Assessment of Appalachian Basin Oil and Gas Resources: Devonian Shale–Middle and Upper Paleozoic Total Petroleum System

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ABSTRACT

The U.S. Geological Survey (USGS) recently completed an assessment of the technically recoverable undiscovered hydrocarbon resources of the Appalachian Basin Province. The assessment province includes parts of New York, Pennsylvania, Ohio, Maryland, West Virginia, Virginia, Kentucky, Tennessee, Georgia and Alabama. The assessment was based on six major petroleum systems, which include strata that range in age from Cambrian to Pennsylvanian. The Devonian Shale – Middle and Upper Paleozoic Total Petroleum System (TPS) extends generally from New York to Tennessee. This petroleum system has produced a large proportion of the oil and natural gas that has been discovered in the Appalachian basin since the drilling of the Drake well in Pennsylvania in 1859.

For assessment purposes, the TPS was divided into ten assessment units (plays), four of which were classified as conventional and six as continuous. The results were reported as fully risked fractiles (F95, F50, F5 and the Mean), with the fractiles indicating the probability of recovery of the assessment amount. Products reported were oil (millions of barrels of oil, MMBO), gas (billions of cubic feet of gas, BCFG), and natural gas liquids (millions of barrels of natural gas liquids, MMBNGL). The mean estimates for technically recoverable undiscovered hydrocarbons in the TPS are: 7.53 MMBO, 31,418.88 BCFG (31.42 trillion cubic feet) of gas, and 562.07 MMBNGL.

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INTRODUCTION

The modern petroleum industry had its beginnings in the Appalachian basin on August 27, 1859, when Col. Edwin L. Drake, while drilling for the Seneca Oil Company, produced oil from a well drilled to a depth of 69.5 feet on Oil Creek, near Titusville in northwestern Pennsylvania (fig. 1). The well was located near surface seeps where oil had been utilized locally, first by Native Americans and then by early settlers. Production was from a relatively thin, stray Venango sandstone (Devonian). The well is reported to have made at least ten barrels of oil per day for a year, which was the first oil produced commercially from a well drilled in the U. S. The well's success ignited an "industrial explosion" that spread rapidly throughout the region and into other areas of the country. A brief history of the Drake well and oil development in the Titusville area has been compiled by the U.S. Department of the Interior (1976). Not known at the time was that the well had discovered the foremost petroleum system in the Appalachian basin, the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System (fig. 2, Tables 1a and 1b) in the rocks of the great Catskill delta.

This report provides a general geological description of the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System (TPS), in support of the U.S. Geological Survey's assessment of the technically recoverable undiscovered oil and gas resources of the Appalachian Basin Province in 2002 (Milici and others, 2003). For assessment purposes, the Petroleum System is subdivided into Assessment Units (AU), that are based primarily upon their geologic characteristics. For this report, Swezey prepared the sections on the Oriskany Sandstone-Structural AU, the Oriskany Sandstone-Stratigraphic AU, the Catskill Sandstones and Siltstones AU, and the Berea Sandstone AU. Milici prepared the remainder of the report.

The following discussion includes a general description of the major stratigraphic units in the petroleum system and of the petroleum geology. For more detailed descriptions of the Devonian stratigraphy, see the references cited herein, especially de Witt and others (1993). The Devonian Shale-Middle and Upper Paleozoic TPS contains some of the more productive source rocks and reservoirs for hydrocarbons in the Appalachian Basin Assessment Province (fig. 3). The regional stratigraphy and geologic framework of the Devonian System in the Appalachian basin and the general depositional model for the Catskill delta have been described by numerous writers, including Oliver and others (1967, 1971); Ettensohn (1985a,b); Lundegard and others (1985); Sevon (1985); Woodrow and Sevon (1985); Boswell and Donaldson (1988); Boswell and Jewell (1988), Hasson and Dennison (1988); Woodrow and others (1988); Bjerstedt (1986); Kammer and Bjerstedt (1986); Bjerstedt and Kammer (1988); Milici and de Witt (1988); de Witt and others (1993); Boswell (1996); Boswell, Heim and others (1996); Boswell, Thomas and others (1996);); Donaldson and others (1996); Flaherty (1996); Harper and Patchen (1996); Matchen and Vargo (1996); Milici (1996a,b); Opritza (1996); Smosna (1996); Tomastik (1996); Van Tyne (1996a,b); Vargo and Matchen (1996); Patchen and Harper (1996); Faill (1997); and Harper (1999).

STRATIGRAPHY

DEVONIAN STABLE SHELF

In general, the Devonian strata in the Appalachian foreland basin may be divided into two groups, pre-orogenic Lower and Middle Devonian strata that are dominated by stable shelf sedimentary deposits, and syn- to post- orogenic Middle Devonian to Early Mississippian strata that resulted from Acadian tectonism, subsidence, and filling of a foreland basin by the Catskill and Price – Rockwell deltas. The deltaic strata are overlain by Mississippian carbonate strata that were deposited on a pre-Alleghanian stable shelf. The discussion is organized into sections that describe the stratigraphy and petroleum geology.

The lower part of the stable shelf strata, represented by 100 to 350 feet of the Helderberg Group, consists generally of Devonian carbonate rock in the upper part of Keyser Formation, the shale and siltstone beds of the Mandata Shale, the chert beds of the Shriver Chert), and some sandstone beds, which are overlain by extensive deposits of fossiliferous marine sandstone (Oriskany Sandstone, Ridgeley Member or Sandstone) **(**Table 2**).** The Oriskany Sandstone, a mature, quartzose sandstone, is locally as much as 360 feet thick and is an important reservoir for natural gas. In much of the basin, the contact between Silurian and Devonian strata lies within limestones of the Keyser Formation **(**Patchen and others, 1985a; Laughrey, 1999; Harper, 1999), and the boundary may located by use of paleontological data **(**Helfrich, 1978; Cook, 1981; Denkler and Harris, 1988**)** or with carbon isotopes **(**Saltzman, 2002; Rodríguez, 2005**).** In northeastern Tennessee and southwestern Virginia, however, the contact is between the Clinch Sandstone (Silurian) and the overlying Wildcat Valley Sandstone (Devonian). Although the contact is unconformable in Tennessee, these Silurian and Devonian sandstones are commonly mapped together **(**Rodgers, 1953; Miller and others, 1964**).**

A mixture of carbonate strata (Onondaga, Columbus, and Bois Blanc Limestones), mudrock and shale (Needmore Shale), and calcareous chert (Huntersville Chert) overlie the Oriskany Sandstone unconformably. The Onondaga Limestone lies below the clastic sequence of the Catskill delta in much of western New York and adjacent Pennsylvania. In Pennsylvania, Onondaga-equivalent limestones grade into the Needmore Shale **(**Woodrow and others, 1988, Hasson and Dennison, 1988**)**. The Needmore Shale, with a maximum thickness of about 200 feet, was deposited in the eastern part of the basin, generally from Pennsylvania to Virginia. The shale grades laterally westward into the Huntersville Chert in western Pennsylvania and West Virginia, and then into limestone beds in Ohio, Pennsylvania, and New York **(**Table 2**).** The siliciclastic sediments of the Needmore Shale may represent the first tectonic pulses of the Acadian orogeny **(**Faill, 1997). Next above the Needmore Shale is the Tioga Bentonite, a stratigraphic unit about 2 feet thick that consists of several discrete, relatively thin volcanic ash falls. Its basal beds are within the uppermost beds of the Onondaga Limestone or Needmore Shale and the uppermost ash bed lies within the lowermost part of the Marcellus or Millboro Shale **(**Woodrow and others, 1988; Hasson and Dennison, 1988; de Witt and others, 1993**)**. The Tioga is widely distributed across the central and northern parts of the Appalachian basin, and is a regional stratigraphic marker bed.

THE ACADIAN DELTA

The regional facies model

In the Appalachian basin, the Late Devonian and Early Mississippian is represented primarily by large volumes of deltaic sedimentary rocks that were deposited in a foreland basin that developed in response to Acadian tectonism to the east and north **(**Faill, 1985, 1997**).** These strata extend from central New York and Pennsylvania westward to Ohio, and then southwestward along the regional strike of the Appalachian Mountains through Virginia and Tennessee to Alabama. In general, these strata were not deformed by the Acadian orogeny. The Acadian delta complex generally consists of two deltas, the Catskill delta of Middle and Upper Devonian age, and the Price-Rockwell (Pocono) delta of Late Devonian and Early Mississippian age **(**Ettensohn, 1985b; Boswell, 1996**).**

In general, the Catskill delta consists of a coarsening-upward suite of rocks. The thickness of Devonian strata is greatest in eastern Pennsylvania, where it is as much as 12,000 feet thick **(**fig. 4**) (**de Witt and others, 1975**).** Devonian strata thin westward across the basin into central Ohio, where they are about 400 feet thick, and southwestward into Tennessee, where the Chattanooga Shale is only about 8 feet thick at its type section in Chattanooga **(**Hayes, 1891**).**

Woodrow and Sevon (1985) noted that the Catskill delta lacked the one or two trunk streams that one might expect in the configuration of a classic delta. Rather, Catskill paleogeography appears to have consisted of many small streams that deposited their sedimentary load along a muddy coastline (coastal alluvial plain) that was hundreds of miles long (Sevon, 1985; Boswell and Donaldson, 1988; Harper, 1999, fig. 7-21).

The time-transgressive magnafacies of the Catskill delta, from west to east, consist of several gross lithosomes that extend widely over the basin (Boswell and Donaldson, 1988). Black gas shales on the west grade laterally eastward and vertically into basinal gray and green silty shales, and then into distal shelf turbidites. These fine-grained turbidites, in turn, grade into coarser-grained strata that were deposited in shallow marine shelf environments, and then into paralic deposits that are transitional to non-marine facies. The section is capped by siliciclastic strata that contain non-marine red beds and coal-bearing rocks.

The general distribution of the Catskill magnafacies (facies I – V) is well illustrated by the schematic diagram of Upper Devonian strata across western Pennsylvania and Ohio that was published by Harper (1999) (fig. 5). Facies I consists of "dark-gray to black, somewhat calcareous, pyritic, sparsely fossiliferous shales" that accumulated as distal bottom muds under anoxic conditions (Harper, 1999, Table 7-1; Ettensohn, 1985b; Milici, 1993). There are at least 8 major depositional cycles, represented by tongues of basinal black gas shale, that are intercalated with coarser-grained siliciclastics (fig. 6). These units range in age from the Middle Devonian Marcellus Shale to the Mississippian Sunbury Shale (Dennison, 1985; de Witt and others, 1993). Facies II of Harper (1999, Table 7-1) consists of sparsely fossiliferous "interbedded dark-gray shales and thin-bedded, light- to medium-gray siltstones" that were deposited as turbidites on a delta-fed submarine ramp (Brallier Formation) (Lundegard and others, 1985). Facies III consists of, "Light- to dark-colored greenish, brownish, purplish, or reddish, highly fossiliferous shales, siltstones, and fine-grained sandstones" that were deposited on a "shallow marine open shelf." This facies is represented by the Riceville, Oswayo, and Chadakoin Formations in western Pennsylvania (Harper, 1999, Table 7-1, p. 121) (Table 1). Facies IV consists of interbedded silty, micaceous mudrocks and fine-to coarse-grained, thin- to thick-bedded siltstones, sandstones, and conglomerates. These strata are moderately to highly fossiliferous and in places contain beds of sparsely to highly fossiliferous limestone. This facies was deposited as a mixture of fluvial-deltaic and linear shoreline deposits that are interspersed with open-marine carbonate strata. The limestones apparently were deposited during episodes of eustatic sea-level rise. Facies IV is represented by the Scherr and Foreknobs Formations (of the Greenland Gap Group in West Virginia and Maryland), as well as by the Elk, Bradford, and Venango Groups. Facies V, represented by the Catskill and Hampshire Formations, consists of gray to red siliciclastic strata that were deposited in "mixed continental, fluvial-deltaic, and marginal marine environments" (Harper, 1999, Table 7-1).

A generalized section transverse trough the Catskill delta (generally along depositional strike) is shown in figure 7a, b (Oliver and others, 1967; de Witt, 1975). This section illustrates the overall coarsening-upward nature of the deltaic strata, with distal deposits of the marine delta at the base grading upward into terrestrial, red-bed-bearing siliciclastics at the top. Figure 8a, b illustrates the Devonian stratigraphy and facies changes across western Pennsylvania in more detail, as determined from well data (Piotrowski and Krajewski, 1977).

The Catskill Delta

Middle Devonian strata

Hamilton Group and equivalent strata:- Black shales at the base of the Catskill delta, the Marcellus and Millboro Shales (Woodrow and others, 1988), extend widely across the Appalachian basin and probably were deposited in relatively deep water as the foreland basin first developed. The Marcellus Shale, in the lower part of the Hamilton Group, is best developed in central Pennsylvania where it is up to 200 feet thick (de Witt and others, 1993). To the south and west, the Hamilton Group grades into silty shales of the Mahantango Formation, which in turn grades laterally into the Millboro Shale in southern West Virginia and Virginia (Table 2). The Millboro Shale is about 1,500 feet thick in western Virginia (Woodrow and others, 1988), where it includes all strata from the top of the Tioga Bentonite to the base of the Brallier Formation (Hasson and Dennison, 1988).

Woodrow and others (1988) showed that the basin of deposition of Hamilton Group and Mahantango siliciclastics was bordered by carbonate platforms in central Ohio, western New York, and adjacent Pennsylvania. In central Pennsylvania and eastern New York, these basinal siliciclastics grade laterally either into the thin limestones and fossiliferous sandstones and shales of a clastic ramp or into littoral deposits of the basin margin.

Tully Limestone:- Overlying the Hamilton Group is a conspicuous limestone formation, the Tully Limestone (uppermost Middle Devonian) (figs. 7b, 8b). The Tully extends from west-central New York, southwestward across Pennsylvania, to northern West Virginia. In general, the formation is a cobbly-weathering silty, fossiliferous limestone, and is as much as 200 feet thick in north-central Pennsylvania (de Witt and others, 1993). Dennison (1985, p. 95) noted that the Tully was deposited during a period of "pronounced sea-level rise" that "may have been eustatic." In western New York, the formation thins and is replaced by a zone of pyrite nodules and pyritized fossils that developed along the edge of the Taghanic unconformity, perhaps one of several unconformities that had developed within the Tully Limestone (Woodrow and others, 1988; Sessa, 2003).

Regional unconformity:- To the south and west, the Tully Limestone and associated strata are absent because of a major Middle Devonian unconformity. The unconformity expands to the south and west, so that Upper Devonian strata overlie Middle Devonian strata in Ohio and eastern Kentucky. In central Tennessee and south-central Kentucky, the unconformity cuts deeper into the section, so that Upper Devonian strata overlie rocks as old as Ordovician around the edges of the Nashville dome in Tennessee and south-central Kentucky (fig. 7a) (de Witt and others, 1993; J.A. Drahovzal, written communication, *in* Wickstrom, 1996). It is in these areas on the Cincinnati arch adjacent to the Appalachian basin that the Devonian shale is the source of some of the hydrocarbons produced from older strata.

Upper Devonian and Lower Mississippian strata

Post- unconformity Devonian and Mississippian black gas shales:- Upper Devonian gas shales (de Witt and others, 1993) include the Renwick and Geneseo Shale Members of the Geneseo Formation, the Burkett Shale Member of the Harrell Shale, the Middlesex Shale Member of the Sonyea Formation, the Rhinestreet Shale Member of the West Falls Formation, the Pipe Creek Shale Member of the Java Formation, the Dunkirk and Hume Shale Members of the Perrysburg Formation, and the Huron Member and Cleveland Members of the Ohio Shale (Facies I of Harper, 1999) (fig. 6). The uppermost gas shale, the Sunbury Shale, is of Mississippian age.

Several depositional models have been proposed to explain Devonian and Mississippian black shale stratigraphy. Filer (1994) proposed that these black shales, including the Marcellus Shale and their associated strata, constitute seven or more third-order cycles of black, gas-rich shales that are intercalated generally with coarser-grained stratigraphic units that contain much less organic material. In general, these cycles may be traced basin-wide, and are even found telescoped within the much thinner Chattanooga Shale to the south in Tennessee (Milici and Roen, 1981). As the basin filled and expanded, the major black shales migrated progressively westward with time (Ettensohn, 1985a,b) and (or) were truncated by the mid-Devonian unconformity (de Witt and others, 1993), so that those shales near the bottom and middle parts of the Devonian stratigraphic section (Marcellus through Rhinestreet shales) occur more easterly within the basin, whereas those shales in the middle and upper parts of the section (Ohio Shale, Sunbury Shale) are more westerly and, in part, overlie the Cincinnati arch (de Witt and others, 1993).

Ettensohn (1985a, b) recognized five major tectonic depositional cycles of finer-grained to coarser-grained rock within the Devonian “Acadian tectophase.” Each cycle apparently began with a period of rapid subsidence in the depositional basin, when the black shales in the lower part of the cycle were deposited during a period of relative sea-level rise. This initial basin subsidence occurred in conjunction with or was followed closely by a period of tectonism and uplift. According to this model, the coarser-grained clastics in the upper part of the cycle were deposited during a second period of subsidence, which followed the main tectonic event. The five cycles described by Ettensohn (1985a, b) begin, in sequence, with the deposition of the Marcellus Shale and the Mahantango Shale cycle (Middle Devonian). This cycle is followed by the Geneseo-Burket, Middlesex, Rhinestreet, and Dunkirk black shale cycles (Upper Devonian) (fig. 6), with each of the black shale formations and the immediately overlying beds of coarser-grained strata constituting one cycle.

Schieber (1998) recognized numerous extensively developed erosion surfaces within the Chattanooga Shale in Central Tennessee and adjacent Kentucky, which he interpreted as subtle sequence boundaries that reflect a temporary lowering of sea level. Schieber (1998) divided the Chattanooga, which is generally less than 10 meters thick in Central Tennessee, into 14 regional sequences.

Filer (2002) described 11 high-frequency marine cycles in an interval of Upper Devonian strata, from the upper part of the Rhinestreet Shale Member of the West Falls Formation to the Dunkirk Shale Member of the Perrysburg Formation in New York. These cycles were correlated through equivalent strata, including parts of the Brallier Formation, Greenland Gap Group, and Ohio Shale, and into the lower black shale member of the Chattanooga Shale, in a region that extends 435 miles or more along the length of the Appalachian basin, from New York southwestward through Pennsylvania, Ohio, and West Virginia to eastern Kentucky and southwestern Virginia. In the distal parts of the delta complex, each of these cycles consists of dark, kerogen-rich shale at the base that grades upward into lighter colored shale that contains less organic material. More proximal facies consist of relatively thin shale beds at the base that grade upward into relatively thick siltstones and sandstones. In general, the cycles range from a few or several meters thick where they are distal on the west, to as much as 70 meters thick for proximal facies on the east. Filer (2002) concluded that these basin-wide high-frequency cycles were effected by glacially-induced eustatic sea level changes. Although the origin of this cyclic sedimentation is not well understood, it appears to have resulted from a mixture of tectonic, eustatic, and climatic events.

Dennison (1985) noted that Middle Devonian sea-level transgressions generally resulted in the deposition of limestone, whereas Upper Devonian flooding events (after the deposition of the Tully Limestone) resulted in the deposition of black shale. He suggested that the Geneseo-Harrell, Rhinestreet, Pipe Creek, Dunkirk, and black shale members of the Chattanooga Shale may have been deposited during periods of relative sea level rise, as deltaic environments generally shifted eastward (de Witt and others, 1993) (fig. 6).

Boswell and Donaldson (1988) compared the sea-level curve of Johnson and others (1985) with the positions of Upper Devonian deltaic shorelines. They showed a correlation between sea level and Famennian shoreline positions, but not with sea level and Frasnian shoreline positions. From this, they concluded that eustasy, perhaps driven by glaciation in Gondwanaland, was an important factor for controlling Famennian sedimentation. In contrast, during the Frasnian the supply of sediments from the Acadian orogeny apparently overwhelmed the effects of glacially-driven sea level changes, so that there is no correlation between Frasnian shore line positions and the Euramerican sea-level curve.

Brallier Formation and equivalent strata:- The tongues of black "gas" shales grade upward and eastward into coarser-grained siliciclastic strata of the Brallier Formation (Facies II of Harper, 1999). Lundegard and others (1985) subdivided the Brallier and overlying beds into five lithofacies: (1) delta-front facies, (2) turbidite-slope facies, (3) interlobe-slope facies, (4) lobe-margin facies, and (5) basinal facies. Their paleocurrent map shows a consistent westward trend for the direction of transport of the Brallier sediments. Partial equivalents of the Brallier include the Scherr and Foreknobs (Greenland Gap Group in West Virginia and Maryland), and the Lock Haven, Trimmers Rock, and Catskill Formations in eastern Pennsylvania (Table 2) (Harper, 1999, figure 7-4).

Major sandstone and siltstone reservoirs of the Elk, Bradford, and Venango plays of the Appalachian gas atlas (Tables 1, 2) (Roen and Walker, 1996) consist of the coarser-grained siliciclastic strata of the Catskill delta that occur generally to the east of time-equivalent Devonian black shales and Brallier siltstones (Boswell, Heim and others, 1996; Boswell, Thomas and others, 1996; Donaldson and others, 1996).

The *Upper Devonian Elk Sandstones and Siltstones Play* is defined as all sandstones and siltstones of Frasnian age (Donaldson and others, 1996). The play extends from central West Virginia, through Pennsylvania, to southwestern New York. The play is generally stratigraphically above the Middlesex Shale Member of the Sonyea Formation (fig. 6), and below the Dunkirk Member of the Perrysburg Formation or the Huron Member of the Ohio Shale. It is generally within the Brallier, Scherr, Foreknobs, and Lock Haven Formations (Table 2). The *Upper Devonian Bradford Sandstones and Siltstones Play* (Boswell, Thomas and others, 1996) extends from the base of the Dunkirk Shale, which is at or near the base of the Famennian Stage, upward to the stratigraphic position of the mid-Famennian transgression at the top of the Chadakoin Formation (Table 2). The Bradford play is restricted to an area in north-central West Virginia and western Pennsylvania. To the south and west, it grades into the interbedded siltstone and green, gray, and black shales of the *Upper Devonian Fractured Black and Gray Shales and Siltstones Play* (Milici, 1996a) of the Appalachian gas atlas (Roen and Walker, 1996). *The Upper Devonian Venango Sandstones and Siltstones Play* (Boswell, Heim and others, 1996) extends stratigraphically upward from the base of the formations deposited during the mid-Famennian transgression to the marine shales beneath the Berea Sandstone. In general, the play extends from southwestern New York through central Pennsylvania to north-central West Virginia.

Price-Rockwell (Pocono) delta

Definition and distribution

The Price-Rockwell (Pocono) delta complex includes strata of Late Devonian and Early Mississippian age. In general, the Price Formation occurs in southwestern Virginia, south central West Virginia, and north-central West Virginia. The Rockwell Formation of Bjerstedt and Kammer (1988) occurs generally in northeastern West Virginia, western Maryland, and nearby Pennsylvania (Table 4). The West Virginia dome in east-central West Virginia, where the deltaic strata are eroded below the sub-Greenbrier unconformity so that the Greenbrier Limestone directly overlies lowermost Mississippian strata, separates the northern area of the Price Formation and the Rockwell Formation from the southern area of the Price Formation.

Although Kammer and Bjerstedt (1986) and Bjerstedt and Kammer (1988) abandoned the term Pocono Formation for the Rockwell Formation in northern West Virginia, Maryland, and Pennsylvania, Filer and others (1996) retained the term Pocono Formation for these Lower Mississippian strata along the eastern edge of the Appalachian Plateaus in West Virginia and southern Pennsylvania, and in the subsurface of southwestern Virginia and West Virginia. In this paper, we follow the usage of Kammer and Bjerstedt (1986), Bjerstedt and Kammer (1988), and Brezinski (1989, 1999), who restrict the term “Pocono” to the Pennsylvanian anthracite coal region. Furthermore, we consider the Price Formation, the Rockwell Formation and its lateral equivalents (Huntley Mountain and Shenango Formations), and the overlying Burgoon (Purslane) Sandstone in the Appalachian bituminous coal region (fig. 2) as the lateral equivalents of the Pocono Formation (Table 4) (Brezinski, 1999).

Price Formation

Virginia and Southern West Virginia: In outcrops along the Appalachian Plateau in southwestern Virginia, Filer and others (1996) placed the base of the Price Formation at the top of the Chattanooga Shale (Table 4). In this area the Chattanooga consists of three members, a lower black shale member, a middle gray siltstone member, and the Big Stone Gap Member. Sunbury Shale equivalents are within the upper 131 feet of the Big Stone Gap Member and consist of gray and grayish-black shales (Filer and others, 1996). Filer and others (1996) also placed the base of the Price Formation at the top of the Sunbury in the subsurface of western Virginia and adjacent West Virginia, where, the Sunbury is about 110 feet thick and consists largely of grayish-black to gray shale (Filer and others, 1996).

To the northeast, in the southern Valley and Ridge of Virginia, the Price Formation encompasses all strata above the non-marine red beds of the Hampshire Group or the marine Greenland Gap Formation (Devonian) and below the Maccrady Formation or Greenbrier Limestone (Table 4) (Bjerstedt and Kammer, 1988). The Price Formation in the southern Virginia Valley and Ridge is a progradational, regressive sequence that ranges from about 150 feet to as much as 1,650 feet thick (Kreisa and Bambach, 1973; Filer and others, 1996). In southern Virginia and adjacent West Virginia, the Price Formation of Bjerstedt and Kammer (1988) contains two named members in the lower part of the formation, the Cloyd Conglomerate Member (Devonian and Mississippian) at or near the base of the formation, and the overlying Sunbury Shale Member (Mississippian).

In its type area in Virginia, the base of the Price consists of shales that were deposited in marine shelf environments. These shales are overlain in turn by prodelta slope sandstones, which are then overlain by the quartz-pebble conglomerates and conglomeratic sandstones of the Cloyd Conglomerate, a unit that may have been deposited in bar and barrier environments (Kreisa and Bambach, 1973).

In nearby West Virginia, the Price is about 850 feet thick. In this area, the Cloyd is 50 to 150 feet thick and consists of massive channel-fill deposits with coaly beds. Next above the Cloyd Conglomerate are offshore and basinal shale deposits of the Sunbury Shale Member. In southern West Virginia, the Sunbury Shale Member of Bjerstedt and Kammer (1988) is a basinal shale unit, about 120 feet thick, that in some places is intercalated with sandy turbidites and in other places has stepped over shelf facies to where it interfingers with deposits of deltaic origin. The basinal deposits are overlain by fan, slope, and shelf deposits that grade upward into a coarsening-upward sequence in the upper half of the formation. As in Virginia, the top of the Price section in West Virginia consists of distributary channel and coal-bearing siliciclastic strata of the delta plain (Bjerstedt and Kammer, 1988). Regardless of the differences in the placement of the stratigraphic position of the various formations, however, the source rocks of the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System include all of the Devonian-Mississippian black shales, whether or not they are classified stratigraphically as within or below the Price Formation.

Northern West Virginia, Maryland, and Pennsylvania: Generally to the north of the 38th parallel (fig. 4), the Price Formation of Bjerstedt and Kammer (1988) consists of three named members: the Oswayo Member (Devonian and Mississippian) at the base, the Riddlesburg Shale Member, and the Rockwell Member in the upper part of the formation. However, there is little agreement about the stratigraphic nomenclature of the Rockwell Formation in the northeastern West Virginia panhandle, western Maryland, and southwestern Pennsylvania (tri-state area). For southwestern Pennsylvania, Berg (1999) published a generalized section that shows the Rockwell Formation as extending from the top of Catskill red beds to the base of the Burgoon Sandstone (Tables 2 and 4). As described, the Rockwell of Berg (1999) extends upward from a basal sandstone that in places contains diamictite, through the Riddlesburg Shale, to the top of the Patton Shale.

In the tri-state area, Bjerstedt (1986) and Bjerstedt and Kammer (1988) placed the base of the Rockwell at the base of a diamictite-bearing sandstone, which in places they called the basal Riddlesburg Sandstone. In Maryland, they placed the top of the Rockwell at the top of a red-bed bearing unit, which they correlated with the Patton Shale in nearby Pennsylvania. In the tri-state area, sandstones and shales of marginal marine origin, which they correlated with the Oswayo Member, were placed in the Hampshire Formation rather than within the Rockwell Formation.

In western Maryland and parts of adjacent south-central Pennsylvania, the stratigraphic equivalent of the marine Devonian and Mississippian Oswayo Sandstone Member (called the Finzel Marine Tongue in Maryland, Dennison and others, 1986; Brezinski, 1989) (Table 4) is classified as the basal unit of the Rockwell Formation. This basal unit consists generally of fossiliferous and bioturbated sandstones, siltstones, and mudstones that were deposited in offshore bar to shoreface, beach, and restricted bay environments (Bjerstedt and Kammer, 1988). In western Maryland, the Finzel Marine Tongue is up to 70 feet thick and was interpreted to represent shallow shelf deposits by Brezinski (1989) and Brezinski and others (2004). Elsewhere, the basal unit of the Rockwell Formation is a sandstone that locally contains up to 70 feet of lenticular polymictic diamictites, which Bjerstedt and Kammer (1988) described as mud flows or debris flows that had been introduced into littoral environments via tidal channels. These diamictite beds are overlain by interbedded sandstone, siltstone, and shale, with coaly beds, and then by the marine Riddlesburg Shale Member (Brezinski, 1989).

The Riddlesburg Shale Member is the approximate lateral equivalent of the Sunbury Shale Member of the Price Formation in southern West Virginia and southwestern Virginia. In general, the Riddlesburg consists of a mixture of marine and non-marine beds. In western Maryland, it consists of about 130 feet of dark gray siltstone and shale with coaly beds in the upper and lower parts of the unit and a marine zone in the middle (Brezinski, 1989). Bjerstedt and Kammer (1988) described the Riddlesburg as consisting of shales, thin-bedded siltstones, and scour-based, fine-grained sandstones that were deposited in environments that ranged from shallow shelf and open-bay to restricted barred-bays and tidal estuaries.

Brezinski (1989) disagreed with Bjerstedt (1986) and Bjerstedt and Kammer (1988) about the placement of the top of the Rockwell Formation. Brezinski (1989) defined the overlying Purslane Formation chiefly on the basis of its lithology, and placed the base of the Purslane at the base of the "lowest thick sandstone interval," thereby including the Patton Shale of Bjerstedt (1986) and Bjerstedt and Kammer (1988) within the Purslane. In places, red shales apparently occur within both the upper part of the Rockwell Formation and in the lower part of the overlying Purslane Formation. At present, however, there does not appear to be sufficient data to demonstrate that the Patton Shale of Bjerstedt (1986) in Maryland is stratigraphically equivalent to the Patton Shale in its type area in Pennsylvania (Table 4) (Brezinski, 1989; written communication, 2005).

Progradational delta deposits:- Overlying the Sunbury and Riddlesburg shales are progradational delta deposits that built into the relatively shallow water facies of the Riddlesburg Shale Member to the north (Rockwell Member of the Price Formation), and into the relatively deep water of the basinal facies of the Sunbury to the south (upper part of Price Formation) (Table 4). In southern West Virginia, the Sunbury is overlain by submarine fan turbidites and outer shelf facies that are represented by fining-upward sandstone turbidites and conglomerates. These deposits, in turn, are overlain by hummocky cross-stratified sandstones and bioturbated silty shales. The deposits of the overlying delta consist generally of shallowing-upward, coarsening-upward strata Bjerstedt and Kammer (1988), and near the top of the Price Formation, include peat that was deposited in swamps associated with delta plain environments (Kreisa and Bambach, 1973).

The Rockwell Formation ranges up to about 400 feet thick in Maryland (Brezinski, 1989) and to about 650 feet thick in Pennsylvania (Berg, 1999). All of these beds, except locally occurring marine zones, are considered to be the deposits of meandering rivers. In Maryland, the upper part of the Rockwell Formation consists of grayish-green to reddish-brown claystones, siltstones, and thin sandstones that contain carbonaceous beds and fossil roots (Brezinski, 1989). In Pennsylvania, equivalent beds below the Patton Shale consist of 50 to 150 feet of sandstone, siltstone, and shale (Berg, 1999, fig. 8-8).

Patton Shale Member:- In northern and eastern West Virginia, western Maryland, and central Pennsylvania, red mudstones are interbedded with sandstones in the uppermost part of the Rockwell Formation and within the overlying Purslane Formation, instead of the relatively thick coal deposits that occur near the top of the Price delta to the south. In Pennsylvania, a red-bed unit, called the Patton Shale Member, is the uppermost member of the Rockwell Formation and consists of 35 to 115 feet of greenish-gray and grayish-red shale and siltstone (Berg, 1999). In places, however, coaly zones are scattered throughout the Rockwell in the beds below the Patton Shale Member and occur, as well, within the overlying Purslane Formation (Brezinski, 1989). In general, the Patton is interpreted to have been deposited upon an alluvial plain (Bjerstedt and Kammer, 1988; Berg, 1999).

Sea level transgressions and unconformities: Bjerstedt and Kammer (1988) recognized four major transgressions, which they designated as T_1 through T_4 (Table 4), in the Upper Devonian-Lower Mississippian section. Transgressions T_1 and T_2 are regional in nature and were recognized in both the Price and Rockwell Formations. The lowermost transgression (T_1) occurred during the latest Devonian. This transgression is at the base of the littoral to shallow marine deposits of the Oswayo Member of the Price Formation in northern West Virginia and adjacent Maryland (Finzel Marine Tongue), and at the base of the equivalent Oswayo Formation in nearby Pennsylvania. Bjerstedt and Kammer (1988) described the T_1 transgression in southern West Virginia as occurring at the base of the Sunbury Shale Member of the Price Formation. As used by them, only the upper part of the Sunbury Shale Member in southern West Virginia and Virginia is equivalent to the Sunbury Shale in Ohio, and the lower part includes silty shales and siltstones that may be equivalent to the Oswayo facies to the north. In some places in east-central West Virginia, Bjerstedt and Kammer (1988) place T_1 at the base of the Riddlesburg Shale Member of the Price Formation; in other places, they place T_2 at the base of the Riddlesburg.

Bjerstedt and Kammer (1988) related the Early Mississippian transgression (T_2) to the worldwide eustatic sea level rise that was described by Ross and Ross (1985). This transgression is represented widely in the Appalachian basin by sandstones of Early Mississippian age, including the Berea Sandstone and the sandstone below the Riddlesburg Shale, which overlie the T_2 unconformity. As the marine transgression progressed, the deposition of sand on Early Mississippian deltas ceased and blanket-like accumulations of black mud (Sunbury Shale), deposited under anoxic conditions, spread widely across the basin except where the Riddlesburg Shale Member was deposited. The sandstone and diamictite beds below Riddlesburg shales overlie the T_2 transgression, and are near the boundary between the Devonian and the Mississippian (Bjerstedt and Kammer, 1988; Brezinski, 1999).

The T_3 transgression is at or near the Kinderhook-Osage boundary. It is marked locally by the occurrence of bioturbated silty (basinal) shales that generally overlie outer shelf facies in the middle of the Price delta (Bjerstedt and Kammer, 1988). The stratigraphic sequence above T_3 consists of generally coarsening-upward units that were deposited in progressively shallower waters. These deposits include basinal shales in the lower part that are overlain by prodelta and shoreface deposits, and are followed by channel-fill and the delta plain deposits that mark the top of the Price delta. The T_4 transgression, which is primarily defined by thin lag deposits of phosphate pebbles and body fossils, was observed locally within the Price Formation in southern West Virginia.

Burgoon and Purslane Formations

Overlying the Rockwell Formation is the Purslane Formation of Maryland and nearby West Virginia, and its approximate lateral equivalent, the Burgoon Sandstone of Pennsylvania (Brezinski, 1989). The Purslane ranges from about 350 feet thick in western Maryland, to 130 feet or less in eastern West Virginia (Brezinski, 1989). It consists of three thick sandstone-dominated units that are separated by relatively thin deposits of red shale and (or) gray, carbonaceous shale. Channel-form sandstones within the Purslane commonly are filled with basal lag deposits of quartz- and shale-pebble conglomerate that contain lenses of transported coal.

The Burgoon is generally composed of cross-bedded sandstone with thin coals and lags of quartz pebbles occurring locally within the sandstones. The Burgoon of Pennsylvania and the Purslane of Maryland and West Virginia are essentially lateral equivalents, although Brezinski (1989) considered the lower part of the Purslane to be equivalent to the upper part of the Rockwell. The Purslane and Burgoon apparently were deposited as fluvial sediments on a braided river plain (Bjerstedt and Kammer, 1988; Brezinski, 1999).

Maccrady Formation

To the south, the Price delta is capped by a younger formation of red siliciclastic strata and evaporites, the Lower Mississippian Maccrady Formation (Tables 2 and 4). It ranges from about 40 to 1,600 feet thick to as much as 1,970 feet thick in a faulted basin in southwestern Virginia, where it contains much evaporite (Butts, 1940; Cooper, 1963, 1966; see Milici and de Witt, 1988, for a summary). The red beds and evaporites of the Maccrady, as well as the red beds in the Patton Shale Member, appear to mark climate changes, from relatively wet during the deposition of the upper part of the Price and within the Rockwell Formation and Purslane Sandstone where there is coal, to relatively dry during the deposition of the upper part of the Rockwell (Patton) and for the beds overlying the Price (Maccrady).

The Berea delta

The Bedford Shale (Upper Devonian) and the Berea Sandstone (Lower Mississippian) (Table 4) in the western part of the Appalachian basin were deposited generally as a shelf margin delta (Pepper and others, 1954). In contrast with the Price and Rockwell deltas, the Berea and the Bedford were formed from clastic detritus that spread southward from cratonic areas to the north into the shallow Mississippian seas, thus forming the deposits of the muddy Red Bedford delta. Berea sands were eroded from the cratonic shield as sea level was lowered slightly. Near the type section of the Berea Sandstone (Berea Grit of Newberry, 1871) at Berea, Ohio, sand-filled channels as much as 85 feet deep were scoured into underlying Devonian shales. The Berea sands that filled the basin from the north and siliciclastic sediments of the Price delta from the east coalesced in eastern Kentucky to form a 100- to 150-foot-thick deposit of sandstone and siltstone (Pepper and others, 1954). Equivalent sandstones (Cussewago Sandstone; Table 2) to the east are generally thicker and coarser-grained, and in places they contain marine fossils. In eastern Kentucky, the deeper-water, more distal strata of the Price-Rockwell delta complex consist of 400 to 600 feet of shaly turbidites of the Borden Formation (Table 4). In Ohio, this part of the section is represented by Cuyahoga and Logan Formations (Moore and Clark, 1970; Rice and others, 1979) (Table 2).

MISSISSIPPIAN STABLE SHELF

Upper Mississippian Greenbrier/Newman Limestones

The stratigraphic interval between Upper Devonian - Lower Mississippian siliciclastic deposits of the Price/Rockwell delta complex (Acadian), below, and the Upper Mississippian and Pennsylvanian siliciclastic deposits above (Alleghanian), consists predominantly of limestone and dolomite, with minor amounts of shale, siltstone, and sandstone. These units, described collectively as *The Upper Mississippian Greenbrier/Newman Limestones Play* in the Appalachian Gas Atlas (Smosna, 1996), extend generally from the southwestern corner of Pennsylvania, through southeastern Ohio, central West Virginia, and eastern Kentucky, to north-central Tennessee.

The play was assessed as the *Greenbrier Limestone AU* by the USGS in the 2002 assessment (Table 3), and was considered a conventional reservoir (Milici and others, 2003). The USGS assessment unit consists of Mississippian carbonate rocks that overlie the Maury Shale in Tennessee, the Borden and equivalent Formations in eastern Kentucky, the Maccrady Formation in Virginia, the Maccrady, Price, and Rockwell Formations in West Virginia, the Purslane Formation in western Maryland, the Burgoon (Big Injun) Sandstone in Pennsylvania, and the Logan Formation in Ohio (Tables 2 and 4). The assessment unit includes the Fort Payne Formation in Tennessee and Kentucky (Milici, 1996c). The Mississippian carbonate strata are overlain by the Pennington Formation (Mississippian and Pennsylvanian?) in eastern Kentucky and Tennessee, by the Bluefield Formation in Virginia and southern West Virginia, by the Mauch Chunk Formation in northern West Virginia, Maryland, and Pennsylvania (all Mississippian), and by Pennsylvanian formations in Ohio (Brezinski, 1989, 1999; Hohn, 1996; Matchen and Vargo, 1996; Smosna, 1996; Vargo and Matchen, 1996).

In West Virginia and Virginia, a sequence stratigraphic study of the Greenbrier by Al-Tawil and others, 2003 has led to the interpretation that these carbonate and siliciclastic rocks were deposited under tropical conditions and on a ramp that was subsiding differentially, perhaps as a result of thrust-loading during the onset of Gondwana glaciation. The combination of tectonically induced subsidence together with eustatic sea level changes related to glaciation has resulted in the formation of a complex array of depositional sequences that extend from the base of the Greenbrier up into the overlying Bluefield Formation.

Tennessee, southwestern Virginia, eastern Kentucky, and southern West Virginia: Stratigraphic terminology of the Greenbrier Limestone AU ranges widely across the basin (Tables 2 and 4). In general, the Greenbrier Limestone (or Group) of southwestern Virginia and West Virginia is correlative with the lower and middle parts of the Newman Limestone in northeastern Tennessee and eastern Kentucky, where in places it is called the Slade Formation, and with the Warsaw, St. Louis, and Monteagle Limestones of the Tennessee Plateau (Stearns, 1963). The assessment unit, however, also includes the overlying Hartselle Sandstone and Bangor Limestone in the Appalachian Plateau region of Tennessee. Toward the northeastern part of the basin, there is a significant hiatus beneath the Greenbrier, so that the lower part of the section is missing. Furthermore, the relative amount of siliciclastic sediment within the limestone strata generally increases to the northeast, to where the limestones become interbedded with the siliciclastic deposits of the Mauch Chunk Formation (Tables 2, 4).

Northern West Virginia: In the northern West Virginia subsurface, the Greenbrier Limestone consists of the Loyalhanna Member in its lower part, which is overlain by relatively pure limestone beds that consist largely of oolitic grainstones. As in Pennsylvania and Maryland, the Loyalhanna Member consists of sandy carbonate strata and calcareous sandstones, which are commonly called the Greenbrier Big Injun or Keener by drillers (Smosna, 1996; Brezinski, 1989a, b) (Table 2). These terms are applied loosely to several sandy zones in the middle and lower parts of the Greenbrier and in the top of the underlying Price Formation (Matchen and Vargo, 1996). In northern West Virginia, the Loyalhanna Member has been interpreted as having been deposited in submarine environments as dunes of mixed quartz and calcium carbonate sand (Carney and Smosna, 1989; Smosna, 1996), and as eolian dunes associated with littoral deposits (Ahlbrandt, 1995).

Pennsylvania and Maryland: The Loyalhanna Member of the Mauch Chunk Formation in southwestern Pennsylvania and the equivalent Loyalhanna Member of the Greenbrier Formation in Maryland consist of carbonate–cemented quartzose sandstone that is as much as 85 feet thick (Brezinski, 1989a, b; Krezoski and others, 2005, 2006). Brezinski (1989a) divided the Greenbrier Formation of Maryland into four members, the Loyalhanna Limestone Member at the base, the Deer Valley Member, the Savage Dam Member, and the Wymps Gap Member at the top (Table 4). The Loyalhanna Member thickens from a feather edge in Alleghany County westward to as much as 40 feet thick in the northwest corner of Maryland. In Garrett County, the unit ranges from about 5 to 20 feet thick. Krezoski and others (2005) recognized sabkhas, eolian dunes, pedogenic calcretes, and fluvial channels within the Loyalhanna Member in Pennsylvania. In Maryland Brezinski (1989a), the overlying Deer Valley Limestone Member consists generally of shelly and oolitic carbonate grainstones, with small amounts of other carbonate and siliciclastic lithologies. The Deer Valley Limestone Member grades upward into the overlying siliciclastics of the Savage Dam Member. The Savage Dam is composed of interbedded sandstones, reddish-brown to greenish-gray siltstones, and shales that resemble those in the Mauch Chunk Formation. The member thins to the west, from about 200 feet thick in western Garrett County, Maryland, to a little less than 40 feet in adjacent West Virginia. The Savage Dam grades into the overlying Wymps Gap Member with an overall decrease in siliciclastic content and a corresponding increase in limestone. The Wymps Gap Member increases in thickness from 10 feet or less in southwestern Pennsylvania and western Maryland, to about 60 feet thick in southwesternmost Maryland and adjacent West Virginia.

Ohio: The Greenbrier equivalent in Ohio, the Mississippian Maxville Limestone, is generally discontinuous throughout its extent because of unconformities that occur below, within, and above the formation. The maximum thickness of the Maxville in the subsurface of southeastern Ohio is about 195 feet (Collins, 1979). In general, the Maxville is a massive to nodular gray limestone with interbeds of light gray fossiliferous, calcareous shale. Sandy carbonate grainstones in the lower part of the formation have been interpreted as representing carbonate eolianites and associated beach deposits or nearshore subtidal sands (Carney, 2002). The Maxville Limestone is overlain unconformably by Pennsylvanian strata.

Regional isopach map: The combined isopach maps of the Greenbrier Limestone in West Virginia (Flowers, 1956) and the Newman Limestone in southeastern Kentucky (MacQuown and Pear, 1983) are shown in figure 9. In general, the Greenbrier thickens from a few to several tens of feet in western West Virginia to over 1,200 feet in southeastern West Virginia. The rate of increase in the thickness of the Greenbrier to the southeast, however, is not constant. A major break in the slope of the isopach lines (hinge zone 1) occurs near the 200-300 foot isopach line, where the thickness of the formation increases more rapidly to the southeast (Donaldson, 1974; Flowers, 1956) (fig 9). A subtle terrace, or flattening of the rate of increase of the thickness of the Greenbrier occurs at about the 500 foot isopach line; and a relatively steep rate of increase in thickness resumes at or near the 700 foot isopach line (hinge zone 2). Furthermore, Kelleher and Smosna (1993) recognized a hinge zone at the 900 foot contour (hinge zone 3). Wynn and Read (2003) attributed differential thickening of the Greenbrier to movement of foreland basement fault blocks. Interestingly, the isopach maps show evidence of erosion and the formation of surficial channels along the northwestern margins of the Greenbrier in eastern Kentucky and West Virginia. These channels, which are cut as much as 100 feet into the Greenbrier, are generally filled unconformably with a greater thickness of Pottsville sandstones and conglomerates than in adjacent areas, where the Greenbrier has not been thinned or removed by erosion (Flowers, 1956) (fig. 9).

PETROLEUM GEOLOGY

GENERAL

Relatively recent assessments of the undiscovered hydrocarbon resources of the Devonian shales in the Appalachian basin were conducted by the U.S. Geological Survey in 1995 (Gautier and others, 1995; Milici, 1995), and Briggs and Tatlock (1999) made estimates of the undiscovered recoverable natural gas resources in Pennsylvania. This current assessment differs from these earlier assessments in that it is based upon an analysis of the major Appalachian petroleum system that is related to Devonian shale source rocks (Magoon and Dow, 1994).

The Assessment Model

For assessment purposes, oil and gas resources are commonly divided into two distinct types, conventional and continuous (unconventional). Conventional resources are characterized by discrete structural, stratigraphic, or combination traps, in which water and gaseous and liquid hydrocarbons are separated into layers by their immiscibility and relative buoyancies. In contrast, continuous accumulations are regional stratigraphic accumulations of hydrocarbons, generally gas, which commonly occur in blanket-like sedimentary deposits such as coal (coalbed methane), shales rich in organic material, and low porosity (tight) basin-center sandstones (Schmoker, 1995, 1999, 2002). These regional continuous accumulations are not segregated into discrete fields that exhibit gravity segregation of hydrocarbons and water. Instead, continuous accumulations produce hydrocarbons, if only in small amounts, wherever they are drilled. In the Appalachian basin, continuous accumulations commonly consist of multiple (multi-storied) sedimentary units that are amalgamated into larger stratigraphic units of regional extent, such as coal beds, sandstone units, or shale beds, in which multiple zones may be drilled, perforated, and completed within a single well.

The *Devonian Shale-Middle and Upper Paleozoic TPS* contains hydrocarbon resources in both conventional and continuous accumulations (Milici and others, 2003). Of the 10 Assessment Units (AUs) identified in this petroleum system, four are conventional and six are continuous (Table 3) (Milici and others, 2003).

Thermal Maturation Data

The USGS 2002 assessment of the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System (TPS) in the Appalachian Basin Province utilized vitrinite reflectance (Ro) data to assist in the definition of assessment units and to contribute to their evaluation. These data were obtained from radioactive shales in the lower part of the Devonian shale section - from the Marcellus Shale on the east, and from slightly younger basal shales on the west where the Marcellus has pinched out. The vitrinite in these samples consists of dispersed fragments of organic matter within a shale and siltstone matrix. The samples were collected under the direction of Robert T. Ryder

(USGS) in cooperation with the State geological surveys, and were analyzed by Humble Geochemical Services, Humble, Texas. Ro isolines (Weary and others, 2000, 2001; Repetski and others, 2002, 2005; personal communication) as well as the limits of oil generation and preservation in Devonian shales, are shown on figure 10. In general, a %Ro value of 0.6 is regarded as the lower limit of thermal maturation for generation of oil, and a %Ro value of 2 is the approximate upper limit for preservation of oil (Tissot and Welte, 1984; Taylor and others, 1998). Although the natural occurrence of oil in the Devonian shales and in the Oriskany Sandstone is generally a little to the west of the 2.0 Ro isoline, the western limit of oil is significantly west of the 0.6 Ro isoline as determined from dispersed vitrinite.

Recent work by Rowan and others (2004a, b) and Rowan (2006) has determined that the Ro values obtained from Pennsylvanian coal beds were, in general, equal to or greater than the values obtained from dispersed vitrinite in the underlying Devonian shale, especially in the western part of the basin. A thermal/burial history model (fig. 11) constructed along Appalachian cross section line E-E' (Ryder and others, in press), utilizing Ro data obtained exclusively from Appalachian coal beds, determined that the Devonian shale Ro = 0.6 isoline may well lie several tens of miles to the west of the line determined from dispersed vitrinite (Rowan and others, 2004a, b; Rowan, 2006; Ryder and others, in press). Thus, much of the oil to the west of the dispersed vitrinite-based Ro = 0.6 isoline may have been generated in place, with little or no lateral migration from source rocks to the east. The probable underestimation of Ro values from Devonian dispersed vitrinite in Ohio, northwestern Pennsylvania, and New York may have been caused by a phenomenon described by Lo (1993) as "vitrinite reflectance suppression."

Basin modeling by Rowan (written communication, December 2004; Rowan, 2006) indicates that the base of the Devonian shale entered the oil window about 275 million years ago (early Permian) in central Ohio, and about 340 million years ago (early Pennsylvanian) in west-central West Virginia. Near the Ohio-West Virginia border, basal Devonian shales entered the oil window at about 330 million years ago (middle Mississippian) and the gas window at about 230 million years ago (Middle Triassic).

Petroleum System Events

Figure 12 summarizes the geological events for the Devonian Shale-Middle and Upper Paleozoic Total Petroleum System. Petroleum source rocks are Middle and Upper Devonian and Lower Mississippian shales of the Catskill delta. Reservoirs range in age from Ordovician limestones in the Cumberland Saddle region of Kentucky and Tennessee, which is outside of the Appalachian basin, to Mississippian sandstones and limestones in the Appalachian Plateaus. Local seals, generally of siltstone and shale, occur throughout the section. The Silurian Salina Group (Table 1) serves as a regional seal in the Dunkard basin (fig. 3) (Drozd and Cole, 1944), so that the strata below it probably have not been charged by hydrocarbons from Devonian source rocks. Stratigraphic traps occur throughout the section, especially those traps that were formed during deposition of the Devonian and Mississippian sandstones and limestones. Structural traps associated with this TPS were formed primarily by extensional deformation during the Late Precambrian and Early Paleozoic formation of the Rome trough, and during the Late Paleozoic Alleghanian deformation, when the eastern part of the basin was folded and faulted. Hydrocarbon generation occurred from latest Mississippian to Early Triassic, and migration and accumulation occurred during hydrocarbon generation and shortly thereafter. The Critical Moment is considered to be the time when a large volume of the source rocks reach thermal maturity and when large amounts of petroleum are generated and expelled from their source rocks. By then, the source rocks and carrier beds were sufficiently fractured to facilitate migration and accumulation of liquid and gaseous hydrocarbons in porous reservoirs.

DEVONIAN SHALE-MIDDLE AND UPPER PALEOZOIC TOTAL PETROLEUM SYSTEM

Part I - Continuous Oil and Gas Resources

Although Devonian and Mississippian strata are widespread across the basin, the greatest thicknesses of productive sedimentary rock occur primarily in New York, Pennsylvania, Ohio, West Virginia, Virginia, and eastern Kentucky (fig. 4). In Tennessee, Devonian strata are thinner, especially in central Tennessee (Conant and Swanson, 1961, Milici and Roen, 1981) and oil and gas production from the petroleum system is relatively small.

The Devonian Shale-Middle and Upper Paleozoic TPS contains source rocks that range in age from Early Devonian to Early Mississippian (Table 1). Reservoirs charged with hydrocarbons generated from the Devonian shales range in age from Ordovician in Cumberland Saddle region of south-central Kentucky to Upper Mississippian in the central part of the Appalachian basin. Most of the resource, however, occurs either as continuous autogenic accumulations (self-sourced reservoirs) within the Devonian black shale source rocks (Milici, 1993) or within overlying and intertonguing Devonian siltstone and sandstone reservoirs (Schmoker, 1995, 1999, 2002). Although the geologic descriptions of many of the assessment units described herein are based on geologic summaries published in Roen and Kepferle (1993) and in the Appalachian Gas Atlas (Roen and Walker, 1996), much data were obtained from other sources, especially those sources funded, prepared, and published under the Department of Energy's Eastern Gas Shales Project.

For the USGS assessment, the Devonian gas shales were divided regionally into four assessment units (AUs) based on regional stratigraphy, net thickness of radioactive black shale, and thermal maturity (fig. 13). These AUs are the Greater Big Sandy, Northwestern Ohio Shale, Devonian Shale and Siltstone, and Marcellus Shale Assessment Units. The petroleum geology of these assessment units is summarized in two plays in *The Atlas of Major Appalachian Gas Plays* (Roen and Walker, 1996). These are: Play UDs: *Upper Devonian black shales* (Boswell, 1996), and *Play Dbg: Upper Devonian fractured black and gray shales and siltstones* (Milici, 1996a).

In general, in the Appalachian basin methane and smaller amounts of other gases occur within the Devonian shales in fractures of various sizes or are adsorbed onto the surfaces of the large amounts of organic matter in the black "gas" shale (de Witt and others, 1993). Charpentier and others (1993) classified these modes of occurrence as domains that contain macrofracture gas, microfracture gas, and sorbed gas. During production of these gases, reservoir pressure is initially reduced as fracture systems are drained of formation waters, if present. Subsequently, as gas is produced from the fracture systems, additional gas is desorbed from organic matter into microfractures, and thence into macrofractures on the way to the well bore. These processes are similar to the desorption and production of methane from coal beds (for a summary, see Markowski, 2001). Bustin and others (2006), however, have shown that the application of coalbed methane desorption techniques to most over-mature gas shales will result in an overestimation of the adsorbed gas content and an underestimation of the free gas capacity of the shales. Instead, the use of production isotherms may result in a better estimation of the total reservoir capacity of gas shale reservoirs.

Greater Big Sandy Assessment Unit (GBS AU)

Introduction: The Greater Big Sandy Assessment Unit occupies parts of eastern Tennessee and Virginia, eastern Kentucky, and West Virginia. The AU is generally defined on the northwest by the 0.6 Ro thermal maturation isoline (based on dispersed vitrinite), and on the southeast by a line that encloses the greatest net thickness of radioactive black shale (fig. 14). Thus defined, the Greater Big Sandy Assessment Unit is stratigraphically gradational with the Devonian Siltstone and Shale Assessment Unit to the east and with the Northwest Ohio Shale Assessment Unit to the west. The assessment unit occupies much of the area of plays 8 (Western Rome Trough), 9 (Tug Fork), and 10 (Pine Mountain), and a small amount of play 11 (Plateau Virginia) of Charpentier and others (1993) (fig. 15) (Table 5). Producing depths range from about 1,700 to 5,595 feet (Boswell, 1996).

Stratigraphy: In general, the GBS AU consists of several black shale units that are interbedded with beds of gray and greenish-gray shales, siltstones, and fine-grained sandstones. The stratigraphy of the Greater Big Sandy Assessment Unit includes all of the strata from the base of Rhinestreet Shale Member of the West Falls Formation (or Marcellus Shale, where present) to the top of the Sunbury Shale (figs. 16 and 17). The Marcellus occurs beneath the Rhinestreet in a small area in the northeastern part of the AU (fig. 17). The major black shale beds in the AU include the Rhinestreet Shale Member, the lower and upper parts of the Huron Member of the Ohio Shale, and the Cleveland Member of the Ohio Shale. The Pipe Creek Shale Member of the Java Formation, although relatively thin, may be productive in places. In general, the upper part of the Huron Member grades into gray or greenish-gray shales, siltstones, and fine-grained sandstones to the east across the assessment unit, and together with Cleveland Member, pinches out to the northeast.

The thickness of the assessment unit decreases from about 2,500 feet in the northeastern part of the area to about 100 feet in the southwest, where the AU is represented by the Chattanooga Shale (fig. 17). Concurrent with the overall increase in thickness of assessment unit strata to the northeast, there is a general increase in the amount of coarser-grained siliciclastic strata (Chagrin Shale) relative to the total amount of radioactive black shales. Depositional strike is generally north-south and follows the general thickness trends of the assessment unit (fig. 14).

Geologic structure: The relation of the Greater Big Sandy Assessment Unit to regional geologic structure is shown in figure 18. In general, gas production in this assessment unit extends from the Pine Mountain block in Kentucky and Virginia northeastward to the western side of the Rome trough in Kentucky and southern West Virginia (Shumaker, 1980). Charpentier and others (1993, Play 8- Western Rome Trough) (fig. 15) related the fracture porosity in the Big Sandy gas field and adjacent areas to late Paleozoic vertical movements of normal faults associated with the Rome trough. Shumaker (1980), however, proposed that limited decollement in radioactive Devonian black shales, rich in organic matter, was responsible for the development of a "porous fracture facies" within these hydrocarbon-rich rocks. Indeed, a "blowout zone" occurs in Devonian shale beneath the Pine Mountain block (Charpentier and others (1993, Play 10 - Pine Mountain) (figs. 15, 18), where the subhorizontal decollement of the Pine Mountain thrust has been intersected by the drill within Devonian shale (Young, 1957).

Where they are of limited extent, decollements apparently enhance fracture development within shales that are rich in organic material. In contrast, where deformation is extreme, relatively small pockets of gas under high pressure are released with explosive intensity from fractured shale (Young, 1957). Intermediate between areas of limited decollement and relatively large-scale decollement is a region (Play 9- Tug Fork) proposed by Charpentier and others (1993), in which both vertical movement along Rome trough faults and deformation related to Appalachian thrusting were responsible for increased fracture porosity in Devonian shales. Shumaker (1993), in his studies of the Midway-Extra and Cottageville fields (fig. 19) in the northern part of the AU in West Virginia, concluded that fracture porosity induced by decollement in hydrocarbon-rich shales was enhanced near or above low-relief basement structures, and that this "fracture permeability formed during Alleghanian detached deformation when the lower Huron shale was overpressured Shumaker (1993, p. K17-K18)."

In addition to the work by Shumaker (1980, 1993), the relationship of limited decollement in coal beds and siliciclastic rocks to the generation of extensional and contractional fracture porosity in the Appalachian region was described in detail by Harris and Milici (1977), Milici (1980), Milici and Statler (1980), Milici and Gathright (1983, 1985), and Milici and others (1986). These studies confirm the observation that strata rich in organic matter, whether coal or shale and perhaps overpressured (Shumaker, 1980, 1993), serve to localize bedding decollement together with the formation of an array of associated extensional fractures.

Devonian shale as a source rock for methane: The Devonian shales are autogenic (self-sourced) gas reservoirs (for example, see Milici, 1993). The source of the gas is the organic matter within the shale. The better gas shale reservoirs are characterized by pervasive gas-filled micropores in laminated black shales, siltstones, and fine-grained sandstones, together with networks of natural fractures (Patchen and Hohn, 1993). The mass of organic carbon per unit area in the stratigraphic section generally exceeds 0.8kg C/cm^2 (1.76 lbs/0.155 sq. in.) of surface area (Schmoker, 1993). Content of total organic carbon (TOC) in weight % ranges widely within the black shales, from less than 1% up to about 27% locally (Zielinski and McIver, 1982), and more commonly range up to about 12%. For the GBS AU, Streib (1981) reported values of organic carbon as great as 5.63% for the Cleveland Shale Member of the Ohio Shale (Table 6).

Gas-in-place data.- Kuuskraa and others (1985) defined a target sequence, which includes the Cleveland, Huron, and Rhinestreet shales, within the Devonian shale section in eastern Kentucky, where present in the general area of the Greater Big Sandy Assessment Unit (fig. 6). For evaluation purposes, they divided eastern Kentucky into several geological settings: Setting I - areas of known production; Setting II - areas of limited production; and Setting III - areas of speculative production. Furthermore, they partitioned Geological Setting I (known production) into four "geophysically and tectonically similar areas," Areas I, II, III, and IV (fig. 20). Target gas-in-place (TGIP) estimates for Geological Setting I range from 16.93 billion cubic feet (Bcf) / sq mi in Area I, Floyd and Martin Counties, to 5.20 Bcf / sq mi in Area IV, Boyd, Johnson, and Lawrence Counties (Fig. 20, Table 7). Overall, TGIP in Geological Setting II in eastern Kentucky was estimated as 4.02 Bcf / sq mi (Table 7).

The West Virginia part of the Greater Big Sandy Assessment Unit includes part of West Virginia Geological Setting I of Kuuskraa and Wicks (1984) (Fig. 20, Table 7). This part of Setting I was partitioned into five areas (Areas I, II, IV, V, and VI) by Kuuskraa and Wicks (1984). In West Virginia, TGIP ranges from 9.87 Bcf / sq mi in Area II, Boone, Logan, and Mingo Counties, to 3.53 Bcf / sq mi in area IV, in Jackson and Mason Counties (Fig. 20, Table 7). This decrease in TGIP values to the north reflects the increased amount of non-black shale siliciclastics that occur in the stratigraphic section there.

Overall gas-in-place data for the Greater Big Sandy Assessment Unit may be approximated from the areas of the AU that are coincident with the play areas (8-11) of Charpentier and others (1993) (Table 5, fig. 15), and from county-specific data published by Kuuskraa and Wicks (1984) and Kuuskraa and others (1985) for West Virginia and Kentucky (Table 7, fig. 20). Using the play data of Charpentier and others (1993) as a base from which to work, it appears that the mean TGIP of the AU would be about 76 trillion cubic feet (Tcf) (Table 5, fig. 15). The county-based data of Kuuskraa and Wicks (1984) and Kuuskraa and others (1985), however, show that the amount of gas-in-place for the Target source rock strata (Cleveland, Huron, and Rhinestreet shales) in the AU is about 60 Tcf (Table 7). Part of the difference between these two estimates appears to result from the relatively low values for the TGIP data (Cleveland, Huron, and Rhinestreet shales) that Kuuskraa and others (1985) assigned to the counties in the western part of the AU (their Setting II, Limited Production), which is the area associated with the Western Rome Trough Play (8) of Charpentier and others (1993). In addition, the GIP values that Kuuskraa and Wicks (1984) and Kuuskraa and others (1985) determined for all stratigraphic intervals are more than double the TGIP values that they obtained for their Target intervals in Geological Setting I, Known Producing Fields.

Thermal Maturity, Generation and Migration:- The thermal maturity of the GBS AU ranges generally from 0.6 to 1.0 (dispersed vitrinite), with a maximum of about 1.5 (fig. 14). In general, kerogen types in the area of the GBS AU are expected to be mixed types I, II, and III (Maynard, 1981; Zielinski and McIver, 1982; Milici, 1993). Model-predicted vitrinite reflectance values (Rowan and others, 2004a, b; Rowan, 2006) indicate that the basal Devonian shales in the northern part of the AU entered the oil window approximately 325-330 million years ago (Mississippian) and the gas window about 230 million years ago (Triassic). In comparison, the upper part of the Ohio Shale appears to have entered the oil window about 260 million years ago (Permian).

Reservoir and production data: In the GBS AU, the principal stratigraphic units completed for gas include the Marcellus Shale, the Rhinestreet Shale Member of the West Falls Formation, the lower and upper parts of the Huron and Cleveland Members of the Ohio Shale, and the Sunbury Shale (fig. 6). Gas is produced from depths that range from about 1,700 feet to nearly 6,000 feet, and log-derived porosity values in the Big Sandy field range from 1.5% to 11%, with an average of 4.3% (Boswell, 1996). Original GIP for the Big Sandy field is estimated to be about 20 Tcf (see *Database of Appalachian Gas Fields and Reservoirs* that accompanies *The Atlas of Major Appalachian Gas Plays*, Roen and Walker, 1996). Original gas reserves for this field were estimated as 3.4 Tcf, gas produced as 2.5 Tcf, and remaining reserves as about 900 Bcf. The distribution of estimated ultimate recovery (EUR) values of gas per well for shale gas wells in eastern Kentucky (by thirds) is illustrated in figure 21. The late third average ranges from an EUR of about 5 million cubic feet of gas (MMcf) for the poorest well to 800 MMcf for the best well, with the average at about 90 MMcf.

Greater Big Sandy AU fields and pools: There are 61 named fields listed in the *Database of Appalachian Gas Fields* and Reservoirs accompanying *The Atlas of Major Appalachian Gas Plays* that lie within the boundaries of the GBS AU (Roen and Walker, 1996) (fig. 19). Several of these fields are near or on the boundaries of adjacent Assessment Units. Although these fields are administrative entities for state regulatory agencies, the fields are part of the continuous accumulation that constitutes the AU. Field average completion thicknesses range generally from 189 to 980 feet, with the greatest average thickness completed, for fields for which we have data, from the Fourmile-Branchland field in West Virginia. Cumulative production data (current as of 9/30/1996), although not available for all of the fields, indicate that at least 3.7 Tcf of gas has been produced from named fields in the GBS AU, and about 2.5 Tcf of gas has been produced from the Big Sandy gas field alone. Although much of the gas production from the Big Sandy field and from many other fields is commingled with production from other stratigraphic units, most of the gas is apparently produced from the Devonian shale.

Assessment results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian Basin, the USGS estimated a mean value of 6,322.67 BCF of gas, and a mean value of 63.23 million barrels (MMB) of natural gas liquids in the Greater Big Sandy AU (Milici and others, 2003).

Northwestern Ohio Shale Assessment Unit (NWOS AU)

Introduction: The Northwestern Ohio Shale Assessment Unit (NWOS AU) occupies the area underlain by Devonian shale that extends generally to the west of the 0.6% Ro line (dispersed vitrinite) in eastern Kentucky, east-central Ohio, western Pennsylvania, and western New York (figs. 11, 13). Thus defined, the NWOS AU is stratigraphically gradational with the GBS AU on the southeast and with the Devonian Siltstone and Shale

(DSS) Assessment Unit on the northeast (fig. 13). The assessment unit occupies all of the area of plays 1 (North-Central Ohio), 2 (Western Lake Erie), 3 (Eastern Lake Erie), 4 (Plateau Ohio), 5 (Eastern Ohio), most of 7 (Southern Ohio Valley), and parts of plays 6 (Western Penn-York), 12 (Pittsburgh Basin), and 15 (Portage Escarpment) of Charpentier and others (1993), (fig. 15), (Table 5). Of these, only Plays 2 and 3 along the shores of Lake Erie, and adjacent Play 15 in western New York were considered to have a good potential for gas production

Stratigraphy: The stratigraphy of the NWOS AU includes all of the strata from the base of Rhinestreet Shale Member of the West Falls Formation to the top of the Sunbury Shale (figs. 22, 23, and 24). Although relatively thin, the Marcellus Shale occurs beneath the Rhinestreet in much of the area of the AU (figs. 23 and 24). The major black shale units in the AU are the Rhinestreet Shale Member of the West Falls Formation and the Huron Member of the Ohio Shale. The Sunbury Shale, the Pipe Creek Shale Member of the Java Formation, and the Cleveland Member of the Ohio Shale, although relatively thin, may produce gas in places. Black gas shales in the upper part of the Huron Member and the Cleveland Member of the Ohio Shale grade eastward across the assessment unit into the gray and greenish-gray shales, siltstones, and fine-grained sandstones of the Chagrin Shale (figs. 23 and 24).

In general, the NWOS AU (fig. 13) contains much of the thicker accumulations of radioactive black shale in the Catskill delta. The thickness of Devonian strata in the assessment unit ranges from about 25 feet in southern Kentucky and adjacent Tennessee, to about 4,000 feet in the northern panhandle of West Virginia (fig. 4). The thickest accumulation of radioactive black shale, however, extends northward from easternmost Kentucky through Ohio (fig. 13), where the net thickness of radioactive black shale ranges generally from 200 to 400 feet.

Geologic Structure: The relation of producing areas in the NWOS AU to geologic structure is shown in figure 25. Although the assessment unit was assessed as a continuous accumulation, the commercial production of hydrocarbons depends largely on the local development of fracture-generated porosity and permeability within the shale reservoirs. In general, both oil and gas production are distributed widely across the AU. In some places, however, natural gas is the only hydrocarbon produced. In other places, gas is produced together with oil. Gas and oil are produced together primarily in the Cumberland Saddle region of south-central Kentucky and adjacent Tennessee, along the Cambridge arch in central Ohio, and in northwestern Pennsylvania. The chief gas-producing areas in the NWOS AU are adjacent to the GBS AU in eastern Kentucky, along the northwestern edge of the Rome trough in southern Ohio, along the Waverly arch in Ohio, and from the Lake Shore fields along the south shore of Lake Erie in northern Ohio, Pennsylvania, and western New York. Gas production along the western margin of the Rome trough in southeastern Ohio may have been enhanced by fracture porosity related to late-stage movement along the western boundary fault (Charpentier and others, 1993).

When compared with the other Devonian shale assessment units, the structure of the NWOS AU is relatively simple. The glacial loading and rebound that followed the incursion and melting of several Pleistocene continental ice sheets appears to have enhanced fracture porosity and permeability in the northwestern and northern parts of the AU, especially in the Lake Shore fields (fig. 25), where fractures extend effectively to depths of 1,000 to 1,500 feet (Charpentier and others, 1993). To the east, in the panhandle of northwestern Pennsylvania and in western New York, beds of relatively brittle siltstone are intercalated with the Devonian black shales and are broken by an extensive network of fractures that also appear to have formed in response to several cycles of glacial loading and crustal rebound. The combination of natural fractures and thin, broken beds of siltstone interbedded with the thick accumulation of black shale source rock has enhanced gas production from the Devonian shale in this area (Charpentier and others, 1993).

East of the Cambridge arch, a relatively large area in eastern Ohio, western Pennsylvania, and northern West Virginia is underlain by Silurian Salina Group evaporites. The evaporite beds contain a widespread subhorizontal bedding-parallel fault that exhibits only a relatively small amount of displacement (limited decollement) (figs. 25, 26) (Frey, 1973). In the region to the east of the NWOS AU, this decollement has had sufficient movement on it to generate numerous blind splay thrusts and a series of relatively low relief sub-parallel superficial anticlines within hanging wall strata. The folding is a reflection of the amount of shortening that has taken place in the strata overlying the Salina decollement (figs. 25, 26). This detachment has been recognized as far west as the Bass Islands trend in southwestern New York (fig. 25) (Beinkafner, 1983; Patenaude and others, 1986; Van Tyne, 1996a). Nevertheless, extension of the detachment, however limited it may be, within the Salina evaporates westward into Ohio to the vicinity Cambridge arch is speculative. Fractures in Devonian strata that are related to movement along the Salina decollement may occur along the northeastern margin of the NWOS AU, generally from southeastern Ohio, through the panhandle of West Virginia, to the Bass Islands trend in New York (Charpentier and others, 1993; Shumaker, 1996, fig. 6).

Devonian shale as a source rock for methane: In general, the greatest thickness of radioactive black shale extends from the GBS AU in eastern Kentucky northward into eastern Ohio, where the cumulative thickness of potential source rocks locally exceeds 400 feet (de Witt and others, 1993, fig. 2) (fig. 13). Kerogen types in this area are generally derived from marine biota, especially the algae (*Tasmanites*), and are commonly of types I and II, which are prone to generate oil as well as natural gas (Maynard, 1981; Zielinski and McIver, 1982, summarized in Milici, 1993). Although vitrinite reflectance data from dispersed organic matter in the Devonian shales indicate that this area is thermally immature with respect to oil generation (fig. 10), oil is found in wells scattered throughout much of the assessment unit (figs. 25, 27). Streib (1981) reported that the organic carbon content of samples from the Cleveland Shale Member of the Ohio Shale averaged about 7.46% in Gallia County, Ohio (Table 6).

Gas-in-Place Data: - The NWOS AU, when compared to the area in the plays of Charpentier and others (1993), would contain about 245 Tcf of GIP (Table 5). This value compares favorably with the approximately 112 Tcf GIP value calculated from data in Kuuskraa and Wicks (1984); Kuuskraa and others (1985); and Lewin and Associates

(1983) for the targeted radioactive Devonian shales (TGIP; Ohio and Rhinestreet shales) in approximately the same area (Table 8).

Lewin and Associates (1983, p. 7) partitioned Ohio into six areas based on "Geologic Characteristics, Tectonophysics, and Simulated Gas Production." Target GIP is greatest in partitioned Area IV in north-central Ohio, (fig. 28), where it is 9.39 Bcf / sq mi, and least in Area V, in the northwestern part of the AU, where the TGIP is 1.28 Bcf / sq mi (Table 8). In contrast, the potential average production per well in Ohio is estimated to be greatest in Area I in southern Ohio (386-1,080 MMCF/well for a large vertical fracture, over 40 years), and least for Area VI in northeastern Ohio (10-47 MMCF/well for a large vertical fracture, over 40 years). These estimates are based on "simulated technology" (Lewin and Associates, 1983, p. 56-60).

Thermal Maturity, Generation, and Migration:- Based on the burial history curve for the Amerada No. 1 Ullman well in Noble County, Ohio (figs. 22, 29), published by Ryder and others (1998), the lower part of the Devonian shale in the eastern part of the NWOS AU appears to have entered the oil window sometime during the Middle Triassic (fig. 29). Subsequent work by Rowan and others (2004a, b) and Rowan (2006) has determined that basal Devonian shales in southeastern Ohio (Ullman well) entered the oil window during the Mississippian and entered the gas window during the latest Permian or earliest Triassic. In this area, the top of the Devonian shale entered the oil window during the latest Permian or earliest Triassic, but remained immature with regard to the thermal generation of natural gas. The western part of the NWOS AU in Ohio is also generally immature with respect to the generation of hydrocarbons (Repetski and others, in preparation).

Reservoir and production data:- In much of Ohio, the Devonian shale source rocks and reservoirs consist predominantly of the Huron and Cleveland Members of the Ohio Shale (figs. 23 and 24). In western New York, the producing formations are the Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Member of the West Falls Formation, and the Marcellus Shale (Tables 2 and 4). Available gas field data show that the average thickness completed by field ranges up to 352 feet in northeastern Kentucky (Naples field), to 600 feet in eastern Ohio (Brookville field), and to 378 feet in western West Virginia (Apple Grove field) (fig. 27). Depths to producing reservoirs range generally from about 2,300 feet in southern Ohio to 365 feet in north-central Ohio (Lewin and Associates, 1983) to 4,000 feet or more in western West Virginia, and adjacent Kentucky. Average log-derived porosity values range from about 3%, to 14% in the Newton field in central Ohio, and up to 16% in the Darlington field in western Pennsylvania (Roen and Walker, 1996). Maximum porosities of 8% and 9% have been reported for other fields (Boswell, 1996). In their report on the *Technically Recoverable Devonian Shale Gas in Ohio*, Lewin and Associates (1983) used nominal values of 1% for shale matrix porosity and 5×10^{-6} md for shale matrix permeability. Soeder and others (1986) observed that shale samples from wells in the lower part of the Huron Member of southeastern Ohio and northwestern West Virginia contain liquid petroleum in their pores. As a result, matrix permeability to gas is very low (in the tens of nanodarcies range), and gas-filled porosity is generally less than 0.1%.

The distribution of EUR values of gas per well for shale gas wells in the NWOS AU (by thirds) is illustrated in figure 30. The late third average ranges from less than 2 MMcf for the least productive wells, to almost 300 MMcf for the most productive wells, with the average EUR about 40 MMcf.

Northwestern Ohio Shale AU fields and pools: There are 49 named gas fields within the boundaries of the NWOS AU (fig. 27). Selected data for these fields are listed in the *Database of Appalachian Gas Fields and Reservoirs* (Roen and Walker, 1996). Although these fields are administrative entities for state regulatory agencies, the fields are part of the continuous accumulation that constitutes the NWOS AU. Cumulative production data are generally not available from these fields, and much of the gas production from the NWOS AU is commingled with production from other stratigraphic units.

Assessment results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian basin, the USGS estimated a mean value of 2,654.07 BCF of gas, and a mean value of 53.08 MMB of natural gas liquids in the Northwestern Ohio Shale AU (Milici and others, 2003).

Devonian Siltstone and Shale Assessment Unit (DSS AU)

Introduction: The Devonian Siltstone and Shale Assessment Unit (DSS AU) extends across the Appalachian basin from western New York State through western Pennsylvania and central West Virginia into southwestern Virginia (figs. 13, 31). The western boundary of the DSS AU lies along the 0.6%Ro isoline in New York, Pennsylvania, and Ohio (fig. 11). To the south, in West Virginia and Virginia, the western boundary of the DSS AU lies along the eastern margin of the GBS AU. Geographically and stratigraphically, the DSS AU generally lies between the eastern limit of the upper black shale tongue of the Huron Member of the Ohio Shale and the eastern limit of the Rhinestreet Shale Member of the West Falls Formation (de Witt and others, 1993) (Table 2). This assessment unit is generally coincident with much of the area occupied by *Play Dbg: Upper Devonian Fractured Black and Gray Shales and Siltstones* (Milici, 1996a) of the Appalachian gas atlas (Roen and Walker, 1996), and the geology of the region is described in more detail there. The DSS AU is intermediate between basinal shale deposits of the GBS AU and the delta front turbidite deposits of the NWOS AU on the west, and the coarser-grained deposits of the Catskill Sandstones and Siltstones AU on the east (Filer, 1985; Donaldson and others, 1996; Boswell, Heim, and others, 1996; Boswell, Thomas and others, 1996). The DSS AU includes the "emerging area" of Patchen and Hohn (1993) in northwestern West Virginia.

Stratigraphy: In general, the stratigraphy of the DSS AU consists of dark-gray to black shales that are interbedded with gray and greenish gray shales and siltstones (de Witt and others, 1993). The DSS AU includes all of the strata from the top of the Sunbury Shale to the base of the Hamilton Group (Marcellus Shale). The principal black shale units within the AU consist of the Marcellus Shale at the base, the Pipe Creek Shale Member, and the lower part of the Huron Member (including the Dunkirk Shale Member of the

Perrysburg Formation in southwestern New York, western Pennsylvania, southeastern Ohio, and northern West Virginia, (de Witt, 1993) (Table 2, figs. 8b, 23, 24). Net thickness of radioactive black shale in the assessment unit ranges from less than 100 feet in the southern part of the AU to a little more than 500 feet in southwestern New York and adjacent Pennsylvania (fig. 13).

The overall thickness of the Devonian section in the area of the AU ranges from 1,000 feet or less in western New York State to 6,000 feet in central Pennsylvania. The Devonian strata in the AU thin farther to the south, to less than 1,000 feet thick in southwestern Virginia (fig 32). Except at its northern end in New York, the DSS AU tends to follow the depositional strike of the Catskill delta throughout much of the basin.

Geologic Structure: The spatial relation of the DSS AU to geologic structure is shown in figures 26 and 31. In general, the AU is deformed to some extent by limited decollement in Devonian shale in the area south of the Rome trough in southern West Virginia and southwestern Virginia. North of the trough, in northwestern Pennsylvania, limited decollement within the salt beds of the Salina Group has resulted in shortening and folding of the hanging wall into a series of relatively low amplitude folds (fig. 26). Together, subhorizontal decollement within the gas shales, the fractured superficial anticlines that were formed by splay faults from the decollement in underlying Silurian evaporites (Filer, 1985; Sweeney, 1986), and perhaps any late-stage movement on the steeply dipping faults associated with the Rome trough (Caramanica, 1988), appear to have increased the fracture porosity within the AU, especially where siltstone and fine-grained sandstone are intercalated with the black shales. In the "emerging area" of Patchen and Hohn (1993) in northwestern West Virginia., the two main pays are the Huron and Rhinestreet shales. Fracture porosity within these shales appears to be related to folds that were formed by limited decollement in underlying Silurian salt beds (Shumaker, 1993).

Devonian shale as a source rock for methane: Except in southwestern New York and western Pennsylvania, the DSS AU lies along the eastern margin of thick basinal shales, where net thickness of radioactive black shale ranges from about 100 feet to as much as 250 feet. In southwestern New York and adjacent Pennsylvania, however, the net thickness of radioactive black shale is 500 feet or more (de Witt and others, 1993, fig. 2) (fig. 13). Because the AU is located in the center of the basin and closer to the source of terrigenous clastics, it is expected that kerogen types would contain greater proportions of type III kerogen than AUs to the west (Maynard, 1981; Zielinski and McIver, 1982). The geochemistry of samples tested from the DSS AU is listed in Table 6 (Streib, 1981). Streib (1981) reported that the Marcellus Shale from a well in Wetzel County, West Virginia, contains 6.19% of organic carbon.

Gas-In-Place Data: - Based on the gas–in–place estimates provided by Charpentier and others (1993), the DSS AU contains approximately 228 Tcf of gas (Table 5). Data from Lewin and Associates (1983) for Ohio and from Kuuskraa and Wicks (1984) for West Virginia indicate that the DSS AU contains a total of about 57 Tcf of gas in these states (fig. 34; Table 9). In addition, Tetra Tech, Inc. (undated, Table 3) has identified 482 Tcf (black shale thickness determined from log data) to 790 Tcf (black shale thickness determined from sample data) of in-place gas resources in Pennsylvania, with relatively favorable areas for shale gas occurring in northeastern Pennsylvania (Rhinestreet and Dunkirk shales) and in west-central Pennsylvania (Marcellus Shale) (fig. 34).

Thermal maturity, generation, and migration: - The DSS AU lies entirely to the east of the 0.6% Ro isoline (determined from dispersed vitrinite, fig. 11), and is thermally mature with respect to the generation of hydrocarbons. To the east, the AU reaches the 2.0% Ro isoline, the eastern limit of oil preservation, in western Pennsylvania, and the 4.0% Ro isoline in southern West Virginia (figs. 10, 11). As a result of the increased fracture porosity in interbedded siltstones, oil is commonly produced with gas in much of the assessment unit area (fig. 31). Where thermal maturity is the greatest in central Pennsylvania and in the southern part of the AU, however, gas is primarily produced.

Model-predicted vitrinite reflection values from three wells in the DSS AU in western West Virginia indicate that the base of the Devonian shales entered the oil window during the Pennsylvanian and the gas window during the Permian (Rowan and others, 2004a, b, Rowan, 2006). Calculated % Ro values for these wells (the No. 1 Gainer-Lee well, the No.1 McCoy well, and the No. 1 Deem well) based on vitrinite reflectance values from Pennsylvanian coal beds, are significantly greater than % Ro values determined from dispersed vitrinite in basal Devonian shale (fig. 11). For example, the calculated % Ro value for the No. 1 Gainer-Lee well is 2.17, which is significantly higher than the 1.5% Ro isoline to the east that was determined from vitrinite dispersed in the shale.

Reservoir and production data:- In the DSS AU, the principal units completed are the Rhinestreet Shale Member, the lower part of the Huron Member, and to a lesser extent, the Marcellus Shale (figs. 23, 24). Completion intervals range generally from 10 to nearly 1,600 feet, final open flow rates from 30 to 1,500 Mcf per day, and initial reservoir pressure from 125 to 2,529 psia. Although the data are limited, log-derived porosity values range up to 8% (See database that accompanies Roen and Walker, 1996). Drilling depths range from several hundred feet or more in New York to about 5,000 feet in West Virginia.

The distribution of EUR values per well calculated from shale gas wells and sorted into thirds based on completion dates are shown in figure 35. At the median, the early third of the wells attained an EUR of about 45 MMcf, the middle third about 22 MMcf, and the late third about 18 MMcf. The progressive decline of EUR values with time suggests that future wells will very likely exhibit poorer yields, unless there is significant improvement in extraction technology.

Devonian Siltstone and Shale Fields and Pools: There are 68 named gas fields within the boundaries of the DSS AU (See database that accompanies Roen and Walker, 1996) (fig. 33). Of the few fields for which there are data, the average thickness completed was greatest for the Blue Creek field in central West Virginia, at 1,590 feet. Although oil and gas exploration has occurred over much of the AU (fig. 31), exploration has been concentrated in west-central West Virginia, the "emerging area" of Patchen and Hohn (1993) (summarized in Milici, 1993, 1996a). Patchen and Hohn (1993, p. L26) concluded "…that the overall emerging area of Devonian shale oil and gas production has been overpromoted and will prove to be non-commercial to many operators and investors." Subsequently, Patchen (written communication, 2005) indicated that wells drilled more recently have improved with time since their 1993 publication as better locations have been drilled. In addition, production from many of these newer shale gas wells is commingled with production from Devonian sandstone reservoirs.

Assessment results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian Basin, the USGS estimated a mean value of 1,293.61 BCF of gas, and a mean value of 31.05 MMB of natural gas liquids in the Devonian Siltstone and Shale AU (Milici and others, 2003).

Marcellus Shale Assessment Unit (M AU)

Introduction: The Marcellus Shale Assessment Unit extends southward from central Pennsylvania, southwestern New York, and eastern Ohio through West Virginia to southwestern Virginia. The area assessed separately as the Marcellus Shale AU, where the thickness of Marcellus radioactive black shale is greater than 50 feet (fig. 36), lies generally to the east of the DSS AU.

Stratigraphy: The AU includes the Millboro Shale in southeastern West Virginia and adjacent Virginia (Table 2). Although the Hamilton Formation and the Millboro Shale may attain thicknesses of 1,000 and 1,500 feet, respectively, the net thickness of radioactive black shale within these units ranges generally from less than 50 feet in Ohio and the western parts of New York, Pennsylvania, and northern West Virginia to about 200 feet in northeastern Pennsylvania (de Witt and others, 1993).

Geologic Structure: The Marcellus Shale AU is underlain by regional decollement in Salina Group evaporites. Accordingly, the Marcellus is folded into numerous rootless folds. Interstratal slip during folding may have increased the fracture porosity within the Marcellus.

Devonian shale as a source rock for methane: Total organic carbon (TOC) values for the Marcellus, presented by Repetski and others (2002, 2005) and Weary and others (2000, 2001) (Table 10), show that organic richness of the Marcellus Shale decreases generally from New York southward to West Virginia. These variations appear to reflect the overall paleogeography of the Acadian delta, with the higher TOC values in the more distal parts (New York) and the lower values in the more proximal parts (West Virginia) of the delta. The TOC data presented in Table 10 include samples of the Marcellus Shale that were collected from wells distributed across several of the assessment units. In general, the highest values for TOC in New York occur in the NWOS AU and in counties that lie along the border of the NWOS and DSS AUs (Table 10) (Weary and others, 2000); TOC data from 19 samples in New York averaged 4.3%. In east-central Pennsylvania, however, TOC values range, with minor exception, from about 3 to 6% and the average value for 36 samples collected across western and central Pennsylvania is 3.61% (Table 10) (Repetski and others, 2002). In contrast, almost all of the 22 samples analyzed from West Virginia contain less than 2% TOC and the average from these samples is 1.4% (Table 10) (Repetski and others, 2005).

Gas-In-Place Data: The gas-in-place data provided by Charpentier and others (1993) indicate that the Marcellus Shale AU contains about 295 Tcf (Table 5). In comparison, Kuuskraa and Wicks (1984) (Table 9) showed that there are about 101 Tcf of gas in eastern West Virginia.

Thermal Maturity, generation and migration: The Marcellus Shale AU generally occupies an area where %Ro ranges from 1.5 to 3 (figs. 10, 11), and much of the AU is outside of the oil window. The depth of burial of the Marcellus in this eastern area ranges from about 5,000 to 8,000 feet below sea level. Because of its more eastward location and greater depth of burial, the Marcellus probably matured earlier in the Paleozoic than stratigraphically higher Devonian shales to the west.

Marcellus Shale Fields and Pools: Although a few hundred wells may have been completed in the Marcellus Shale AU, the only field reported in Roen and Walker (1996) is the Genegants field in New York (fig. 33). Wells in this field have been drilled to 2,000 feet, or more, and may bottom in Lower Devonian limestones.

Assessment results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian basin, the USGS estimated a mean value of 1,925.18 BCF of gas, and a mean value of 11.55 MMB of natural gas liquids in the Marcellus Shale AU (Milici and others, 2003).

Catskill Sandstones and Siltstones Assessment Unit

Introduction: The Catskill Sandstones and Siltstones Assessment Unit (fig. 37) is part of the Devonian Shale – Middle and Upper Paleozoic Total Petroleum System of the Appalachian basin (Tables 1 and 3). This assessment unit (AU) is equivalent to the following three plays described in *The Atlas of Major Appalachian Gas Plays*: (1) “Play Dvs: Upper Devonian Venango Sandstones and Siltstones” (Boswell, Heim and others, 1996); (2) “Play Dbs: Upper Devonian Bradford Sandstones and Siltstones” (Boswell, Thomas and others, 1996); and (3) “Play Des: Upper Devonian Elk Sandstones” (Donaldson and others, 1996). The AU consists of numerous Upper Devonian sandstones and siltstones that intermingle to the west with gray and black shale (Facies II, III, IV, and V in figure 5; see also figures 8a, 8b, and 38). Upper Devonian strata attain a maximum thickness of about 7,200 ft in eastern Pennsylvania (Filer, 2003). Drilling depths to the base of the Devonian black shale sequence range from approximately 3,000 to 8,000 ft in West Virginia and Pennsylvania, and drilling depths range up to approximately 5,000 ft in eastern Kentucky, eastern Ohio, and southern New York (Roen and Kepferle, 1993).

Oil and gas production from the Catskill Sandstones and Siltstones AU began in 1859 with the drilling of the Drake well in Venango County, Pennsylvania (fig. 1). Early production was from the upper stratigraphic intervals of the AU, and was associated with anticlinal structures. Subsequent production has gradually progressed to older and deeper stratigraphic intervals within the AU, and has focused on both anticlinal structures and stratigraphic traps (Harper and others, 1999; see also fig. 39).

Stratigraphy: Although the term “Catskill” has been used in various contexts to describe Devonian siliciclastic strata in the Appalachian basin (e.g., Chadwick, 1933a, b; Woodrow and Sevon, 1985), the stratigraphic boundaries of the Catskill Sandstones and Siltstones AU are shown schematically in figure 38. The base of the Catskill Sandstones and Siltstones AU corresponds with the top of the Devonian Middlesex Shale Member of the Sonyea Formation (figs. 23 and 24), and with the base of Elk play of Donaldson and others (1996). The top of the Catskill Sandstones and Siltstones AU corresponds with the base of the marine shales directly underlying the Berea Sandstone, and with the top of Venango play of Boswell, Heim and others, 1996). The Catskill Sandstones and Siltstones AU encompasses numerous producing units, including the following formal and informal stratigraphic terms (some shown on fig. 38): Alexander, Balltown, Bayard, Benson, Boulder, Bradford, Brallier, Briery Gap, Cataraugas, Catskill, Chadakoin, Chemung, Cherry Grove, Chipmunk, Clarendon, Cooper, Deer Lick, Dew Drop, Eighty Foot sand, Elizabeth, Elk, Fifth sand, Fifty Foot sand, Foreknobs, Fourth sand, Fox, Fulmer Valley, Gantz, Gartland, Glade, Gordon, Hampshire, Harrisburg Run, Haskill, Haverty, Humphrey, Hundred Foot sand, Kane, Klondike, Knox sandstone, Laona, Leopold, Lewis Run, Lock Haven, Lytle, Magee Hollow, McDonald, Murrysville, Nineveh, Oswayo, Panama conglomerate, Penney, Pink Rock, Portage, Porter, Pound, Queen, Red Valley, Rice Brook, Riceville, Richburg, Riley, Salamanca conglomerate, Sartwell, Scio, Sheffield, Shira, Sliverville, Snee, Speechley, Sugar Run, Sweet Richard, Sycamore grit, Thirty Foot sand, Tiona, Trimmers Rock, Venango, Warren, Watsonville, Waugh, and Wolf Creek.

Depositional Environments: In terms of depositional environments, the Catskill Sandstones and Siltstones AU is interpreted as a large package of siliciclastic sediments (the “Catskill Delta Complex” of Boswell and others, 1993) that prograded into the Appalachian basin from east to west (fig. 5). These siliciclastic strata are traditionally associated with the Acadian Orogeny, although the role of climate may also have been important (Cecil and others, 1998; Swezey, 2002). In detail, much of the lower and middle Catskill strata are interpreted as distal shelf and slope deposits (Boswell and Donaldson, 1988; Boswell, Thomas and others, 1996; Donaldson and others, 1996). Exceptions include areas in western Maryland and Pennsylvania, where lower Catskill strata are interpreted as “shoreline and terrestrial” deposits (Donaldson and others, 1996), and in central Pennsylvania, where lower Catskill strata are interpreted as deltaic and shoreline deposits (Donaldson and others, 1996). Interpretations of upper Catskill strata include fluvial, deltaic, shoreline, shelf, and slope environments (Boswell, Heim and others, 1996).

Petroleum System Model: In terms of petroleum systems (fig. 12; Table 3), the Catskill Sandstones and Siltstones AU is assessed as a continuous gas accumulation, although some older production included abundant oil (particularly in western Pennsylvania). The petroleum source rocks are Middle and Upper Devonian black shales that are below, above, and interbedded with Upper Devonian sandstones and siltstones (fig. 12). Hydrocarbon generation and migration occurred during the late Mississippian to Early Triassic (Rowan and others, 2004; Rowan, 2006), as the Catskill sandstones and siltstones (and interbedded shales) were buried by siliciclastic sediments associated with the Alleghanian Orogeny. Hydrocarbon traps in the AU are primarily stratigraphic, and hydrocarbon seals are the shales that intermingle with and overlie the sandstone and siltstone reservoirs.

Catskill Fields and Pools: The names and locations of selected oil and gas fields and pools within the Catskill Sandstones and Siltstones AU are shown in fig. 37. Detailed isopach maps and cross-sections through some of these fields are described in Boswell, Heim and others (1996), Boswell, Thomas and others (1996), and Donaldson and others (1996). Reservoir quality is best within the main sandstone belt where most of the oil and gas fields are located (fig. 37). To the west, reservoir quality declines because the reservoirs contain more shale and because the sandstones are more lenticular. To the east, reservoir quality declines because the sandstones contain more cement (Boswell, Heim and others, 1996). Other characteristics of Catskill reservoirs are as follows (summarized from Boswell, Heim and others, 1996; Boswell, Thomas and others, 1996; Donaldson and others, 1996; Roen and Walker, 1996):

(1) Average depth to top of reservoir (n = 1,567):
    min = 684 ft; max = 6,860 ft; mean = 3,111 ft; median = 2,899 ft.
(2) Average pay thickness (n = 279):
    min = 2 ft; max = 160 ft; mean = 13 ft; median = 8 ft.
(3) Average log-derived porosity (n = 293):
    min = 3%; max = 22%; mean = 7%; median = 7%.
(4) Average core porosity (n = 1):
    value = 11%.
(5) Average core permeability (n = 1):
    value = 960 md.
(6) Average reservoir water saturation (n = 277):
    min = 13%; max = 83%; mean = 44%; median = 45%.
(7) Average well spacing (n = 652):
    min = 1 acre/well; max = 727 acres/well;
    mean = 94 acres/well; median = 83 acres/well.

Assessment Results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian basin, the USGS estimated a mean value of 11,741 Tcf of gas and a mean value of 235 MMb of natural gas liquids in the Catskill Sandstones and Siltstones AU (Milici and others, 2003). Values showing the distribution of estimated ultimate recovery (EUR) of gas per well in the Catskill Sandstones and Siltstones AU are given in figure 40. These values of EUR distributions show that the better wells have produced about 350 MMcf of gas (95th percentile), that the poorer wells have produced about 15 MMcf of gas (5th percentile), and that the average is about 80 MMcf of gas (50th percentile). When sorted into three groups based on completion dates (fig. 41), the EUR distributions at the 50th percentile show about 70 MMcf of gas for the first group of wells (early average), about 90 MMcf of gas for the second group of wells (middle average), and about 70 MMcf of gas for the third group of wells (late average). These values indicate that the second group of wells was better than the first group of wells, and that the second group of wells was also better than the third group of wells. This trend suggests that most future wells may be expected to produce about 70 MMcf of gas or less.

Berea Sandstone Assessment Unit

Introduction: The Berea Sandstone Assessment Unit (figs. 42 and 43) is part of the Devonian Shale – Middle and Upper Paleozoic Total Petroleum System of the Appalachian basin (Tables 1 and 3). This assessment unit (AU) is equivalent to the following play described in *The Atlas of Major Appalachian Gas Plays*: (1) "Play MDe: Lower Mississippian-Upper Devonian Berea and Equivalent Sandstones" (Tomastik, 1996). The "Devonian-Mississippian" age given for this AU follows Tomastik (1996). Most of the rocks in this AU consist of medium-grained to fine-grained muddy sandstones (Pepper and others, 1954), although coarser grain sizes are present in northern Ohio and central West Virginia (de Witt and others, 1979). Sandstones in this AU are generally 20 to 60 ft thick, although thicknesses of about 100 ft are present in northeastern Ohio (Dutton and others, 1993; Pashin and Ettensohn, 1995). Drilling depths to gas reservoirs in the Berea Sandstone AU range from 1,200 to 2,000 ft in Ohio, from 2,500 to 3,500 ft in West Virginia and Kentucky, and from 3,300 to 6,000 ft in Virginia (Pepper and others, 1954; Dutton and others, 1993).

As summarized by Tomastik (1996), gas production from the Berea Sandstone began in 1859 or 1860 in Columbiana County, Ohio (fig. 34). From 1860 to 1970, gas fields in the Berea Sandstone were discovered elsewhere in Ohio, and also in Pennsylvania, West Virginia, and Kentucky. Since 1970, however, most new gas fields in the Berea Sandstone have been discovered in Virginia and Kentucky.

Stratigraphy: The Berea Sandstone was originally named the "Berea Grit" from outcrops at Berea, Ohio (Newberry, 1871). The Berea Sandstone AU, however, encompasses several producing units, including the following formal and informal stratigraphic terms: Berea, Butler, Cloyd, Corry, Cussewago, Devonian-Mississippian, Gas Sand, Murrysville, and Waverly (some shown on fig. 42). In many places throughout the basin, an unconformity is present at the base of the Berea Sandstone and associated stratigraphic units (fig. 42).

Depositional Environments: The sandstones of the Berea Sandstone AU are interpreted as deposits from the following three environments (Potter and others, 1983; Tomastik, 1996): (1) fluvial-deltaic; (2) shallow marine near-shore and coastal; and (3) barrier island. Most of the sediments that comprise the Berea Sandstone AU are thought to have prograded into the basin from east to west (Pepper and others, 1954). Pashin and Ettensohn (1995) suggested that the Berea Sandstone is essentially a lowstand wedge that developed in response to a forced regression in the Appalachian basin.

Petroleum System Model: In terms of petroleum systems (fig. 12; Table 3), the Berea Sandstone AU is assessed as a continuous gas accumulation, although some older production included abundant oil. The petroleum source rocks are Middle and Upper Devonian black shales that are beneath, above, and are interbedded with the Berea Sandstone AU (fig. 42). Hydrocarbon generation and migration occurred during the late Mississippian to Early Triassic (Rowan and others, 2004a, b; Rowan, 2006), as the Berea Sandstone and adjacent strata were buried by siliciclastic sediments associated with the Alleghanian Orogeny. Hydrocarbon traps in the AU are primarily stratigraphic, caused by porosity pinch-outs associated with changes in grain size and abundance of cement (de Witt and others, 1979). Hydrocarbon seals are the Lower Mississippian Sunbury Shale (which overlies the Berea Sandstone; fig. 42) and possibly other shales within the AU.

Berea Sandstone Fields and Pools: The names and locations of selected oil and gas fields and pools within the Berea Sandstone AU are shown in figure 43. Detailed isopach maps and cross-sections through some of these fields are described in Tomastik (1996). Solution gas is the dominant drive mechanism in Berea Sandstone reservoirs (Tomastik, 1996), and the volume of gas produced from the Berea Sandstone is not related to the position of wells with respect to anticlinal and synclinal structures (Harris and Roen, 1984). Selected reservoir data from a few fields are shown in Table 11, figure 44, and figure 45. Other characteristics of Berea Sandstone reservoirs are as follows (summarized from Tomastik, 1996; Roen and Walker, 1996):

(1) Average depth to top of reservoir (n = 251):
min = 361 ft; max = 5,283 ft; mean = 1,793 ft; median = 1,599 ft.
(2) Average pay thickness (n = 155):
min = 2 ft; max = 81 ft; mean = 17 ft; median = 13 ft.
(3) Average log-derived porosity (n = 91):
min = 2%; max = 18%; mean = 10%; median = 10%.
(4) Average core porosity (n = 6):
min = 13%; max = 17%; mean = 15%; median = 16%.
(5) Average core permeability (n = 16):
min = 1 md; max = 296 md; mean = 44 md; median = 22 md.
(6) Average reservoir water saturation (n = 70):
min = 16%; max = 77%; mean = 36%; median = 35%.

(7) Average well spacing (n = 111):
min = 1 acre/well; max = 589 acres/well;
mean = 115 acres/well; median = 59 acres/well; mode = 10 acres/well.

Assessment Results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian basin, the USGS estimated a mean value of 6,800 Bcf of gas and a mean value of 163 MMb of natural gas liquids in the Berea Sandstone AU (Milici and others, 2003). Values showing the distribution of estimated ultimate recovery (EUR) of gas per well in the Berea Sandstone AU are given in figure 46. These values of EUR distributions show that the better wells have produced about 125 MMcf of gas (95th percentile), that the poorer wells have produced about 5 MMcf of gas (5th percentile), and that the average is about 20 MMcf of gas (50th percentile). When sorted into three groups based on completion dates (fig. 46), the EUR distributions at the 50th percentile show about 15 MMcf of gas for the first group of wells (early average), about 20 MMcf of gas for the second group of wells (middle average), and about 30 MMcf of gas for the third group of wells(late average). These values indicate that the third group of wells was better than the first group and second group of wells. This trend suggests that most future wells may be expected to produce about 30 MMcf of gas or less.

Part II - Conventional Oil and Gas Resources

Oriskany Sandstone Stratigraphic and Structural Assessment Units

Introduction: For the purpose of this study, the Oriskany Sandstone and the Huntersville Chert are divided into the following two assessment units (figs. 47 and 48): (1) the Oriskany Sandstone Stratigraphic Assessment Unit, and (2) the Oriskany Sandstone Structural Assessment Unit. The Oriskany Sandstone Stratigraphic Assessment Unit (AU), which is present in the western half of the Appalachian Basin, contains mostly gas fields that are stratigraphic traps (and structural controls are of secondary importance). In contrast, the Oriskany Sandstone Structural AU, which is present in the eastern half of the Appalachian basin, contains mostly gas fields that are in structural traps located along the crests of anticlines. Both of the Oriskany Sandstone AUs are part of the Devonian Shale – Middle and Upper Paleozoic Total Petroleum System of the Appalachian Basin (Table 1). These two AUs are equivalent to the following four plays described in *The Atlas of Major Appalachian Gas Plays*: (1) *Play Dho: Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone* (Flaherty, 1996); (2) *Play Dos: Lower Devonian Oriskany Sandstone Structural Play* (Harper and Patchen, 1996); (3) *Play Doc: The Lower Devonian Oriskany Sandstone Combination Traps Play* (Patchen and Harper, 1996); and (4) *Play Dop: Lower Devonian Oriskany Sandstone Updip Permeability Pinchout* (Opritza, 1996).

The Oriskany Sandstone is a white to light gray, texturally mature, coarse-grained to medium-grained quartz sandstone (Edmunds and Berg, 1971; Patchen and Harper, 1996), whose type section is located at Oriskany Falls, New York (Vanuxem, 1839). The Oriskany Sandstone and equivalent stratigraphic units are more quartz-rich and coarser-grained to the east, and intergranular cement is more abundant to the east (Patchen and Harper, 1996). In most places, the sandstones are cemented by calcite, and silica cement is common near the top of the formation at some locations (Edmunds and Berg, 1971; Patchen and Harper, 1996). In some places, however, the Oriskany Sandstone is poorly cemented, and is easily mined for the manufacture of glass (Fettke, 1918; Woodward, 1959). Brachiopod shell fragments are common throughout the Oriskany Sandstone (Opritza, 1996). An unconformity (the "Acadian Discontinuity") is present at the base of the Oriskany Sandstone (Wheeler, 1963), and another unconformity is present at the top of the sandstone in many areas of the basin (Flaherty, 1996).

The Huntersville Chert, which is included in the Oriskany Sandstone Structural AU, is a Lower and Middle Devonian chert that in places immediately overlies the

Oriskany Sandstone (figs. 47 and 49). The type section of the Huntersville Chert is located at a quarry in Huntersville, West Virginia (Price, 1929). This chert contains zones of quartz sandstone and siltstone, as well as a phosphatic and glauconitic zone at the base of the formation. The Huntersville Chert is characterized by a limited fauna (dominated by brachiopods), although there are a few local areas of abundant, diverse fauna (Dennison and others, 1996).

In the Oriskany Sandstone Stratigraphic AU, sandstone thicknesses are less than 100 ft and drilling depths range from approximately 1,800 ft to 8,500 ft (Diecchio and others, 1984; de Witt, 1993). In the Oriskany Sandstone Structural AU, sandstones thicknesses range generally from 50 to 100 ft (although they attain a maximum thickness of about 350 ft in western Maryland) and drilling depths range from approximately 1,800 ft to 8,500 ft (Diecchio and others, 1984; Diecchio, 1985; de Witt, 1993).

As summarized by de Witt (1993), Patchen and Harper (1996), and Opritza (1996), gas production from the Oriskany Sandstone Stratigraphic AU began in 1900 in northeastern Ohio. From 1900 through the 1920s, many additional gas fields were discovered throughout eastern Ohio. Gas production from the Oriskany Sandstone was extended to West Virginia in the 1930s with the discovery of the giant Elk-Poca field in Kanawha County (Patchen and others, 1992), and gas production was later extended to Pennsylvania in 1946 with the discovery of the Erie field in Erie County, Pennsylvania (fig. 48). Since 1960, however, there has been a general decline in Oriskany Sandstone drilling activity.

As summarized by de Witt (1993), Flaherty (1996), and Harper and Patchen (1996), gas production from the Oriskany Sandstone Structural AU began in 1919 with production from the Devonian Huntersville Chert at Lycippus field in Westmoreland County, Pennsylvania (fig. 48). Within this AU, gas production from the Oriskany Sandstone was later established in 1930 at the Wayne-Dundee field in Schuyler County, New York (fig. 48). In 1937, the first combined production from both the Huntersville Chert and the Oriskany Sandstone was established at Summit field in Fayette County, Pennsylvania (fig. 48). Much exploration and gas production from the Oriskany Sandstone Structural AU took place from 1930 to 1960, but there has been a general decline in drilling activity since 1960.

Stratigraphy: The Oriskany Sandstone Stratigraphic AU encompasses several producing units throughout the Appalachian basin, including the following formal and informal stratigraphic terms (some shown on fig. 47): Austinburg, Oriskany, Ridgeley, Springvale, and Sylvania. The Oriskany Sandstone Structural AU also encompasses several producing units, including the following formal and informal stratigraphic terms: Austinburg, Huntersville Chert, Oriskany, Ridgeley, and Springvale.

Depositional Environments: The Oriskany Sandstone has been interpreted as having accumulated in shallow marine, nearshore, and (or) shelf environments (Flaherty, 1996; Harper and Patchen, 1996; Patchen and Harper, 1996). A modification of this interpretation was given by Cecil (2004), who suggested that the quartz grains of the Oriskany Sandstone were transported by wind prior to deposition in a marine environment. The Huntersville Chert is also thought to have accumulated in a shallow marine environment, but one that was predominantly anaerobic to dysaerobic (Dennison and others, 1996). Similarly, Cecil, 2004 suggested that the chert of the Huntersville was originally wind-blown quartzose dust that had accumulated in a shallow water marine environment

Petroleum System Model: In terms of petroleum systems (fig. 12; Table 3), the Oriskany Sandstone Stratigraphic AU and the Oriskany Sandstone Structural AU are assessed as conventional accumulations that contain mostly gas. The petroleum source rocks are Middle and Upper Devonian black shales (primarily the Hamilton Shale, Marcellus Shale, and Needmore Shale) that overlie the Oriskany Sandstone (figs. 12 and 47; Tables 1 and 2). In addition, Patchen and others (1992) include the Upper Devonian Rhinestreet Shale Member of the West Falls Formation (fig. 47) as a major source of gas at the Elk-Poca field. Hydrocarbon generation and migration occurred during the late Mississippian to Early Triassic (Rowan and others, 2004a, b; Rowan, 2006), as the Oriskany Sandstone was buried by siliciclastic sediments associated with the Alleghanian Orogeny. Hydrocarbon traps are primarily stratigraphic to the west and structural (anticlines) to the east. In other words, most of the gas fields within the Oriskany Sandstone Stratigraphic AU are stratigraphic traps, and structural controls are of secondary importance (Diecchio, 1985; de Witt, 1993; Patchen and Harper, 1996; Flaherty, 1996; Opritza, 1996). In contrast, as shown in figure 48, most of the gas fields within the Oriskany Sandstone Structural AU are structural traps that are located on the crests of anticlines (Diecchio, 1985; de Witt, 1993; Flaherty, 1996; Harper and Patchen, 1996). Some of these anticlines have extremely complex structures, as shown in Harper and Patchen (1996). In the fields with structural traps, gas accumulation is dependent upon fracture porosity, and this porosity is developed best on the crests of anticlines (e.g., Petzet, 1990). Hydrocarbon seals within both Oriskany AUs are the black shales (Marcellus Shale) and micritic limestones (Onondaga Limestone) that overlie the Oriskany Sandstone and equivalent units (fig. 49).

Oriskany Sandstone Fields and Pools: The names and locations of selected oil and gas fields and pools within the Oriskany Sandstone AUs are shown in figure 48. Detailed isopach maps and cross-sections through some of these fields are described in Flaherty (1996), Harper and Patchen (1996), Patchen and Harper (1996), and Opritza (1996). There are definite gas-water contacts in Oriskany Sandstone reservoirs (Rothrock, 1949), and the dominant drive mechanism in many Oriskany fields is by water or salt water (Patchen and Harper, 1996). In some fields, however, production may be driven by gas expansion (Patchen and Harper, 1996). Selected reservoir data from a few fields are shown in Table 12. Other characteristics of Oriskany Sandstone reservoirs are listed below.

Oriskany Sandstone Stratigraphic AU (summarized from Opritza, 1996; Patchen and Harper, 1996; Roen and Walker, 1996):

(1) Average depth to top of reservoir (n = 70):
    min = 1,675 ft; max = 7,246 ft; mean = 3,911 ft; median = 4,114 ft.

(2) Average pay thickness (n = 37):
    min = 2 ft; max = 60 ft; mean = 14 ft; median = 9 ft.

(3) Average log-derived porosity (n = 35):
min = 3%; max = 15%; mean = 8%; median = 8%.
(4) Average core porosity (n = 3):
min = 8%; max = 17%; mean = 13%; median = 17%.
(5) Average core permeability (n = 1):
value = 58 md.
(6) Average reservoir water saturation (n = 24):
min = 10%; max = 92%; mean = 38%; median = 29%.
(7) Average well spacing (n = 58):
min = 10 acres/well; max = 269 acres/well;
mean = 85 acres/well; median = 61 acres/well; mode = 20 acres/well.

Oriskany Sandstone Structural AU (summarized from Flaherty, 1996; Harper and Patchen, 1996; Roen and Walker, 1996):
(1) Average depth to top of reservoir (n = 174):
min = 1,882 ft; max = 9,271 ft; mean = 6,740 ft; median = 7,197 ft.
(2) Average pay thickness (n = 15):
min = 10 ft; max = 79 ft; mean = 29 ft; median = 14 ft.
(3) Average log-derived porosity (n = 69):
min = 2%; max = 19%; mean = 8%; median = 8%.
(4) Average core porosity (n = 1):
value = 8%.
(5) Average core permeability (n = 1):
value = 11 md.
(6) Average reservoir water saturation (n = 64):
min = 9%; max = 57%; mean = 30%; median = 25%.
(7) Average well spacing (n = 138):
min = 36 acres/well; max = 704 acres/well;
mean = 179 acres/well; median = 139 acres/well; mode = 125 acres/well.

Assessment Results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian basin, the USGS estimated a mean value of 65 Bcf of gas and a mean value of 0.5 MMb of natural gas liquids in the Oriskany Sandstone Stratigraphic AU, and a mean value of 386 Bcf of gas and a mean value of 2 MMb of natural gas liquids in the Oriskany Sandstone Structural AU (Milici and others, 2003). In the Oriskany Sandstone Stratigraphic AU, field size data (original gas reserves) are shown in Table 13. When sorted into two groups based on completion dates, the median grown size of discovered gas accumulations is 17.2 Bcf of gas for the first group and 5.3 Bcf of gas for the second group. This trend shows that the first group of gas fields was better than the second group. This trend also suggests that most undiscovered gas fields in the Oriskany Sandstone Stratigraphic AU may be expected to produce about 5.2 Bcf of gas or less. In the Oriskany Sandstone Structural AU, field size data are shown in Table 14. When sorted into three groups based on completion dates, the median grown size of discovered gas accumulations is 20.8 Bcf of gas for the first group, 17.1 Bcf of gas for the second group, and 7.5 Bcf of gas for the third group. This trend shows that the first group of gas fields was better than the second group, and that the second group of wells was better than the third group. This trend also suggests that most undiscovered gas fields in the Oriskany Sandstone Structural AU may be expected to produce about 7.5 Bcf of gas or less.

Graphs describing the estimated ultimate recovery (EUR) per well for the Oriskany assessment units are presented in figures 50 to 53. According to these graphs, the better wells in the Oriskany Sandstone-Stratigraphic AU, may be expected to produce 550 MMcf of gas, with the average wells producing about 150 MMcf (figs. 50 and 51). The better wells in the Oriskany Sandstone-Structural AU may be expected to produce as much as 4 Bcf of gas, with the average wells producing about 400 MMcf (figs. 52 and 53). However, data describing the EUR per well for the Oriskany Sandstone are sparse, and the graphs presented in figures 50 to 53 should be regarded as preliminary.

Mississippian Sandstone Assessment Unit (MS AU)

Introduction: The Mississippian Sandstone Assessment Unit (MS AU) includes all of the Lower Mississippian strata between the base of the Price and Rockwell Formations, and their lateral equivalents in the Appalachian basin, to the base of the Greenbrier Limestone (Upper Mississippian) or Maccrady Formation (Lower Mississippian), where present (Table 2). The assessment unit ranges generally from 300 to 600 feet thick and consists of the strata deposited as part of the Price/Rockwell (Pocono) delta (figs. 54 - 58) (Boswell, 1996). The assessment unit is truncated to the north and west by the pre-Pennsylvanian unconformity, and to the east by the pre-Greenbrier unconformity (Vargo and Matchen, 1996). To the south and west, the assessment unit grades into the basinal deposits of the Grainger Formation and siliceous carbonates of the Fort Payne Formation in Tennessee and Kentucky. Sandstone and fractured turbidite reservoirs within the assessment unit have produced both oil and gas for over a century (Bell and others, 1993; Hohn and others, 1993; Zou and Donaldson, 1994). The following discussion, however, is based primarily on the descriptions of *Play Mbi: Lower Mississippian Big Injun Sandstones*, and *Play Mws: Lower Mississippian Weir Sandstones* (Vargo and Matchen, 1996; Matchen and Vargo, 1996).

Stratigraphy: The MS AU includes sandstones known to drillers as the Weir, Squaw, and (Pocono) Big Injun (Tables 2, 4). The term “Weir” is applied to sandstones in the lower part of the section (figs. 54, 55), generally within one or two hundred feet of the base, whereas the term “Big Injun” generally refers to sandstone beds in the upper part of the deltaic section (figs. 56, 57). Collectively, these sandstones were assessed together as a single assessment unit (fig. 58). In some places, the Weir interval is divided into lower, middle, and upper sandstones, depending upon the complexity of the stratigraphy. In other places, sandstones below the Big Injun but higher stratigraphically than the Weir have been called Squaw. To compound the stratigraphic terminology, sandstones in the lower part of the Greenbrier Limestone have been mistakenly called Big Injun, and another sandstone, called the Keener Sandstone, has been assigned by drillers and geologists either to the Price/Rockwell Formations or to the Greenbrier Limestone (Tables 2, 4). To clarify these differences, the Big Injun sandstones are commonly called Pocono Big Injun or Greenbrier Big Injun depending upon their stratigraphic location.

The term, Keener, has subsequently been applied only to sandstones in the Greenbrier Limestone (Smosna, 1996; Vargo and Matchen, 1996).

Regionally, Weir sandstones occur within the Rockwell and Price Formations from Pennsylvania to southwestern Virginia and southern West Virginia, and in the lower part of the Cuyahoga Formation in Ohio. Big Injun sandstones occur within the Burgoon Formation in south-central to southwestern Pennsylvania, the Black Hand Member of the Cuyahoga Formation of Ohio, and the Price Formation of southern West Virginia and southwestern Virginia. Both the Weir and Big Injun sandstones occur within the Borden Formation of eastern Kentucky (Tables 2, 4) (Vargo and Matchen, 1996; Matchen and Vargo, 1996).

Matchen and Vargo (1996) recognized four progradational units within Lower Mississippian clastic sequences between the top of the Sunbury Shale and the pre-Greenbrier unconformity. Each of these units contains depositional facies that range from delta plain deposits on the east to basinal turbidites on the west. Weir sandstones, which are generally located in the lower part of the section, were deposited in environments that ranged from prodelta to fluvial (fig. 54), whereas the Big Injun sandstones, which are higher in the section, commonly represent depositional environments that ranged from fluvial and deltaic in Pennsylvania and northern West Virginia to delta front or interdistributary bay in Kentucky. Big Injun fields are generally small and well defined in the southern part of the MS AU, but have coalesced into county-sized units in central and northern West Virginia (Vargo and Matchen, 1996). A composite of the Weir and Big Injun plays is shown as the Mississippian Sandstone AU on figure 58. The assessment unit was assessed as a conventional accumulation, although the distribution of oil and gas occurrences has some of the aspects of a continuous accumulation.

Geologic Structure: The principal geologic structures of the central Appalachian Plateau region are gently folded anticlines and synclines. The anticlines are generally larger in northern West Virginia and Pennsylvania, where natural gas within Big Injun sandstones commonly occurs in the anticlines, and oil and water are within the associated synclines (Hohn and others, 1993; Vargo and Matchen, 1996). In West Virginia, the extent of Weir production may not be controlled everywhere by geologic structure, although in places structure may enhance flow rates. In Kentucky, Weir production is associated with the Paint Creek uplift (fig. 54), whereas Big Injun production from the Warfield gas field (figs. 54, 57) is on the southern part of the Warfield anticline (Vargo and Matchen, 1996; Matchen and Vargo, 1996).

Thermal maturation, source rocks, and seals: Almost the entire assessment unit lies in a region that is thermally mature with respect to hydrocarbon generation from Devonian shale source rocks (fig. 58). Source rocks for hydrocarbons in the MS AU in southwestern West Virginia are probably the Sunbury Shale, Ohio Shale, and the Rhinestreet Shale Member of the West Falls Formation (Table 2). To the northeast in Pennsylvania, the principal Devonian black shale source rocks are the Marcellus Shale and the Genesee Formation (Vargo and Matchen, 1996; Matchen and Vargo, 1996). Thermal maturation of the underlying source rocks ranges generally from 0.6 to 2.0% Ro (fig. 58). Local seals are the less permeable shales and siltstones intercalated with the reservoir sandstones within the AU, as well as the overlying Maccrady Formation, where present. The overlying Greenbrier Limestone may serve as a regional seal.

Reservoirs and field size data: The Rockwell-Price deltas and their equivalents to the west, the Borden Formation in eastern Kentucky, together with the Cuyahoga Group in Pennsylvania and Ohio, and the overlying Burgoon and Purslane Sandstones in Pennsylvania, western Maryland, and northern West Virginia, contain several productive sandstone reservoirs in the central part of the Appalachian basin. In general, Weir sandstones occur in the lower part of the Price Formation in Virginia and West Virginia, in the Borden Formation of eastern Kentucky, and within the Cuyahoga Group and Shenango Formation of western Pennsylvania (Matchen and Vargo, 1996) (Tables 2 and 4). Big Injun sandstones occur in the Burgoon Formation in western Pennsylvania and in the upper part of the Price Formation in Virginia and West Virginia. The approximate stratigraphic equivalents of the Big Injun are the Black Hand Member of the Cuyahoga Formation in Ohio, and the upper part of the Borden Formation of eastern Kentucky (Vargo and Matchen, 1996).

Big Injun fields are relatively shallow, and most occur between depths of 500 and 1,500 feet below sea level. Depths to the top of Weir fields range from 618 feet for the Isonville field in eastern Kentucky to 5,140 feet for the Ashland- Clark Gap-Eckman field in southern West Virginia (fig. 55). In northern and central West Virginia, stacked Weir sandstones attain thicknesses of as much as 200 feet (fig. 54), which may contain one or two productive zones. Reservoir sandstones generally thin to the south, and in Kentucky fractured Borden reservoirs consist of relatively thin discontinuous turbidites. Although cumulative thicknesses of Weir sandstones in Kentucky may reach 125 feet, pay zones are relatively thin and discontinuous. Pay thicknesses average 50 feet in delta front and delta slope deposits, and average 25 feet in prodelta deposits. Average porosities of Weir sandstones range generally from 2 to 20%; and commonly from about 7% in delta front-delta slope reservoirs to 15% in fractured prodelta reservoirs. The highest porosity values, however, are from fields that produce from shallow marine shelf sandstones (figs. 54). Permeabilities are relatively low and are generally less than 10 md. Final open flow rates range from 57 to 4,738 Mcf/d and average about 900 Mcf (Roen and Walker, 1996, database; Matchen and Vargo, 1996).

In northern West Virginia, the Big Injun interval (figs. 56, 57, and 58) is up to 200 feet thick, or more, and contains several pay zones which may be up to 50 feet thick. From central West Virginia to Kentucky, the Big Injun interval is thinner (up to 60 feet thick) and the pay includes the whole formation. Average porosities from producing Big Injun fields range from 4 to 20.3%, with the largest values from fields producing from reservoirs in fluvial-deltaic deposits. Permeabilities are considered fair to moderate, although there is little published data. Average field final open flow rates range from 10 to 3,000 Mcf/d (Roen and Walker, 1996, database; (Vargo and Matchen, 1996).

Mississippian Sandstone AU Fields and Pools: There are 398 fields listed in the database that accompanies *The Atlas of Major Appalachian Gas Plays* (Roen and Walker, 1996). Of these, 69 produce from Weir sandstones and 329 from Big Injun sandstones (figs. 55 and 57). In eastern Kentucky, Weir fields along the Paint Creek uplift generally produce both oil and gas. The three largest Weir fields are the Ashland-Clark Gap-Eckman, Burnwell, and Slaughter Creek fields, all producing from fluvial-deltaic deposits (fig. 55). The three largest Big Injun fields are the Smithton-Flint-Sedalia, Amma-Looneyville-Newton, and the Elk Run fields (fig. 57). These fields produce hydrocarbons from fluvial-deltaic and mixed fluvial-deltaic and carbonate shelf deposits (Vargo and Matchen, 1996; Matchen and Vargo, 1996).

Field Size data: The field size data (original reserves) available for the Mississippian Sandstone AU from the *Database of Appalachian Gas Fields and Reservoirs*, to accompany the Appalachian gas atlas (Roen and Walker, 1996) contain field size data primarily from Kentucky (Table 15, fig. 59). Sorted by discovery date, original gas reserves by field show a conspicuous decline from the initial discovery of the Warfield DBS field in Kentucky in 1905 to the discovery of the Emery Creek DBS field in 1990. All fields in the database with a minimum size of 3 Bcf, or more, were discovered prior to 1923. This indicates that, in Kentucky at least, fields discovered in the future will be of comparatively small size. It is interesting to note that the West Finley field in Pennsylvania, discovered in 1905, was assigned 30 Bcf for original GIP, and that at an 80% recovery factor, its gas reserves would be 24 Bcf, a much larger number than the original gas reserves of the Warfield DBS field.

Assessment results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian basin, the USGS estimated a mean value of 5.08 MMB of oil, 112.93 BCF of gas, and a mean value of 1.36 MMB of natural gas liquids in the Mississippian Sandstone AU (Milici and others, 2003).

Greenbrier Limestone Assessment Unit (GL AU)

Introduction: The following discussion is based primarily on *Play Mgn: Upper Mississippian Greenbrier/Newman Limestones* (Smosna, 1996), and on *Play Mfp: The Lower Mississippian Fort Payne Carbonate Mound Play* (Milici, 1996c), published in Roen and Walker (1996). The Greenbrier Limestone Assessment Unit (GL AU) generally includes all of the strata above the Burgoon, Price (Rockwell), Maccrady, and Borden Formations, and below the Pennington, Bluefield, and Mauch Chunk Formations (Tables 1, 2, 3, and 4). For assessment purposes, the Fort Payne Formation (Chert) (Tables 2 and 4) was included within the lower part of the GL AU in Tennessee and eastern Kentucky (Milici, 1996c). The GL AU extends from southern Pennsylvania and eastern Ohio through West Virginia, Virginia, and eastern Kentucky to the Tennessee Cumberland Plateau (fig. 60) (Smosna, 1996).

Stratigraphy: The Greenbrier Limestone assessment unit consists of a variety of formations that consist generally of limestone, dolomite, and sandstone. In West Virginia, gas-producing zones include the Greenbrier Big Injun, the Keener Sandstone, and ooid grainstones within the upper part of the Greenbrier Limestone (Smosna, 1996) (Table 2, fig. 61). The Greenbrier Big Injun and Keener are the major reservoirs in northern West Virginia; the Big Lime oolite is the principal reservoir in southern West

Virginia; and a basal porous, skeletal dolomitic limestone and overlying ooid grainstones comprise the Newman Limestone (Table 4) reservoir in Kentucky (MacQuown and Pear, 1983; Smosna, 1996). Porous vuggy crinoidal limestones within the Fort Payne Formation in the Cumberland Saddle region of Kentucky (fig. 25) have historically produced gas. In Tennessee, oil and gas are produced from oolitic and bioclastic zones within the Monteagle Limestone as well as from bryozoan-rich, Waulsortian-like carbonate buildups in the Fort Payne Formation (Tables 2 and 4) (Milici, 1996c).

Smosna and Koehler (1993) determined that oolite beds within the Greenbrier were deposited under tidal conditions in the area of the West Virginia dome (fig. 56) in northeastern West Virginia. South of the dome in southeastern West Virginia, porosity trends follow along the crests of tidal bars that consist of ooid grainstones, and limestones along the edges of these shoals contain shaly interbeds. The tidal bar belt apparently followed a hinge line that separated a subsiding basin from the more stable shelf (fig. 9, Hinge Zone 2) (Kelleher and Smosna, 1993; Cavallo and Smosna, 1997).

Geologic Structure: Hydrocarbons are produced primarily from stratigraphic traps in the Greenbrier Limestone Assessment Unit, with little structural control. Large scale geologic structures, such as the regional dip eastward from the Cincinnati arch (fig. 25), the West Virginia Dome (fig. 56) (Smosna and Koehler, 1993), the Waverly arch and Paint Creek uplift in eastern Kentucky (fig. 54) (MacQuown and Pear, 1983), and hinge zones along the eastern edge of the carbonate platform (fig. 9), have controlled depositional facies to some extent. In addition, Waulsortian-like reefs in the Fort Payne Formation of Tennessee probably were deposited on topographic highs that resulted from gentle anticlinal trends in the underlying Chattanooga Shale (Milici, 1996c).

Thermal maturation, source rocks and seals: Source rocks for hydrocarbons in the GL AU in southwestern West Virginia are probably the Sunbury Shale, Ohio Shale, and the Rhinestreet Shale Member (Table 2). To the northeast in Pennsylvania, the principal Devonian black shale source rocks are the Marcellus Shale and the Genesee Formation (Vargo and Matchen, 1996; Matchen and Vargo, 1996). Thermal maturation of the underlying source rocks ranges generally from 0.6 to 2.0%Ro (compare fig. 60 with fig. 58). Local seals are the less dense limestones intercalated with the oolitic and biohermal limestone reservoirs within the GL AU. The overlying Pennington, Bluestone, and Mauch Chunk Formations (Tables 2, 4) may serve as regional seals where present.

Reservoirs and field size data: Big Lime fields with oolitic limestone reservoirs occur generally from West Virginia through eastern Kentucky and Virginia to Tennessee. Depths to Big Lime reservoirs generally increase from west to east across the assessment unit, from as little as 760 feet in eastern Kentucky to as much as 5,400 feet in Virginia. Thicknesses of pay zones range from as little as 6 feet in eastern Kentucky to as much as 97 feet in West Virginia and 194 feet in Virginia, where the pays consist of multiple stacked reservoirs of oolitic limestones separated by non-oolitic limestones. Log-derived porosities range from about 3 to 30%, and are commonly in the 10 to 12% range. Permeabilities in West Virginia range from about 5 to 15 md. Final open flow rates have been as great as 12,228 MCF of gas per day in West Virginia, 4,581 Mcfg/d in eastern Kentucky, and 1,082 Mcfg/d in Virginia (Smosna, 1996).

Greenbrier Big Injun fields are generally located in northern West Virginia, where depths to pay zones range from about 1,200 feet to 2,500 feet. Thicknesses of pay zones may be as much as 70 feet, although they are commonly 15 to 30 feet thick. Porosities average 13% and permeabilities are about 1 md (Smosna, 1996).

Depths to the basal Newman porous dolomite beds in eastern Kentucky range from about 900 to 3,800 feet. Pay zones commonly range from 10 to 25 feet thick. Porosities range from 4 to 26%, and permeabilities average about 19.4 md. Final open flow rates range from 36 to 4,581 Mcfg/d (Smosna, 1996 and Gas Atlas database in Roen and Walker, 1996).

Available field size data (original reserves), entirely from Kentucky, are shown in Table 16 and figure 62. The earliest discovery was in 1904. Since then, there have been 127 more fields discovered in Kentucky in the assessment unit, with nine fields greater in size than 20 Bcf discovered intermittently throughout exploration history. The largest field discovered in the Greenbrier Limestone AU in Kentucky is the Bull Creek Consolidated DBS (figs. 60), which was discovered in 1958 and has a reported original gas reserve of 77.3 Bcf. The field size distribution with time suggests that there may be room for several more discoveries of fields greater than 20 Bcf.

For the Fort Payne Formation in Tennessee, drilling depths to pays in some 44 fields range from a little less than 1000 to almost 2000 feet, average pay thickness ranges from 10 to 36 feet, and average field porosities from logs range from about 4 to 22%. Of these fields, 6 produce associated gas and 38 produce non-associated gas. Production from 11 Fort Payne fields is commingled with production from the Greenbrier Limestone (Milici, 1996c; database in Roen and Walker, 1996). Oil production from selected fields as of 1980 was reported by MacQuown and Perkins (1982), and gas production for selected fields as of 1991 was reported by Milici (1996c). Several fields have produced more than a 1 MMb of oil and others have produced more than 2 Bcf of gas.

Greenbrier Limestone AU Fields and Pools:- There are 689 fields within the GL AU that are listed in the database that accompanies Roen and Walker (1996). Of these, 60 produce from the Fort Payne Formation and 629 from the Greenbrier Limestone. Of the Greenbrier fields, 285 produce gas associated with oil, and 339 fields produce non-associated gas. The three largest Greenbrier fields are Glenville South, Glenville North, and Minnora. These fields are located in northern West Virginia (fig. 60) and produce from reservoirs that were deposited in shallow marine environments, probably from the Greenbrier Big Injun sandstones (Roen and Walker, 1996; database; Smosna, 1996).

Assessment results: For the 2002 assessment of undiscovered, technically recoverable petroleum resources of the Appalachian basin, the USGS estimated a mean value of 2.45 MMB of oil, 128.49 BCF of gas, and a mean value of 1.40 MMB of natural gas liquids in the Greenbrier Limestone AU (Milici and others, 2003).

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