gas and minor condensate from fractured vuggy dolomite at a depth of 6,700 ft. An ultimate recovery of 14 BCFG is expected for the field.

About 14 small gas fields, some with minor associated oil, have been discovered in the Knox Group in Kentucky. The largest gas accumulation is a deeper pool extension of the Mine Fork field, Johnson County, Kentucky, discovered in 1980 by Ashland Oil Company. Located along the Irvine-Paint Creek basement fault, this 3- to 4-well field has yielded an unknown quantity of gas from the Knox Group. A group of subcommercial gas fields (Raccoon Mountain, Fogertown, Trixie, and Chavie), with commingled production from Knox dolomite and Middle Ordovician limestone reservoirs, is along the basement controlled Rockcastle River uplift in Laurel, Clay, and possibly Perry Counties, Kentucky.

Resource potential: This play has potential for a modest number of undiscovered oil and gas fields greater than 1 MMBO or 6 BCFG. Prospective stratigraphic and anticlinal traps are very subtle and could easily have been overlooked in previous seismic surveys and exploration phases. The relatively late discovery (1980) of the largest gas field in the play and recent discoveries of oil and gas in Licking and Pickaway Counties, Ohio, in Cambrian dolomite and sandstone suggest that more fields remain to be found. There are large areas that are sparsely drilled to the Knox and Beekmantown Groups. A limiting factor in the play may be that reservoirs east and south of the Morrow County trend are widely scattered and of low quality.

6704. ROSE RUN/GATESBURG/THERESA SANDSTONE GAS PLAY

The Rose Run/Gatesburg/Theresa Sandstone Gas Play is defined by gas trapped in Upper Cambrian(?) shelf sandstone reservoirs by truncation traps, paleotopographic highs, and low-amplitude, basement-controlled anticlines. Stratigraphically, the play involves the Upper Cambrian(?) Rose Run Sandstone, lower and upper sandy members of the Gatesburg Formation, lower and upper sandstone members of the Copper Ridge Dolomite, and Theresa Formation.

The play covers western New York, western Pennsylvania, eastern Ohio, westernmost Maryland, western West Virginia, and northeastern Kentucky. In Ohio, the western limit of the play is marked by the northeast-trending subcrop of the Rose Run Sandstone beneath the Knox unconformity. The truncated western limit of Cambrian sandstones in the play continues from Ohio into northwesternmost Pennsylvania and western New York. The western boundary of the play in eastern Kentucky is defined by the depositional limit of the Rose Run Sandstone. Prospective sandstone in the play extends eastward to a poorly defined depositional limit in eastern New York, central Pennsylvania, eastern West Virginia, and southeast Kentucky controlled in part by post-rift subsidence of the Rome Trough. Most of the play area is northwest of the Valley and Ridge part of the Appalachian Fold and Thrust Belt and contains few, if any, bedding plane detachment structures in pre-Upper Ordovician rocks. The play is confirmed, and its prospective reservoirs are classified as conventional.

Reservoirs: The reservoirs in the play are sandstone of shallow-marine shelf and peritidal origin. They are in 50–150-foot-thick sandstone-dominated sequences containing numerous thin- to medium-sized beds of dolomite. Commonly the sandstone beds in the sequences thicken progressively upward at the expense of the dolomite beds. In the Rome Trough of southern Pennsylvania the sandstone-dominated sequences are as thick as 400 ft. Lateral continuity and reservoir quality of the sandstones are diminished by their close depositional and diagenetic association with dolomite lithofacies.

The sandstones consist of quartzarenite, subarkose, and arkose. Secondary intergranular porosity, caused by dissolution of feldspar grains and dolomite cement, is the dominant porosity type. Porosity values in the Ohio and northwestern Pennsylvania part of the play range from <1 to 25 percent (avg ~7), and permeability values range from <0.1 to 240 mD (avg ~5). Drilling depths to reservoirs in this part of the play range from about 6,000–8,000 ft. These reservoirs are among the most porous and continuous in the play because of their location either directly beneath or within several hundred feet of the Knox unconformity. Lower porosity and permeability values are expected in easternmost Ohio, central West Virginia, and west-central Pennsylvania where drilling depths to the Upper Cambrian sandstones exceed 9,000 ft and the dolomite section between the Knox unconformity and the sandstones is thicker. There, tectonic fracturing and extreme dissolution of unstable grains and cement are necessary to increase reservoir quality.

Source rocks: Black shale and argillaceous limestone in the Middle Ordovician Utica Shale, Antes Shale, Trenton Limestone, and Dolly Ridge Formation of the Trenton Group are the most likely sources of gas and local oil in the play. The thickness of the black shale and limestone sequences ranges from 200 to 400 ft. Approximately 1,000 – 1,500 ft of downward migration is required for oil and gas to reach Cambrian sandstones directly beneath the Knox unconformity, whereas 2,000 – 3,000 ft of downward migration is required to reach sandstones separated from the Knox unconformity by dolomite from the Beekmantown Group. Shale and argillaceous limestone in the Middle to Late Cambrian Conasauga Group and equivalent Pleasant Hill Limestone may be a source of gas in the eastern Kentucky part of the play where Middle Ordovician source beds are absent and in central Pennsylvania and central West Virginia where about 3,000 ft of micrite and dolomicrite separate sandstone reservoirs from Middle Ordovician source beds.

TOC values in the Middle Ordovician black shale and limestone sequences range from about 0.5 to 3 percent. Organic matter largely consists of type II kerogen. Based on CAI and T_{max} values, Middle Ordovician source beds across most of the play are in the gas generation zone. The gas generation zone extends into eastern Kentucky where Cambrian shale and limestone in the Rome Trough, rather than Middle Ordovician shale and limestone, are probable source beds for the play. Middle Ordovician source beds in a narrow zone that adjoins the Allegheny structural front in Pennsylvania are overmature with respect to oil and gas generation. The oil generation zone for Middle Ordovician source beds crosses most of the Ohio part of the play and extends into northwesternmost Pennsylvania and New York. Although Middle Ordovician rocks in southern Ohio and east-central Kentucky are in the oil generation zone, they contain no known source rocks. Dry and wet thermal gas and local oil and condensate are the expected hydrocarbon types in the play.

Timing and migration: Peak oil and gas generation from the Middle Ordovician shale and argillaceous limestone source beds probably occurred between Late Pennsylvanian and Early Triassic time when these rocks were deeply buried under an eastward thickening wedge of orogenic sediments and thrust sheets. Much of the oil and gas that was generated from Middle Ordovician source beds migrated up the gently dipping northwest flank of the basin along porous carbonate horizons beneath the Knox unconformity. Numerous stratigraphic traps and a modest number of anticlinal traps were available along the Rose Run Sandstone subcrop to entrap migrating hydrocarbons. East of the subcrop belt, some oil and gas may have worked their way downsection through 1,000 ft or more of Beekmantown Group dolomite to the Rose Run Sandstone and became trapped in anticlinal structures.

Cambrian source beds in the Rome Trough of Kentucky, West Virginia, and Pennsylvania probably reached the oil and gas generation zone in latest Ordovician to Late Devonian time. Some of this oil and gas may have migrated vertically upward into Upper Cambrian sandstone reservoirs and become trapped in basement-involved fault blocks and anticlines.

Traps: Truncation traps and paleotopographic hills beneath the Knox unconformity are principal traps in the play. Commonly, these traps are combined with small anticlines, anticlinal noses, and faults. Paleotopographic hills typically cover an area of 80 acres or less but locally may be a large as 2,000 acres. Low-amplitude anticlines controlled by basement tectonics also may be important traps in the play. In general, these structural traps are larger than the stratigraphic traps and, because of their history of recurrent growth, may be associated with fracture-enhanced reservoirs.

Important seals in the play are green shale and argillaceous dolomite in the Middle Ordovician Wells Creek Formation, Shadow Lake Formation, and Pamelia Formation that directly overlie the Rose Run Sandstone subcrop. Also, dolomicrite beds in the Beekmantown Group are good seals for Rose Run Sandstone gas accumulations east of the subcrop belt.

Exploration status: Exploration along the Rose Run Sandstone subcrop trend in eastern Ohio, between the late 1970's and the present, has led to the discovery of about 25 gas fields. Most of the fields are concentrated in Coshocton County, Ohio, and adjoining Holmes and Tuscarawas Counties; however, fields are scattered over at least six additional counties. The trend continues into northwesternmost Pennsylvania and western New York where small gas fields produce from the upper sandy member of the Gatesburg Formation and Theresa Formation, respectively. Drilling depths to the Rose Run Sandstone reservoir in Ohio range from 6,000 to 8,000 ft. Through 1991 about 21.5 BCFG and 0.5 MMBO have been produced from the Rose Run Sandstone. Three fields are equal to or greater than 6 BCFG in size: Baltic, (Holmes Co., Ohio), discovery date 1965, ultimate recovery ~50 BCFG; White Eyes, (Coshocton Co., Ohio), discovery date 1975, ultimate recovery ~8 BCFG; and Bakersville West, (Coshocton Co., Ohio), discovery date 1980, ultimate recovery ~6 BCFG.

The number of gas fields in the Rose Run Sandstone diminishes markedly east of the subcrop belt. Gas was briefly produced from subcommercial one-well fields in Noble County, Ohio, (drilling depth ~9,000 ft), Harrison County, Ohio, (drilling depth ~8,500 ft), and McKean County, Pennsylvania, (Minard Run pool, drilling depth ~10,000 ft). Basement-controlled fault blocks and anticlines have trapped these minor accumulations.

Resource potential: This play has potential for a modest number of undiscovered gas fields greater than 6 BCFG. Many prospective stratigraphic and anticlinal traps are very subtle and could easily have been overlooked in previous seismic surveys and exploration phases. The recent surge of discoveries in the play and the extension of the play southward into Licking and Pickaway Counties, Ohio, suggest that more fields remain to be found. There are large areas that have been sparsely drilled to the Rose Run Sandstone and equivalent Upper Cambrian reservoirs. Limiting factors for the play east of the subcrop trend may be (1) reservoirs are widely scattered and of low quality and (2) Middle Ordovician source beds are too far removed to charge the reservoirs.

6706. TRENTON/BLACK RIVER CARBONATE OIL/GAS PLAY

The Trenton/Black River Carbonate Oil/Gas Play is defined by oil and gas trapped in Middle Ordovician platform limestone reservoirs by facies-change stratigraphic traps, low-amplitude basement-controlled anticlines, dolomitized fracture zones, and natural fractures. The play involves Middle Ordovician limestone approximately between the Allegheny structural front and the western limit of the Appalachian basin. This play area is northwest of the Valley and Ridge part of the Appalachian Fold and Thrust Belt and contains few, if any, bedding-plane detachment structures in pre-Upper Ordovician rocks. Stratigraphically, the play involves the Middle Ordovician Trenton Group (Limestone), Black River Group (Limestone), Lexington Limestone (in part Upper Ordovician), High Bridge Group, Stones River Group, Nashville Group (in part Upper Ordovician), and Chickamauga Group (Limestone). Also included in the eastern Kentucky part of the play is quartzose sandstone of the St. Peter Sandstone that rests directly on the Knox unconformity.

The play is confirmed and extends across parts of New York, Pennsylvania, Ohio, West Virginia, Kentucky, Virginia, Tennessee, and Alabama. Most prospective reservoirs in the play are conventional.

Reservoirs: Fractured micrite of the Trenton Limestone is an important gas reservoir in north-central New York. Fractures are most common in the transition zone between the Trenton Limestone and overlying Utica Shale where limestone beds are intercalated with thin black shale beds. Recurrent movement of fault-bounded basement blocks and differential stretching of anticlinal flanks account for most of the fracturing. Fractured limestone reservoirs in New York State cover an area as large as 10,000 acres.

Narrow fault-controlled zones of dolomitized limestone, akin to those in the Albian-Scipio field of the Michigan Basin, are recognized in the Trenton and Black River Limestones of central New York and east-central Ohio. Coarsely crystalline sparry dolomite in the dolomitized fracture zones provide high-quality reservoirs with vuggy and intercrystalline porosity.

Another reservoir in the play is bioclastic limestone that has vuggy (biomoldic) porosity. Vugs were formed mostly by the leaching of fossil fragments during brief periods of subaerial exposure. These reservoirs are most commonly present in the

Lexington Limestone and High Bridge Group of Kentucky and the Nashville and Stones River Groups in Tennessee.

Source rocks: Black shale and argillaceous limestone in the Middle Ordovician Utica Shale, Antes Shale, Trenton Limestone, and Dolly Ridge Formation of the Trenton Group are the most likely sources of oil and gas in the New York, Pennsylvania, Ohio, and West Virginia parts of the play. The black shale and limestone sequences are between 200 and 400 ft thick and they rest directly on or within several hundred feet of reservoir units. In Kentucky and adjoining western West Virginia, shale and argillaceous limestone in the Middle and Upper Cambrian Conasauga Group in the Rome Trough may be the source of oil and gas.

Black shale and argillaceous limestone in the Middle Ordovician Jacksonburg Limestone, Liberty Hall Formation, Paperville Shale, Sevier Formation, and Athens Shale--located outside the play area in far-traveled thrust sheets along the eastern margin of the Valley and Ridge--may be source beds of secondary importance. These shale and limestone sequences are generally thicker and of deeper water origin than those sequences in the play area, but hydrocarbons generated from them would have migrated a long distance to charge available reservoirs. Oil and gas in the Virginia, Tennessee, and Alabama parts of the play probably depend on these source rocks.

TOC values in the Middle Ordovician black shale and argillaceous limestone sequences range from about 0.5 to 3 percent. Organic matter mostly consists of type II kerogen. Based on CAI and T_{max} values, Middle Ordovician source beds in the New York, Pennsylvania, eastern Ohio, and West Virginia parts of the play are in the gas generation zone. The gas generation zone continues into Kentucky where Cambrian shale and limestone in the Rome Trough, rather than Middle Ordovician shale and limestone, are probable source beds for the play. Middle Ordovician source beds in a narrow zone that adjoins the Allegheny structural front in Pennsylvania and New York are overmature with respect to oil and gas generation. In most of central and eastern Ohio, Middle Ordovician source beds are in the oil generation zone. Although Middle Ordovician rocks in southern Ohio and contiguous Kentucky, Tennessee, and Alabama are in the oil generation zone, they contain no known source beds. Oil and thermal gas are the expected hydrocarbon types in the play.

Timing and migration: Peak oil and gas generation from Middle Ordovician shale and argillaceous limestone source beds probably occurred between Late Pennsylvanian and Early Triassic time when these beds were deeply buried under an eastward-thickening wedge of orogenic sediments and thrust sheets. Much of the oil and gas that was generated from Middle Ordovician source beds migrated up the gently dipping northwest flank of the basin along porous carbonate horizons beneath the Knox unconformity. Some of this oil and gas was trapped in Trenton and Black River Limestones as it migrated to the Knox unconformity. A modest number of stratigraphic and anticlinal traps were available to trap the migrating hydrocarbons. As the zone of oil and gas generation expanded northward and westward with increasing burial, traps on the homoclinal northwest flank of the basin became charged with locally-derived hydrocarbons.

Cambrian source beds in the Rome Trough of Kentucky and adjoining West Virginia probably reached the oil and gas generation zone in latest Ordovician to Late Devonian time. Some of this oil and gas may have migrated vertically upward into Middle Ordovician limestone reservoirs and become trapped in basement-involved fault blocks and anticlines.

Traps: A variety of oil and gas traps are present in the play. They consist of stratigraphic traps of the facies-change variety, diagenetic traps characterized by fault-controlled coarsely crystalline dolomite pinching out into nonporous micrite, low-amplitude, basement-controlled anticlines, and highly fractured limestone.

Important seals in the play are black shale of the Middle Ordovician Utica and Antes Shales and thick gray shale of the Upper Ordovician Reedsville Shale, Lorraine Shale, and Clays Ferry Formation. In the southern part of the play the seals consist of shale and argillaceous micrite of the Upper Ordovician part of the Nashville Group and the Upper Ordovician Sequatchie Formation.

Exploration status: Between 1879 and 1933, 11 gas fields were discovered in fractured Trenton Limestone reservoirs in north-central New York. Drilling depths to the reservoir vary from less than 1,000 to about 2,500 ft. Most of the fields are now abandoned. A twelfth field, the Blue Tail Rooster, discovered in 1966, is still producing. The largest fields in the trend are Pulaski, ultimate recovery ~23 BCFG; Baldwinsville, ultimate recovery ~17 BCFG; and Rome, ultimate recovery ~9 BCFG.

Several gas and associated oil accumulations have been discovered in dolomite and dolomitic limestone associated with fracture and(or) fault zones. The Harlem field, discovered in Delaware County, Ohio, in 1964, is the largest of the accumulations, having produced an unknown quantity of gas and oil from 5 or 6 wells. Additional fields of this type are subcommercial 1-well accumulations discovered in the mid-1980's in the Finger Lakes region of north-central New York and in the early 1990's along the Starr fault zone in southeastern Ohio. The depth to the reservoir in these areas is between 6,000 and 9,000 ft.

About 15 small gas fields, some with minor associated oil, have been discovered in the High Bridge Group, Lexington Limestone and St. Peter Sandstone in Kentucky and in the Stones River and Nashville Groups of Tennessee. Most of these accumulations are trapped in basement-controlled fault blocks and anticlines but a few of them may be trapped by facies-change stratigraphic traps.

Resource potential: This play has potential for a modest number of undiscovered gas and oil fields greater than 1 MMBO or 6 BCFG. Middle Ordovician source beds have adequate organic richness and are in an optimum location to charge many of the reservoirs. Prospective structural and diagenetic traps and fractured reservoirs are very subtle and could easily have been overlooked in earlier periods of exploration. There are large areas in the play that have been sparsely drilled to the Middle Ordovician carbonate sequence. A limiting factor in the play may be that reservoirs are widely scattered and of low quality.

6708. QUEENSTON/BALD EAGLE SANDSTONE GAS PLAY

The Queenston/Bald Eagle Sandstone Gas Play is defined by gas trapped in the Upper Ordovician Bald Eagle (Oswego) Sandstone and sandy facies of the Upper Ordovician Queenston Formation. Traps consist of low-amplitude anticlines controlled by basement faults and facies-change stratigraphic traps. Fractures play an important role in both types of accumulation. The play area covers most of central Pennsylvania and central New York between the depositional limits of the Bald Eagle (Oswego) Sandstone and sandy facies of the Queenston Formation on the west and the Allegheny structural front in Pennsylvania on the east. The northeast limit of the play is in east-central New York where Upper Ordovician sandstone units are truncated. A narrow piece of the play extends into West Virginia approximately between the western depositional limit of the Oswego Sandstone and the western limit of detached anticlines in Upper Ordovician and older strata. The play is confirmed, and its prospective reservoirs are conventional.

Reservoirs: The reservoirs in the play are sandstone of nearshore shallow-marine and fluvial origin deposited near the distal end of the Upper Ordovician Queenston delta. In central New York the sandstone reservoirs that occur in the upper 300 ft of the 700-to

800-foot-thick Queenston Formation are fine-grained. The sandstone reservoir in central Pennsylvania is fine- to medium-grained and produces gas from a 130-foot-thick zone near the middle part of the approximately 1,000-foot-thick Bald Eagle Sandstone.

The sandstones are mainly litharenites that contain abundant metamorphic fragments and minor feldspar. Primary intergranular porosity supplemented by fracture porosity is the dominant porosity type in the central New York part of the play. Pore-filling clay minerals have reduced the permeability of the reservoirs. Porosity values range from 2 – 13 percent (avg ~4 percent), and permeability values range from <0.1 to 5 mD (avg ~0.2 mD). Drilling depths to the sandstone reservoirs of the Queenston Formation in central New York range from about 1,500 – 5,500 ft. Fracture porosity dominates the porosity of the Bald Eagle Sandstone reservoir in central Pennsylvania where drilling depths to the reservoir range from 10,000 to 13,000 ft.

Fractures in the Queenston Formation of New York formed mostly by recurrent movement of fault-bounded basement blocks. A recent study indicates that many of the fractures in the Bald Eagle Sandstone of central Pennsylvania formed by hydraulically induced stress in regions of high abnormal formation pressure.

Source rocks: Black shale and argillaceous limestone in the Middle Ordovician Utica Shale, Antes Shale, and Trenton Limestone are the most likely sources of gas in the play. The thickness of the black shale and limestone sequences ranges from 200 to 400 ft. Approximately 1,000 – 1,500 ft of upward vertical migration is required for gas to reach Upper Ordovician sandstone reservoirs. TOC values in the Middle Ordovician black shale and limestone range from about 0.5 to 3 percent. Organic matter mostly consists of type II kerogen.

Based on CAI and T_{max} values, Middle Ordovician source beds in the play are in the gas generation zone. Middle Ordovician source beds in a narrow zone that adjoins the west side of the Allegheny structural front in Pennsylvania are overmature with respect to oil and gas generation. Dry thermal gas is the expected hydrocarbon in the play.

Timing and migration: Peak gas generation from Middle Ordovician shale and argillaceous limestone source beds probably occurred between Late Pennsylvanian and Early Triassic time when these beds were deeply buried under an eastward-thickening wedge of orogenic sediments and thrust sheets. Much of the gas that was generated from Middle Ordovician source beds migrated up the gently dipping northwest flank of the basin along porous carbonate horizons beneath the Knox unconformity; however, an equal amount or more of the gas migrated vertically upward, through available fracture systems, to the Upper Ordovician sandstone reservoirs. A modest number of stratigraphic and anticlinal traps were available to trap the vertically migrated gas.

Traps: Facies-change stratigraphic traps and low-amplitude basement-controlled anticlines are the major traps in the play. Truncated strata beneath the widespread Taconic unconformity may have trapped some gas in east-central New York. A northward decrease in sandstone grain size and an increase in shale beds in the upper part of the Queenston Formation are responsible for the permeability barrier in many of the stratigraphically trapped gas fields in New York. The seals for these fields are clay-rich siltstone and silty shale of the Lower Silurian Medina Group. Several of the larger fields are crossed by northeast-trending fracture systems that have improved reservoir quality.

The northeast-trending anticline that has trapped gas in the Grugan field in central Pennsylvania is bounded by a down-to-the-northwest basement fault. Major fractures parallel the fold axis. Low-permeability sandstone and mineralized fractures in the Bald Eagle Sandstone provide the seal.

Exploration status: Gas fields in the Queenston Formation of central New York were discovered between 1895 and the mid-1980's. The largest of about 14 fields in the trend are Auburn West, (Cayuga Co., N.Y.), discovery date 1960, ultimate recovery ~60 BCFG; and Fayette-Waterloo, (Seneca Co., N.Y.), discovery date 1962, ultimate recovery ~18 BCFG. The Grugan gas field, (Clinton Co., Penn,), was discovered in 1982. Approximately 7 BCFG has been produced in three wells through 1991. The ultimate recovery of the field is about 10 BCFG.

Exploration still continues for gas fields in the Queenston Formation and Bald Eagle Sandstone. In the mid-1980's several dry holes were drilled to the Bald Eagle Sandstone in central Pennsylvania in search of Gugan-like accumulations. The sandstone reservoirs in the play have tight formation status.

Resource potential: This play has potential for a modest number of undiscovered gas fields greater than 6 BCFG. There are large areas in the play that have been sparsely drilled to Upper Ordovician sandstone reservoirs. A limiting factor in the play may be the lack of pervasive fracture systems that greatly improve reservoir quality and facilitate the 1,500 – 2,000 ft of vertical gas migration from Middle Ordovician source rocks.

6714. KEEFER/BIG SIX SANDSTONE GAS PLAY

The Keefer/Big Six Sandstone Gas Play is defined by gas trapped in the Middle Silurian Keefer Sandstone, Big Six sandstone, Oneida Sandstone, and Herkimer Sandstone by facies-change stratigraphic traps, combination traps, and low-amplitude anticlines. The main part of the play covers eastern Kentucky where the Big Six sandstone was named by early drillers, central and western West Virginia where the Keefer Sandstone is present, and southwestern Pennsylvania where the Keefer Sandstone is present. A small part of the play covers northeastern Pennsylvania, near the northern limit of the Keefer Sandstone, and adjoining southeastern New York, where Keefer Sandstone equivalents, the Middle Silurian Oneida and Herkimer Sandstones, are present. The play is confirmed because several gas fields in eastern Kentucky probably exceed 6 BCF of gas in size. The reservoirs in the play are conventional.

Reservoirs: Quartzose sandstone of littoral and offshore marine origin constitutes the reservoir in the play. The grain size of the sandstone is quite variable; along the eastern boundary of the play the sandstone is medium to coarse grained and contains quartz pebbles, whereas along the west side of the play, near the depositional limit of the Keefer, the sandstone is very fine to fine grained. Most commonly, the quartz grains are cemented with dolomite, but locally silica and calcite cement are present. Although porosity of the sandstone reservoirs may be as high as 20 percent, in most localities it averages about 4 to 5 percent. Primary intergranular porosity is the dominant porosity type, but secondary intergranular porosity and fracture porosity may be present locally.

The Keefer Sandstone and Big Six sandstone generally range in thickness from about 25 to 50 ft. Drilling depths to the sandstone reservoir range from about 1,800 to 3,000 ft in Kentucky and southeastern New York and from about 3,700 to 7,000 ft in West Virginia.

Source rocks: The source of gas in the Kentucky and adjoining West Virginia part of the play is the Upper Devonian black shale sequence that rests unconformably on Silurian and Lower and Middle Devonian strata within 100–600 ft of the underlying Big Six sandstone. The Upper Devonian black shale sequence in eastern Kentucky is 50–400 ft thick and has TOC contents between 3 and 7. Vitrinite reflectance data suggest that the Upper Devonian black shale sequence in Kentucky and adjoining West Virginia is in the oil zone of generation and the beginning of the gas zone of generation. Wet thermal gas and local oil are the expected hydrocarbon types.

The source of gas in the remainder of the play is less certain. The most plausible candidates are (1) shale and argillaceous limestone of the Middle Ordovician Utica Shale, Antes Shale, and Trenton Limestone and (2) black shale of the Middle and Upper Devonian sequence. Both proposed source rock sequences are relatively thick (200–400 ft for the Middle Ordovician sequence; 50–300 ft for the Middle and Upper Devonian sequence), adequately rich (TOC 0.5-3 percent for the Middle Ordovician sequence; TOC 1-5 percent for the Middle and Upper Devonian sequence), and have organic matter dominated by type II kerogen. Gas generated from these source bed sequences however is not particularly accessible to the sandstone reservoirs. For example, between 1,500 and 2,000 ft of vertical migration through predominantly shale and siltstone is required for gas derived from the Middle Ordovician shale sequence to reach the reservoirs. In contrast, between 1,500 and 3,000 ft of downward migration, through at least 500 ft of evaporite and evaporitic dolomite, is required for Middle and Upper Devonian shale gas to reach the sandstone reservoirs. A slight preference is given to Middle Ordovician source beds because upward vertical migration is more plausible than downward migration.

Based on CAI and T_{max} data for the Middle Ordovician sequence and vitrinite reflectance data for the Middle and Upper Devonian sequence, both source bed sequences in the West Virginia, Pennsylvania, and New York part of the play are in the zone of gas generation. A narrow part of the play area in eastern West Virginia, southwestern Pennsylvania, and northeastern Pennsylvania and adjoining southeastern New York that contains Middle Ordovician and Devonian source beds is overmature with respect to oil and gas generation. Wet and dry thermal gas are the expected hydrocarbon types whether the source is the Middle Ordovician or Devonian shale sequence.

Timing and migration: Peak gas generation from the Middle Ordovician and Devonian shale sequences probably occurred between Late Pennsylvanian and Early Triassic time when these beds were deeply buried under an eastward-thickening wedge of orogenic sediments. Gas migrated vertically upsection or downsection to the reservoir depending on which of the two proposed source rock sequences it was generated from. A modest number of facies-change stratigraphic traps, combination traps, and low-amplitude anticlines were available to trap the vertically migrated gas.

Traps: Facies-change stratigraphic traps, combination traps, and low-amplitude anticlines are the major traps in the play. The combination traps formed by facies changes and locally diagenetic changes that occurred on the flanks and noses of gently plunging, low-amplitude anticlines. The seal for the traps consist of dolomicrite of the overlying Middle Silurian Lockport Dolomite.

Exploration status: Gas production from the Big Six sandstone was established in the late 1890's and early 1900's during exploration for oil-bearing zones in the Silurian and Devonian "Corniferous" reservoirs. Most of the 30 or 40 Big Six sandstone gas fields produce from multiple reservoirs that include the Middle Silurian Lockport Dolomite, Middle Silurian Salina Formation, Middle Devonian Boyle Dolomite, and many Mississippian formations. Most of the Big Six sandstone has been explored, but the Keefer Sandstone in many parts of West Virginia remains untested. Moreover, southeastern New York, where several fields were discovered in the late 1950's and early 1960's, is still sparsely drilled. Sandstone reservoirs in parts of the play have tight formation status.

Resource potential: This play has potential for a small number of undiscovered gas fields greater than 6 BCFG. The most attractive aspect of the play is its updip continuity with the prolific oil and gas fields of the "Corniferous" limestone. In addition, large areas in the play have been sparsely drilled to the Keefer Sandstone, and parts of prospective structures remain untested. Limiting factors in the play may be low-quality reservoirs and their poor accessibility to known source rock sequences.

6715. "CORNIFEROUS" LIMESTONE/BIG SIX SANDSTONE OIL/GAS PLAY

The "Corniferous" Limestone/Big Six Sandstone Oil/Gas Play is defined by oil and gas trapped in Middle and Upper Silurian carbonate units, commonly referred to by the driller's term "Corniferous" limestone, and in the underlying Big Six sandstone. Traps consist of truncation traps, facies-change traps, combination traps, and low-amplitude anticlines. Carbonate units included in the "Corniferous" limestone are the Middle Silurian Lockport Dolomite, Middle Silurian Bisher Dolomite, Upper Silurian Salina Formation, and Middle Devonian Boyle Dolomite. The play is confined to a small area in north-central Kentucky where oil and associated gas are produced from the "Corniferous" limestone and Big Six sandstone. The contiguous Keefer/Big Six Sandstone Gas Play (6714) and the Silurian Carbonate Gas Play (6717) are mostly gas plays. The play is confirmed, and the reservoirs are classified as conventional.

Reservoirs: Primary reservoirs in the play are vuggy dolomite formed by karst processes during regional pre-Upper Devonian uplift and erosion. Intercrystalline porosity supplements the vuggy porosity. Highly dolomitic, very fine to fine grained quartzose sandstones of the Big Six sandstone, which has primary intergranular porosity, is important locally. Tectonic fractures, probably resulting from differential movement of fault-bounded blocks, may have improved the reservoir quality of the vuggy, intercrystalline, and intergranular porosity zones. The dolomite and sandstone reservoirs in the play are of very high quality. Porosity ranges from about 4 to 18 percent (avg 9 percent) and permeability ranges from 0.2 to 575 mD (avg 75 mD). Thickness of "Corniferous" limestone reservoirs range from 10 to 50 ft thick whereas that of the Big Six sandstone reservoir ranges from 25 to 50 ft. The drilling depth to the "Corniferous" limestone and Big Six sandstone reservoirs ranges from less than 1000 to 1,500 ft.

Source rocks: The source of oil and gas in the play is the Upper Devonian black shale sequence that rests unconformably on the "Corniferous" limestone. The Upper Devonian black shale sequence in eastern Kentucky is 50–400 ft thick, has TOC values between 3 and 7 percent, and its organic matter consists mostly of type II kerogen. Vitrinite reflectance data suggest that the Upper Devonian black shale sequence in the play area either is at the beginning of the oil generation zone or is immature with respect to oil and gas generation. The low maturation of the Upper Devonian black shale in the play area suggests that oil and gas accumulations resulted from short-range migration from the south and east where the Upper Devonian black shale is thicker and within the zone of oil generation. Oil and wet thermal gas are the expected hydrocarbon types.

Timing and migration: Peak oil and gas generation from the Upper Devonian black shale sequence probably occurred between Late Pennsylvanian and Early Triassic time when it was buried under an eastward-thickening wedge of orogenic sediments. Most of the oil and gas probably migrated into the play from a short distance to the east and south where higher levels of thermal maturation had been achieved. The migrating oil and gas was trapped in a variety stratigraphic, combination, and anticlinal traps.

Traps: Most of the traps in the play are truncation traps, anticlinal traps, and combination traps where truncation has occurred on the flanks of low-amplitude anticlines. Locally, facies changes have trapped oil and gas either alone or in combination with anticlinal flanks and noses. The seal for the truncation traps and many of the anticlinal traps is the Upper Devonian Ohio Shale. The facies-change traps and a few anticlinal traps depend on dolomicrite of the Lockport Dolomite and Salina Formation for their seals.

Exploration status: Most of the oil and gas production in the play was established between 1900 and 1920. The largest fields in the trend are Irvine-Furnace (discovery date 1914) and Big Sinking (discovery date 1918), which have a combined ultimate recovery, including the smaller Pilot field, of about 100 MMBO. The Campton field, discovered in 1903, has an ultimate recovery of about 3 MMBO. Including a few small fields found in the 1980's, between 60 and 70 oil and (or) gas fields have been discovered in the play.

Resource potential: This play has no potential for undiscovered oil and gas fields greater than 1 MMBO or 6 BCFG. The shallow depth of the reservoirs and the high drilling density in the play area suggest that the play is exhausted except for very small accumulations.

6716. UPPER SILURIAN SANDSTONE GAS PLAY

The Upper Silurian Sandstone Gas Play is defined by gas trapped in the Upper Silurian Williamsport Sandstone (Newburg sand of drillers) by facies-change stratigraphic traps and combination traps. The play has an unusual outline: several long, thin lobes are caused by the distribution of the cleanest and thickest sandstone beds in the Williamsburg Sandstone. Most of the play is in west-central and southern West Virginia, but small parts of the play are in northern and north-central West Virginia, western Maryland, southwestern Pennsylvania, and western and northwestern Virginia. The play is confirmed, and the reservoirs are conventional.

Reservoirs: Fine- to coarse-grained quartzose sandstone of littoral and offshore-marine origin constitutes the reservoir in the play. Cementation of commonly well sorted and rounded quartz grains is variable; it ranges from tightly cemented with silica to poorly cemented with dolomite, clay, and minor silica. Primary intergranular porosity, ranging from 6 to 24 percent (avg 12 percent) is the dominant porosity in the reservoir. Permeability of the sandstone reservoir is as high as 183 mD. In the southern and eastern parts of the play, fracture porosity may be needed to improve reservoir quality.

The Williamsport Sandstone ranges in thickness from 10 to 40 ft in most of the play area except in southern West Virginia where it ranges in thickness from 80 to 120 ft. The thickness of the producing part of the Williamsburg Sandstone ranges from 3 to 10 ft. Drilling depths to the Williamsburg Sandstone in known fields are between 4,800 and

6,800 ft. In the deeper parts of the play, the drilling depth to the Williamsport Sandstone is as much as 8,000 ft.

Source rocks: The source of gas in the play is uncertain. The most plausible candidates are (1) shale and argillaceous limestone of the Antes Shale, Trenton Limestone, and Dolly Ridge Formation of the Trenton Group, (2) black shale of the Middle and Upper Devonian sequence, and (3) dispersed organic matter in salt beds of the Salina Group. Only the Middle Ordovician and Middle and Upper Devonian sequences can be evaluated using existing geochemical data. These proposed source rock sequences are relatively thick (200–400 ft for the Middle Ordovician sequence; 50–300 ft for the Middle and Upper Devonian sequence), adequately rich (TOC 1–3 percent for both sequences), and have organic matter dominated by type II kerogen; however, gas generated from these source bed sequences is not particularly accessible to the reservoir. For example, between 2,100–3,000 ft of vertical migration, through predominantly shale and siltstone, is required for gas derived from the Middle Ordovician shale-limestone sequence to reach the Williamsport Sandstone. In contrast, between 1,000 and 2,500 ft of downward migration, through at least 500 ft of evaporite and evaporitic dolomite, is required for Devonian shale gas to reach the sandstone reservoir. A slight preference is given to Middle Ordovician source beds because upward vertical migration is more plausible than downward migration.

Based on CAI and T_{max} data for the Middle Ordovician sequence and vitrinite reflectance data for the Middle and Upper Devonian sequence, both source bed sequences are in the zone of gas generation. Dry thermal gas is the expected hydrocarbon type whether the source is the Middle Ordovician or Devonian shale sequence.

Timing and migration: Peak gas generation from the Middle Ordovician and Devonian shale sequences occurred between Late Pennsylvanian and Early Triassic time when these beds were buried under an eastward-thickening wedge of orogenic sediments. Gas migrated vertically upsection or downsection to the sandstone reservoir depending on which of the two proposed source rock sequences it was generated from. Facies-change stratigraphic traps in combination with anticlinal closure and noses were available to trap the vertically migrated gas.

Traps: Depositional pinchouts of the Williamsport Sandstone in combination with anticlinal flanks and noses represent the major trapping mechanism in the productive part of the play. This trap type may be present in other parts of the play in addition to low-amplitude basement-controlled anticlines and ramp anticlines above a zone of detachment in the lowermost part of the Salina Group or Upper Ordovician shales. Very likely, reservoirs in these types of anticlines must be enhanced by fracture porosity to be gas productive. The seals for the play are evaporites and evaporitic dolomicrite of the Upper Silurian Salina Group.

Exploration status: Most of the nine gas fields in the play were discovered in the late 1960's. The largest of these gas fields Rocky Fork, (Kanawha and Putnam Cos., W. Va.), discovery date 1966, ultimate recovery ~130 BCFG; North Ripley (Jackson Co., W. Va.), discovery date 1970, ultimate recovery ~86 BCFG, and Kanawha Forest (Kanawha and Boone Cos., W. Va.), discovery date 1939, ultimate recovery ~42 BCFG. Although exploration continues for new fields in the play, none have been found since 1970.

Resource potential: This play has potential for a small number of undiscovered gas fields greater than 6 BCFG. The most attractive aspect of the play is that more than half of the discovered fields are greater than 6 BCFG in size. Apparently, smaller fields in the population have not yet been found and perhaps several of them are greater than 6 BCFG in size. In addition, a large area in west-central West Virginia only has been sparsely drilled to the Williamsport Sandstone. Limiting factors in the play may be low-quality reservoirs and their poor accessibility to known source rock sequences.

6717. SILURIAN CARBONATE GAS PLAY

The Silurian Carbonate Gas Play is defined by gas and local oil trapped in Middle and Upper Silurian platform carbonates by facies-change stratigraphic traps including (reefs), low-amplitude basement-controlled anticlines, and combination traps. Stratigraphically, the play involves the Middle Silurian Lockport Dolomite, Middle Silurian Newburg "zone," Middle Silurian McKenzie Formation (Limestone), Upper Silurian Salina Group (Formation), and Upper Silurian Bass Islands Dolomite. The play extends across central and southern New York, northwestern Pennsylvania, eastern Ohio, western West Virginia, eastern Kentucky, and a small part of southwestern Virginia.

The eastern boundary of the play is defined arbitrarily in west-central Pennsylvania, central West Virginia, and southern New York as the eastern limit of stratigraphic traps and basement-involved low-amplitude anticlines in the Middle and Upper Silurian carbonate sequence. Silurian carbonate gas fields east and south of this arbitrary limit are considered to be in the Silurian and Devonian Carbonate Thrust Belt Play (6718).

Traps in play 6718 are faulted ramp anticlines, imbricate thrust slices, and fracture zones largely controlled by Upper Silurian Salina Group bedding plane detachment. Because bedding-plane detachment at the Salina level, with overlying thin-skinned structures, extends across western Pennsylvania, most of southern and western New York, and easternmost Ohio, the Silurian and Devonian Carbonate Thrust Belt Play (6718) and the Silurian Carbonate Gas Play (6717) overlap by 100–125 mi.

The northern boundary of the play is defined by the outcrop limit of the Silurian carbonate sequence at the north end of the Appalachian Basin in New York and by the United States-Canada border in the middle of Lake Erie. The western boundary of the play in Ohio is marked by the outcrop limit of the Silurian carbonate sequence, whereas the western boundary of the play in Kentucky is marked by the province boundary and the outline of play 6715. The play is confirmed, and most of its reservoirs are conventional.

Reservoirs: Many reservoirs in the play are dolomitized bioherms and pinnacle reefs that formed on shallow-water carbonate shelves and along margins of deeper water basinal settings. Corals, brachiopods, pelmatozoans, and sponges dominate the diverse fauna of the reef assemblage. Nonreef carbonate facies also are good reservoirs in the play. For example, in Ohio, porous zones at the base and top of the Lockport Dolomite are probably too widespread and continuous to have been caused by bioherm- and reef-building processes alone. The uppermost porous zone, 80–100 ft below the top of the Lockport Dolomite, was named the “Newburg zone” by drillers. Possibly, these porous dolomite zones formed by karst processes that evolved during widespread subaerial exposure of the carbonate shelf. Moderately to highly fractured oolitic and biomicrite facies, containing local dissolution vugs may also be gas reservoirs. Fractures are most common along zones of bedding-plane detachment and near basement-controlled anticlines. Vuggy and moldic porosity are the dominant porosity types in both the reef and nonreef facies. Locally, intercrystalline and fracture porosity are important. The vugs, molds, and fractures have been filled to varying degrees by calcite and dolomite. Porosity in the vuggy zones range from 2 to 37 percent and average about 8–10 percent. Permeability values range from 0.10 to 50 mD. The net thickness of the reservoirs is between 3 and 55 ft. Drilling depths to Silurian carbonate reservoirs vary according to State: Ohio, less than 1,000 to 5,000 ft; New York, less than 1,000 to 6,000 ft; Pennsylvania, 2,000–7,000 ft; West Virginia, 3,500–6,000 ft; and Kentucky, 1,500–2,700 ft.

Source rocks: The source of gas and local oil in the Kentucky, Virginia, and West Virginia parts of the play is the Upper Devonian black shale sequence that either rests unconformably on the Silurian carbonate sequence or overlies it by less than 1,000 ft. The Upper Devonian black shale sequence in eastern Kentucky is 50–400 ft thick and has TOC values between 3 and 7 percent. Vitrinite reflectance data suggest that the Upper Devonian black shale sequence in Kentucky and adjoining Virginia and West Virginia is in the zone of oil generation and the beginning part of the zone of gas generation. Wet thermal gas and local oil are the expected hydrocarbon types. Devonian black shales in northern Kentucky are immature with respect to oil and gas generation. Therefore, gas trapped in Silurian carbonates here resulted from short-range migration from the south and east where the black shale sequence is thicker and within the zone of oil and gas generation.

The source of gas in the remainder of the play is less certain. The most plausible candidates are (1) shale and argillaceous limestone of the Middle Ordovician Utica Shale, Antes Shale, and Trenton Limestone, (2) black shale of the Middle and Upper Devonian sequence, and (3) dispersed organic matter in salt beds of the Salina Group. Only the Middle Ordovician and Middle to Upper Devonian sequences can be evaluated using existing geochemical data. These proposed source rock sequences are relatively thick (200–400 ft for the Middle Ordovician sequence; 50–300 ft for the Middle and Upper Devonian sequence), adequately rich (TOC 0.5-3 percent for the Middle Ordovician sequence; TOC 1-10 percent for the Middle and Upper Devonian sequence), and have organic matter dominated by type II kerogen; however, gas and local oil generated from these source bed sequences are not particularly accessible to the carbonate reservoirs. For example, between 2,000 and 3,000 ft of vertical migration, through predominantly shale and siltstone, is required for gas and oil derived from the Middle Ordovician shale-limestone sequence to reach the Silurian carbonates. In contrast, between 800 ft and 2,000 ft of downward migration, through at least 500 ft of evaporite and evaporitic dolomite is required for Devonian gas and oil to reach the carbonate reservoir. A slight preference is given to the Middle Ordovician source beds because upward vertical migration is more plausible than downward migration.

Based on CAI and T_{max} data, Middle Ordovician source rocks in the play are in the gas and oil generation zone. Dry and wet thermal gas and local oil are the expected hydrocarbon types derived from Middle Ordovician source rocks. Vitrinite reflectance dates suggest that Middle and Upper Devonian source rocks in the play have achieved several levels of thermal maturity. Devonian source rocks in eastern and central New

York, northwestern Pennsylvania, and easternmost Ohio are in the zone of gas generation, whereas those in western New York, northwesternmost Pennsylvania, and eastern Ohio are in the zone of oil generation. Devonian source rocks in east-central Ohio and offshore northern Ohio (Lake Erie) are immature with respect to oil and gas generation. Oil and wet thermal gas are the expected hydrocarbon types derived from the Middle and Upper Devonian source rocks.

Timing and migration: Peak oil and gas generation from the Middle Ordovician and Devonian shale sequences occurred between Late Pennsylvanian and Early Triassic time when these beds were buried under an eastward-thickening wedge of orogenic sediments. Oil and gas migrated vertically upsection or downsection depending on which of the proposed source rock sequences they were derived from. Oil and gas may have migrated laterally along porous zones in the Lockport Dolomite into east-central Ohio from areas to the east where higher levels of thermal maturity were achieved. A variety of stratigraphic traps, combination traps, and low-amplitude anticlines trapped the gas and local oil.

Traps: Bioherms, pinnacle reefs, low-amplitude basement-controlled anticlines, and combination traps are the major traps in the play. The bioherms and reefs cover an area between 350 and 700 acres, whereas anticlinal closure covers an area as large as 3,500 acres. The largest fields discovered to date are associated with anticlines and combination traps. Combination traps are present where permeability barriers, caused by depositional and diagenetic facies changes and truncation, cross noses and flanks of anticlines. Seals for the traps are Upper Devonian black shale and evaporite beds and evaporitic dolomicrite in the Upper Silurian Salina Group.

Exploration status: Tens of thousands of holes have been drilled through all or part of the Silurian carbonate sequence in eastern Kentucky, Ohio, northwestern Pennsylvania, and western New York. Since the late 1890's, between 100 and 120 gas and local oil fields have been discovered. Many of the fields consist of 1 or 2 wells and are subcommercial. Moreover, in about a third of the fields, the Silurian carbonate gas production is commingled with gas production from the Clinton sandstone, Oriskany Sandstone, Devonian black shale, and a variety of Mississippian sandstones. The largest gas fields in the play are: Oneida (Clay County, Ky.), discovery date 1928, ultimate recovery 26.6 BCFG; Artemus-Himyar (Knox County, Ky.), discovery date 1931, ultimate recovery 18.8 BCFG; Mayfield (Cuyahoga County, Ohio), discovery date 1938 (Lockport part), ultimate recovery 11.8 BCFG; 4) Green (Summit County, Ohio), discovery date 1928, ultimate recovery 9.8 BCFG; and Henderson dome-Kilgore, (Mercer County, Pa.), discovery date 1966 (Lockport part), ultimate recovery 8.7 BCFG. Exploration drilling continues in the deeper parts of the play in New York, Pennsylvania, Ohio, and West Virginia.

Resource potential: This play has potential for a modest number of undiscovered gas fields greater than 6 BCFG. Most of the undiscovered fields probably are in sparsely drilled deeper parts of the play in western New York, northwestern Pennsylvania, eastern Ohio, and western West Virginia and in undrilled Lake Erie. Prospective reefs and anticlinal traps are very subtle and may have been overlooked in previous exploration phases; however, the small size of the traps may limit the available gas resources in the play.

6718. SILURIAN AND DEVONIAN CARBONATE THRUST BELT PLAY

The Silurian and Devonian Carbonate Thrust Belt Play is defined by gas and local oil trapped in Upper Silurian, Lower Devonian, and Middle Devonian shelf carbonates by faulted ramp anticlines, salt anticlines, imbricate fault slices, and fracture zones associated with bedding plane detachment in the Upper Silurian Salina Group. Also, ramp anticlines associated with zones of bedding plane detachment in Cambrian and Ordovician strata may have trapped gas in Middle Silurian carbonates. Stratigraphically, the play involves the Middle Silurian McKenzie Formation; Upper Silurian Salina Group, Bass Islands Dolomite and Tonoloway Limestone; Upper Silurian and Lower Devonian Rondout Limestone and Keyser Limestone; Lower Devonian Helderberg Limestone; Lower and Middle Devonian Bois Blanc Formation; and Middle Devonian Onondaga Limestone. The play extends across south-central New York, northeastern, central, and southwestern Pennsylvania, western Maryland, eastern West Virginia, and narrow pieces of west-central and southwestern Virginia.

The western and northern boundaries of the play are marked by the approximate western and northern limit of high-amplitude salt anticlines, and (or) ramp anticlines formed by bedding-plane detachment and flowage in salt beds of the Salina Group. A narrow zone of imbricate faults and intense fracturing that involves Silurian and Devonian carbonates, called the Bass Islands trend, marks the limit of the play in northwestern New York and adjoining Pennsylvania. The eastern boundary of the play is defined by the eastern limit of Silurian and Devonian carbonate strata in the Appalachian Fold and Thrust Belt. The play is confirmed, and its reservoirs are conventional.

Reservoirs: Fractured dolomite and limestone are the most important reservoirs in the play. Depositional settings of these carbonates include shallow-water carbonate platform, tidal flat, deeper water platform and basin, and restricted basin. Carbonate rocks in the play consist mainly of sparsely fossiliferous micrite and dolomicrite; however, moderately fossiliferous zones, crinoidal calcarenite bars, and coral-stromotoporoid bioherms have been reported locally. The largest bioherms and pinnacle reefs in the Silurian and Devonian sequence are in the Silurian Carbonate Gas Play (6717) and Devonian Carbonate Gas Play (6719). Zones of vuggy porosity may have formed by karst processes that evolved during brief periods of subaerial exposure of the carbonate shelf. Strata with vuggy and (or) moldic porosity probably require fracture porosity to be good reservoirs.

Fractured Upper Silurian and Lower Devonian carbonates in the Bass Islands trend have porosity values ranging from 10 to 15 percent. Drilling depths to the carbonate reservoirs in the trend are between 1,800 and 3,000 ft. In contrast, drilling depths to the carbonate reservoirs over most of the play are between 4,000 and 9,000 ft.

Source rocks: Middle and Upper Devonian black shale is the source of gas and local oil in the play. In most parts of the play, the Devonian black shales either rest directly on the carbonate reservoirs or within 1,000 ft above them. The Middle and Upper Devonian black shale sequence in the play is 50 ft–200 ft thick, and has TOC values between 3 and 5 percent; its organic matter is dominated by type II kerogen. Vitrinite reflectance data suggest that about a third of the Middle and Upper Devonian black shale sequence in the play area is in the zone of gas generation, whereas two-thirds of the sequence is overmature with respect to oil and gas generation. The black shale sequence in the Bass Islands trend is in the zone of oil generation. Dry thermal gas is the expected hydrocarbon type in the play.

Timing and migration: Peak gas generation from the Middle and Upper Devonian black shale sequence occurred between Late Pennsylvanian and Early Triassic time when it was buried under an eastward-thickening wedge of orogenic sediments. Gas migrated a short distance downsection into available structural traps.

Traps: Faulted ramp anticlines, salt anticlines, imbricate fault slices and fracture zones associated with bedding plane detachment in the Salina Group are the major traps in the play. Also, highly fractured faulted ramp anticlines and imbricate fault slices associated with older zones (Cambrian and Ordovician) of bedding-plane detachment may be traps in the play. Most traps are very complex in that structural closure and (or) fracturing commonly occurs at several structural and stratigraphic levels and in different geographic localities. The seals for the traps are unfractured to sparsely fractured micrite and dolomicrite and mineralized fractures in the Middle Silurian through Middle Devonian carbonate sequence.

Exploration status: Gas and local oil fields discovered in the Bass Islands trend in the early 1980's are the largest known accumulations in the play. An ultimate recovery of 30–40 BCFG and 2.5 MMBO is expected from the 10 or 12 fields in the trend. The Gerry field (Chautauqua County, N.Y.), discovery date 1981, ultimate recovery 18 BCFG, 1 MMBO and the North Harmony field (Cattaraugus County, N.Y.), discovery date 1981, ultimate recovery 11 BCFG,
1 MMBO are the largest fields in the Bass Island trend.

Several small subcommercial gas fields have been discovered in the play in north-central Pennsylvania. The Boot Jack pool, discovered in Elk County, Pennsylvania, in 1973 has produced 20 MMCFG through 1986 from the Helderberg Limestone. No current drilling is designed specifically to test for gas in fractured Silurian and Devonian carbonate reservoirs; however, these intervals may be tested as secondary objectives in holes drilled to the Lower Devonian Oriskany Sandstone and Middle Devonian Huntersville Chert.

Resource potential: This play has potential for a modest number of undiscovered gas fields greater than 6 BCFG. The fractured reservoirs required for the play are commonly very subtle and may have been overlooked in previous seismic and exploration programs. Future gas fields in the play probably will be discovered by chance in drilling for more predictable targets in the Lower Devonian Oriskany Sandstone and the Middle Devonian Huntersville Chert. A limiting factor in the play is that many of the prospective fracture zones may be cemented by syn- and post-tectonic episodes of burial and fluid flow.

6719. DEVONIAN CARBONATE GAS PLAY

The Devonian Carbonate Gas Play is defined by gas trapped in pinnacle reefs of the Middle Devonian Onondaga and Columbus Limestones. The play extends across central and southern New York, northwestern Pennsylvania, eastern Ohio, western West Virginia, eastern Kentucky, and a small part of southwestern Virginia.

The eastern boundary of the play is defined in west-central Pennsylvania, central West Virginia, and south-central New York as the eastern limit of pinnacle reefs in the

Middle Devonian Onondaga Limestone. Middle Devonian carbonate gas fields east and south of the boundary are considered to be in the Silurian and Devonian Carbonate Thrust Belt Play (6718). Traps in play 6718 are faulted ramp anticlines, imbricate thrust slices, and fracture zones mostly controlled by Upper Silurian Salina Group bedding-plane detachment. Because bedding-plane detachment at the Salina level, with overlying thin-skinned structures, extends across western Pennsylvania, most of southern and western New York, and easternmost Ohio, the Silurian and Devonian Carbonate Thrust Belt Play (6718) and the Devonian Carbonate Play (6719) overlap by 100–125 mi.

The northern boundary of the play is defined by the outcrop limit of the Devonian carbonate sequence at the north end of the Appalachian Basin in New York and by the United States–Canada border in the middle of Lake Erie. The western boundary of the play in Ohio is marked by the outcrop limit of the Columbus Limestone, whereas the western boundary of the play in Kentucky is marked by the subcrop limit of the Onondaga Limestone. The play is confirmed, and its reservoirs are conventional.

Reservoirs: Pinnacle reefs that formed on a shallow-water carbonate shelf and along a transition zone between shelf and deeper water basinal settings are the reservoirs in the play. Reef facies consist of bioclastic limestone as thick as 180 ft that has good to excellent vuggy and interskeletal porosity. The net pay thickness of the reef reservoirs averages about 80–100 ft. Interreef strata are about 50 ft thick and consist of biomicrite and local biosparite. Pinnacle reefs in the play cover an area between 350 and 500 acres. Drilling depths to the Onondaga reef facies across most of the trend range from 3,500 to 5,000 ft.

Source rocks: The source of gas in the play is the Middle and Upper Devonian black shale sequence that overlies the Onondaga and Columbus Limestones by 500 ft or less. The Middle and Upper Devonian black shale sequence in the play area is between 50 and 400 ft thick and has TOC values between 1 and 10 percent. Vitrinite reflectance data indicate that Middle and Upper Devonian source rocks in the play have achieved several levels of thermal maturity. Devonian source rocks in eastern and central New York, northwestern Pennsylvania, and easternmost Ohio are in the zone of gas generation, whereas those in western New York, northwesternmost Pennsylvania, and eastern Ohio are in the zone of oil generation. Devonian source rocks in east-central Ohio and offshore northern Ohio in Lake Erie are immature with respect to oil and gas generation. Wet thermal gas and local oil are the expected hydrocarbon types derived from the Middle and Upper Devonian source rocks.

Timing and migration: Peak oil and gas generation from the Middle and Upper Devonian black shale sequence occurred between Late Pennsylvanian and Early Triassic time when these beds were buried under an eastward-thickening wedge of orogenic sediments. Gas migrated a short distance downsection to the Onondaga reefs. Gas and local oil in the Columbus Limestone, in thermally immature parts of Ohio, probably migrated there from east of the play area where higher levels of thermal maturity were achieved. The Lower Devonian Oriskany Sandstone may have been the carrier bed for laterally migrated gas and oil.

Traps: Pinnacle reefs constitute the trap in the play and surrounding micrite and biomicrite are the seals.

Exploration status: Tens of thousands of holes have been drilled through the Onondaga Limestone in eastern Kentucky, northwest Pennsylvania, and western New York and the Columbus Limestone in Ohio in search of deeper objectives. The first gas fields in the Onondaga Limestone to be recognized as pinnacle reefs were discovered in the late 1960's and early 1970's in south-central New York and adjoining Pennsylvania. To date, about 17 fields in New York, 2 fields in Pennsylvania, and about 6 fields in Ohio produce gas and local oil from Onondaga-Columbus Limestone reefs. Several of these fields were discovered in the late 1980's and early 1990's. The Adrian Reef field (Steuben County, N. Y., discovery date 1971, ultimate recovery 8.2 BCFG), Thomas Corners field (Steuben County, N. Y., discovery date 1971, ultimate recovery ~6 BCFG), and Cyclone (McKean County, Pa., discovery date 1974, cumulative production through 1990 ~2.3 BCFG) are the largest fields discovered in the play.

Resource potential: This play has potential for a small number of undiscovered gas fields greater than 6 BCFG. Reefs are very subtle features that may have been overlooked in previous seismic and exploration programs. Most of the undiscovered fields are in sparsely drilled deeper parts of the play in western New York, northwestern Pennsylvania, eastern Ohio, and western West Virginia and in undrilled Lake Erie. Some fields will be discovered by chance in search of deeper objectives. A limiting factor in the play may be that the largest reefs are restricted to a 5- or 6-county area in west-central New York and adjoining north-central Pennsylvania.

6720. ORISKANY SANDSTONE GAS/FAULTED ANTICLINES PLAY

The Oriskany Sandstone Gas/Faulted Anticlines Play (6720) and the Oriskany Sandstone Gas Play (6721) are contiguous plays in the Lower Devonian Oriskany Sandstone depositional system. This sandstone system was deposited on a storm-dominated marine shelf. The Oriskany Sandstone Gas/Faulted Anticlines Play, the easternmost of the two plays, is defined by gas trapped in highly faulted ramp anticlines, salt anticlines, imbricate fault slices, and combination traps above bedding plane detachment in the Upper Silurian Salina Group and (or) Cambrian and Ordovician shale sequences. In addition to the Oriskany Sandstone, the play involves gas-bearing fractured chert in the overlying Middle Devonian Huntersville Chert. The play extends across south-central New York, northeastern, central and southwestern Pennsylvania, western Maryland, central and eastern West Virginia, and narrow parts of western Virginia.

The western and northern boundaries of the play are marked by the approximate western and northern limit of high-amplitude salt anticlines and (or) highly faulted ramp anticlines formed by bedding plane detachment and flowage in salt beds of the Salina Group. Bedding-plane detachment at the Salina level continues west of the play area into New York, Pennsylvania, and easternmost Ohio; however, stratigraphic pinch-outs and low-amplitude basement controlled anticlines are the dominant traps in the Oriskany Sandstone here. Oriskany Sandstone reservoirs in these more mildly deformed parts of the basin are included in the Oriskany Sandstone Gas Play (6721). The Oriskany Sandstone in mildly deformed southeastern New York and adjoining northeasternmost Pennsylvania is included with play 6720.

The eastern boundary of the play is defined by the eastern limit of the Oriskany Sandstone in the Appalachian Fold and Thrust Belt. The play is confirmed, and the reservoirs are conventional.

Reservoirs: The primary reservoir in the play is the Oriskany Sandstone, a quartz-rich, calcite- and silica-cemented, fine- to coarse-grained sandstone sequence. Although primary intergranular porosity is important locally, secondary intergranular and fracture porosity are the dominant porosity types in the Oriskany Sandstone. Fracture porosity also is present in the Huntersville Chert, commonly the primary reservoir in the play. Secondary intergranular porosity in the Oriskany Sandstone resulted from the dissolution of calcite cement and unstable grains such as chert and calcareous fossil fragments. Porosity for the sandstone ranges from 3 to 20 percent and averages 8 percent. The thickness of the producing part of the Oriskany Sandstone reservoir ranges from 6 to 150 ft, whereas the thickness of the producing part of the Huntersville Chert ranges from about 60 to 170 ft. Drilling depths to the Oriskany Sandstone reservoir in the play range from about 6,000 to 9,000 ft.

Source rocks: The source of gas in the play is the Middle and Upper Devonian black shale sequence that overlies the Oriskany Sandstone by 500 ft or less. The Middle and Upper Devonian black shale sequence in the play area is between 50 ft and 400 ft thick and has TOC values between 3 and 5 percent. Vitrinite reflectance data indicate that Middle and Upper Devonian source rocks in the play have achieved several levels of thermal maturity. Devonian source rocks in about the northern and western third of the play area are in the zone of gas generation whereas Devonian source rocks in the remainder of the play are overmature with respect to the generation of oil and gas. Dry thermal gas is the expected hydrocarbon type in the play.

Timing and migration: Peak oil and gas generation from the Middle and Upper Devonian black shale sequence occurred between Late Pennsylvanian and Early Triassic time when it was buried under an eastward-thickening wedge of orogenic sediments. Gas migrated a short distance downsection into available structural traps. Local solid hydrocarbon coatings on quartz grains suggest that some oil was originally trapped in the play and later converted to gas as thermal maturation levels increased.

Traps: Highly fractured, faulted ramp anticlines, salt anticlines, and imbricate fault slices above bedding plane detachment at Cambrian, Ordovician, and Silurian stratigraphic levels are the major traps in the play. Depositional and (or) erosional pinchouts of sandstone in combination with anticlinal flanks also are important traps. Most traps are very complex in that structural closure and (or) fracturing commonly occurs at several structural levels and in different geographic localities. The seals for the traps are micrite in the Onondaga Limestone and black shale in the Middle Devonian Marcellus Shale.

Exploration status: Gas was first discovered in the play in the early 1930's in south-central New York and adjoining Pennsylvania. Drilling depths to the Oriskany Sandstone in this region range from 2,000 to 5,500 ft. By the 1950's and 1960's exploration in the play had successfully expanded into central Pennsylvania, southern Pennsylvania, western Maryland, and eastern West Virginia where drilling depths to the Oriskany were 7,000–8,000 ft. Successful exploration continues today for Oriskany-Huntersville gas in generally deeper and most eastward parts of the play. Between 1930 and 1990 approximately 110 gas fields were discovered in the play, and about half of them are greater than 6 BCFG in size. The most recently discovered fields that exceed 6 BCFG are the Jordan Run (Grant County, W. Va., discovery date 1982, ultimate recovery ~25 BCFG) and Stagecoach (Tioga County, N.Y., discovery date 1987, ultimate recovery ~ 8 BCFG).

The largest fields in the play are Driftwood, (Cameron Co., Pa.), discovery date 1951, ultimate recovery ~253 BCFG; Helvetia, (Clearfield Co., Pa.), discovery date 1960, ultimate recovery ~153 BCFG; Dubois, (Clearfield Co., Pa.), discovery date 1960, ultimate recovery ~107 BCFG; and Leidy, (Clinton Co., Pa.), discovery date 1950, ultimate recovery ~94 BCFG.

Resource potential: This play has potential for a modest number of undiscovered gas fields greater than 6 BCFG. Drilling is still active for structurally trapped Oriskany Sandstone gas, and several fields greater than 6 BCFG in size were discovered in the 1980's. Many sparsely drilled parts of the play having complex structure probably contain undiscovered fields. A limiting factor in the play is that reservoir quality of the Oriskany Sandstone diminishes in the deeper parts of the play. Commonly, fractures and pore space are tightly cemented making porosity very difficult to predict.

6721. ORISKANY SANDSTONE GAS

The Oriskany Sandstone Gas Play (6721) and the Oriskany Sandstone Gas/Faulted Anticlines Play (6720) are contiguous plays in the Lower Devonian Oriskany Sandstone depositional system. This sandstone system was deposited on a storm-dominated marine shelf. The Oriskany Sandstone Gas Play, the westernmost of the two plays, is defined by gas and local oil trapped by depositional and erosional pinchouts, combination traps, and low-amplitude anticlines. The play extends across northwestern Pennsylvania, eastern Ohio, offshore Ohio and Pennsylvania in Lake Erie, western West Virginia, and small parts of western New York, eastern Kentucky, and southwestern Virginia. The Oriskany Sandstone is absent in several large areas of the play in Ohio, Pennsylvania, and New York due to erosion and (or) nondeposition.

The eastern boundary of the play is marked by the approximate limit of high-amplitude salt anticlines and (or) ramp anticlines formed by bedding-plane detachment and flowage in salt beds of the Salina Group. Oriskany Sandstone reservoirs in these highly deformed regions of the basin are included in the Oriskany Sandstone Gas/Faulted Anticlines Play (6720). Bedding plane detachment at the Salina level continues into New York, Pennsylvania, and easternmost Ohio parts of the play area; however, stratigraphic pinch-outs and low-amplitude, basement-controlled anticlines are the dominant traps in the Oriskany Sandstone here.

The western and northern boundaries of the play are defined by the depositional and (or) erosional limit of the Oriskany Sandstone. The depositional limit of the Oriskany Sandstone is undefined in Lake Erie and may extend as far north as the United States-Canada border. The play is confirmed, and the sandstone reservoirs are conventional.

Reservoir: The reservoir in the play is the Oriskany Sandstone, a quartz-rich, calcite- and silica-cemented, fine- to coarse-grained sandstone sequence. Although secondary intergranular and fracture porosity are important locally, primary intergranular porosity is the dominant porosity type. Porosity for the sandstone ranges from 6 to 22 percent and averages 12 percent, whereas permeability for the sandstone ranges from 10 to 60 mD and averages 27 mD. The total thickness of the gas producing parts of the Oriskany Sandstone ranges from 5 to 50 ft. Drilling depths to the Oriskany Sandstone in the play are between 2,000 and 6,000 ft.

Source rock: The source of gas in the play is the Middle and Upper Devonian black shale sequence that overlies the Oriskany Sandstone by 500 ft or less. The Middle and Upper Devonian black shale sequence in the play area is between 100 and 400 ft thick and has TOC values between 3 and 5. Vitrinite reflectance data indicate that Middle and Upper Devonian source rocks in the play have achieved several levels of thermal maturity. Devonian source rocks in western New York, northwestern Pennsylvania, easternmost Ohio, southern West Virginia, and southwestern Virginia are in the zone of gas generation, whereas those in northwesternmost Pennsylvania, eastern Ohio, western West Virginia, and eastern Kentucky are in the zone of oil generation. Devonian source rocks in east-central Ohio, offshore northern Ohio in Lake Erie, and northeastern Kentucky are immature with respect to oil and gas generation. Wet thermal gas and oil are the expected hydrocarbon types derived from the Middle and Upper Devonian source rocks.

Timing and migration: Peak oil and gas generation from the Middle and Upper Devonian black shale sequence occurred between Late Pennsylvanian and Early Triassic time when these beds were buried under an eastward-thickening wedge of orogenic sediments. Gas migrated a short distance downsection to the Oriskany Sandstone. Gas and local oil in the Oriskany Sandstone, in thermally immature parts of Ohio, probably migrated there from southeast of the play area where thermal maturity levels were higher.

Traps: Depositional updip pinchouts of the Oriskany Sandstone and combination traps, where the Oriskany Sandstone pinches out along anticlinal flanks or noses, have trapped the largest accumulations in the play. Low-amplitude anticlines controlled by basement fault blocks or minor bedding-plane detachment in the Salina Group also are traps. Seals are micrite in the Middle Devonian Onondaga Limestone.

Exploration status: The first fields in the play were discovered in northeastern Ohio, close to Lake Erie, between 1899 and 1915. By 1935, about 18 gas and local oil fields had been discovered in the Ohio part of the play. Active drilling for Oriskany Sandstone gas had also begun in West Virginia by the mid-1930's, and shortly afterward the giant Elk-Poca field was discovered. Between 1899 and 1986, approximately 100 gas fields were discovered in the play, eleven of them are equal to or greater than 6 BCFG in size. No fields of this size have been discovered since 1967. Tens of thousands of holes have been drilled to or through the Oriskany Sandstone in the play. Several Oriskany Sandstone fields have been discovered in northwestern Pennsylvania in the 1980's, but they are less than 1 BCFG in size.

The largest fields in the play are Elk-Poca (Sissonville), (Kanawha and Jackson Cos., W.V.), discovery date 1936, ultimate recovery 1.0 TCFG; Blue Creek (Falling Rock), (Kanawha Co., W.V.), discovery date 1944, ultimate recovery 67 BCFG; Campbell Creek-Malden, (Kanawha Co., W.V.), discovery date 1930, ultimate recovery 28 BCFG; and Birds Run, (Guernsey Co., Ohio), discovery date 1942, ultimate recovery ~ 26 BCFG.

Resource potential: This play has potential for a small number of undiscovered gas fields greater than 6 BCFG. Probably the undiscovered fields are located in undrilled Lake Erie. Outside of Lake Erie, this play is exhausted except for very small accumulations.

TUSCARORA SANDSTONE–CLINTON/MEDINA SANDSTONE PLAYS

6727. TUSCARORA SANDSTONE GAS PLAY

The conventional Tuscarora Sandstone Gas Play (6727), Clinton/Medina Sandstone Gas plays (unconventional continous-type plays 6728, 6729, 6730, 6731), and the conventional Clinton/Medina Sandstone Oil/Gas Play (6732) are contiguous plays that occupy progressively westward parts of the widespread Lower Silurian sandstone depositional system. Although sandstones of fluvial and distributary channel origin are recognized locally, most of the sandstone was deposited in littoral marine, deltaic, and offshore-marine settings. This group of plays extends westward from near the Allegheny structural front in Pennsylvania, West Virginia, and Virginia, where sandstone beds are thickest and have minor shale interbeds (Tuscarora Sandstone), to the depositional limit of the Lower Silurian "Clinton" sandstones in east-central Ohio and eastern Kentucky, where sandstone beds are thinner and intercalated with abundant shale and siltstone. The Lower Silurian sandstone system extends into New York as far north as the outcrop limit of the Lower Silurian Medina Group and as far east as the subcrop of the Tuscarora Sandstone beneath the Middle Silurian Oneida Sandstone.

The Tuscarora Sandstone Gas Play is defined by gas trapped in the Lower Silurian Tuscarora Sandstone by low-amplitude basement-controlled anticlines commonly in combination with diagenetic traps. The most easterly of the Lower Silurian sandstone plays, this play covers large parts of New York, Pennsylvania, and West Virginia; the southwesternmost end of the play includes small parts of Virginia and Kentucky. On the east side, the play is bounded by the approximate western limit of detached anticlines involving Upper Ordovician and older strata, whereas, on the west side, it is bounded by an arbitrary line separating the Tuscarora Sandstone from Clinton–Medina sandstones. The play is confirmed and its prospective reservoirs are conventional.

Reservoirs: Fine- to medium-grained sandstones consisting mostly of quartzarenite constitute the reservoirs in the play. Compaction and burial diagenetic processes have plugged most of the primary intergranular porosity with silica and minor calcite cement. Locally, primary porosity may be preserved by clay coatings that inhibit the formation of quartz overgrowths. The dominant porosity types are: secondary intergranular porosity caused by dissolution of chert grains, rock fragments, and calcite cement and fracture porosity probably caused by tectonic activity. Porosity values are as high as 13 percent but generally average 4 percent or less. Permeability values are less than 1 mD. The thickness of the Tuscarora Sandstone in the play ranges from about 100 to 325 ft, and sandstone to shale ratios generally exceed 3. Drilling depths to the Tuscarora Sandstone range from 5,000 to 11,000 ft.

Source rocks: The source of gas in the play is uncertain. The most plausible candidates are shale and argillaceous limestone of the Middle Ordovician Utica Shale, Antes Shale, and Trenton Limestone or black shale of the Middle and Upper Devonian sequence. Both proposed source rock sequences are relatively thick (200–400 ft for the Middle Ordovician sequence; 50–250 ft for the Middle and Upper Devonian sequence), adequately rich (TOC 0.5-3 percent for the Middle Ordovician sequence; TOC 1-5 percent for the Middle and Upper Devonian sequence), and have organic matter dominated by type II kerogen. However, gas generated from these source-rock sequences is not particularly accessible to the reservoir. For example, between 2,000 and 3,000 ft of vertical migration, through predominantly shale and siltstone, is required for gas derived from the Middle Ordovician shale sequence to reach the Tuscarora Sandstone. In contrast, between 1,500 and 3,000 ft of downward migration, through at least 500 ft of evaporite and evaporitic dolomite, is required for Middle and Upper Devonian shale gas to reach the Tuscarora Sandstone. A slight preference is given to the Middle Ordovician source beds because upward vertical migration is more plausible than downward migration.

Based on CAI and T_{max} data for the Middle Ordovician sequence and vitrinite reflectance data for the Middle and Upper Devonian sequence, both proposed source-bed sequences in the play area are in the zone of gas generation. A narrow region that contains Middle Ordovician and Devonian source beds along the west side of the Allegheny structural front in Pennsylvania and part of adjoining West Virginia is overmature with respect to oil and gas generation. Dry thermal gas is the expected hydrocarbon type whether the source is the Middle Ordovician or Middle and Upper Devonian shale sequence.

Timing and migration: Peak gas generation from the Middle Ordovician and Devonian shale sequences probably occurred between Late Pennsylvanian and Early Triassic time when these beds were deeply buried under an eastward-thickening wedge of orogenic sediments and thrust sheets. Gas migrated vertically upsection or downsection to the reservoir depending on which of the two proposed source-rock sequences it was generated from. A modest number of anticlinal and combination traps were available to trap the vertically migrated gas.

Traps: Basement-controlled anticlines and combination traps are the major traps in the play. The combination traps are formed by diagenetically produced permeability barriers that cross the flanks and noses of gently plunging, low-amplitude anticlines. The seal for the traps consists of red shale and silty shale of the Middle Silurian Rose Hill Formation.

Exploration status: Gas production from the Tuscarora Sandstone was established in the mid-1970's by deeper drilling in the Campbell Creek-Malden and Hernshaw-Bull Creek oil fields in central West Virginia. The Indian Creek field, largest of three fields in Kanawha County, West Virginia, has an ultimate recovery of about 32 BCFG. Several subcommercial 1-well fields have been discovered in northern West Virginia and southern Pennsylvania along the trend of the Chestnut Ridge anticline. One of these accumulations, the Heyn pool, Fayette County, Pennsylvania, produces gas from fractured Tuscarora Sandstone probably caused by minor bedding-plane detachment in underlying Upper Ordovician shale. Additional 1-well, Tuscarora Sandstone fields are scattered around Pennsylvania and West Virginia and many of them are associated with basement-controlled anticlines. Exploration for gas fields in the Tuscarora Sandstone continues in Pennsylvania and West Virginia, at the rate of several drill holes per year.

Resource potential: This play has potential for a modest number of undiscovered gas fields greater than 6 BCFG. The most attractive aspect of the play is its lateral updip continuity with the prolific oil and gas fields of the Clinton and Medina sandstones. In addition, there are large areas in the play that have been sparsely drilled to the Tuscarora Sandstone, and some parts of prospective structures remain untested. Limiting factors in the play may be (1) low-quality reservoirs, (2) poor accessibility to known source rock sequences, and (3) a high percentage of noncombustible gas mixed with the methane gas.

CLINTON/MEDINA SANDSTONE GAS PLAYS

6728. CLINTON/MEDINA SANDSTONE GAS HIGH POTENTIAL
6729. CLINTON/MEDINA SANDSTONE GAS MEDIUM POTENTIAL (HYPOTHETICAL)
6730. CLINTON/MEDINA SANDSTONE GAS MEDIUM-LOW POTENTIAL (HYPOTHETICAL)
6731. CLINTON/MEDINA SANDSTONE GAS PLAYS LOW POTENTIAL (HYPOTHETICAL)

The Tuscarora Sandstone Gas Play (6727), Clinton/Medina Sandstone Gas Plays (6728, 6729, 6730, 6731), and Clinton/Medina Sandstone Oil/Gas Play (6732) are contiguous plays that occupy progressively westward parts of the widespread Lower Silurian sandstone depositional system. Although sandstones of fluvial and distributary channel origin are recognized locally, most of the sandstone was deposited in littoral marine, deltaic, and offshore-marine settings. This group of plays extends westward from near the Allegheny structural front in Pennsylvania, West Virginia, and Virginia, where sandstone beds are thickest and have minor shale interbeds (Tuscarora Sandstone), to the depositional limit of the Lower Silurian "Clinton" sandstone in east-central Ohio and eastern Kentucky, where sandstone beds are thinner and intercalated with abundant shale and siltstone. The Lower Silurian sandstone system extends into New York as far north as the outcrop limit of the Lower Silurian Medina Group and as far east as the subcrop of the Tuscarora Sandstone beneath the Middle Silurian Oneida Sandstone.

The Clinton/Medina Sandstone Gas plays are defined as parts of a continuous-type gas accumulation. These plays are characterized as continuous-type accumulations because of low-permeability reservoirs, abnormally low formation pressure, coalesced gas fields, gas shows or production in most holes drilled, and general lack of control by anticlinal closure on gas accumulations. Four Clinton/Medina Sandstone Gas plays are recognized according to their estimated potential for undiscovered gas resources. The Clinton/Medina Sandstone Gas High Potential Play (6728), the largest of the plays, is down-dip and along strike of the Clinton/Medina Sandstone Oil and Gas play (6732). It extends across western New York, northwestern Pennsylvania, and eastern Ohio and includes the offshore Lake Erie and Lake Ontario part of these states. The relatively small Clinton/Medina Sandstone Gas Medium Potential Play (6729) consists of two parts: an east-central New York part attached to the north end of Clinton/Medina Sandstone Gas High Potential Play 6728 and a southern Ohio, northeastern Kentucky, and westernmost West Virginia part attached to the south end of play 6728. The

Clinton/Medina Sandstone Gas Medium-Low Potential Play (6730) consists of three parts: (1) a long narrow piece of northern and western West Virginia and adjoining southwestern Pennsylvania attached to the downdip side of plays 6728 and 6729, (2) a narrow piece of north-central New York between the outcrop and plays 6728 and 6729, and (3) a small piece of south-central New York attached to the down dip side of play 6729. The two parts of the Clinton/Medina Sandstone Gas Low Potential Play (6731) mark the extreme northern and southern ends of the proposed continuous-type accumulation. The northern part of the play is in east-central New York, whereas the southern part is in southeastern Kentucky and adjoining Virginia.

Stratigraphically, the plays involve the "Clinton" sandstone and its informal driller's subunits--the red, white, and stray Clinton sands--in Ohio and the Whirlpool Sandstone, stray sandstones in the Cabot Head Shale, and Grimsby Sandstone of the Medina Group in New York and Pennsylvania. The "Clinton" sandstone (or sands) in Ohio correlates with the Lower Silurian Medina Group of New York and not with the Middle Silurian Clinton Group of New York as originally believed; however, the term is so popular in the petroleum industry that its usage continues.

Flanked by the Tuscarora Sandstone Play (6727) on the east and the Clinton/Medina Sandstone Oil/Gas Play (6732) on the west, the plays cover large parts of New York, Pennsylvania, Ohio, and West Virginia; the southern end of the plays includes small parts of Kentucky and Virginia. On the east side the plays are bounded by an arbitrary line separating the Tuscarora Sandstone from Clinton/Medina sandstones, whereas, on the west side, they are bounded by the approximate limit of oil production in the Clinton/Medina sandstones. The United States–Canada border in the middle of Lake Erie marks the northern limit of the play.

The plays are confirmed, and their prospective reservoirs are classified as unconventional because of the probable continuous nature of the gas accumulations.

Reservoirs: Very fine- to fine-grained sandstone consisting of quartzarenite and local sublitharenite and subarkose constitutes the reservoir in the plays. Compaction and burial diagenesis have greatly reduced the primary intergranular porosity of the reservoir. Silica cement and authigenic clay minerals are the primary pore-filling materials. Locally, calcite, dolomite, anhydrite, and hematite cement may be abundant. Secondary intergranular porosity, caused by the dissolution of rock fragments, feldspar grains, and cement, and fracture porosity, caused by movement between basement-involved fault blocks, are the important porosity types in the play. Porosity for the reservoirs ranges from 3 to 11 percent and average 5 percent. Permeability is as high as 0.2 to 0.6 mD but it generally averages less than 0.01 mD. The thickness of the Clinton sandstone sequence and the Medina Group in the plays ranges from 120 to 210 ft, and sandstone to shale ratios vary from 0.6 to 1. The net reservoir thickness ranges from 2 to 90 ft and averages about 25 ft. Drilling depths to the sandstone reservoirs in eastern Ohio and northwestern Pennsylvania range from 4,000 to 6,300 ft and in southwestern Pennsylvania they may be as much as 10,000 ft. In New York the drilling depths to the Medina Group are between 1,000 and 4,000 ft, whereas in southern Ohio and adjoining eastern Kentucky the drilling depths to the "Clinton" sandstone are between 2,000 and 3,000 ft.

Source rocks: The source of the gas in the plays is uncertain. The most plausible candidates are (1) shale and argillaceous limestone of the Middle Ordovician Utica Shale, Antes Shale, and Trenton Limestone and (2) black shale of the Middle and Upper Devonian sequence. Both proposed source rock sequences are relatively thick (200–400 ft for the Middle Ordovician sequence; 50–300 ft for the Middle and Upper Devonian sequence), adequately rich (TOC 0.5-3 percent for the Middle Ordovician sequence; TOC 1-5 percent for the Middle and Upper Devonian sequence), and have organic matter dominated by type II kerogen. However, gas generated from these source bed sequences is not particularly accessible to the reservoir sandstones. For example, between 1,500 and 2,000 ft of vertical migration, through predominantly shale and siltstone, is required for gas derived from the Middle Ordovician shale sequence to reach the Clinton/Medina sandstone reservoirs. In contrast, between 1,500 and 3,000 ft of downward migration, through at least 500 ft of evaporite and evaporitic dolomite, is required for Middle and Upper Devonian shale gas to reach the sandstone reservoirs. A slight preference is given to Middle Ordovician source beds because upward vertical migration is more plausible than downward migration.

Based on CAI and T_{max} data, Middle Ordovician source rocks in the plays are in the gas generation zone. Although Middle Ordovician rocks in southernmost Ohio and eastern Kentucky are in the zone of gas generation, they contain no known source beds. Dry and wet thermal gas are the expected hydrocarbon types derived from Middle Ordovician source beds. Vitrinite reflectance data suggest that Middle and Upper Devonian source rocks in the plays have achieved several levels of thermal maturity. Devonian source rocks in western Pennsylvania, eastern Ohio, and northern West Virginia are mainly in the zone of gas generation, whereas those source rocks in western New York and eastern Ohio are in the zone of oil generation. Devonian source rocks in offshore northern Ohio (Lake Erie) and southern Ohio probably are immature with respect to oil and gas generation. Wet thermal gas and local oil are the expected hydrocarbon types derived from the Middle and Upper Devonian source rocks.

Timing and migration: Peak gas generation from the Middle Ordovician and Devonian shale sequences occurred between Late Pennsylvanian and Early Triassic time when these beds were deeply buried under an eastward-thickening wedge of orogenic sediments and thrust sheets. Gas migrated vertically upsection or downsection to the sandstone reservoirs depending on which of the two proposed source rock sequences it was generated from. Numerous facies-change stratigraphic traps, some in combination with subtle anticlinal closure and noses, were available to trap the vertically migrated gas.

Traps: Facies-change stratigraphic traps are the most important traps in the play; however, commonly the permeability barriers produced by facies changes, and to a lesser extent by diagenetic changes, are in combination with subtle anticlinal flanks and noses. In general, anticlinal closure has exerted only subtle influence, if any, on gas accumulations in the plays. Water block has been suggested by several petroleum geologists as a possible trapping mechanism for gas in the Clinton/Medina sandstones. This type of trap is created by low-permeability sandstone sequences whose permeability to water is much greater than their permeability to gas. If the model is applicable to these plays, it would imply the presence of a basin-center gas accumulation.

Seals for the stratigraphic traps are shale beds within the Clinton/Medina interval and Middle Silurian shale and micrite beds of the Packer Shell limestone, Dayton Limestone, Rochester Shale, and Clinton Group.

Exploration status: Gas was first discovered in the play in the mid to late 1880's in western New York and in the late 1890's in southern Ohio. Drilling depths to the Clinton and Medina sandstones in these regions range from less than 1,000 to about 2,000 ft; however, because of the low permeability of the Lower Silurian sandstones, most of the exploration was concentrated in east-central Ohio where reservoir quality was higher and oil was produced as well as gas. By the late 1950's and early 1960's, exploration activity had successfully expanded into eastern Ohio, northwestern Pennsylvania, and western New York where lower quality sandstone reservoirs occur, drilling depths commonly exceed 4,000 ft, and gas is the dominant hydrocarbon type. Successful exploration for gas continues today in sparsely drilled parts of the play such as southern and east-central New York, northwestern Pennsylvania, and eastern Ohio. In Pennsylvania and Ohio, drilling depths to the Clinton and Medina sandstones exceed 6,000 ft. An offshore gas well drilled in 1958 in Pennsylvania and numerous offshore wells drilled since 1913 in Canada indicate that gas in the play extends into Lake Erie at least as far north as the United States–Canada border. Most sandstone reservoirs in the play have tight formation status.

The most important factor that insured exploration success in low-permeability sandstone reservoirs was the development of hydraulic fracturing techniques. Wells that originally had a very low natural flow of gas were transformed by hydraulic stimulation into wells producing as much as 1–2 MMCFGPD. Field size has little meaning in the plays because older fields tend to merge together into continuous-type accumulations with additional drilling. For example, the three or four Medina gas fields that were discovered in Chautauqua County, western New York, in the 1960's have now merged into the giant Lakeshore field, which has an ultimate recovery of about 650 BCFG.

Resource potential: This group of plays has the potential for yielding a large volume of undiscovered gas in a continuous-type accumulation. Undiscovered gas in the plays is assessed using a continuous-type unconventional resource model. This model incorporates: (1) estimated ultimate recovery (EUR) per well probability distributions, (2) optimum area that a well can drain (spacing), (3) number of untested drill sites having the appropriate spacing area, (4) success ratio of previously drilled holes, and (5) risk.

EUR values for producing wells in the Clinton/Medina Sandstone Gas High Potential Play (6728) range from 5 (F95) to 330 (F5) MMCFG and have a median (F50) of about 70 MMCFG. Smaller EUR values are recorded for producing wells in the Clinton/Medina Sandstone Gas Medium Potential Play (6729); they range from 5 to 150 MMCFG and have a median (F50) of about 50 MMCFG. Low EUR values, high risk, and a low success ratio are assigned to the Clinton/Medina Sandstone Gas Medium-Low Potential (6730) and Clinton/Medina Sandstone Gas Low Potential Plays (6731). A well spacing of 40 acres is selected for all plays.

6732. CLINTON/MEDINA SANDSTONE OIL/GAS PLAY

The Tuscarora Sandstone Gas Play (6727), Clinton/Medina Sandstone Gas Plays (6728, 6729, 6730, 6731), and Clinton/Medina Sandstone Oil/Gas Play (6732) are contiguous plays that occupy progressively western parts of the widespread Lower Silurian sandstone depositional system. Although sandstones of fluvial and distributary channel origin are recognized locally, most of the sandstone was deposited in littoral marine, deltaic, and offshore-marine settings. This group of plays extends westward from near the Allegheny structural front in Pennsylvania, West Virginia, and Virginia where sandstone beds are thickest and have minor shale interbeds (Tuscarora Sandstone), to the depositional limit of the Lower Silurian "Clinton" sandstones in east-central Ohio and eastern Kentucky, where sandstone beds are thinner and intercalated with abundant shale and siltstone. The Lower Silurian sandstone system extends into New York as far north as the outcrop limit of the Lower Silurian Medina Group and as far east as the subcrop of the Tuscarora Sandstone beneath the Middle Silurian Oneida Sandstone.

The Clinton/Medina Sandstone Oil and Gas Play (6732) is defined by oil and gas trapped in the Lower Silurian "Clinton" sandstones and Medina Group sandstones by facies-change stratigraphic traps and combination traps. The play is confirmed, and it has many aspects of continuous-type accumulations such as abnormally low formation pressure, coalesced oil and gas fields, and a general lack of control by anticlinal closure on accumulations; however, because of the high drilling density of the play, it is most conveniently described as conventional and its resources--except for those in Lake Erie--assessed as reserve growth.

Stratigraphically, the play involves the "Clinton" sandstone and its informal driller's subunits, the red, white, and stray Clinton sands, in Ohio and the Whirlpool Sandstone, stray sandstones in the Cabot Head Shale, and Grimsby Sandstone of the Medina Group in New York and Pennsylvania. The "Clinton" sandstone (or sands) in Ohio correlates with the Lower Silurian Medina Group of New York and not with the Middle Silurian Clinton Group of New York as originally believed, however, the term is so popular in the petroleum industry that its usage continues. The most westerly of the three Lower Silurian sandstone plays, this play covers most of east-central Ohio and a very small part of northwestern Pennsylvania. On the east side the play is bounded by an arbitrary line that marks the approximate eastern limit of oil production in the Clinton/Medina sandstones, whereas on the west side it is bounded by the approximate depositional limit of the Clinton/Medina sandstones. The northern part of the play extends into Lake Erie.

Reservoirs: Very fine to fine grained sandstone consisting of quartzarenite and local sublitharenite and subarkose constitute the reservoir in the play. Compaction and burial diagenesis have reduced the primary intergranular porosity of the sandstone reservoirs but not to as extreme a degree as in the sandstone reservoirs of the adjoining Clinton/Medina Sandstone Gas Plays. Porosity for reservoirs in the play ranges from 8 to 15 percent and averages 12 percent. Most of this porosity is caused by primary intergranular porosity, but fracture porosity, caused by movement between basement-involved fault blocks, may be important locally. Permeability ranges from <0.1 to 75 mD and averages 5 mD. The thickness of the Clinton sandstone sequence and the Medina Group in the play ranges from 100 to 200 ft and sandstone to shale ratios range from 0.2 to 1.0. The net reservoir thickness ranges from 6 to 105 ft and averages about 40 ft. Drilling depths to the sandstone reservoirs in the play range from 1,000 to 5,000 ft.

Source rocks: The source of the oil and gas in the play is uncertain. The most plausible candidates are (1) shale and argillaceous limestone of the Middle Ordovician Utica Shale, Antes Shale, and Trenton Limestone and (2) black shale of the Middle and Upper Devonian sequence. Both proposed source rock sequences are relatively thick (200-400 ft for the Middle Ordovician sequence; 50-300 ft for the Middle and Upper Devonian sequence), adequately rich (TOC 0.5-3 percent for the Middle Ordovician sequence; TOC 1-5 percent for the Middle and Upper Devonian sequence), and have organic matter dominated by type II kerogen. However, oil and gas generated from these source bed sequences are not particularly accessible to the reservoir sandstones. For example, between 1,500 and 2,000 ft of vertical migration, through predominantly shale and siltstone, is required for oil and gas derived from the Middle Ordovician shale sequence to reach the Clinton/Medina sandstone reservoirs. In contrast, between 1,500 and 3,000 ft of downward migration, through at least 500 ft of evaporite and evaporitic dolomite, is required for Middle and Upper Devonian-derived oil and gas to reach the sandstone reservoirs. A slight preference is given to Middle Ordovician source beds because upward vertical migration is more plausible than downward migration.

Based on CAI and T_{max} data for the Middle Ordovician sequence and vitrinite reflectance data for the Middle and Upper Devonian sequence, both source bed sequences are located in the zone of oil generation; however, Devonian source rocks in about half the play are immature with respect to oil and gas generation. Oil and wet thermal gas are the expected hydrocarbon types whether the source is the Middle Ordovician or Devonian shale sequence.

Timing and migration: Peak oil and gas generation from the Middle Ordovician and Devonian shale sequences occurred between Late Pennsylvanian and Early Triassic time when these beds were buried under an eastward-thickening wedge of orogenic sediments and thrust sheets. Most of the oil and gas was generated east of the play, probably in the vicinity of the Clinton/Medina Sandstone Gas plays and the Tuscarora Sandstone Gas Play (6727). Oil and gas migrated vertically upsection or downsection to Lower Silurian sandstones, depending on which of the two proposed source rock sequences they were generated from, and then migrated up the gently dipping northwest flank of the basin to east-central Ohio. Numerous facies-change stratigraphic traps, some in combination with subtle anticlinal flanks and noses, were available to trap the laterally migrated oil and gas.

Traps: Facies-change stratigraphic traps are the most important traps in the play; however, commonly, permeability barriers produced by facies changes, and to a lesser extent by diagenetic changes, are in combination with subtle anticlinal flanks and noses. Seals for the stratigraphic traps are shale beds within the Clinton/Medina interval and Middle Silurian shale and micrite beds of the Packer Shell limestone, Dayton Limestone, Rochester Shale, and Clinton Group.

Exploration status: Oil and gas was first discovered in the play in the mid- to late-1880's in Knox, Licking, Fairfield, and Perry Counties in east-central Ohio. Clinton sandstones are relatively shallow in this region and range from depths of 2,000 to 2,800 ft. In a short time, the trend had spread northward across all of east-central Ohio to the southern shore of Lake Erie. For about 70 years this region has yielded large quantities of oil and gas from reservoirs of good to moderate quality. Most of the oil and gas fields found at this time began to coalesce with later infill drilling. By the late 1950's and early 1960's, exploration for oil and gas in the Lower Silurian sandstones had successfully expanded into eastern Ohio where drilling depths were commonly greater than 4,000 ft and reservoir quality had diminished.

The most important factor that insured exploration success along the eastern part of the play was the development of hydraulic fracturing techniques. Wells that originally had very low natural flows of oil and gas were transformed by hydraulic stimulation into wells producing as much as 150 BOPD and 1 to 2 MMCFGPD. The largest oil field in the play is East Canton (Stark Co., Ohio, discovery date 1966, ultimate recovery ~100 MMBO). The exploration phase of the play is now over and sandstone reservoirs in its eastern parts have tight formation status.

Resource potential: This play has potential for a small number of undiscovered oil and gas fields greater than 1 MMBO or 6 BCFG. The undiscovered fields are in undrilled Lake Erie. Outside of Lake Erie, this play is exhausted except for very small oil and gas accumulations.

6737. UPPER DEVONIAN SANDSTONE OIL/GAS PLAY

The Upper Devonian Sandstone Oil/Gas Play (6737) and the unconventional Upper Devonian Sandstone Gas plays (6733, 6734, 6735, 6736) are contiguous plays in the sandstone depositional system of the Upper Devonian Catskill Delta. Most of the sandstone was deposited in littoral-marine, deltaic, offshore shallow-marine, and offshore deeper water marine (turbidite) settings. The Upper Devonian Sandstone Oil/Gas Play is defined by oil and gas trapped in Upper Devonian sandstone and local siltstone by facies-change stratigraphic traps in combination with diagenetic traps or fractured reservoir traps. The play is confirmed, and it has many aspects of continuous-type accumulations such as abnormally low formation pressure, coalesced oil and gas fields, and a general lack of structural control on accumulations. Because of the high drilling density, the play is most conveniently described, however, as conventional, and its resources are assessed as reserve growth. The play covers western New York, northwestern Pennsylvania, southeastern Ohio, and north-central West Virginia.

Stratigraphically, the play involves numerous formal and informal sandstone units deposited during multiple regressive events. In Pennsylvania, Upper Devonian sandstones are organized into four major sequences, in ascending order, the Braillier Formation, Elk Group, Bradford Group, and Venango Group. In West Virginia, Upper Devonian sandstones are organized, in ascending order, into the Braillier Formation, Greenland Gap Formation, Venango Formation, and Oswayo Formation. Farther to the westward in West Virginia, the Greenland Gap Formation changes facies and is replaced by shale and siltstone of the Braillier Formation. Pennsylvania and West Virginia nomenclature correlate approximately as follows: (1) the lower part of the Elk Group and underlying Braillier Formation in Pennsylvania correlate with the lower part of the Braillier Formation in West Virginia; (2) the upper part of the Elk Group, the Bradford Group, and the lower part of the Venango Group in Pennsylvania correlate with the Greenland Gap Formation in West Virginia; and (3) the middle and upper parts of the Venango Group in Pennsylvania correlate with the Venango Formation and Oswayo Formation in West Virginia.

The eastern boundary of the play is marked by the approximate limit of oil production in the Upper Devonian sandstone sequence, whereas the western boundary of the play is the approximate depositional limit of the Upper Devonian sandstone and siltstone sequence.

Reservoirs: Coarse siltstone, very fine to fine grained sandstone, medium-grained sandstone, and local pebbly sandstone, classified as sublitharenite, subarkose, quartzarenite, and quartzwacke, constitute the reservoirs in the play. Primary intergranular porosity, although reduced somewhat by silica and calcite cement and authigenic clay minerals, is the dominant porosity type in the play. Porosity types of lesser importance are (1) secondary intergranular porosity caused by dissolution of detrital grains (feldspar, metamorphic rock fragments) and silica and (or) calcite cement, (2) fracture porosity caused by movement between basement-involved fault blocks, and (3) moldic porosity caused by fossil fragment dissolution. Porosity values for reservoirs in the play range from 2 to 26 percent and average about 14 percent. Permeability values range from 0.07 mD to several thousands of millidarcies and average about 10 mD.

A variety of sandstone bodies differing in depositional setting, orientation to paleoshoreline, and degree of lateral continuity are recognized in the play. Among the most common types are (1) sheetlike sandstone bodies deposited along deltaic and interdeltaic shorelines, (2) long, narrow pebbly sandstone bodies deposited as offshore bars subparallel to the shoreline, and (3) discontinuous sandstone bodies deposited normal to the shoreline representing reworked delta distributary channels, distributary mouth bars, and turbidites. The thickness of the producing part of the sandstone reservoirs ranges from about 10 to 40 ft and averages about 10 ft. Commonly, more than one sandstone reservoir is productive in a given well. Drilling depths to the sandstone reservoirs are from less than 1,000 to 5,000 ft.

Source rock: The sources of oil and gas in the play are the Middle Devonian Marcellus Shale that underlies the Upper Devonian sandstone sequence and the Upper Devonian black shales that are located west of and intertongue with the Upper Devonian sandstone sequence. The Middle and Upper Devonian black shale sequence in the play is between 100 and 500 ft thick and has TOC values between 3 and 5 percent. Vitrinite reflectance data indicate that Middle and Upper Devonian source rocks in the play have achieved several levels of thermal maturity. Devonian source rocks in western New York and northwestern Pennsylvania are in the zone of oil generation, whereas

Devonian source rocks in west-central Pennsylvania, southeastern Ohio, and northern and north-central West Virginia are in the zone of gas generation. The southeastern part of the play in southwestern Pennsylvania and adjoining West Virginia may be overmature with respect to the generation of oil and gas. Oil and wet thermal gas are the expected hydrocarbon types in the play.

Timing: Peak oil and gas generation from the Middle and Upper Devonian black shale sequence occurred between Late Pennsylvanian and Early Triassic time when the sequence was buried under an eastward-thickening wedge of orogenic sediments. Oil and gas migrated short distances laterally and upsection to the sandstone reservoirs. A variety of facies-change stratigraphic traps, diagenetic traps, and fractured-reservoir traps were available to trap the oil and gas.

Traps: Facies-change stratigraphic traps, commonly in combination with anticlinal flanks, anticlinal noses, diagenetic traps and fractured-reservoir traps, are the most important traps in the play. In general, anticlinal closure has exerted only subtle influence, if any, on oil and gas accumulations in the play. Seals for the stratigraphic traps are shale and fine-grained siltstone intercalated with the Upper Devonian sandstone sequence.

Exploration status: Oil and associated gas in the play was discovered in the Drake well, Venango County, Pennsylvania, in 1859. This oil discovery marked the beginning of a prolific oil and gas trend in Upper Devonian sandstones that stretches from western New York, across northwestern Pennsylvania, to northern West Virginia. Most oil fields in the trend were identified by the early 1920's, and many of the larger fields were exploited using secondary recovery techniques, mainly water flooding, in the 1930's. Gas fields containing minor associated oil continued to be discovered along the eastern margin of the play in the 1950's and 1960's. Approximately 800 oil and (or) gas fields have been discovered in the play since 1859, of which about 50 have been converted to gas storage facilities. The exploration phase of the play is now over, and current drilling consists of infill wells that add small amounts of oil and gas to existing fields. Many of the sandstone reservoirs in the eastern part of the play have tight formation status.

Among the largest oil fields in the play are Bradford (McKean Co., Pa. and Allegheny Co., N.Y.), discovery date 1871, ultimate recovery 680 MMBO; Saxonburg (Butler Co., Pa.), discovery date 1866, ultimate recovery 59 MMBO; Salem-Wallace-Zinnia (Harrison and Doddridge Cos., W. Va.), discovery date 1899, ultimate recovery 41 MMBO;

Mannington (Marion Co., W. Va.), discovery date 1899, ultimate recovery 32 MMBO; and Bullion-Clintonville (Venango Co., Pa.), discovery date 1876, ultimate recovery 29 MMBO.

Resource potential: This play has no potential for undiscovered oil and gas fields greater than 1 MMBO or 6 BCFG. The shallow depth of the reservoirs and the high drilling density in the play area suggest that the play is exhausted except for very small accumulations.

UPPER DEVONIAN SANDSTONE GAS PLAYS

6733. UPPER DEVONIAN SANDSTONE GAS HIGH POTENTIAL
6734. UPPER DEVONIAN SANDSTONE GAS MEDIUM POTENTIAL (HYPOTHETICAL)
6735. UPPER DEVONIAN SANDSTONE GAS MEDIUM-LOW POTENTIAL (HYPOTHETICAL)
6736. UPPER DEVONIAN SANDSTONE GAS LOW POTENTIAL (HYPOTHETICAL)

The unconventional Upper Devonian Sandstone Gas plays (6733, 6734, 6735, 6736) and the conventional Upper Devonian Sandstone Oil/Gas Play (6737) are contiguous plays in the sandstone depositional system of the Upper Devonian Catskill Delta. Most of the sandstone was deposited in littoral-marine, deltaic, offshore shallow-marine, and offshore deeper-water marine (turbidite) settings. The unconventional Upper Devonian Sandstone Gas plays (6733, 6734, 6735, 6736) located east of the conventional play (6737) are defined as a continuous-type gas accumulation because of (1) low-permeability reservoirs, (2) abnormally low formation pressure, (3) coalesced gas fields, (4) gas shows or production in most holes drilled, and (5) general lack of control by anticlinal closure on gas accumulations.

Four Upper Devonian sandstone gas plays are recognized. The Upper Devonian Sandstone Gas High Potential Play (6733), the largest of the plays, is down-dip of the conventional Upper Devonian Sandstone Oil/Gas Play (6737). It extends across most of central Pennsylvania and part of north-central West Virginia. The relatively small Upper Devonian Sandstone Gas Medium Potential Play (6734) consists of two parts: a northeastern Pennsylvania part attached to the northeast end of play 6733 and a south-central Pennsylvania, western Maryland, and eastern West Virginia part attached to the down-dip side of play 6733. The Upper Devonian Sandstone Gas Medium-Low Potential Play (6735) also consists of two parts. The southern part of the Upper Devonian Sandstone Gas Medium-Low Potential Play (6735) occupies most of southeastern West Virginia and small pieces of adjoining Virginia and is attached at its north end to plays 6733, 6734, and 6737. The northern part of the Upper Devonian Sandstone Gas Medium-Low Potential Play (6735) occupies small parts of northeastern Pennsylvania and adjoining south-central New York and is attached along its west side to plays 6734 and 6737. The Upper Devonian Sandstone Gas Low Potential Play (6736) wraps around the northern parts of plays 6734 and 6735 in a large part of southeastern New York and northeastern Pennsylvania.

Stratigraphically, the play involves numerous formal and informal sandstone and siltstone units deposited during multiple regressive events. In Pennsylvania, Upper Devonian sandstones and siltstones are organized into four major sequences, in ascending order, the Braillier Formation, Elk Group, Bradford Group, and Venango Group. Westward in Pennsylvania the Elk, Bradford, and Venango Groups change facies and are replaced by siltstone and shale of the Braillier Formation, whereas eastward and southward the Elk, Bradford, and Venango Groups are replaced, respectively, by the Scherr, Foreknobs, and Catskill Formations. In West Virginia, Upper Devonian sandstones are organized, in ascending order, into the Braillier Formation, Greenland Gap Formation, Hampshire Group, and Price Formation (part). Farther to the west in West Virginia, the Hampshire Group and Price Formation (part) are replaced, respectively, by the Venango and Oswago Formations, and the Greenland Gap Formation changes facies and is replaced by shale and siltstone of the Braillier Formation. Pennsylvania and West Virginia nomenclature correlates approximately as follows: (1) the lower part of the Elk Group and underlying Braillier Formation in Pennsylvania correlate with the lower part of the Braillier Formation in West Virginia; (2) the upper part of the Elk Group, the Bradford Group, and the lower part of the Venango Group in Pennsylvania correlate with the Greenland Gap Formation in West Virginia; and (3) the middle and upper parts of the Venango Group in Pennsylvania correlate with the Hampshire Group and lower part of the Price Formation in West Virginia.

The eastern boundary of the play in West Virginia, Virginia, Maryland, central and northeastern Pennsylvania, and southeastern New York and the northern boundary of the play in east-central New York are marked by the erosional limit of the Upper Devonian sandstone sequence. The western boundary of the play in west-central New York, west-central Pennsylvania, and north-central West Virginia is marked by the approximate limit of oil production in the Upper Devonian sandstone sequence. The western limit of the play in southern West Virginia is the depositional limit of the Upper Devonian sandstone and siltstone sequence.

The plays are confirmed and their prospective reservoirs are classified as unconventional because of the continuous nature of the gas accumulations.

Reservoirs: Coarse siltstone and very fine to fine grained sandstone, classified as sublitharenite, quartzwacke, subarkose, and quartzarenite constitute the reservoirs in the play. Compaction and burial diagenesis have greatly reduced the primary intergranular porosity of the reservoir. Silica and calcite cement and authigenic clay minerals are the primary pore-filling materials. Secondary intergranular porosity, caused by dissolution of detrital grains (feldspar, metamorphic rock fragments), and silica and (or) calcite cement, and fracture porosity, caused by movement between basement-involved fault blocks, are the important porosity types in the play. Porosity types of secondary importance are moldic porosity caused by fossil fragment dissolution and reduced primary intergranular porosity in medium-grained quartzarenites. Porosity for reservoirs in the play ranges from 0.5 to 15 percent and averages 5 percent. Permeability is as high as 2 mD, but generally averages less than 0.01 mD. Porosity and permeability values are higher than average along the crests of anticlines.

Lateral continuity of the sandstone reservoirs ranges from discontinuous lens-shaped sandstone bodies to continuous sheet like sandstone bodies. The net thickness of the sandstone reservoirs ranges from about 10 to 25 ft. Commonly, more than one sandstone reservoir is productive in a given well. Drilling depths to the sandstone reservoirs are between 2,000 and 6,000 ft.

Source rocks: The sources of gas in the play are the Middle Devonian Marcellus Shale that underlies the Upper Devonian sandstone sequence and the Upper Devonian black shales that are west of and intertongue with the Upper Devonian sandstone sequence. The Middle and Upper Devonian black shale sequence in the play area is between 50 and 400 ft thick and has TOC values between 3 and 5 percent. Vitrinite reflectance data indicate that Middle and Upper Devonian source rocks in the play have achieved several levels of thermal maturity. Devonian source rocks in the northern and southern parts of the play area are in the zone of gas generation, whereas Devonian source rocks in the central and eastern parts of the play are overmature with respect to the generation of oil and gas. Dry and wet thermal gas are the expected hydrocarbon types in the play.

Timing and migration: Peak gas generation from the Middle and Upper Devonian black shale sequence occurred between Late Pennsylvanian and Early Triassic time when the sequence was buried under an eastward-thickening wedge of orogenic sediments. Gas migrated a short distance laterally and upsection to the sandstone reservoirs. A variety of facies-change stratigraphic traps, diagenetic traps, and fractured-reservoir traps were available to trap the gas.

Traps: Facies-change stratigraphic traps, commonly in combination with anticlinal flanks, anticlinal noses, diagenetic traps, and fractured-reservoir traps, are the most important traps in the play. In general, anticlinal closure has exerted only subtle influence, if any, on gas accumulations in the play. Water block, a suggested trapping mechanism for the Clinton/Medina Sandstone Gas Plays, also may apply to the Upper Devonian Sandstone Gas plays. This type of trap is created by low-permeability sandstone sequences whose permeability to water is much greater than their permeability to gas. If the model is applicable to this play, it would imply the presence of a basin-center gas accumulation.

Seals for the stratigraphic traps are shale and fine-grained siltstone intercalated with the Upper Devonian sandstone sequence.

Exploration status: The first 15–20 gas fields in the play were discovered from 1865 through 1900 in Armstrong, Cambrian, Elk, Indiana, Jefferson, and Westmoreland Counties, Pennsylvania. These early fields, whose drilling depths to Upper Devonian sandstone reservoirs range from 1,500 to 3,000 ft, are along the eastern perimeter of the prolific Upper Devonian sandstone oil and gas trend (play 6737) discovered in 1859. For the next 60 years, new fields were discovered in Pennsylvania along the margins of the Upper Devonian oil and gas trend at the approximate rate of one field per year. In the 1960's, gas field discoveries in the play showed a modest increase, and 11 new fields were discovered in Pennsylvania (drilling depth ~3,000 to 5,000 ft). This modest increase signaled a shift in exploration to deeper parts of the play where gas is trapped in low-permeability sandstone reservoirs. An abrupt increase in the amount of gas discovered in low-permeability sandstone reservoirs occurred in the 1970's and 1980's when approximately 70 new fields were discovered in Pennsylvania and 2 new fields were discovered in West Virginia. The number of gas fields discovered in West Virginia in the 1970's and 1980's is probably under represented here because Upper Devonian sandstone gas discoveries were reported as deeper extensions of existing fields rather than new fields. Successful exploration continues today in west-central Pennsylvania and east-central West Virginia where drilling depths range from about 3,000 to 7,000 ft. Most sandstone reservoirs in the plays have tight formation status.

An important factor that insured exploration success in low-permeability sandstone reservoirs in the plays was the development of hydraulic fracturing techniques. Wells that originally had a very low natural flow of gas were transformed by hydraulic stimulation into wells producing as much as 1–2 MMCFGPD. Field size has little meaning in the plays because older fields tend to merge together into a regional-type accumulation with additional drilling. For example, three or four Upper Devonian sandstone fields that were discovered in Centre and Clinton Counties, Pennsylvania, in the early 1980's have now merged into a single accumulation having an ultimate recovery of about 250 BCFG.

Resource potential: This group of plays has potential for a large quantity of undiscovered gas in a proposed continuous-type accumulation. Undiscovered gas in the plays is assessed using a continuous-type unconventional resource model. This model incorporates (1) estimated ultimate recovery (EUR) per well probability distributions, (2) optimum area that a well can drain (spacing), (3) number of untested drill sites having the appropriate spacing area, (4) success ratio of previously drilled holes, and (5) risk.

EUR values for producing wells in the Upper Devonian Sandstone Gas High Potential Play (6733) range from 7 (F95) to 197 (F5) MMCFG and have a median (F50) of about 54 MMCFG. Slightly smaller EUR values are estimated for producing wells in the Upper Devonian Sandstone Gas Medium Potential Play (6734); they range from 5 (F95) to 200 (F5) MMCFG and have a median (F50) of about 50 MMCFG. Low EUR values, high risk, and a low success ratio are assigned to the Upper Devonian Sandstone Gas Medium-Low Potential (6735) and Upper Devonian Sandstone Gas Low Potential (6736) Plays. A well spacing of 40 acres was selected for all plays.

DEVONIAN BLACK SHALE GAS PLAYS

by R.C. Milici

6740. DEVONIAN BLACK SHALE–GREATER BIG SANDY PLAY
6741. DEVONIAN BLACK SHALE–GREATER SILTSTONE CONTENT
6742. DEVONIAN BLACK SHALE–LOWER THERMAL MATURITY (HYPOTHETICAL)
6743. DEVONIAN BLACK SHALE–UNDEVELOPED NE OHIO AND WESTERN PENNSYLVANIA PLAY (HYPOTHETICAL)

Black gas-producing shale of Devonian and Mississippian age is present in much of the Appalachian Basin, in an area that extends from New York generally southwestward through Pennsylvania, Maryland, Ohio, West Virginia, and eastern Kentucky, into Tennessee. In general, the shale was deposited in a foreland basin along the distal margins of the Acadian Catskill delta. Sediment input into this basin was from the northeast, from erosion of Acadian highlands that were elevated by the collision of ancestral North America with European sialic crust (Perroud and others, 1984).

Throughout much of their occurrence, the Devonian and Mississippian black shales are inclined gently to the east or southeast into the Appalachian Basin, away from the crest of the Cincinnati Arch. The western boundary of the play is along the outcrop of the Devonian shale along the western margin of the basin, where it is exposed on the eastern flanks of the Nashville and Jessamine Domes in Tennessee and Kentucky, and along the trace of the shale outcrop in central Ohio. The southern boundary of the play is in the Appalachian Plateau regions of Tennessee, where the entire black shale sequence thins to 50 ft or less. At the northern end of the Appalachian Basin, Devonian-Mississippian gas shales are exposed in western and central New York, where they trend easterly and dip generally to the south. The eastern margin of the play in general is within the Appalachian Plateau, where the black-shale-dominated deltaic sequence gives way eastward to coarser grained siltstone and gray shale that contain relatively less organic matter.

In general, the plays are a combination conventional-unconventional continuous-type accumulations. The black shales serve both as source and reservoir for the gas and, thus, are autogenic (Milici, 1993). Production depends upon the coincidence of several factors, including relatively abundant organic matter at suitable thermal maturity and a reservoir that is significantly enhanced by a naturally occurring fracture system.

Reservoirs: In its productive area, the Devonian-Mississippian Catskill delta sequence consists of interbedded black shale facies and gray shale and siltstone facies (de Witt and others, 1993; Milici, 1993). Devonian black shales include the Marcellus Shale, Rhinestreet Shale Member of the West Falls Formation, Pipe Creek Shale Member of the Java Formation, lower and upper parts of the Huron Member of the Ohio Shale, and Cleveland Member of the Ohio Shale. The black Sunbury Shale is the only gas shale of Mississippian age in this sequence. A Mississippian heterogeneous, multifacies sandstone, the Berea Sandstone, is beneath the Sunbury throughout much of the area and is a significant reservoir within the shale sequence. The greatest thickness of combined black-shale units is in the depocenter in central Pennsylvania, where together the units are about 1,400 ft thick and constitute about 15 percent of the deltaic sequence (Milici, 1993). In the productive area in southwestern Virginia, black shale beds constitute about 40 percent of the section, although the entire sequence is only about 400 ft thick.

Gas shale reservoir quality depends to a large degree on the occurrence of an integrated natural fracture system within the shale. In the southern part of the play area, in southwestern Virginia, eastern Kentucky, southern Ohio, and West Virginia, fracturing within the shale probably is related to subhorizontal decollement (Schumaker, 1980; Milici, 1993). In the Lake Shore fields of northern Ohio and northwestern Pennsylvania, fracture porosity in the shale may be related to deformation caused by glacial loading and differential isostatic rebound (White, 1992).

Source rocks: Stratigraphically, the source rocks of these autogenic shales are the same as the reservoirs. In general, the greatest amount of organic carbon in the shale sequence (2 percent or more) extends in a broad band northward from eastern Kentucky and adjacent West Virginia into central Ohio (Schmoker, 1993). On the western side of the Appalachian Basin, kerogen types I and II predominate, indicating that their principal sources were algae or marine biota (Zeilinski and McIver, 1982). On the eastern side of the basin, woody and coaly types predominate (type III), and by using carbon isotopes Maynard (1981) showed that the only likely source of this land-derived carbon was to the east. In general, R_o values of vitrinite increase from about 0.5 to 2.0 percent eastward across the Appalachian Basin (Maynard, 1981; Schmoker, 1993). In the productive areas in Virginia, Kentucky, and West Virginia, R_o values range from about 0.6 to 1.5 percent.

Timing and migration of hydrocarbons: Depending on location within the Appalachian Basin, generation of hydrocarbons probably occurred during maximum burial late in the Pennsylvanian, and westward migration of hydrocarbons probably occurred during thrust loading of the eastern side of the basin during the Alleghenian deformation.

Traps: The Devonian gas shales are best described as regional accumulations having variable production characteristics. Production depths may range from several tens of feet to several hundreds of feet in some areas, such as in the Lake Shore fields, to 5,000 feet or more in the deeper parts of the play in southwestern Virginia. Evidence from drilling indicates that zones of decollement and associated extensional and contractional fractures are much more likely to be present within the kerogen-bearing black shales rather than in the interbedded gray shale and siltstone (Young, 1957; Milici, 1993). Productive horizons thus are separated from one another and sealed by less fractured fine-grained siliciclastic units having relatively low carbon content.

Exploration status: The Devonian Black Shale Gas plays are the oldest gas plays in the United States. The first well drilled for gas in the United States was drilled in Fredonia, New York, in 1821, in shale beds overlying the black Dunkirk Shale (deWitt and others, 1993). Since then, Devonian shales have yielded about 3.0 TCFG, and it is estimated that recoverable reserves are about 20 TCFG (Charpentier and others, 1993).

At present, gas is produced from Devonian and Mississippian black shales from three general regions, as well as from numerous scattered localities in the Appalachian basin. A major producing area in southernmost Ohio, eastern Kentucky, southwestern West Virginia, and southwestern Virginia includes the Big Sandy gas field and several nearby smaller fields. This area constitutes the Greater Big Sandy Gas Play (Play 6470), the most productive shale-gas play in the Appalachian Basin. In this area, the cumulative thickness and organic richness of the black gas shales within the Devonian shale sequence is relatively great. Although the kerogen is generally oil prone in this part of the Appalachian Basin, natural gas is commonly produced instead of oil because of the relatively low thermal maturity of the source beds in this area. Abundant decollement-related fracture porosity is an essential characteristic of the reservoir, and these fractures provide the permeability necessary for the gas to migrate to the well bore. More than 10,000 wells were drilled and produced more than 2.5 TCFG from the Big Sandy gas field between 1921 and 1985 (Hunter and Young, 1953; Brown, 1976; Charpentier and others, 1993).

An extension of the Big Sandy producing area is present to the north, in West Virginia, and is called "the emerging area" by Patchen and Hohn (1993). The "emerging area" of Patchen and Hohn (1993) in western West Virginia extends into nearby counties in southeastern Ohio. For the purposes of this assessment, this shale-gas play is characterized by its greater siltstone content (play 6741). It is of considerable economic interest for exploration, however, primarily because it produces oil as well as gas from the Devonian shale sequence. The occurrence of both liquid and gaseous hydrocarbons in the Devonian shale sequence in this region is a result of the almost unique coincidence of suitable source rock composition, thermal maturity, matrix porosity in fine-grained siliciclastics, and abundant fracture porosity (Zielinski and McIver, 1982). In general, the Upper and Middle Devonian stratigraphic sequence in this area contains a significant stratigraphic component that has a relatively low organic content. The black and gray shale formations, rich in organic matter, are interstratified (diluted) with gray and greenish-gray shales and siltstones, and in places, with very fine-grained sandstones, all relatively lean in organic matter. As a result of this overall low content of organic matter, this play may ultimately prove marginal or non-commercial.

Low-pressure fields have been producing gas from fractured Devonian shales in the Lake Shore fields for than 100 years in an area of relatively low thermal maturity (play 6742). Almost all of northern Ohio and adjacent parts of Pennsylvania and nearby New York were subjected to several episodes of continental glaciation within the last 1,000,000 years during the Pleistocene Epoch. White (1992) suggests that ice as thick as 4,000 to 6,500 ft effectively produced a decollement in Silurian salt measures that resulted in the formation of southeastward verging salt-cored anticlines around the periphery of the Laurentide ice lobe. Indeed, glacial loading and post-glacial isostatic rebound in the gas-producing regions to the south of the Great Lakes appears to have created the fractured pathways for gas to have migrated from black shale source rocks into intercalated brittle silty and sandy reservoirs, as well as to have fractured and enhanced the storage capacity of these reservoirs. Drilling commenced in Pennsylvania in the 1850's and was extended into Ohio a decade later (Janssens and deWitt, 1976). Hundreds of wells have been drilled, chiefly for domestic production. In general, initial production ranges from 1 to 50 MCF/D. The wells decline slowly and may produce gas for 50 years or more. Production is probably from silty and sandy zones within the shale sequence, and fracture porosity is of secondary importance (Broadhead, 1993).

Resource potential: The Devonian Black Shale Gas plays are a regional accumulation that has produced moderate quantities of natural gas over many years. Reserves previously estimated are large, and their future production depends primarily on the economics of the natural gas industry and on improved technology for production of the gas. Most favorable areas are those having relatively high amounts of organic matter, suitable thermal maturation, and naturally enhanced fracture porosity. A dozen or more shale-gas wells were drilled in western Pennsylvania to the south of the Lake Shore fields during the late 1970's and early 1980's. Although most of these wells either produced natural gas or have the potential to produce gas from the Devonian shale and siltstone sequence, the area is relatively untested (play 6473). In addition, Milici (1993) identified two relatively large, untested areas in northeastern Ohio and western Pennsylvania that initially, at least, may be favorable for exploration.

6725. MISSISSIPPIAN AND PENNSYLVANIAN SANDSTONE/CARBONATE PLAY

The Mississippian and Pennsylvanian Sandstone/Carbonate Play is defined by oil and gas trapped in shallow-marine sandstone and shelf limestone by facies-change stratigraphic traps, combination traps, unconformity traps, and local anticlinal traps. Stratigraphically, the play involves numerous formal and informal sandstone units and several limestone units. Among the important reservoirs are the Lower Mississippian (recently changed to Upper Devonian) Berea Sandstone (Ohio, West Virginia, Kentucky, Virginia), Lower Mississippian (recently changed to Upper Devonian) Murrysville Sandstone (Pennsylvania), bioherms in the Lower Mississippian Fort Payne Formation (Tennessee), Lower Mississippian Big Injun, Squaw, and Weir sandstones (West Virginia, Ohio, Kentucky), Upper Mississippian Greenbrier and Newman Limestones (West Virginia, Kentucky), Upper Mississippian Monteagle Limestone (Tennessee), Upper Mississippian Mauch Chunk and Pennington Formations (Kentucky, Pennsylvania, West Virginia), Upper Mississippian Ravencliff Sandstone Member of the Hinton Formation (West Virginia, Virginia), Lower and Middle Pennsylvanian Salt sands of the Lee Formation (Kentucky, West Virginia), Lower and Middle Pennsylvanian sandstone of the Pottsville Formation (Pennsylvania), Upper Pennsylvanian Cow Run Sandstone (Pennsylvania, Ohio, West Virginia, Kentucky), The previously named sandstone and limestone reservoirs are combined into a single play because they occupy the uppermost part of the sedimentary section in the basin that has been penetrated by hundreds of thousands of drill holes. Subdividing this highly explored sedimentary sequence into numerous plays seems unnecessary in view of the small number of undiscovered oil and gas fields, greater than 1 MMBO and 6 BCFG in size, that remain.

The play covers parts of Pennsylvania, Ohio, West Virginia, Maryland, Kentucky, Virginia, Tennessee, Georgia, and Alabama. The eastern and northern boundary is defined by the erosional limit of Mississippian strata. Several isolated coal basins, east of the erosional limit, in northeastern and south-central Pennsylvania and east-central Alabama, are included in the play. The western boundary of the play is marked by the western boundary of the Appalachian Basin Province (067), except in Ohio where it is marked by the erosional limit of Mississippian strata. The play is confirmed and the sandstone and limestone reservoirs are conventional.

Reservoirs: Very fine to medium grained sandstone and pebbly coarse-grained sandstone, classified as litharenite, sublitharenite, and quartzarenite, constitute the sandstone reservoirs in the play. Primary intergranular porosity, although reduced somewhat by silica, dolomite, and calcite cement and authigenic clay minerals, is the dominant porosity type in the play; however, secondary intergranular porosity, created by the dissolution of cements and detrital grains such as feldspar and metamorphic rock fragments, is also important. Porosity for sandstone reservoirs in the play ranges from 3 to 25 percent and averages between 6 and 18 percent, depending on the age, composition, and drilling depth of the reservoir. Permeability ranges from <0.1 mD to several hundreds of millidarcies and averages between 6 and 10 mD. The average thickness of the producing part of the sandstone reservoir is between 10 and 15 ft. Drilling depths to the sandstone reservoirs range from 1,500 to 3,000 ft but are as great as 5,000 ft in the eastern parts of the play area.

Carbonate reservoirs in the play consist of oosparite, crinoidal bioherms, vuggy dolomite, and crystalline dolomite. Commonly, the limestone and dolomite reservoirs in the Greenbrier/Newman Limestone (Big Lime) contain 20–30 percent of very fine to fine grained quartz sand. Vuggy, intercrystalline, oomoldic, and intergranular (oolitic) porosity are the common porosity types in the limestone and dolomite reservoirs. Locally, fracture porosity has been identified. Porosity for carbonate reservoirs in the play ranges from 2 to 24 percent and averages between 6 and 14 percent, depending on the rock type, porosity type, and drilling depth of the reservoir. Permeability ranges from 0.1 to about 50 mD and averages between 1 and 4 mD. The average thickness of the producing part of the carbonate reservoir is between 9 and 18 ft. Drilling depths to the carbonate reservoirs range from about 1,500 to 2,000 ft.

Source rocks: The sources of oil and gas in the play are the Middle Devonian Marcellus Shale, Upper Devonian black shales and the Lower Mississippian Sunbury Shale. The Middle and Upper Devonian black shale sequence in the northern part of the play is between 50 and 500 ft thick and has TOC values between 3 and 5 percent. In the

Tennessee and Alabama part of the play the Upper Devonian and Lower Mississippian black shale sequence is between 25 and 50 ft thick and has TOC values between 5 and 10 percent.

Vitrinite reflectance data indicate that Middle and Upper Devonian and Lower Mississippian source rocks in the play have achieved several levels of thermal maturity. Devonian and Mississippian source rocks in northwesternmost Pennsylvania, east-central Ohio, western West Virginia, southeastern Kentucky, east-central Tennessee, northwesternmost Georgia, and northeastern Alabama are in the zone of oil generation. Devonian and Mississippian source rocks in the zone of oil generation are flanked on the east by Devonian and Mississippian source rocks in the zone of gas generation that extends from northwestern Pennsylvania, through northern and central West Virginia, to southwestern Virginia. In southwestern Pennsylvania, western Maryland, and eastern West Virginia, Devonian and Mississippian source rocks are overmature with respect to the generation of oil and gas, whereas, in central Ohio and northern Kentucky, Devonian and Mississippian source rocks are immature with respect to the generation of oil and gas. Oil and wet thermal gas are the expected hydrocarbon types in the play.

Timing: Peak oil and gas generation from the Middle Devonian, Upper Devonian, and Lower Mississippian black shale sequences occurred between Late Pennsylvanian and Early Triassic time when the sequences were buried under an eastward-thickening wedge of orogenic sediments. Oil and gas migrated short distances laterally and upsection to the sandstone and carbonate reservoirs. A variety of facies-change stratigraphic traps, combination traps, diagenetic traps, truncation traps, and local high-amplitude anticlines were available to trap the oil and gas.

Traps: Facies-change stratigraphic traps, commonly in combination with subtle anticlinal flanks, anticlinal noses, and diagenetic traps, are the most important traps in the play. Locally important traps are anticlinal closure and truncation traps situated above and below unconformities. Seals for the traps are shale, siltstone, and micrite in the Mississippian and Pennsylvanian sequence.

Exploration status: Oil and gas in the play were first discovered in Beaver County, Pennsylvania, in 1859, the same year that the Drake well was completed. In the 1860's, most of the exploration drilling was concentrated in southwestern Pennsylvania (Beaver, Greene, and Lawrence Counties), southeastern Ohio (Gallia, Meigs, Morgan, and Washington Counties), and northern West Virginia (Hancock, Marion, Monongalia, Pleasant, Ritchie, and Wirt Counties). Most of the fields discovered in the 1860's produced oil and gas from a variety of sandstone reservoirs of Pennsylvanian age and a few sandstones of Mississippian age. The first field in the Kentucky part of the play was discovered in Knott County in 1892. By the turn of the century, approximately 125 fields had been discovered in the play.

Lower Mississippian sandstone reservoirs and Upper Mississippian carbonate reservoirs were the chief exploration objectives in the play in the early 1900's. Most oil fields in the trend were identified by the early 1930's and many of the larger fields were exploited using secondary recovery techniques, mainly water flooding, in the 1930's and 1940's. Nonassociated gas fields and a few oil fields continued to be discovered in the play in the 1950's and 1960's. Exploration in the play was rejuvenated in 1969 with the discovery of oil in bioherms of the Lower Mississippian Fort Payne Formation, Scott County, Tennessee. About 7 or 8 Fort Payne Formation oil fields greater than 1 MMBO were discovered in east-central Tennessee in the 1970's and early 1980's.

Approximately 900 to 1,000 oil and (or) gas fields have been discovered in the play since 1859. Many of these fields have commingled oil and (or) gas production from Upper Devonian sandstone and Upper Devonian black shale, but production from Mississippian and (or) Pennsylvanian reservoirs is dominant. Parts or all of about 35 fields in the play have been converted to gas storage facilities. The exploration phase of the play is almost complete, and most of the current drilling consists of infill wells that add small amounts of oil and gas to existing fields. Many of the sandstone and carbonate reservoirs in the play have tight formation status.

Among the largest oil fields in the play are Fairview-Statler Run-Mt. Morris (Monongalia and Marion Cos., W.Va.), discovery date 1890, ultimate recovery ~23 MMBO; Blue Creek (Kanawha Co., W.Va.), discovery date 1911, ultimate recovery ~19 MMBO; and Sistersville (Tyler Co., W.Va.), discovery date 1890, ultimate recovery ~15 MMBO.

Resource potential: This play has potential for a small number of oil and gas fields greater than 1 MMBO or 6 BCFG; however, the shallow drilling depths of the reservoirs and the high drilling density in the play area suggest that the play is almost exhausted. Most undiscovered fields greater than 1 MMBO or 6 BCFG are probably located along the eastern margin of the play where drilling has been less intense.

COALBED GAS PLAYS

By Dudley D. Rice and Thomas M. Finn

For the purposes of coal geology, the Appalachian Basin province is divided into three northeast-southwest trending basins: Northern, Central, and Cahaba (plays 6750 through 6753). The Northern Appalachian Coal Basin covers an area of approximately 30,000 sq mi and is located in parts of five States–Pennsylvania, West Virginia, Ohio, Kentucky, and Maryland. The Central Appalachian Coal Basin is smaller (about 23,000 sq mi) and occupies parts of Tennessee, Kentucky, Virginia, and West Virginia. The Cahaba Basin is a small, tectonically complex area located within the Appalachian Thrust Belt of Alabama.

Northern Appalachian Basin

The Northern Appalachian Basin is divided into 2 coalbed gas plays, the Northern Appalachian Basin Anticline Play (6750) and the Northern Appalachian Basin Syncline Play (6751).

A geologic overview of the coalbed gas potential of the Northern Appalachian Basin is given by Kelafant and others (1988), Patchen and others (1991), and Schwietering and others (1992). Zebrowitz and others (1991) and Hunt and Steele (1992) provide summaries of reservoir characteristics and technology development for coalbed gas in the entire Appalachian Basin. Diamond and others (1993) described production of coalbed gas associated with underground coal mining.

The coal-bearing interval of the Northern Appalachian Basin is the Pennsylvanian Allegheny, Conemaugh, and Monongahela Groups and the Permian Dunkard Group. The main targets for coalbed gas are seams assigned to, in ascending order, the Clarion/Brookville, Kittanning, Freeport, Mahoning, Pittsburgh, Sewickly, and Waynesburg Coal Groups. Each of these coal groups may contain several individual coal seams that were deposited mainly in a fluvial environment. Data from oil and gas wells indicate that the cumulative coal thickness of all the groups ranges from 10 to 19 ft. The Pittsburgh seam is the thickest (as much as 12 ft), most widespread, and has been mined extensively underground. Many of the coal groups show a eastward trend of increasing number and thickness of individual coal seams. In comparison, data from some proprietary coreholes in West Virginia indicate that the average thickness of the coals more than 2 ft thick over this same interval is greater than 25 ft. Although the coal beds are as deep as 2,000 ft in the basin, the target coal beds for coalbed gas are generally in the depth range of 500 to 1,200 ft.

Coal rank in the basin increases in an eastward direction from high-volatile B bituminous to low-volatile bituminous; a large portion of the coal is actually high-volatile A bituminous in rank. In general, coalification probably resulted from maximum burial during late Paleozoic and early Mesozoic at which time thermogenic gases were generated. However, along the Allegheny Structural Front localized areas of higher rank may have been controlled by advective heating due to fluid flow. As much as 9,000 to 10,000 ft of Permian and Pennsylvanian strata have probably been eroded starting in early Permian time. This uplift and erosion resulted in degassing of some of the original coalbed gas, particularly at shallow depths.

The coalbed gases, as determined from desorbed samples, are composed mostly of methane with variable amounts of CO_2 (as much as 10 percent). The gases are probably of thermogenic origin, although some mixing of relatively recent biogenic gas may have occurred.

Coal-bearing Pennsylvanian strata were folded into many northeast-southwest trending anticlines, which are parallel to the trend of the basin, during the main phase of the Allegheny Orogeny (Permian through Triassic time). Face cleats are oriented perpendicular or at high angles to the axes of the anticlines (NW-SE). Because the cleats are perpendicular to bedding, even on steeply dipping limbs of folds, they probably formed prior to the main phase of the Allegheny Orogeny.

Gas contents in the Northern Appalachian Basin generally vary according to rank and depth. Although gas contents as high as 400 Scf/ton have been reported, the values are generally less than 200 Scf/ton because of the low rank (high-volatile A bituminous) and relatively shallow depths (generally less than 1,200 ft). In addition to having relatively low gas contents, coals from the Northern Appalachian Basin have longer desorption times (as much as 600 days) as compared to those from other productive basins.

Coalbed gas and conventional oil and gas reservoirs are usually underpressured as compared to hydrostatic pressure (average 0.3 psi/ft). This underpressuring is probably the result of extensive underground coal mining and/or partial degassing of original thermogenic gas.

Information on coalbed hydrology is limited. However, in Indiana County, Pennsylvania, several wells produce water at rates up to 200 barrels per day. The water is supposedly potable, and a permit has been issued for surface discharge.

The in-place coalbed gas resources of the Northern Appalachian Basin in coal beds greater than 1 ft thick and deeper than 300 ft are estimated to be about 61 TCF. The majority of this resource is concentrated in the deeper Brookville/Clarion, Kittanning, and Freeport coal groups. This represents, by far, the largest in-place coalbed gas resource in the Paleozoic coal-bearing provinces of Central and Eastern United States (Eastern Interior and Midcontinent regions). However, the economic recoverability of the resource may be adversely affected in this basin by the long desorption time which will probably result in lower production rates.

Major quantities of Pennsylvanian coal are mined underground in the Northern Appalachian Basin and large amounts of methane are emitted in the process. Greene County of Pennsylvania and Monongalia County of West Virginia are two of the top five underground mining counties in the U.S. based on 1991 tonnage statistics. Large mined-out areas occur in the Kittanning, Freeport, and Pittsburgh Coal Groups, particularly in the Pittsburgh, which is the shallowest of these three groups. Some of the largest coal mine emissions rates in the United States have been documented from the Pittsburgh mines in north-central West Virginia. In 1988, West Virginia and Pennsylvania were ranked first and fourth, respectively, in terms of methane emissions from underground mines. In West Virginia, emissions were from both the Northern and Central Appalachian Basins.

The history of coalbed gas production in the Northern Appalachian Basin goes back at least 50 years. Gas was produced from the Pittsburgh coal bed in the Big Run field in Wetzel County, West Virginia starting in 1932. More than 2 BCF of coalbed gas was produced from the field until 1988. Four other gas fields and pools are also reported to have produced coalbed gas: Oakford, Gump, and Waynesburg in Pennsylvania and Pine Grove in West Virginia. During the 1970's and 1980's, the Bureau of Mines and Department of Energy, in association with mining companies, undertook a variety of projects directed toward development of the coalbed gas resource. These projects were only marginally successful because of low production rates (generally <100 MCFGPD) and technical problems, including attempted production from only a single coal seam and inadequate reservoir stimulation. Current activity is limited to one project in Indiana County, Pennsylvania, where 20 wells were drilled in 1992. Six wells were put on production, which was characterized by high water rates initially (as much as 200 bbl/D per well). In addition to technical problems, the development of coalbed gas in the Northern Appalachian Basin has been hindered by questions of gas ownership (coal versus gas rights) and environmental problems, mainly disposal of water.

Much of the Northern Appalachian Basin is underlain by shallow gas fields, with reservoirs of Mississippian and Pennsylvanian age that have been producing for many years. Therefore, an infrastructure is in place for the development of the shallow coalbed gas resource.

The area of potential Pennsylvanian coalbed gas reserves in the northern Appalachian coal basin corresponds with the area where the Kittanning Coal Group has more than 0.5 BCF/sq mi in-place which generally corresponds to depths of burial greater than 300 ft. The Kittanning has the largest in-place resources of coalbed gas in the basin, and the areas of potential reserves for other coal zones are generally within this same Kittanning area.

6750. NORTHERN APPALACHIAN BASIN–ANTICLINE PLAY
6751. NORTHERN APPALACHIAN BASIN–SYNCLINE PLAY (HYPOTHETICAL)

This target area for potential coalbed gas reserves is subdivided into two plays based on structure: (1) anticline (Northern Appalachian Basin–Anticline Play 6750), and (2) syncline (Northern Appalachian Basin–Syncline Play 6751). The anticline play is located on the crests and shallow flanks of the tightly folded northeast-southwest trending anticlines. Although the gas contents are generally lower because of the shallower depths and partial degassing, the permeability may be tectonically enhanced. In addition, the gas production from both desorption and from the cleats will probably be water free. All the past production of coalbed gas in the basin has come from this play. In the Big Run field, the only field where production records are available, gas was produced from generally unstimulated wells with no water. The undiscovered potential for this play is rated as good. Limiting factors are long desorption times that may affect production rates and low gas contents.

The syncline play, which covers more area, is located in the broad structural lows of the basin and below the gas-water contact. The gas contents in this play, as compared to the anticline play, will undoubtedly be higher because of the greater depth; however the gas production will be accompanied by water. In addition, the permeability values may be lower because of greater depth of burial and lack of enhancement by tight folding. Although no production has been established and the play is hypothetical, its potential for undiscovered resources is considered to be good. Possible limiting factors are long desorption times that may affect production rates and low gas contents.

Central Appalachian Basin

The Central Appalachian Basin contains one coalbed gas play, the Central Appalachian Basin Basin–Central Basin Play (6752).

Adams (1984) and Kelafant and Boyer (1988) described the geologic controls of coalbed gas potential of the Central Appalachian Basin. Summaries of reservoir characteristics and development of technology for coalbed gas in the entire Appalachian Basin are provided by Zebrowitz and others (1991) and Hunt and Steele (1992). Recovery and utilization of coalbed gas from underground mining operations in the Central Appalachian Basin is characterized by von Schonfeldt and others (1982).

The coal-bearing rocks of the Central Appalachian Basin are of Pennsylvanian age, but they are older (Lower and Middle Pennsylvanian) and thicker (as much as 5,000 ft) than those of the Northern Appalachian Basin. The coals are assigned to formations of the Pottsville Group; the formation names and individual coal bed names commonly change across State borders. In southwestern Virginia, where commercial production of coalbed gas is taking place, the main coal-bearing interval is assigned to the Pocahontas, Lee, and Norton Formations. The Pocahontas No. 3 is the deepest (as much as 3,000 ft deep), thickest (as much as 7 ft), and most extensive seam, and the seam is the main target for both underground mining and coalbed gas development. Younger target coal beds for gas are Pocahontas No. 4, Lower Horsepen/Firecreek, War Creek/Beckley, Lower Seaboard/Sewell, and Jawbone/Iaeger (Virginia name followed by West Virginia name). The target coal beds commonly occur in the depth range of 1,500 to 2,500 ft which is considerably deeper than the Northern Appalachian Basin.

The rank of the prospective coals for gas increases to the east from medium- to low-volatile bituminous, considerably higher than the Northern Appalachian Basin. As in the Northern Appalachian Basin, the coalification pattern was probably controlled by maximum depth of burial in late Paleozoic time, which increased to the east toward the terrigenous source area. Uplift and erosion of a considerable amount of rock probably took place in early Mesozoic time.

Produced coalbed gases in the Virginia portion of the Central Appalachian Basin are composed mainly of methane with as much as 4 percent heavier hydrocarbons and as much as 2 percent CO_2. Isotopic analyses indicate that the gases are of thermogenic origin.

Pennsylvanian strata dip gently to the northwest, whereas Mississippi and older strata dip to the southeast. Structural features of the Central Appalachian Basin are mainly the result of thin-skin tectonics of the Pine Mountain Overthrust Block that moved along d□collement zones of shale and coal generally below the Pennsylvanian coal zone. The overthrust block was transported as much as 5 mi to the northwest, which might have resulted in enhanced permeability in the overlying coals. Broad northeast-southwest folds formed prior to thrusting and close to time of deposition. Thin-skin thrusting and strike-slip faulting, which are at high angles to the thrusting, occurred during the Allegheny Orogeny (late Pennsylvanian to Permian time). The Russell Fork Fault is a prominent example of a strike-slip fault with as much as 4 mi of lateral displacement. Permeability has probably been enhanced along these faults, which might have resulted in some natural degassing of the coal beds.

In contrast to the Northern Appalachian Basin, cleat-and-joint patterns display two dominant trends that reflect two periods of structural deformation. A northeast-southwest set probably formed first and the second set (north-south) was superimposed on it during later deformation associated with movement of the Pine Mountain Overthrust Block. Some relaxation of the cleats might have occurred during Tertiary time.

Within the area of potential additions to reserves, gas contents are reported to be as high as 700 Scf/ton in the Pocahontas No. 3 coal seam, which is extensively mined underground. At equivalent depths and ranks, gas contents in the Central Appalachian Basin are much higher than those in the Northern Appalachian Basin. The variation in gas content between the two basins might be attributed to different maximum burial depths, and burial and tectonic histories. An additional factor is that the Central Appalachian coals desorb in a time period of a few days (1 to 3) as compared to the Northern Appalachian coals that commonly take a few hundred days. These shorter desorption times indicate that gas production rates from individual wells will be higher.

Reservoir pressures measured in the Pocahontas No. 3 seam are close to hydrostatic (0.35 to 0.43 psi/ft) and are higher than those reported from the Northern Appalachian Basin. The pressures may be locally lowered by underground mining activities.

Only minor amounts of water are produced from wells in the Central Appalachian Basin (several bbl/D per well). The total dissolved solids (TDS) of this water are commonly very high (greater than 30,000 ppm) and injection is required. Although precipitation is relatively abundant and some coal beds are thick and continuous, ground-water flow is restricted because the area with potential reserves is fault-bounded and the coal beds do not crop out for possible recharge.

The latest estimate for in-place coalbed gas resources of the Central Appalachian Basin for the six major coal beds (Pocahontas No.'s 3 and 4, Lower Horsepen, War Creek, Lower Seaboard, and Jawbone) is 5 TCF. Additional in-place resources are undoubtedly present in other coal seams. This resource figure is considerably lower than a range of 10 to 48 TCF, which was reported at an earlier date. The earlier large number resulted mainly from having no depth cutoff, which is critical in this area of high relief where coal beds commonly crop out on hill sides and have probably degassed.

Major quantities of coal are mined in the Central Appalachian Basin, both underground and on the surface. Five counties (Pike, Kentucky; Mingo, Boone, and Logan, West Virginia;, and Buchanan, Virginia) are in the top ten mining counties in the United States based on 1991 statistics, and Buchanan County, Kentucky, was fourth in the country in terms of total tonnage from underground mining. The majority of the underground mining is in the Pocahontas No's. 3, and 4, and Beckley seams. West Virginia and Virginia ranked number. 1 and 3, respectively, in the United States in 1988 for methane emissions from underground mines. However, parts of West Virginia are located in both the Northern and Central Appalachian Basin.

As is the case with the Northern Appalachian Basin, there have been several cooperative projects between mines and Federal agencies during the past 20 years to produce coalbed gas, most of which were marginally successful and information is not readily available. The cooperative projects were a result of the need to degasify the underground coal mines. Much of the early technology (horizontal and gob wells) to degas underground mines was actually developed in the Virginia part of the basin.

In the Central Appalachian Basin, the State of Virginia and the Federal government in 1990 adopted a version of "forced pooling" to reduce the obstacle created by uncertainty of gas ownership. This "forced pooling" procedure in Virginia resulted in a dramatic increase in the development and production of coalbed gas during the period of 1990 to 1993. In 1992, southwest Virginia had more than 280 coalbed wells that produced about 10 BCF. These wells were completed mostly in the Nora and Oakwood fields and were drilled both in association with and away from underground coal mines. As of 1993, the coalbed gas reserves in Virginia are estimated to be about 220

BCF. West Virginia has recently passed legislation regulating, and perhaps encouraging, the development of coalbed gas.

The prospective area for coalbed gas in the Central Appalachian Basin is underlain by oil and gas fields and an infrastructure for these hydrocarbons is in place. Over the past couple of years, many miles of pipeline have been constructed in southwestern Virginia for the collection of coalbed gas from many wells, which have been drilled and are producing in association with and away from underground coal mining.

The topography of the Central Appalachian Basin is characterized by considerable relief (as much as 1,500 ft), and many of the coal seams crop out along hillsides or are less than 500 ft below drainage. This condition severely limits the coalbed gas potential to about 20 percent (5,000 sq mi in West Virginia and Virginia) of the total area. One play is identified in the Central Appalachian Basin, and it is confined to that area where coal beds have gas contents of at least 86 Scf/t and reservoir pressures of at least 215 psi. These values correspond to depths of burial greater than 500 ft. The play area (5,000 sq mi) represents approximately 22 percent of the total coal-bearing part of the Central Appalachian Basin and the gas is contained in about 15 percent of the coal reserves.

6752. CENTRAL APPALACHIAN BASIN–CENTRAL BASIN PLAY

The play can be divided into two areas based on the total gas in place per section, which is the result of coal thickness, depth, and gas content. In the central area, the coal beds are thick and occur at depths greater than 1,000 ft deep indicating higher gas content. In this area, gas in-place is as much as 5 BCF per sq mi. The Nora and Oakwood fields of southwest Virginia are located within this area.

The other area surrounds this central part, and the major seams, such as the Pocahontas No. 3 and 4 and War Creek, are thinner and shallower. The gas in-place volume is less than 1 BCF per sq mi. Only a few wells, which are in Roaring Fork field, have been drilled in this play, and it is essentially undeveloped. The undiscovered potential for this play is considered to be good, although the production rates for individual wells will probably be lower than for the central area. The potential for additions to reserves for this entire play is considered to be very good.

Cahaba Basin

The fourth coalbed gas play in the Appalachian Basin province (067) is the Cahaba Coal Field play (6753) in the Cahaba Basin.

Coalbed gas potential of the Cahaba Basin is described by Telle and Thompson (1987) and Pashin and Carroll (1993). Production information for the basin's only field, Gurnee, is commonly reported with the Black Warrior Basin.

The Cahaba Basin contains one of the principal coal fields within the Appalachian Thrust Belt, a foreland thrust system. To date, most development of coalbed gas has taken place in gently deformed foreland basins, such as the adjacent Black Warrior Basin. The Cahaba coal field, although small in size, provides an example from another tectonic setting where the potential for coalbed gas exists, but its controls reflect an interaction between sedimentation, tectonism, and coalification.

The coal field is situated along the southeast side of the northeast-southwest trending Cahaba Basin which is part of an Alleghenian Thrust Sheet. Thrusting probably occurred near the margin of a relict rift basin. The basin is bound on the northwest by the Birmingham Anticlinorium and on the southeast by the Helena Thrust Fault. The basin was an actively subsiding depression behind an uplifting thrust ridge during deposition of Lower Pennsylvanian Pottsville Formation.

The Lower Pennsylvanian Pottsville Formation is the principal coal-bearing interval in the Cahaba coal field. A comparison of the Pottsville section in the adjacent Black Warrior Basin with that in the Cahaba coal field indicates a different depositional history in the Cahaba area, which is related to syndepositional tectonism (subsidence and thrusting). In the Cahaba, the Pottsville is as much as 9,000 ft thick and can be divided into a lower quartz-arenite measures, middle mudstone measures, and an upper conglomerate measures. It contains 20 informal coal zones and as many as 60 individual beds. About 25 beds are thick enough to be of economic importance, and they are primarily in the mudstone measures. Individual beds are as much as 7 ft thick and the net coal thickness can be more than 45 ft thick. Some of the economically important coal zones, in ascending order, are the Gould, Harkness, Wadsworth, Coke, Gholson, Thompson, Montavello, and Maylene.

Coals at the surface in the Cahaba field are high-volatile A bituminous rank, and the rank increases to the southeast. Rank also increases with depth; in the southeast part of the basin the rank of the coal is low-volatile bituminous at 9,000 ft. The rank of these deeper coals increases to the northwest. The diverse relation between rank patterns and structure indicates a complicated burial and thermal history. The main coalification phase occurred during time of maximum burial and thrusting. However, this regional coalification pattern is overlain by a significant post-tectonic component. This post-tectonic coalification resulted from meteoric recharge in the shallow coal beds and from expulsion of warm orogenic fluids during thrusting in the deeper coalbeds.

Although biogenic gas was probably generated in the shallower coal beds, thermogenic gas was generated in deeper coal beds (greater than 2,500 ft) in the structurally deeper parts of the basin. The best potential for thermogenic gas probably occurs in the coal beds of the mudstone measures.

Strata in the Cahaba Basin dip gently to the southeast. The southwest part of the coal field contains numerous folds. The field narrows to the northeast where *en echelon* folds and thrust faults occur in the center of the synclinorium.

In most foreland basins, rectilinear face-butt cleat systems are dominant. These cleats form in a tensile stress field and gas and water are able to flow through them. However, inclined fractures, which result from shearing by structural slip, are abundant in the folded coal beds of the Cahaba coal field. These fractures strike roughly parallel to bedding and dip approximately 60¡ to bedding. The fractures are best developed where the bedding is dipping steeper than 15¡. Thrust faults and associated folds are also common in the dipping coal beds, but, as is the case with the inclined fractures, they do not penetrate the bounding sandstone and mudstone. The ability of gas and water to flow through compressional fractures in thrust belts, such as the Cahaba coal field, is not well understood. However, similar inclined fractures do produce coalbed gas in the Black Warrior Basin along the Blue Creek Anticline.

The desorbed gas contents measured in a core hole in the southeast part of the Cahaba coal field were as much as 380 Scf/t and show a relation between rank and depth. Because of the complex burial and thermal history of the basin, more measurements and modeling of gas contents will be required for basin-wide evaluation. On the basis of the measured gas content values and the estimated coal resources by depth, rank, and location, about 2 TCF of in-place coalbed gas resources have been estimated for the basin with the highest resource potential occurring in the southeast part of the basin.

Although some coal is being mined on the surface, no underground mining has taken place in the Cahaba coal field for a number of years. Most of the underground mining was in the southeast part of the basin where the coal rank is higher.

Coalbed gas production was established in the Gurnee field in 1990, the only degasification field in the coal field. In 1993, 64 wells produced about 432 MMCF of coalbed gas. In comparison, 140 wells produced about 542 MMCF of coal gas in 1992.

6753. CAHABA COAL FIELD PLAY

Only one coalbed gas play is identified in the Cahaba Basin, the Cahaba Coal Field play, and it coincides with the areal extent of the Pottsville Formation. On the basis of the structural complexity of the coal field and the production histories of the existing wells to date, the play is estimated to have fair potential for additional reserves of coalbed gas. However, more detailed studies are needed on foreland thrust systems, such as the Cahaba, to understand the geologic factors controlling the development of potentially large resources of recoverable coalbed gas.

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