Adding Value to the Atlas of Major Appalachian Gas Plays

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Abstract

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Natural gas is produced from more than 100 stratigraphic levels in more than 1000 named fields in a broad trend that extends from New York to Tennessee and includes large portions of Pennsylvania, Ohio, West Virginia, and eastern Kentucky. In the new Atlas of Major Appalachian Gas Plays these gas-bearing reservoirs have been organized into 30 major plays that have both historic significance and future potential. A "play" as used in the atlas is a group of geologically similar drilling prospects having similar source, reservoir and trap controls of gas migration, accumulation, and storage. Thus, they share some common elements of risk with regard to the possible occurrence of gas within them. The 30 Appalachian gas plays have been designated by their reservoir lithology and by reference to trap type or the geologic conditions that control production within the play. Eighteen of the 30 plays are designated by the depositional environment that produced the reservoir lithology; the other 12 are designated by the geologic factors that control production in the play.

Products of this five-year, DOE-funded and GRI-supported research effort include the atlas, an electronic data base containing information on more than 5100 gas reservoirs, a second electronic data base with more than 10,000 searchable references to the geologic and engineering literature, and a third data base with reservoir data compiled for more than 300 oil reservoirs.

The atlas consists of 200 pages (22 by 17 inches), that include 30 play descriptions, four introductory sections, more than 600 illustrations, references to nearly 1000 published works, and data tables for each play that collectively include up to 46 geologic and engineering parameters for 426 gas pools. The companion data base includes up to 70 parameters for 5100 reservoirs in seven states, ranging in age from Pennsylvanian to Cambrian. One of the parameters in the data base is a field centroid, which allows mapping of numerous field averages to establish regional trends within a play.

Production from the 30 plays has been estimated by play authors to exceed 43 trillion cubic feet of gas (tcf), with an estimated 95 to 158 tcf remaining as proved reserves, probable resources and undiscovered possible resources. The largest plays, in terms of estimated cumulative production, are the Upper Devonian Bradford and Venango sandstone plays, the Lower Silurian Cataract/Medina sandstone play, and the Lower Mississippian Big Injun sandstone play. More than 60% of all production has been from Devonian plays, most of which are sandstone plays. In all 30 plays, more than 80% of the cumulative production is from plays with sandstone reservoirs. Within the 18 plays defined by environment of deposition, nearly 40% of the production has come from shallow shelf sandstones, with another 45% from fluvial deltaic and near shore sandstone plays. The 12 plays controlled by geologic factors other than environment of deposition of reservoir rock have contributed less than 20% of cumulative production, mostly from fractured Devonian shale reservoirs.

Most of the remaining gas, both discovered and undiscovered, is within black Upper Devonian shales which produce from fractured reservoirs. Estimates of this resource range from 26 to 89.5 tcf, compared to the range for all 30 plays in the basin of 95 to 158.5 tcf. Six additional plays are

estimated to contain more than 5 tcf in reserves and resources, of which five produce from sandstone reservoirs. The sixth play produces from Devonian fractured siltstone and shales adjacent to the fractured black shale play.

The consensus of the play authors is that the nation's oldest producing basin still has more gas to produce than has been produced, although many of the more productive plays have reached the half way point in their estimated ultimate recovery. Prolific plays in which the resource/production ratio is less than one include the Upper Devonian Venango, Bradford, and Elk sandstone plays, and the Mississippian Greenbrier/Newman limestone play. Fortunately, however, 19 of the 30 plays have resource/production ratios greater than one. Among established plays, the Devonian fractured shale and siltstone plays, Pennsylvanian and Mississippian sandstone plays, and the various Oriskany Sandstone plays have the most future potential. Of the currently smaller plays, the Knox unconformity play, Tuscarora Sandstone fractured anticlinal play, and pre-Knox Group play are estimated to contain from 0.5 to 2.4 tcf of remaining producible gas.

Including a centroid for each of the 5100 reservoirs in the data base allows one to make interesting and potentially useful trend maps of each play, or of similar plays, such as all fluvial deltaic sandstone plays. The centroid location becomes a control point for all averaged reservoir data, similar to a well control for mapping within a field. Using the control points and data base, regional trend maps of pay thickness, average initial potential, reservoir depth, reservoir pressure, pressure gradient, and recovery factor, among others can be made. Such maps can be used to determine what area of a play one should go into, as well as which plays to get involved in. Finally, the centroid location and the fact that most of the atlas was computer drafted, will allow for a more rapid conversion of the atlas figures to be imported into a Geographic Information System (GIS).

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Introduction

The text and figures that follow are organized into two parts. Part one will describe the atlas and companion database, and part two will describe how the atlas and database can be used to develop a basin-wide summary of past production and future resources. It should be noted that part two contains summaries of undiscovered resources as estimated by the authors for the 30 gas plays described in the Atlas of Major Appalachian Gas Plays. In many cases, the authors offered more than one estimate. In making the graphs, charts and tables that are included in this paper, we selected one of the options offered, and used it for each of the plays. The one exception is the wide range of resources suggested for the Devonian black shale play. Anyone using the atlas may choose a different resource number for any number of plays. Therefore, resource numbers used in this report should not be quoted and incorporated into future papers without reading the individual play descriptions first, and evaluating the numbers chosen by us.

It also must be noted that much of what was presented in DOE's Natural Gas Conference was designed to make users of the atlas think about what they could do with the atlas, to go beyond what was written to more fully evaluate the potential of the basin and various plays in the basin. Much of what is presented may have little or no significance to individual readers. The purpose of the workshop, and of this description of what was presented, is to encourage atlas users to think and to add their own value to the atlas.

Producing the Atlas and Database

In a 1996 report titled "Technology and Related Needs of US Oil and Natural Gas Producers" the Petroleum Technology Transfer Council concluded that independent oil and gas operators had inadequate access to geologic and production data, and inadequate well and reservoir level geologic and production data, case studies and analogs. The report cited the Appalachian basin as the prime example of this deficiency. In the Appalachian basin, where oil and gas have been produced for more

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than 125 years, there has been no attempt by either the public or private sector to compile regional data on all of the major gas plays, or on each of the gas reservoirs in the plays. Only recently has the U.S. Geological Survey made an attempt to separate gas reservoirs into plays, and to collect geologic and engineering data on reservoirs in the Medina ("Clinton") sandstone play and the Oriskany Sandstone play. These were the first attempts to use the play concept in an analysis of the Appalachian basin, and to estimate proven reserves and undiscovered resources within plays.

The Appalachian Oil and Natural Gas Research Consortium, a partnership among the state geological surveys in West Virginia, Pennsylvania, Kentucky and Ohio and the departments of Geology and Geography and Petroleum and Natural Gas Engineering at West Virginia University, submitted an unsolicited proposal to the Department of Energy's Morgantown Energy Technology Center, or METC (now the Federal Energy Technology Center, or FETC) to apply the play concept to the gas-producing areas of the Appalachian basin, and produce an atlas of the major gas plays and a companion database of geologic and reservoir data for all reservoirs assigned to each play. Five years later the consortium had produced an atlas of 30 major gas plays, an electronic database containing information on more than 5100 gas reservoirs, a digital database containing more than 10,000 references to the geologic and engineering literature, and enhanced well-specific databases in four Appalachian basin states.

Description of the Atlas of Major Appalachian Gas Plays. The atlas consists of 200 pages, each 17 x 22 inches, containing nearly 600 maps, cross sections and other figures that illustrate 30 play descriptions, stratigraphic and structural overviews of the basin, and a description of the reservoir-level database. A bibliography with nearly 1000 cited references is included in the back of the atlas. Each play description contains a data table for key fields in the play. The tables contain 46 rows for specific geologic and engineering parameters, and a column of each of the main reservoirs in a key gas field. The 30 play descriptions combined contain 426 columns of reservoir data.

The companion database contains data on 70 parameters for more than 5100 reservoirs. These parameters are separated into basic field information (field name, play, discovery date, formation, number of wells, etc), reservoir parameters (pay thickness, porosity, temperature, pressure, etc), fluid properties (gas gravity, gas and water saturations, etc), and volumetric data (original gas in place, estimated cumulative production, known or reported production, remaining reserves, etc). A key data element is a centroid location for each of the reservoirs in the database. This allows database users to map any parameter on a regional scale to determine basin-wide trends.

Play Description Format. As a guide to authors, and to establish uniformity among play descriptions, we decided to create a rigid format for all play descriptions. Each consists of the same eight main headings, in this order: Location, Production History, Stratigraphy, Structure, Reservoir, Description of Key Fields, Resources and Reserves, and Future Trends. Also, eight key illustrations were required for each play: the size and extent of each play; a key field location map; a stratigraphic column; a correlation chart; a regional map, either stratigraphic or structural; a regional cross section, either stratigraphic or structural; a type log; and a pay or porosity map. Authors could include as many additional illustrations as desired.

Defining Gas Plays. At the beginning of the project a research team from six states met to organize all producing intervals into plays, using the definition of White (1980, 1988) that a play is a group of geologically similar drilling prospects having basically the same source, reservoir and trap controls of gas accumulation, migration and storage. Thus, they share some common elements of risk with respect to the possible occurrence of natural gas. Plays are commonly designated by their reservoir lithology (e.g., Oriskany Sandstone Play), although play names can be modified by reference to trap type (the Oriskany Structural Play) or some other geologic similarity (the Knox Unconformity Play). Our approach was to define stratigraphically and geographically restricted geologic plays based largely on age, lithology and deposition of reservoir rocks under similar environments of deposition that have undergone similar structural and diagenetic histories. The end result should be a set of reservoirs with common geologic and engineering characteristics. This approach was applied to the more than 100 stratigraphic intervals from which gas is produced in more than 1000 named fields in eight Appalachian basin states.

In the Appalachian basin, production in 18 of the 30 gas plays is thought to be controlled by the environment of deposition of the reservoir rock in one of seven types of depositional systems: fluvial deltaic sandstone (six plays), nearshore sandstone (one play), shallow shelf sandstone (three plays), turbidites or slope sandstones (one play), transgressive sandstones (two plays), shallow shelf carbonates (two plays), and reefs and carbonate mounds or bars (three plays). Production in the remaining 12 plays is associated with or controlled by unconformities (three plays), anticlines and combination traps (three plays) and fractured reservoirs (six plays) (Table 1).

The Appalachian basin is a broad, elliptical basin that is broader on the north than on the south. The youngest Paleozoic sediments, ranging from Mississippian to Permian, are in the center of the basin, flanked by older Devonian and Silurian rocks, and eventually Cambrian and Ordovician rocks on the basin margin. Structural complexity increases from west to east from the relatively flat plateau rocks through the high amplitude folds immediately west of the Allegheny Front, to the highly deformed "Eastern Overthrust Belt" east of the front. Fractured anticlinal and structural plays are confined to areas of Pennsylvania and West Virginia east of the front, whereas the fractured Huntersville and Oriskany play is in the foreland area west of the front, and the fractured black shale play is farther west. Stratigraphically-controlled plays in younger rocks are confined to the center of the basin, whereas plays in older rocks are restricted to the western side of the basin in Ohio and Kentucky where these rocks are at relatively shallow depths as compared to the basin center.

Fluvial-deltaic Sandstone Plays. Six fluvial-deltaic sandstone plays have been defined and described in the atlas. These include the Pennsylvanian Allegheny and Pottsville sandstones and associated coal plays, the Mississippian Mauch Chunk, Big Injun and Weir sandstone plays, and the Mississippian-Devonian Berea Sandstone play (Figure 1a-c). With the exception of the Berea Sandstone play, these plays are confined to the center of the basin.

The uppermost play, the Middle Pennsylvanian Allegheny Sandstone play, is confined to the tri-states area of Ohio, Pennsylvania and West Virginia, and produces from thin sandstones called Burning Springs, Gas and Horseneck by drillers. Coal beds associated with these sandstones include the Upper and Lower Freeport, Upper and Lower Kittanning, and the Clarion/Brookville at the base. The underlying Lower Pennsylvanian Pottsville, New River and Lee Sandstone play is more extensive, with significant production to the southwest in Kentucky. Production is from sandstones often saturated with salt water in commercial quantities, giving rise to the name Salt sands. Associated coals include the Sewell, Beckley and Pocahontas nos. 3 and 4.

The Upper Mississippian Mauch Chunk Sandstone play produces in a geographic area similar in size to the Pottsville-Lee Sandstone play. Production is from numerous lenticular fluvial-deltaic sandstones, of which the Maxon and Ravencliff are the most important. The more important Lower Mississippian Big Injun Sandstone play has been a prolific play in West Virginia, where more than 8,000 wells are estimated to have produced nearly four trillion cubic feet of gas from subtle structural and stratigraphic traps within the area of preserved sandstone. The underlying Weir Sandstone play includes extensive fluvial-deltaic sandstones in West Virginia, and more offshore, deeper-water sandstones in Kentucky. The Berea Sandstone play at the base of the Mississippian-top of Devonian is the most extensive of the six fluvial-deltaic plays, reflecting more extensive preservation of rock in the basin with depth and age. Important production has been established in Ohio, Pennsylvania, Kentucky and West Virginia.

Nearshore and Shelf Sandstone Plays. Nearshore and shelf sandstone plays include the Upper Devonian Venango and Bradford Sandstone plays, the Upper Silurian Newburg sandstone play, and the Lower Silurian Medina-Cataract ("Clinton") sandstone play.

Gas is produced in the large Venango play from stacked, marginal marine sandstones with excellent reservoir quality in Pennsylvania and West Virginia. Reservoir sandstones are both shoreline parallel and shoreline perpendicular, and number more than a dozen from the Gantz sandstone at the top to the First Warren at or near the base of the play section. Other important reservoirs are developed in the Gordon, Venango, Fourth, Fifth and Bayard sandstones. Current development has moved to the northwest to an area with coastal plain and shelf sandstones with lower permeability.

The Bradford Sandstone play is the uppermost of the three shelf sandstone plays. Production is from multiple shelf to nearshore sandstones that were deposited parallel to the paleoshoreline. Key producing sandstones include the Warren, Speechley, Balltown and Bradford. Current exploration is in areas of previously bypassed shelf and basinal siltstones in northern West Virginia. The Bradford play is the middle of three Upper Devonian sandstone plays in a progradational wedge that migrated farther west with time. Sandstones in this play correspond in time to the Huron-Dunkirk black shale facies farther to the west.

The Upper Silurian Newburg sandstone play is a small, but prolific play from which nearly 300 bcf of gas were produced from approximately 300 wells during the late 1960s and early 1970s. Production was from the western, updip edge of the sandstone body in combination stratigraphic-structural traps. The older Medina-Cataract play, better known as the Clinton sandstone play in Ohio, is the largest play in the basin. The play developed in three stages, with each moving progressively eastward and deeper with advances in technology, notably rotary drilling, hydraulic fracturing and better logging tools. More than 76,000 gas wells have been completed, and 6 tcf of gas have been produced from the Grimsby (red facies) and Whirlpool (white facies) in stratigraphic traps created by variations in porosity and permeability.

Turbidites and Transgressive Sandstone Plays. Gas production from sandstones interpreted to be turbidites or slope sandstones are confined to the Upper Devonian Elk Sandstone play, the lowest of the three progradational sandstone packages in Pennsylvania and West Virginia. Production occurs in ten to 12 fine-grained sandstones or siltstones, of which the Benson sandstone is the most important. Recent development has been in the deeper Elk sandstones 500 to 1500 feet below the Benson.

The Middle Ordovician St. Peter Sandstone and various pre-Knox Group sandstones from which gas has been produced in small areas of Kentucky have been interpreted to be transgressive sandstone bodies. Traps in the St. Peter are structural in nature, and are associated with the Kentucky River and Irvine-Paint Creek fault zones. There is potential for this play to extend into West Virginia above the Rome Trough. Gas production from pre-Knox sandstones and carbonates is confined to fewer than 100 wells in eastern Kentucky and one well in West Virginia (Figure 1f).

Shallow Shelf Carbonate Plays. The nearly 10,000 wells in the Mississippian Greenbrier-Newman Limestone play have produced 2.9 tcf of gas from dolomitized sandstones, sandy dolostones and oolitic limestones of the drillers' Greenbrier Big Injun, Keener and Big Lime reservoirs Figure 1b). The dolomitic sandstones are interpreted as submarine dunes deposited in a nearshore sandstone environment. The upper oolitic zones formed as tidal bars perpendicular to a structural hinge line, and repeat geographically in a predictable spacing pattern. Lower oolitic zones are associated with a regional unconformity below the Greenbrier.

Gas is produced from the Ordovician Trenton Limestone in both stratigraphic and structural traps in Kentucky and New York (Figure 1f) where drilling depths to the Trenton are relatively shallow. Production is from bioclastic carbonate bars and secondary porosity in linear zones of secondary dolomitization.

Reef and Carbonate Bar Plays. Gas wells have been completed in the Lower Mississippian Ft. Payne Formation in seven counties in Tennessee and four counties in adjacent Kentucky (Figure 1b). Production is associated with oil in most areas, with reservoirs developed in bryozoan-rich, Waulsortian-type carbonate mounds. In contrast, gas production in the Middle Devonian Onondaga Limestone reef play is from Edgecliff Member pinnacle reefs up to 200 feet high that cover up to 100 acres. Six fields have been discovered in New York, and one in Pennsylvania (Figure 1e). These reefs are hard to map and find where the Onondaga is more than 100 feet thick.

Gas is produced from the Upper Silurian Lockport Dolomite and underlying Keefer Sandstone in numerous small fields in eastern Kentucky (the Big Six sandstone), and from the Lockport in northern Ohio (Figure 1e). Production is from porous patch reef bioherms or skeletal sand shoals in 60 fields. Combination stratigraphic-structural traps formed draped over closure or along pinchouts on structural flanks.

Plays Due to Unconformities and Structure. The Lower Devonian Oriskany Sandstone updip permeability pinchout play is confined to the western and northern margins of the basin (Figure 1e) where permeability is lost as the Oriskany thins updip toward its zero edge. The play is flanked downdip by the Oriskany combination traps play. The Lower Devonian-Upper Silurian unconformity play produces from porous carbonate and sandy carbonate reservoirs, collectively called "Corniferous limestone," below a regional unconformity in eastern Kentucky (Figure 1e). Good potential exists to extend the play northward into Ohio where organic-rich black shales occur above the unconformity. The Cambro-Ordovician Knox Group unconformity play is more extensive, with gas production occurring in a broad trend along the western and northern margin of the basin from Tennessee to New York (Figure 1f). Paleotopographic reservoirs dominate the play in Ohio, whereas fractured reservoirs are more important in Kentucky and Tennessee. Reservoirs are developed in the Beekmantown Dolomite and Rose Run sandstone; therefore, in parts of Ohio portions of the play are referred to as the Rose Run play.

The Lower Devonian Oriskany Sandstone structural play is the easternmost of the three Oriskany plays, with production confined to a narrow trend that broadens northward along the eastern side of the basin from West Virginia through Pennsylvania to New York. Most of the gas fields are located on anticlines within 50 miles west of the Allegheny structural front, or on large, regional anticlines east of the front in the Valley and Ridge provence. The Lower Silurian Tuscarora Sandstone fractured anticlinal play is smaller, yet occurs in a broader area across Pennsylvania and West Virginia where the brittle, quartz-cemented sandstone is fractured on structural highs, including those in the western, low-amplitude fold provence. Gas produced in this play commonly contains a high percent of inert gas, either nitrogen or carbon dioxide.

Fractured Reservoir Plays. Fractured reservoir plays occur in a broad geographic area, collectively throughout the basin, and in a broad stratigraphic range from upper Devonian black and gray shales to Cambrian carbonates. Six fractured reservoir plays have been defined and described in the atlas.

The Upper Devonian black shales play is the most important of the six plays, with approximately 3 tcf of cumulative production from roughly 10,000 gas wells in Kentucky , West Virginia and Ohio. Black shales ranging in age from Middle Devonian to Early Mississippian have potential, but the majority of gas produced from this play has come from the Upper Devonian Huron Shale Member of the Ohio Shale (Figure 1d) or its eastern Dunkirk Shale equivalent. The play is flanked to the east by the Upper Devonian fractured black and gray shales and siltstone play. This play is intermediate, both stratigraphically and geographically, between the black shale play and the Bradford sandstones and siltstones play. Gas productivity generally decreases within the play to the east and north as the percentage of black shale interbeds decreases, with the exception of the fields associated with the Burning Spring anticline, where there is a higher incidence of fracturing, and in the southeastern edge of the play, where production is commingled with shallower sandstone reservoirs.

Gas production from fractured Middle Devonian Huntersville Chert reservoirs is often associated with production from the underlying Lower Devonian Oriskany Sandstone in a broad trend within the high amplitude fold provence from southeastern West Virginia to central Pennsylvania (Figure 1e). In contrast, gas production in the Upper Silurian Bass Islands play is confined to a narrow, 84-mile long trend in southwestern New York that marks the western extent of Appalachian-type thrust faulting and folding. Fractured reservoirs in the trend occur in stratigraphic units ranging in age from Late Silurian to early Middle Devonian.

The Upper Ordovician Bald Eagle Formation fractured anticlinal play is the smallest play described in the atlas, but one that may have big potential for the future. Currently, production is confined to the Grugan field in Pennsylvania (Figure 1f). The Middle Ordovician fractured carbonates play is geographically quite extensive, with production along the western edge of the basin in Tennessee, Kentucky, Ohio and Ontario, Canada. An easternward projection of the play in eastern Kentucky is associated with fractured carbonate reservoirs above the Rome trough. Reservoirs within this play are developed in the Trenton, Black River and Wells Creek carbonate formations (Figure 1f).

Manipulating Gas Production and Resource Values in the Atlas

This portion of the text emphasizes the types of summaries that one can make from the 30 play descriptions by looking at the atlas as a whole, as a sum of its parts, resulting in compilations not found in the atlas.

Play Production Summary. Cumulative gas production from all 30 gas plays has been estimated by the play authors to exceed 43 tcf. The ten most productive plays (Figure 2) have produced 90 percent of the estimated production, led by the Upper Devonian Bradford (17.9%) and Venango (17.4%) nearshore and shelf sandstone plays, and the Lower Silurian Cataract/Medina Sandstone play (13.9%). More than 60 percent of the estimated cumulative production has come from Devonian plays (Figure 3) followed by production from Mississippian plays (20.7%) and Silurian plays (15.2%).

Sandstones reservoirs have produced more than 80 percent of the gas production (Figure 4) attributed to the 30 major plays. Production from finer clastics - shales and siltstones - essentially equals production from all plays with carbonate reservoirs, (7 and 8%, respectively). This domination by sandstone reservoirs also is reflected in a comparison of production versus environment of deposition of reservoir rock (Figure 5). Shallow shelf sandstone plays have produced 32.5 percent of the estimated cumulative production, followed by fluvial-deltaic sandstone plays (20%), and nearshore sandstone plays (17.4%). Plays in which environments of deposition are the most important factor in controlling production have produced 84 percent of the estimated cumulative gas.

Plays in which other geologic controls are the dominating factor in controlling production account for 16% of the estimated basin production. Of these, fractured reservoirs are the most important, having yielded an estimated 10 percent of all production (Figure 6). Fractured shales have yielded most of the gas in fractured reservoir plays (Figure 7) (7% of all production; 68% of all production from fractured plays).

Appalachian basin cumulative gas production also can be subdivided by age and environment of deposition of reservoir rock (Figure 8). Mississippian-aged fluvial-deltaic sandstone plays, Devonian nearshore and shallow shelf sandstone plays, and Silurian shallow shelf sandstone plays dominate this classification. A similar display comparing production by age versus other geologic controls (Figure 9) illustrates the dominating influence of fractured Devonian plays. Lumping all plays controlled by environments and all plays with geologic controls into two groups subdivided by age (Figure 10) illustrates the importance of environmental control, particularly in Devonian age rocks.

Reserve and Resource Summary. Play authors provided their best estimate of remaining gas reserves and undiscovered probable and possible resources. In many cases, authors provided more than one estimate. Thus, different readers of the atlas could tabulate several different estimates of remaining reserves and resources. For this reason, the numbers that follow in this section should be used for comparative purposes only, and not be repeated as the only estimate of remaining reserves and resources for different plays, ages, and rocks produced in various environments of deposition.

A conservative estimate of remaining gas resources, using estimates by play authors, ranges from 95 to 158.5 tcf, where the total variation in the range is attributed to the range in resources for fractured Devonian black shales of 26 to 89.5 tcf. The low end of the range, 95 tcf, is more than twice the estimated cumulative production (43 tcf); the upper end, 158.5 tcf, is nearly four times the estimated cumulative production. Acceptance of either figure acknowledges that the mature Appalachian basin still should have more gas remaining to be produced than has been produced throughout the long productive history of the basin.

Approximately one half to three quarters of the remaining gas in the basin will be found in Devonian-aged rocks (Figure 11). Using the lower end for the range in estimated remaining resources, 95 tcf, 74 percent will be in Devonian rocks, with another 10.5 percent in Pennsylvanian rocks and 7.2% in Mississippian rocks. As expected, nearly 70 percent of remaining gas is expected to be found in shales (Figure 12), with less than 30 percent in sandstones, the reservoir lithology that has produced more than 60 percent of the gas to date.

Sandstone plays, particularly fluvial-deltaic and shallow shelf sandstones, are significant when resources are grouped by environment of deposition of reservoir rock (Figure 13) as was done with estimated gas production. Estimated resources in fluvial-deltaic sandstones represent approximately 20 percent of the total; resources in shallow shelf sandstones another 10 percent. Approximately half of the gas to be found in fluvial-deltaic plays will be in Pennsylvanian rocks (Figure 14), another reflection of the rather surprising estimate that 10 percent of all undiscovered resources will be in Pennsylvanian-aged rocks.

Fractured reservoirs will contain from 35 to 60 percent of remaining gas, depending on which end of the estimated resource range one chooses. More than half of the remaining resources will be in fractured black shale plays, with only five percent in all other fractured lithologies. When comparing remaining resources by various types of geologic controls of plays, fractured reservoirs dominate plays in this category (Figure 15).

Pennsylvanian and Mississippian fluvial-deltaic sandstone plays, Silurian and Devonian shallow shelf sandstone plays, and Devonian fluvial-deltaic sandstone plays are projected to be the only important plays controlled by environment of deposition, with a significant amount also to be found in Devonian nearshore sandstones (Figure 16). However, when comparing plays controlled by geology other than environment of deposition (Figure 17), or when comparing plays controlled by environment of deposition of reservoir rock versus those with other geologic controls (Figure 18), the total dominance of Devonian fractured plays is overwhelming.

Examining What is Left Versus What Was. Of the 30 major gas plays described in the atlas, seven are expected t contain more than five tcf of undiscovered reserves, with another seven holding more than one tcf but less than 5 tcf. These 14 plays combined contain 98 percent of the estimated resource. The top seven plays in terms of resources (Figure 19) are all established plays, most of which have had substantial cumulative production. The second group of seven plays (Figure 20) also are well established, with the exception of the Knox unconformity play and the Tuscarora structural play. The Knox unconformity play in particular is expected to add resources with continued drilling because few wells have been drilled in this play relative to the other plays in this resource category.

When estimates of remaining resources are compared to estimates of cumulative production, some interesting observations can be made. Nineteen of the 30 plays have a resource to production, or R/P, ratio greater of one. These 19 plays can, in turn, be divided into three groups, determined by those with an R/P ratio greater than 3, with a second factor being the size of the play. Twelve plays have an R/P ratio greater than 3. Six of these plays have had relatively minor gas production, all less than 200 bcf (Figure 21), whereas the other six plays have been relatively higher production, from 500 bcf to 3,000 bcf (Figure 22).

Four of the six smaller plays are in stratigraphically older rocks from which production has been established on the western side of the basin where drilling depths to these reservoirs is considerably shallower than in the basin center. The Lower Silurian Tuscarora Sandstone play, although also in older rocks, is currently located in the eastern fold belt and the adjacent high-amplitude fold provence. Of these plays, only the Allegheny fluvial-deltaic sandstones, Knox unconformity and Tuscarora Sandstone fractured anticlinal plays are expected to produce more than one tcf of gas.

The seven plays that have had significantly higher production also are expected to have significant remaining resources, with estimates ranging from 2,150 to 89,500 bcf. In general, these plays are in stratigraphically younger rocks, Pennsylvanian to Devonian in age, located more in the center of the basin, with a high variation in drilling depths.

The seven remaining plays with an R/P ratio greater than 1.0 (Figure 23) have a wide range in location, drilling depth, and age of reservoir rock. Included are three Mississippian fluvial-deltaic sandstone plays, all located in the center of the basin with drilling depths less than 4000 feet, and plays with Lower Devonian to Upper Ordovician targets located on both the western (shallow depths) and eastern (deeper depths) sides of the basin. These seven plays also exhibit a wide variation in estimated cumulative production and estimated future potential. Four of the seven have produced less than 350 bcf, whereas the other three have produced between 1.8 and 6.0 tcf. The same four are expected to produce less than 400 additional bcf, whereas the remaining three all have large resources, estimated to range from 3.1 to 8.2 tcf.

In contrast, the 11 remaining plays all have resource estimates that are less than their estimated cumulative production to date. Five of these have been large plays, in terms of production, that have passed their peak, whereas the other six are small plays that are not expected to become large plays.

The larger, historically more important plays include the three Upper Devonian sandstone plays, the Bradford, Venango and Elk, and the Oriskany combination traps play and Greenbrier-Newman shallow shelf carbonate play (Figure 24). Although each has produced more than one tcf, only the Venango and Bradford are expected to produce more than one additional tcf. However, drilling to the other three is not expected to terminate in the near future. For example, it has taken approximately 10,000 wells to produce the 2.8 tcf from the Greenbrier Limestone play, so it will take many years at current drilling rates in this play to drill enough wells to find and produce the estimated 800 bcf in remaining resources.

Of the remaining six historically smaller plays, none is expected to have significant future production, according to the play authors (Figure 25). These estimates beg the question, If these are really resource estimates, why would anyone look for new gas in these plays? The answer may be that several of the play authors were too conservative to estimate undiscovered resources for small plays that have unknown geographic boundaries. This is especially true for the Onondaga reef, Ft. Payne carbonate mound and Bass Island plays. Estimates given by play authors are probably proved reserves, not undiscovered resources.

Where Will Explorationists Look? Each play description included figure 1, a map of the basin on which all known producing wells in the play were plotted, and on which a boundary of the expected limits of the play was drawn. These maps can be used to visually estimate which plays have been important in the various Appalachian basin states, and which plays should be important in each of the states in the future. As an exercise prior to making this workshop presentation, visual estimates were made of the percent of wells in each play in each state, and the amount of future play area in each state. These percentages were then applied to estimates of cumulative production and estimated undiscovered resources to rank the future potential of different states in the basin.

As an initial check, estimates of production within each state were compared to estimates published by the Independent Petroleum Association of America (IPAA) in their annual yearbook. Estimates made from drilling density from the figure 1's in the atlas were within 10 percent of estimates published by IPAA. With this in mind, we proceeded with the exercise. The estimates rank West Virginia, Pennsylvania, Ohio, Kentucky and New York, in that order, in terms of production.

The seven most productive plays include the three Upper Devonian sandstone plays developed in the progradational sandstone packages, and the Mississippian and Devonian fluvial-deltaic sandstone plays, as well as the Greenbrier Limestone play, Cataract/Medina play, and Oriskany combination traps play. Six of the seven are important in West Virginia, although several extend into Pennsylvania and Kentucky. Ohio has had the benefit of most of the Clinton play.
In general, the distribution of these largest plays reflects the overall distribution of production among the various states.

Estimates of resources in each state also were made from a visual comparison of potential areas in the figure 1's. These estimates were compared to proven reserve figures published by IPAA to determine if we were in the ballpark before proceeding. There appeared to be little problem with New York, West Virginia and Ohio, but our estimates appear low in Pennsylvania, and high in Kentucky. The optimism of authors in Kentucky, and the pessimism in Pennsylvania, may both be related to the future of the fractured black shale play. Kentucky has it, Pennsylvania does not. And, because this single play dominates the resource picture and skews all of the data, Kentucky looks good in the future, relative to what it has produced, whereas Pennsylvania does not look as good.

Playing With the Gas Atlas Database. Because each of the 5100 gas reservoirs in the gas atlas database contains a centroid location, mapping of most of the data elements in the database on a regional scale is possible. These maps could be quite simple, merely maps of centroid locations of all fields in a play, or all fields in all plays, or contoured maps could be produced of pay thickness, average field initial open flows, or estimates of cumulative production for all fields in a play to show variation across the productive trend. It should be noted however, that many of the 70 data elements for each reservoir in the database are missing for many reservoirs in many plays. Therefore, some desired regional map cannot be produced with the data at hand.

Examples of maps produced for the Houston workshop included a series of maps with average pay depths sorted into 1000 foot increments, a time-depth analysis of drilling in two plays, maps of reservoirs of various lithologies, and maps of reservoirs sorted by environment of deposition of reservoir rock. Other maps that could be produced include all fractured reservoirs, separated by lithology if desired; maps of reservoirs with different traps specified; or maps of commingled production from stacked reservoirs and pays. In this last category, maps could be produced showing fields with multiple reservoir potential in a given play, or fields that produce from multiple plays. Depth and lithology screens can be applied as well.

Digitizing the Atlas. The suggestion has been made that eventually we should completely digitize the atlas and make it available on a compact disc (CD rom) or on the Internet. Although we do not plan to do so in the near future, this could be accomplished with less effort then the recent project to hand digitize one of the atlases produced by GRI and the Texas Bureau of Economic Geology. All of our text is in WordPerfect, and most of our 600 illustrations were computer drafted using AutoCAD and smoothed using AutoScript. Software exists to transfer these digital files into a Geographic Information System (GIS) environment. Furthermore, many of our maps have latitude-longitude designations, or county or state lines, and most maps have a digital UTM designations built into the AutoCAD drafting files. Therefore, our drawings are in digital format, and have a digital geographic component that can be migrated into a GIS with more speed and efficiency than hand digitizing would require.

Summary

This five year project had two original goals: to produce and publish an atlas of gas plays in the Appalachian basin that included all known production, and to produce a digital database of all known reservoirs in each play. Additional products that were developed include a database with 10,000 geologic and engineering references, and enhanced well-specific databases in each of the four state geologic surveys that contributed to the atlas.

The atlas can be used as a valuable reference tool, reading one play at a time to become more familiar with a play and characteristics of reservoirs within the play, or it can be used as a whole to develop basin wide summaries of historical production and future potential sorted by plays, reservoir lithology, environment of deposition of reservoir rock, or by geologic controls on play production. Play authors have estimated that more than 43 tcf of gas have been produced from thee 30 plays, and 95 to 168.5 tcf remain as undiscovered resources.

The purpose of the workshop in Houston and of this report was to summarize the atlas and the effort required to produce the atlas and data base, and to stimulate thought by users of the atlas in how to add value to the atlas and database during their own quest for basin wide data that will help them make future decisions in the nation's oldest gas producing basin.

Acknowledgments

The authors would like to acknowledge the patience and support of Harold Shoemaker, our Contracting Officer's Representative from FETC, during the five year period required to produce this product. We also acknowledge the efforts of the individual play authors, and the four geological surveys who served as subcontractors for this project. Finally, we would like to thank Dan Barker and Kathy Newcome for producing slides used in the workshop presentation of the Atlas of Major Appalachian Gas Plays.

References

Petroleum Technology Transfer Council, 1996, Technology and related needs of U.S. oil and natural gas producers. 88 p.

White, D.A. 1980. Assessing oil and gas plays in facies-cycle wedges. American Association of Petroleum Geologists Bulletin, v. 64, p. 1158-1178.

White, D. A. 1988. Oil and gas play maps in exploration and assessment. American Association of Petroleum Geologists Bulletin, v. 72, p. 944-949.

Table 1. Play Classifications and Codes

Fluvial-Deltaic Sandstone Plays
- Play Paf: Middle Pennsylvanian Allegheny Formation/Group Sandstone Play
- Play Pps: Lower and Middle Pennsylvanian Pottsville, New River and Lee Sandstone Play
- Play Mmc: Upper Mississippian Mauch Chunk Group and Equivalent Strata
- Play Mbi: Lower Mississippian Big Injun Sandstones
- Play Mws: Lower Mississippian Weir Sandstones
- Play MDe: Lower Mississippian-Upper Devonian Berea and Equivalent Sandstones

Nearshore Sandstone Plays
- Play Dvs: Upper Devonian Venango Sandstones and Siltstones

Shallow Shelf Sandstone Plays
- Play Dbs: Upper Devonian Bradford Sandstones and Siltstones
- Play Sns: Upper Silurian Newburg Sandstone Play
- Play Scm: Lower Silurian Cataract/Medina Group ("Clinton") Sandstone Play

Turbidite Sandstones Play
- Play Des: Upper Devonian Elk Sandstones

Transgressive Sandstones Plays
- Play Osp: Middle Ordovician St. Peter Sandstone
- Play Cpk: Cambrian Pre-Knox Group Play

Shallow Marine Shelf Carbonate Plays
- Play Mgn: Upper Mississippian Greenbrier/Newman Limestones
- Play Obc: Middle and Upper Ordovician Bioclastic Carbonate ("Trenton") Play

Reef and Carbonate Bar Plays
- Play Mpf: Lower Mississippian Fort Payne Carbonate Mound Play
- Play Dol: Middle Devonian Onondaga Limestone Reef Play
- Play Sld: Upper Silurian Lockport Dolomite-Keefer (Big Six) Sandstone

Plays Due to Unconformities
- Play Dop: Lower Devonian Oriskany Sandstone Updip Permeability Pinchout
- Play DSu: Lower Devonian-Upper Silurian Unconformity Play
- Play COk: Cambrian-Ordovician Knox Group Unconformity Play

Fractured Anticlines and Combination Traps Plays
- Play Dos: Lower Devonian Oriskany Sandstone Structural Play
- Play Doc: Lower Devonian Oriskany Sandstone Combination Traps Play
- Play Sts: Lower Silurian Tuscarora Sandstone Fractured Anticlinal Play

Fractured Reservoir Plays

- Play UDs: Upper Devonian Black Shales
- Play Dbg: Upper Devonian Fractured Black and Gray Shales and Siltstones
- Play Dho: Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone
- Play Sbi: Upper Silurian Bass Islands Trend
- Play Obe: Upper Ordovician Bald Eagle Formation Fractured Anticlinal Play
- Play MOf: Middle Ordovician Fractured Carbonates

Figures

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
PENNSYLVANIAN	UPPER		**MONONGAHELA GROUP** *Goose Run*	**MONONGAHELA GROUP** *Minshall* *Murphy* *Moundsville*	**MONONGAHELA GROUP**		
			CONEMAUGH GROUP *First Cow Run* *Macksburg 300-Foot*	**CONEMAUGH GROUP** *Cow Run* *Little Dunkard* *Big Dunkard*	**CONEMAUGH GROUP** *Little Dunkard* *Big Dunkard*		
	MIDDLE	**BREATHITT FORMATION OF ALLEGHENY GROUP**	**ALLEGHENY GROUP** *Second Cow Run* *Macksburg 500-Foot* Paf	**ALLEGHENY GROUP** *Burning Springs* *Gas* *Lower Gas* *Horseneck* Paf	**ALLEGHENY GROUP** *Gas* *Upper Gas* *Lower Gas* Paf	**ALLEGHENY GROUP**	
	LOWER	**LEE FORMATION OF POTTSVILLE GROUP** *Salt Sand* *First Salt* *Second Salt* *Horton* *Third Salt* *Williamsburg*	**POTTSVILLE SANDSTONE** *Macksburg 700-Foot* *Salt* *Sharon (Maxton)* Pps	**POTTSVILLE SANDSTONE** *First Salt* *Second Salt* *Third Salt* Pps	**POTTSVILLE SANDSTONE** *First Salt* *Second Salt* *Third Salt* Pps	**POTTSVILLE GROUP**	

Figure 1a. Stratigraphy of the Pennsylvanian System (Alleghenian flysch). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
MISSISSIPPIAN	**UPPER**	**PENNINGTON FORMATION** *Ravencliff* **CARTER CAVES SANDSTONE** *Maxon* *Bradley* *Little Lime* Mmc		**MAUCH CHUNK GROUP** *Princeton* *Ravencliff* *Maxon* *Lower Maxon* *Blue Monday* Mmc	**MAUCH CHUNK FORMATION** *Maxton* Mmc		
		NEWMAN LIMESTONE *Big Lime* *Keener* Mgn	**MAXVILLE LIMESTONE** *Jingle Rock* Mgn	**GREENBRIER LIMESTONE** *Big Lime* *Keener* *Greenbrier Big Injun* Mgn	**GREENBRIER FORMATION AND LOYALHANNA FORMATION** *Keener* Mgn		
	LOWER	**FORT PAYNE FORMATION** Mfp					
		BORDEN FORMATION *Big Injun* *Keener* Mbi	**LOGAN FORMATION** *Keener* **CUYAHOGA FORMATION** *Injun* *Squaw* Mbi	**MACCRADY FORMATION** *Red Injun* **PRICE FORMATION** *Big Injun* *Squaw* Mbi	**BURGOON SANDSTONE** *Big Injun* Mbi		
		BORDEN FORMATION *First Weir* *Second Weir* Mws	**CUYAHOGA FORMATION** *Weir* Mws	**PRICE FORMATION** *Upper Weir* *Lower Weir* Mws	**SHENANGO FORMATION AND CUYAHOGA FORMATION** *Squaw* *Upper 30-Foot* Mws	**SHENANGO FORMATION AND CUYAHOGA FORMATION**	

Figure 1b. Stratigraphy of the Mississippian System (Lower Carboniferous flysch, molasse, and stable shelf sequence and Mississippian portion of Acadian flysch sequence). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA		SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
DEVONIAN	UPPER	**SUNBURY SHALE** *Coffee Shale* **BEREA SANDSTONE** *Berea* MDe	**SUNBURY SHALE** *Coffee Shale* **BEREA SANDSTONE** *First Berea* **BEDFORD SHALE** *Second Berea* MDe	**SUNBURY SHALE RIDDLESBURG MEMBER OF PRICE FORMATION AND BEREA SANDSTONE** *Berea* **CLOYD MEMBER OF PRICE FORMATION** MDe		**BEREA SANDSTONE** *Berea -Murrysville* **BEDFORD SHALE** **CUSSEWAGO SANDSTONE** *Cussewago* MDe	**BEREA SANDSTONE AND CORRY SANDSTONE** *Berea-Corry* **BEDFORD SHALE** **CUSSEWAGO SANDSTONE** *Cussewago* MDe	
		CLEVELAND SHALE MEMBER OF OHIO SHALE UDs	**CLEVELAND SHALE MEMBER OF OHIO SHALE** *Gantz* UDs	**OSWAYO MEMBER OF PRICE FORMATION** Dbg	**OSWAYO MEMBER OF PRICE FORMATION** *Gantz*	**"VENANGO GROUP"** *Gantz*	**RICEVILLE FORMATION AND OSWAYO FORMATION** *First Venango*	**CONEWANGO GROUP**
		CHAGRIN SHALE MEMBER OF OHIO SHALE Dbg	**CHAGRIN SHALE MEMBER OF OHIO SHALE** *Gordon* *Fifth* Dbg	**VENANGO FORMATION AND GREENLAND GAP FORMATION** *Fifty-Foot* *Thirty-Foot* *Gordon Stray* *Gordon* *Fourth* *Fifth* *Bayard* *Elizabeth* *Warren* Dbg	**VENANGO FORMATION AND GREENLAND GAP FORMATION** *Fifty-Foot* *Thirty-Foot* *Gordon Stray* *Gordon* *Fourth* *Fifth* *Bayard* *Elizabeth* *Warren* Dvs	*Hundred-Foot* *Fifty-Foot* *Thirty-Foot* *Nineveh-Snee* *Gordon Stray-Gordon* *Fourth* *Fifth/McDonald* *Bayard* *Elizabeth* *Sweet Richard* **CHADAKOIN FORMATION** *First Warren* Dvs	**"VENANGO GROUP"** *Red Valley* *Second Venango* *Third Venango Stray* *Third Venango* **CHADAKOIN FORMATION** *First Warren* Dvs	**CONNEAUT GROUP**

Figure 1c. Stratigraphy of the upper half of the Upper Devonian Series (part of the Acadian flysch). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

<table>
<tr><th></th><th></th><th>KENTUCKY</th><th>OHIO</th><th colspan="3">WEST VIRGINIA</th><th>SOUTHWESTERN PENNSYLVANIA</th><th>NORTHWESTERN PENNSYLVANIA</th><th>NEW YORK</th></tr>
<tr><td rowspan="4">DEVONIAN</td><td rowspan="4">UPPER</td><td rowspan="4">OHIO SHALE
Cinnamon
UDs</td><td>CHAGRIN SHALE
Dbg</td><td colspan="2">GREENLAND GAP FORMATION</td><td rowspan="2">GREENLAND GAP FORMATION
Speechley
Balltown
Bradford
Riley
Dbs</td><td rowspan="2">"BRADFORD GROUP"
Upper Warren
Lower Warren
Speechley Stray
Speechley
Tiona
First Balltown
Second Balltown
Sheffield
First Bradford
Second Bradford
Third Bradford
Kane
Dbs</td><td rowspan="2">"BRADFORD GROUP"
Second Warren
Third Warren
First Bradford/Glade
Clarendon Stray
Clarendon
Balltown
Cherry Grove
Speechley/Tiona
Cooper Stray
Second Bradford
Harrisburg Run
Sliverville
Third Bradford
Lewis Run
Kane
Dbs</td><td rowspan="2">CANADAWAY GROUP
Glade
First Bradford
Chipmunk
Second Bradford
Harrisburg Run
Richburg
Third Bradford
Waugh and Porter
Dbs</td></tr>
<tr><td colspan="2">HURON SHALE MEMBER OF OHIO SHALE
Big Cinnamon
UDs</td><td>Dbg</td></tr>
<tr><td>JAVA FORMATION
Dbg</td><td>BRALLIER FORMATION
Benson
Leopold
Alexander
Second Elk
Third Elk
Haverty
Fox
Sycamore
Dbg</td><td colspan="2">BRALLIER FORMATION
First Elk
Second Elk
Third Elk
Kane
Des</td><td>"ELK GROUP"
First Elk
Second Elk
Fourth Elk
BRALLIER FORMATION
Des</td><td>"ELK GROUP"
Elk
Sartwell/Haskill
Humphrey
JAVA FORMATION
Des</td><td>WEST FALLS GROUP</td></tr>
<tr><td>WEST FALLS FORMATION INCLUDING RHINESTREET SHALE MEMBER
MARCELLUS SHALE
UDs</td><td>TULLY LIMESTONE MAHANTANGO FORMATION MARCELLUS SHALE
UDs</td><td colspan="2">TULLY LIMESTONE MAHANTANGO FORMATION MARCELLUS SHALE
Dbg</td><td>RHINESTREET SHALE MEMBER OF WEST FALLS FORMATION SONYEA FORMATION GENESEE FORMATION TULLY LIMESTONE HAMILTON GROUP INCLUDING MARCELLUS SHALE
Dbg</td><td>RHINESTREET SHALE MEMBER OF WEST FALLS FORMATION SONYEA FORMATION GENESEE FORMATION TULLY LIMESTONE HAMILTON GROUP INCLUDING MARCELLUS SHALE
Dbg</td><td>RHINESTREET SHALE MEMBER OF WEST FALLS FORMATION SONYEA FORMATION GENESEE FORMATION HAMILTON GROUP INCLUDING MARCELLUS SHALE</td></tr>
</table>

Figure 1d. Stratigraphy of the lower half of the Upper Devonian Series (part of the Acadian flysch). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
DEVONIAN	**MIDDLE**	**ONONDAGA LIMESTONE** *Corniferous* DSu	**ONONDAGA LIMESTONE** *Big Lime*	**ONONDAGA LIMESTONE**	**ONONDAGA FORMATION**	**ONONDAGA FORMATION** Dol	**ONONDAGA LIMESTONE** Dol
	LOWER	Dsu	**BOIS BLANC FORMATION**	**HUNTERSVILLE CHERT** Dho	**HUNTERSVILLE CHERT** Dho	**BOIS BLANC FORMATION** *"Oriskany Sandstone"*	
		ORISKANY SANDSTONE DSu	**ORISKANY SANDSTONE** Dop, Doc	**ORISKANY SANDSTONE** Dos	**RIDGELEY SANDSTONE** **SHRIVER FORMATION** Dos, Doc	Dop, Dos	**ORISKANY SANDSTONE** Doc, Dos
SILURIAN	**UPPER**	**HELDERBERG FORMATION** DSu	**HELDERBERG FORMATION**	**HELDERBERG FORMATION**	**MANDATA SHALE** **CORRIGANVILLE LIMESTONE** **NEW CREEK LIMESTONE**		
		BASS ISLANDS FORMATION DSu	**BASS ISLANDS DOLOMITE**		**KEYSER FORMATION**	**BASS ISLANDS FORMATION** *Bass Islands zone* Sbi	**BASS ISLANDS FORMATION** *Bass Islands zone* Sbi
		SALINA FORMATION DSu	**SALINA FORMATION**	**SALINA FORMATION** *Newburg* Sns	**SALINA GROUP**	**SALINA FORMATION**	**SALINA FORMATION**
		LOCKPORT DOLOMITE Sld	**LOCKPORT FORMATION** Sld	**LOCKPORT DOLOMITE** Sld	**LOCKPORT DOLOMITE**	**LOCKPORT DOLOMITE** Sld	**LOCKPORT DOLOMITE**
	LOWER	**BIG SIX SANDSTONE** *Big Six* **ROSE HILL SHALE** Sld	**CLINTON GROUP** *Packer Shell*	**KEEFER FORMATION** **ROSE HILL FORMATION** Sld	**CLINTON GROUP**	**CLINTON GROUP**	**CLINTON GROUP**
		"Clinton sandstone" Scm	**CATARACT FORMATION** *Stray Clinton* *Red Clinton* *White Clinton* *Medina* Scm	**TUSCARORA SANDSTONE** Sts	**TUSCARORA SANDSTONE** Sts	**MEDINA GROUP INCLUDING GRIMSBY SANDSTONE CABOT HEAD SHALE WHIRLPOOL SANDSTONE** Scm	**MEDINA GROUP INCLUDING GRIMSBY SANDSTONE WHIRLPOOL SANDSTONE** Scm

Figure 1e. Stratigraphy of the Middle and Lower Devonian Series and the Silurian System (post-Taconic molasse and carbonate shelf). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
ORDOVICIAN	UPPER	**DRAKES FORMATION** **RICHMOND GROUP** *Queenston*	**QUEENSTON SHALE** *Red Medina*	**JUNIATA FORMATION**	**QUEENSTON SHALE/JUNIATA FORMATION**	**QUEENSTON SHALE/JUNIATA FORMATION**	**QUEENSTON SHALE**
		MAYSVILLE GROUP **EDEN GROUP**		**OSWEGO SANDSTONE** **MARTINSBURG FORMATION**	**BALD EAGLE SANDSTONE** **REEDSVILLE SHALE** **UTICA SHALE THROUGH HATTER FORMATION** Obe	**REEDSVILLE SHALE** **UTICA SHALE THROUGH HATTER FORMATION**	**OSWEGO SANDSTONE** **LORRAINE GROUP**
		TRENTON GROUP Obc	**TRENTON LIMESTONE** MOf	**TRENTON**	**LOYSBURG FORMATION**	**LOYSBURG FORMATION**	**TRENTON LIMESTONE**
	MIDDLE	**STONES RIVER-HIGH BRIDGE GROUP** *St. Peter Sandstone* Osp	**BLACK RIVER LIMESTONE** **GULL RIVER LIMESTONE** **WELLS CREEK FORMATION** MOf	**BLACK RIVER LIMESTONE** **WELLS CREEK FORMATION**	**BEEKMANTOWN GROUP**	**BEEKMANTOWN GROUP**	**BLACK RIVER GROUP**
	LOWER	**KNOX GROUP** **BEEKMANTOWN GROUP** **ROSE RUN SANDSTONE** **COPPER RIDGE DOLOMITE** COk	**KNOX GROUP** COk	**BEEKMANTOWN GROUP**			**TRIBES HILL FORMATION**
CAMBRIAN	UPPER		**ROSE RUN** **TREMPEALEAU** **COPPER RIDGE DOLOMITE** *Krysik sandstone* COk	**ROSE RUN** **COPPER RIDGE DOLOMITE**	**GATESBURG FORMATION** **WARRIOR FORMATION**	**GATESBURG FORMATION** **WARRIOR FORMATION** COk	**LITTLE FALLS FORMATION** **THERESA FORMATION** **POTSDAM FORMATION**
	MIDDLE	**CONASAUGA FORMATION**	**CONASAUGA FORMATION**	**CONASAUGA FORMATION**	**POTSDAM SANDSTONE**	**POTSDAM SANDSTONE**	
	MIDDLE / LOWER	**ROME FORMATION** **TOMSTOWN DOLOMITE** Cpk	**ROME FORMATION**	**ROME FORMATION** **TOMSTOWN DOLOMITE**			
	LOWER	**ANTIETAM SANDSTONE** *Basal Sandstone* Cpk	**MT. SIMON SANDSTONE**	**MT. SIMON SANDSTONE** *Basal Sandstone*			

Figure 1f. Stratigraphy of the Ordovician and Cambrian Systems (Taconic flysch and Iapetan rift and passive margin sequences). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

Most Productive Gas Plays

- Bradford (17.9%)
- Venango (17.4)
- Cataract/Medina (13.9)
- Big Injun (9.2)
- Elk (7.0)
- Devonian Black Shales (7.0)
- Greenbrier/Newman (6.5)
- Berea (4.4)
- Weir (4.2)
- Oriskany Combination Traps (3.0)

Figure 2. Most productive gas plays in the Appalachian basin.

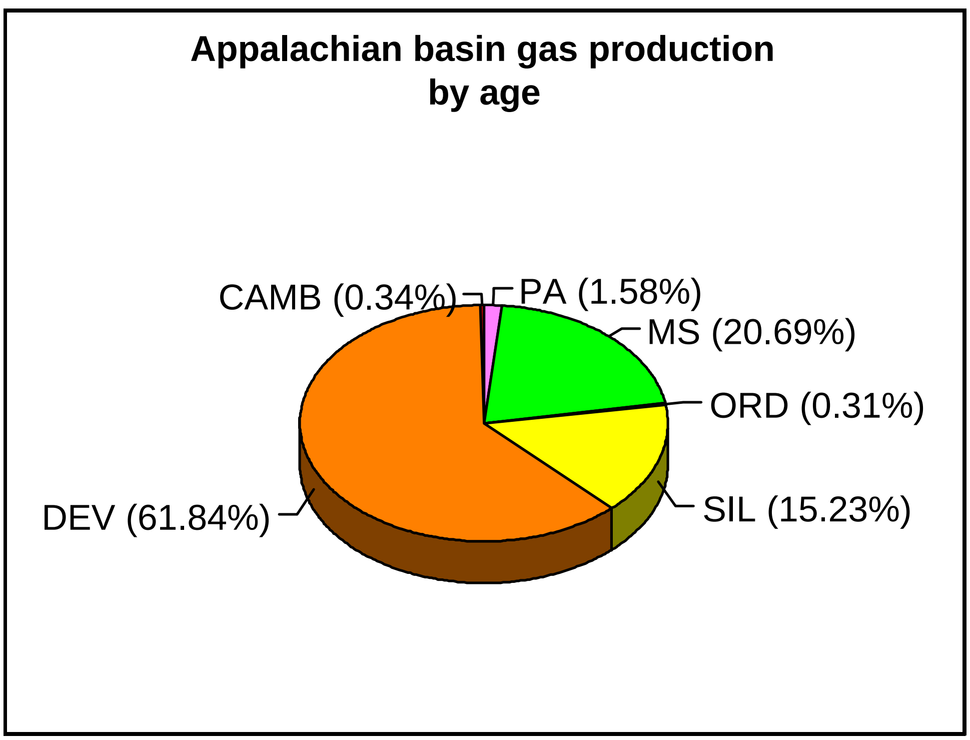

Figure 3. Appalachian gas production by age.

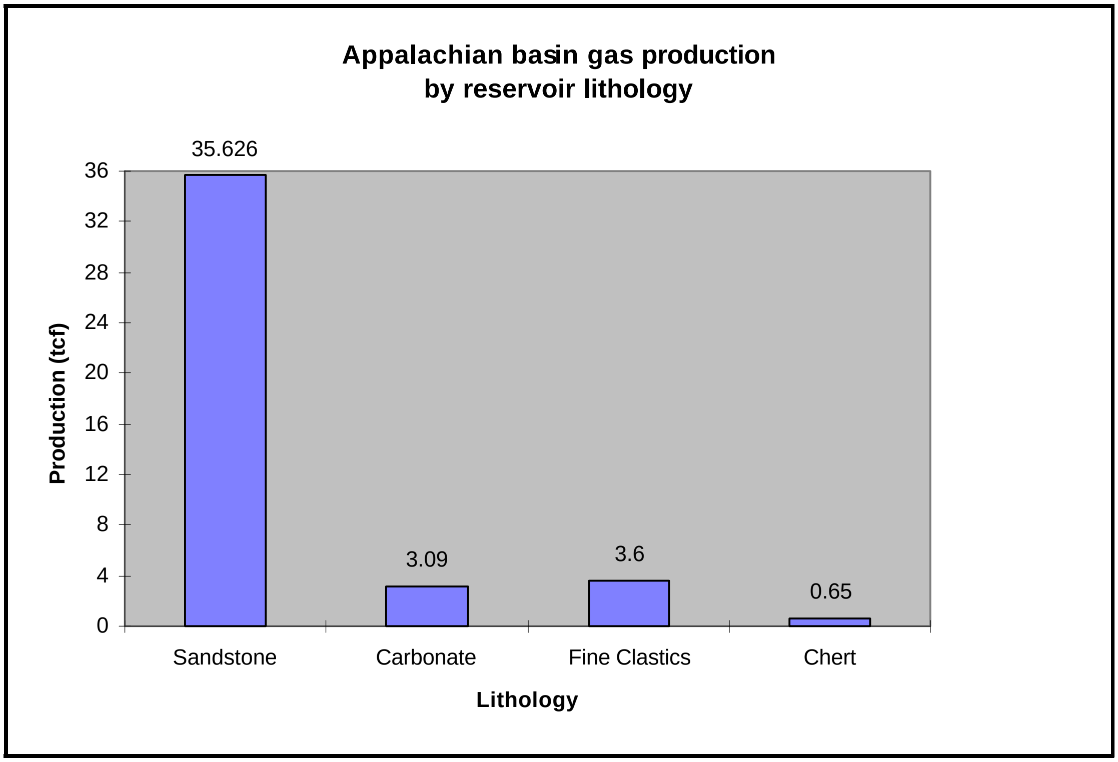

Figure 4. Appalachian basin gas production by reservoir lithology.

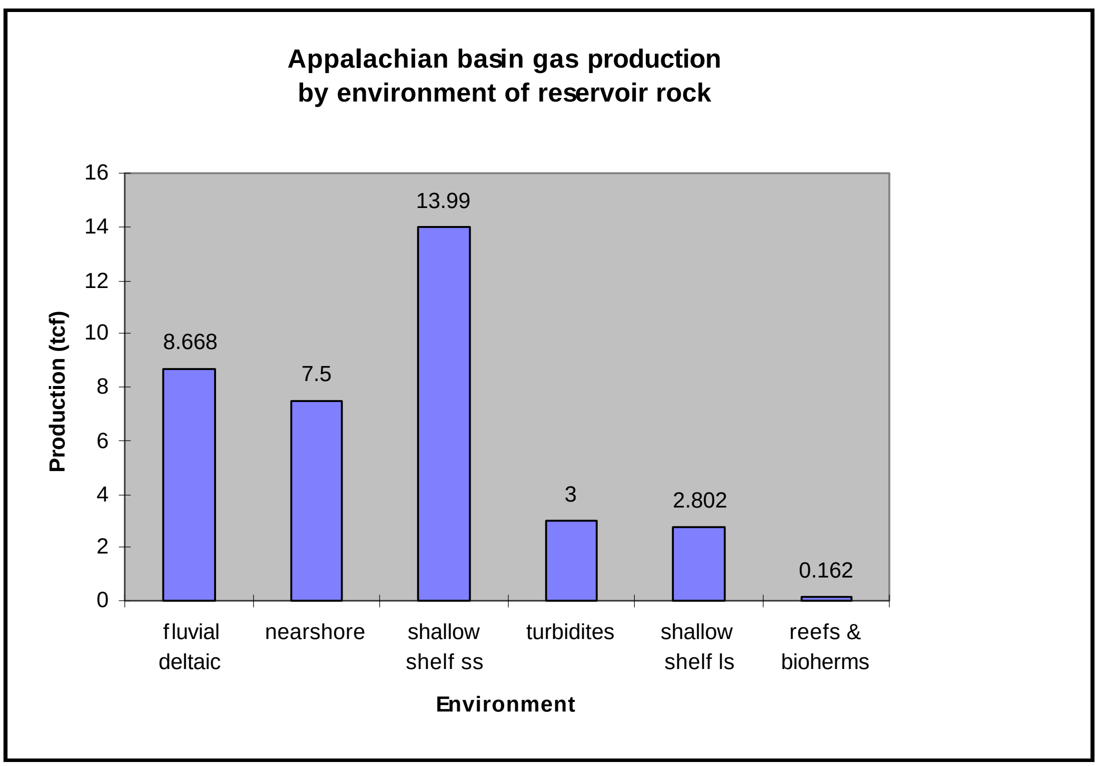

Figure 5. Appalachian basin gas production by environment of reservoir rock.

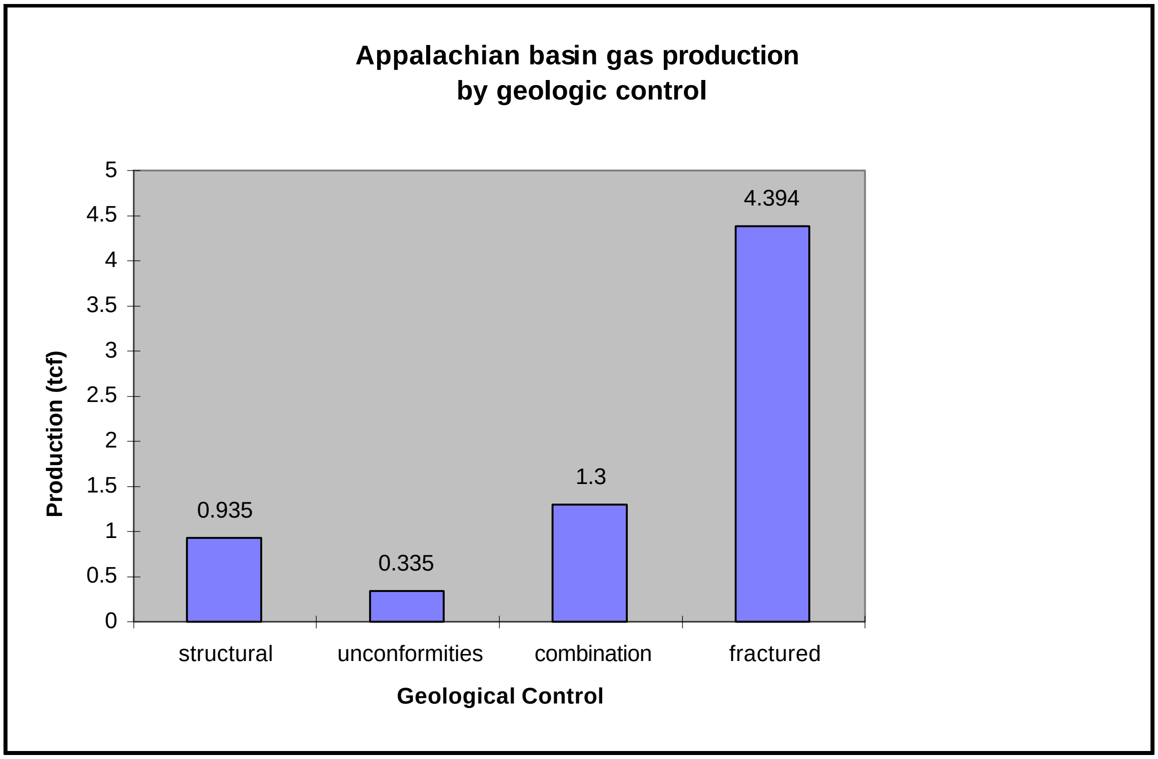

Figure 6. Appalachian basin gas production by geologic control.

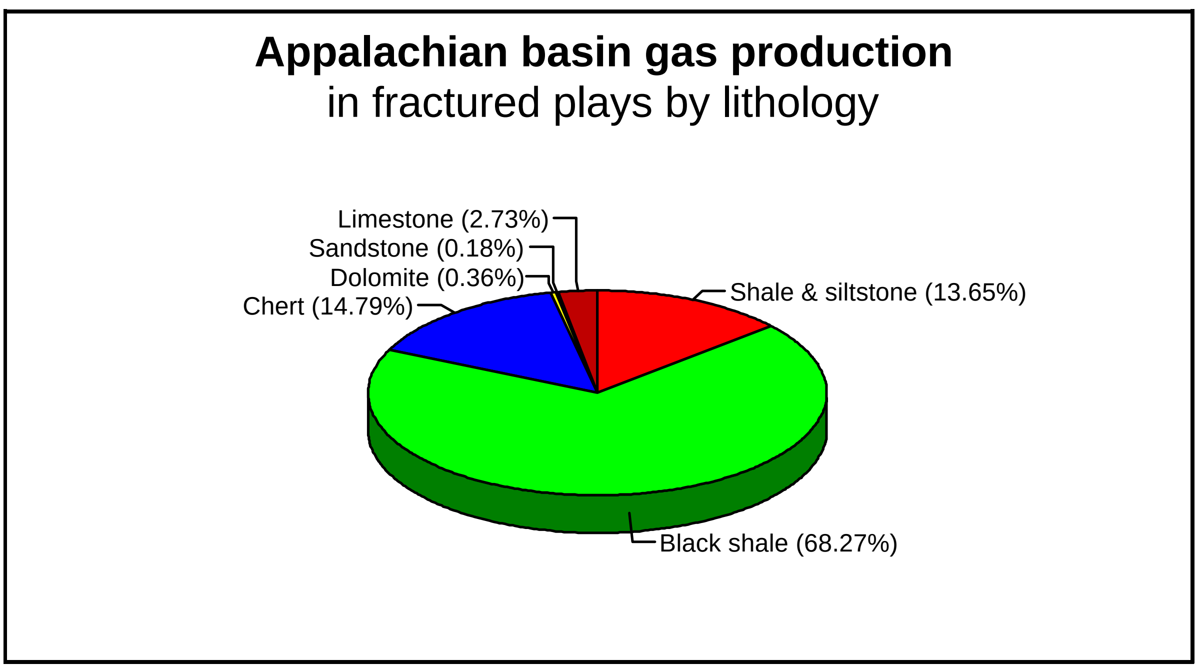

Figure 7. Appalachian basin gas production in fractured plays by lithology.

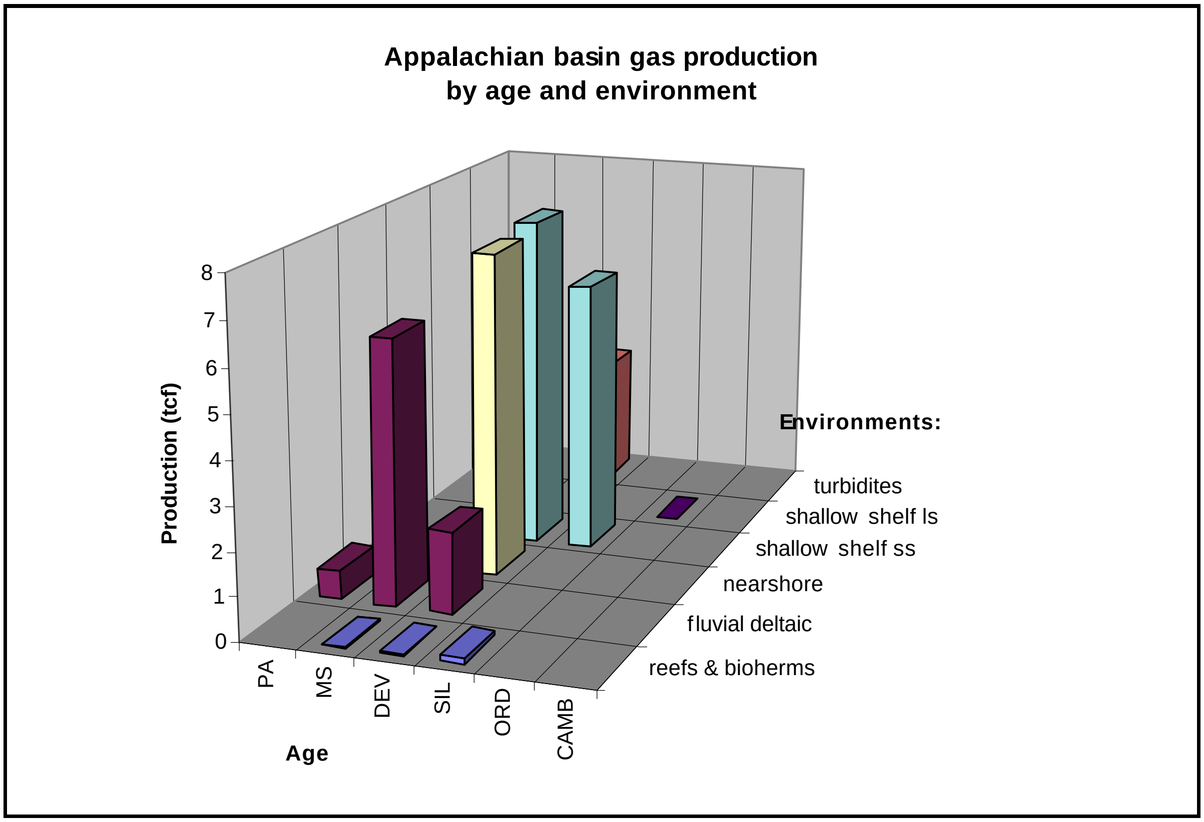

Figure 8. Appalachian basin gas production by age and environment.

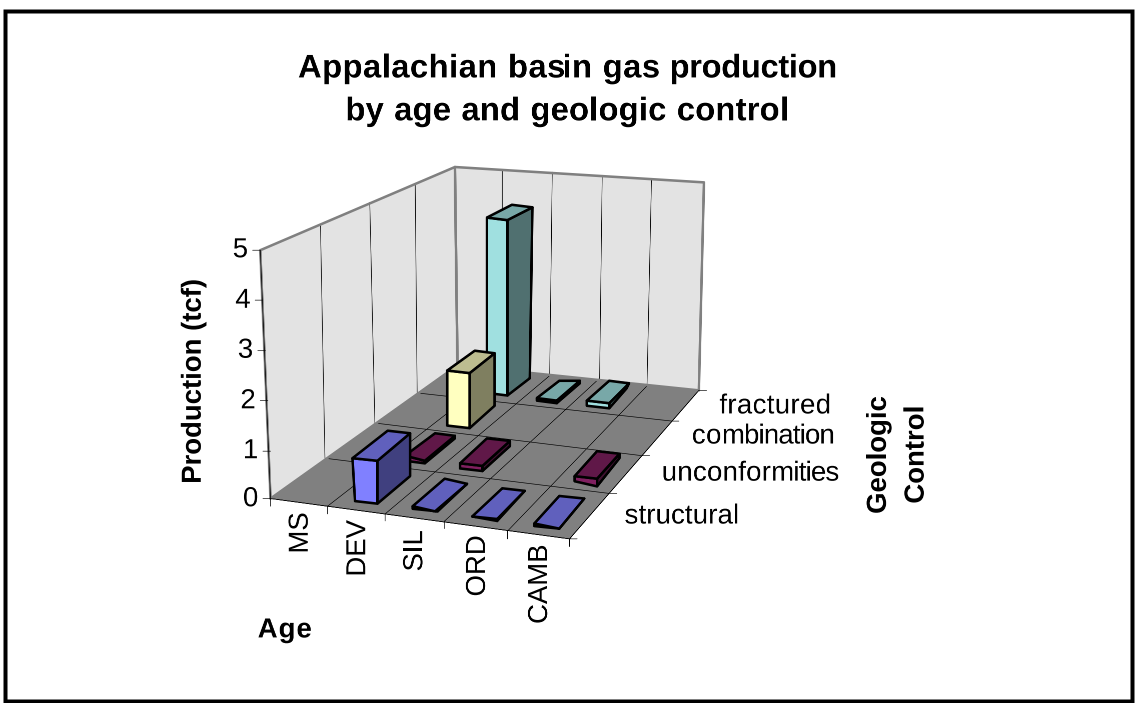

Figure 9. Appalachian basin gas production by age and geologic control.

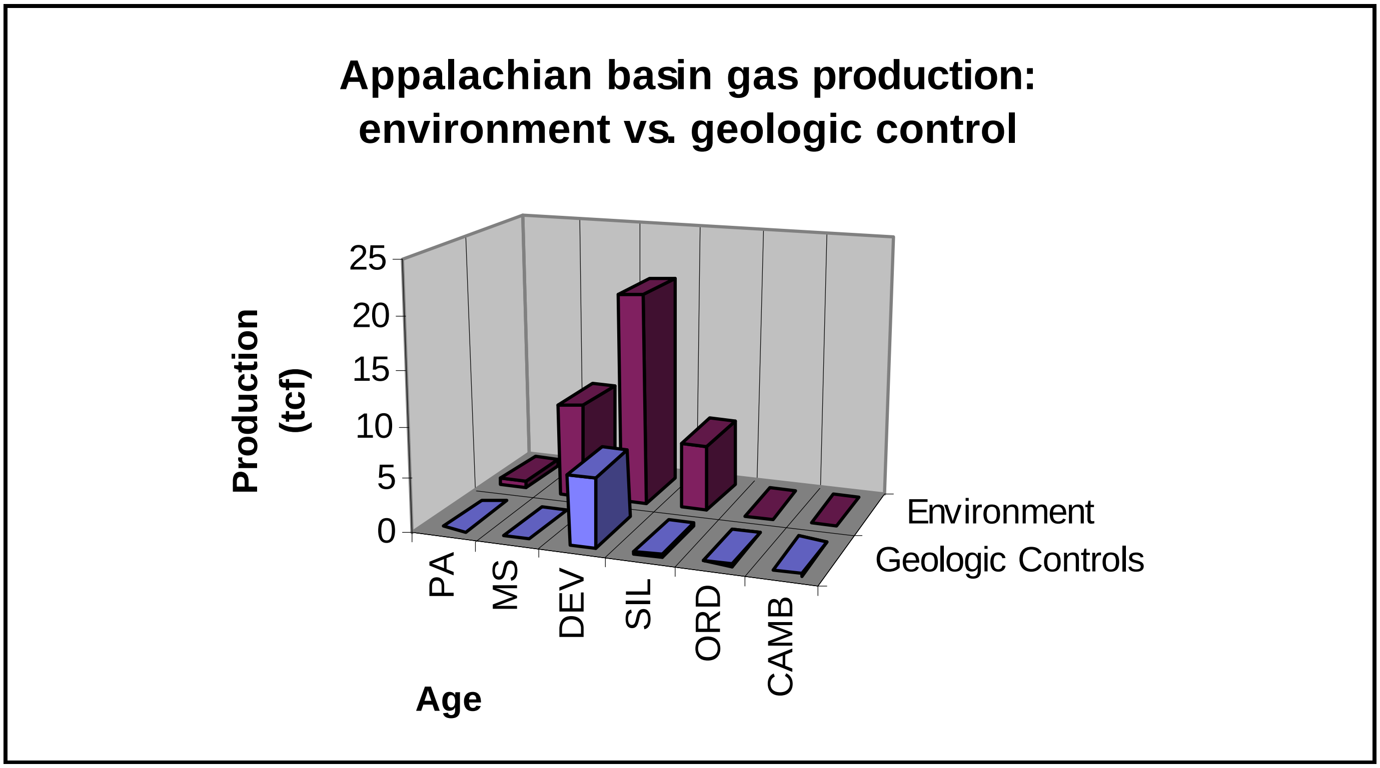

Figure 10. Appalachian basin gas production: environment versus geologic control.

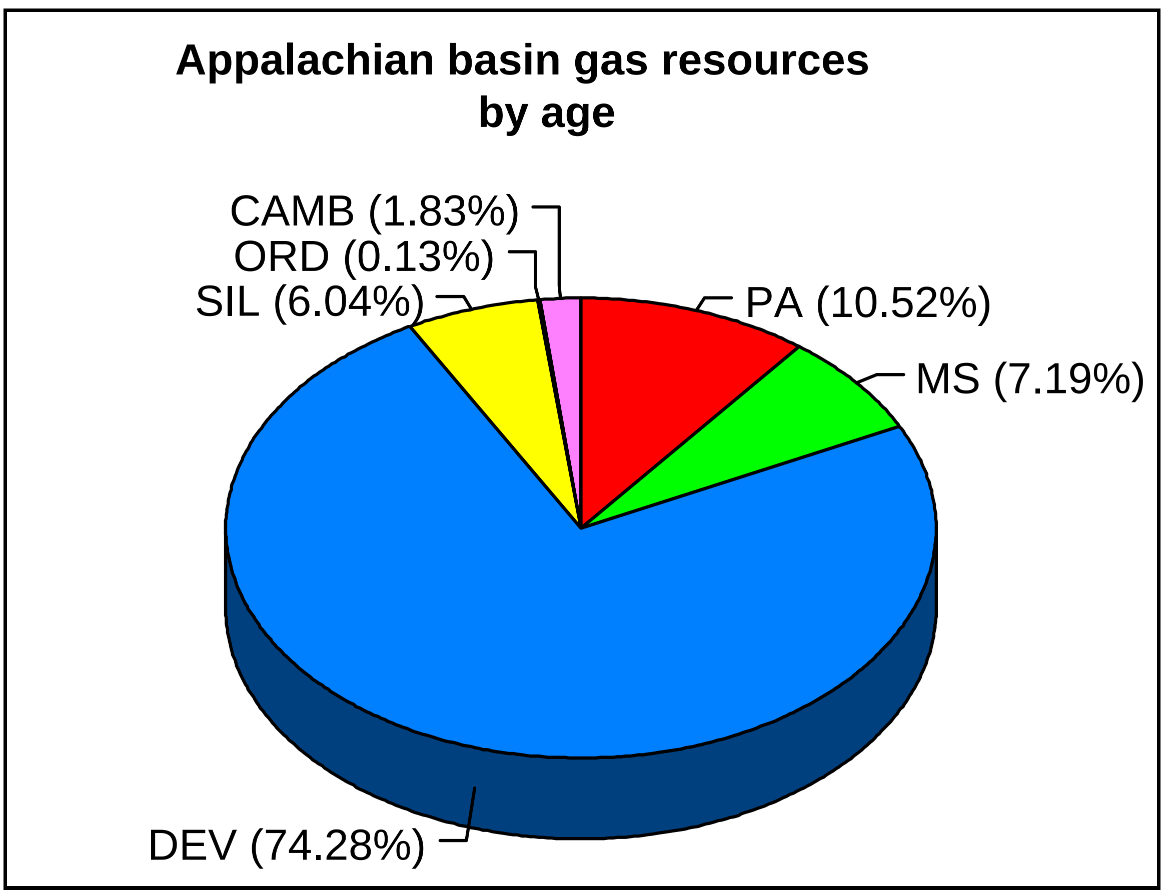

Figure 11. Appalachian basin gas resources by age.

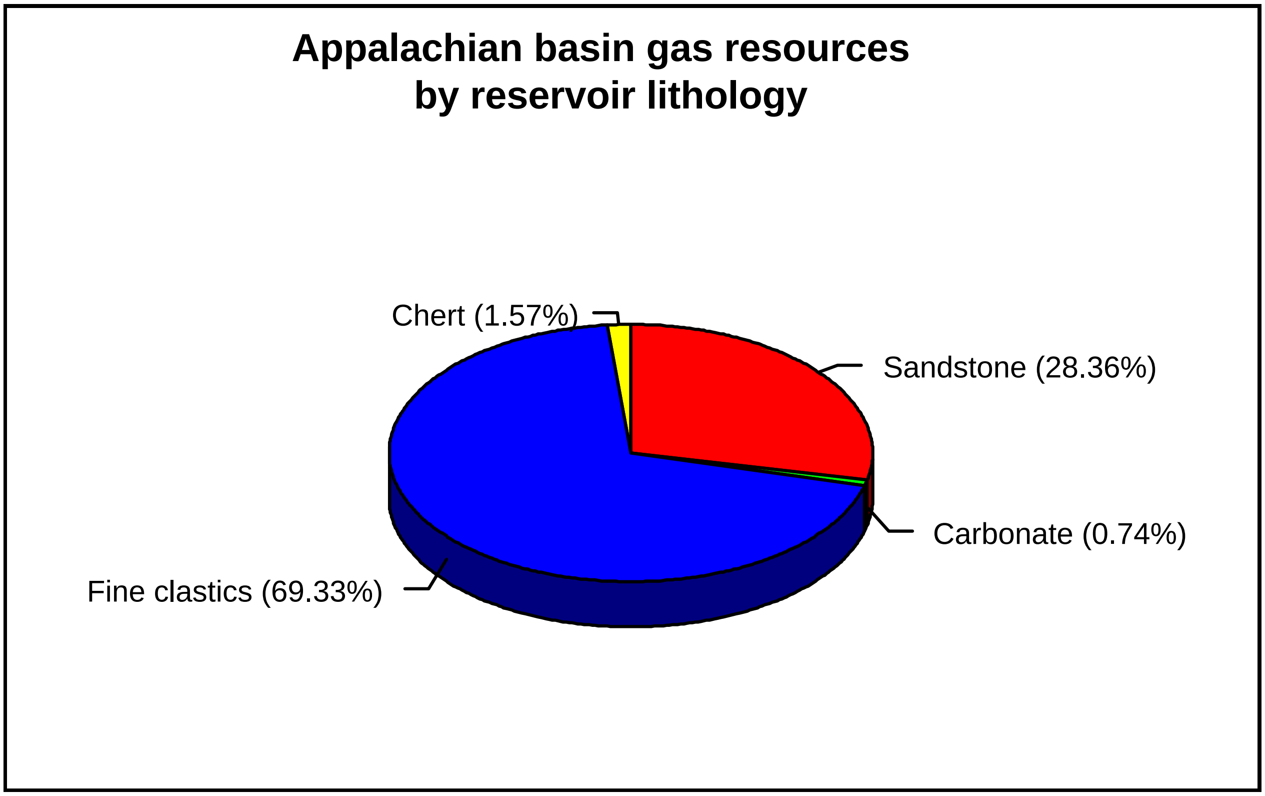

Figure 12. Appalachian basin gas resources by reservoir lithology.

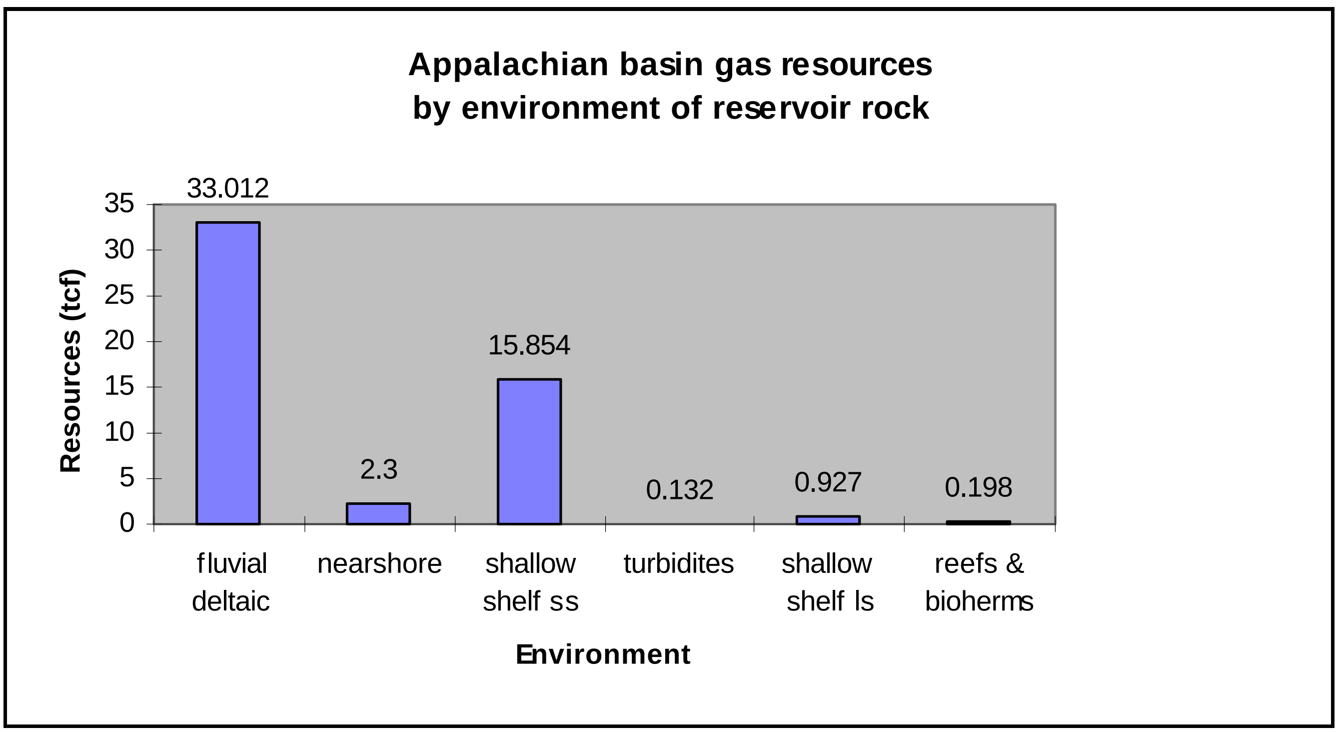

Figure 13. Appalachian basin gas resources by environment of reservoir rock.

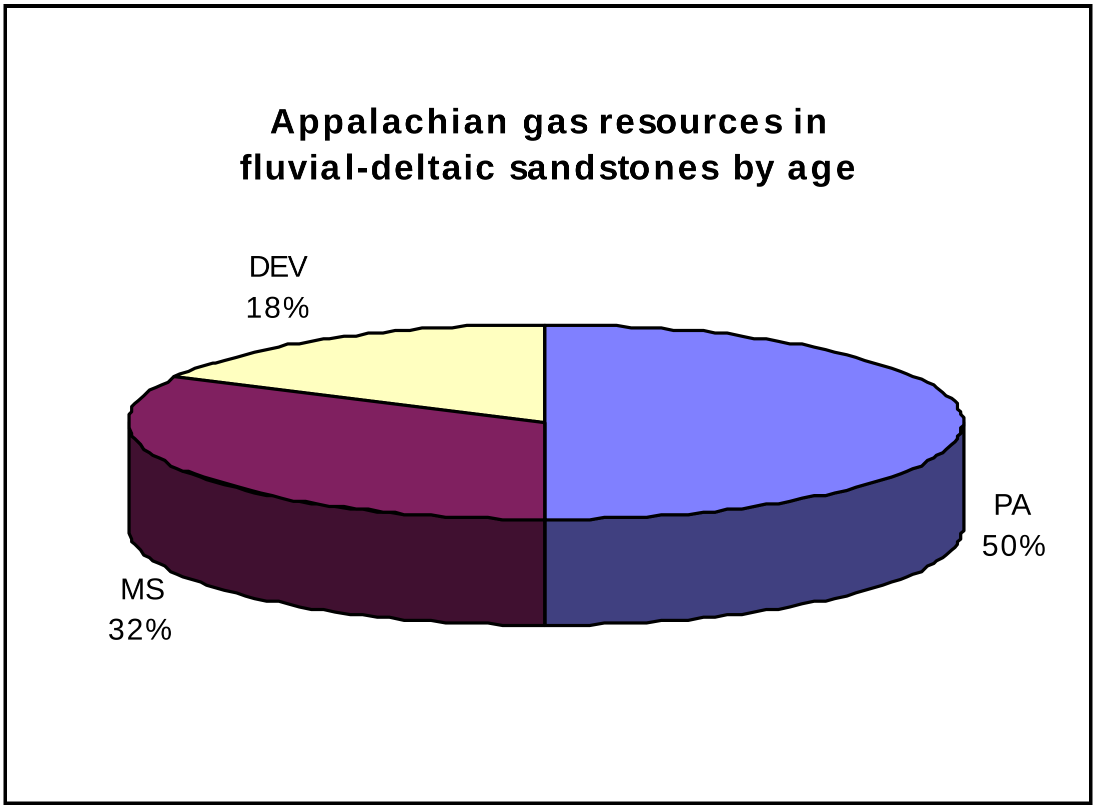

Figure 14. Appalachian basin gas resources in fluvial-deltaic sandstones by age.

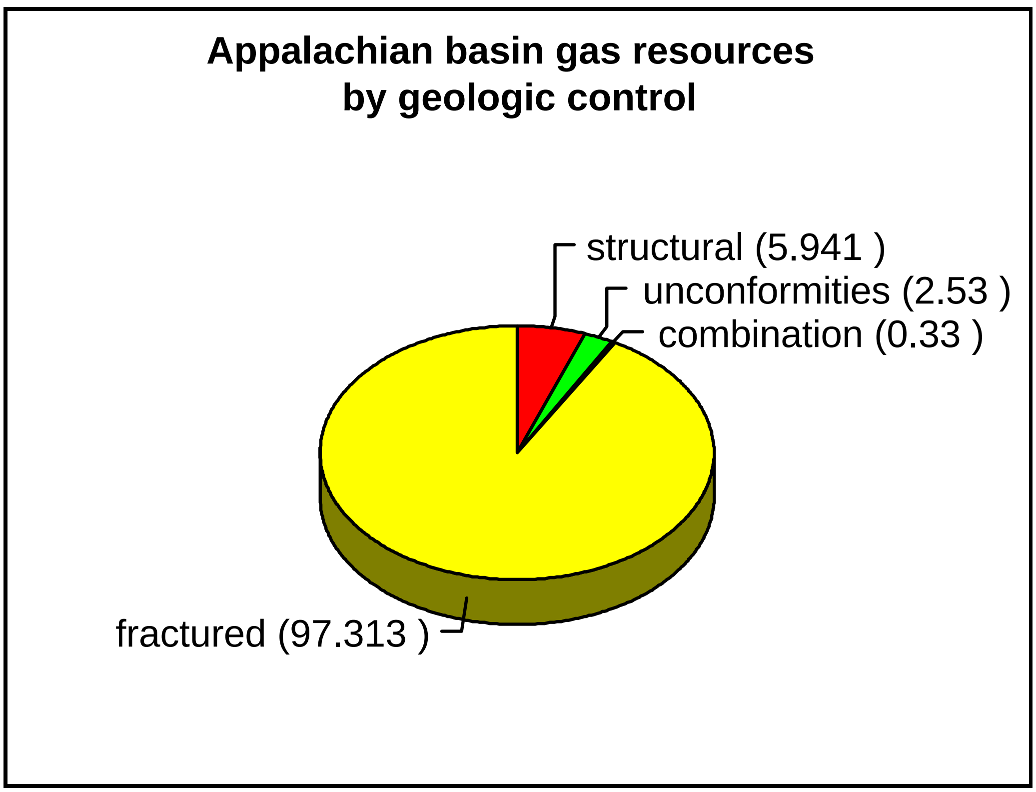

Figure 15. Appalachian basin gas resources by geologic control.

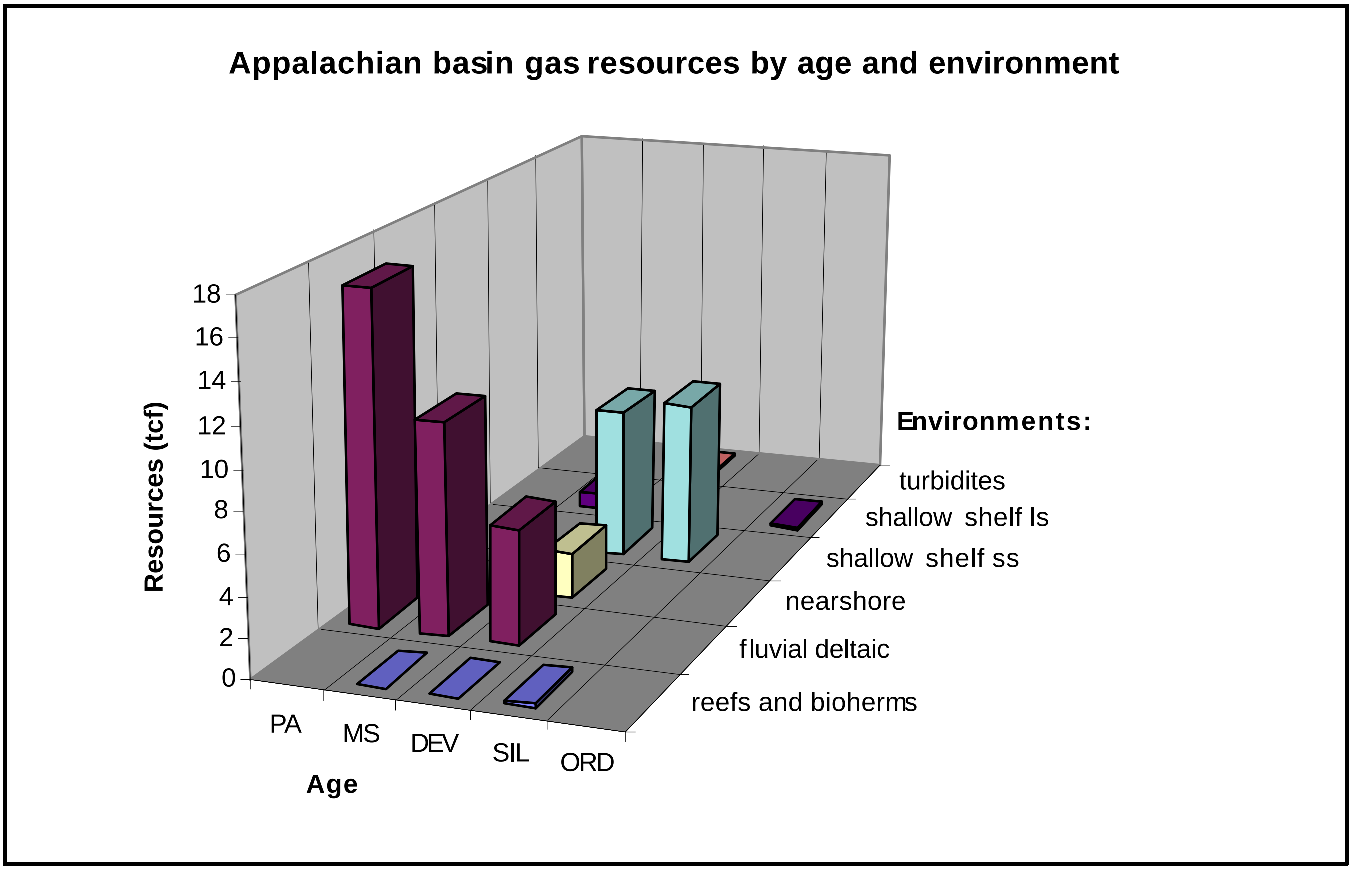

Figure 16. Appalachian basin gas resources by age and environment.

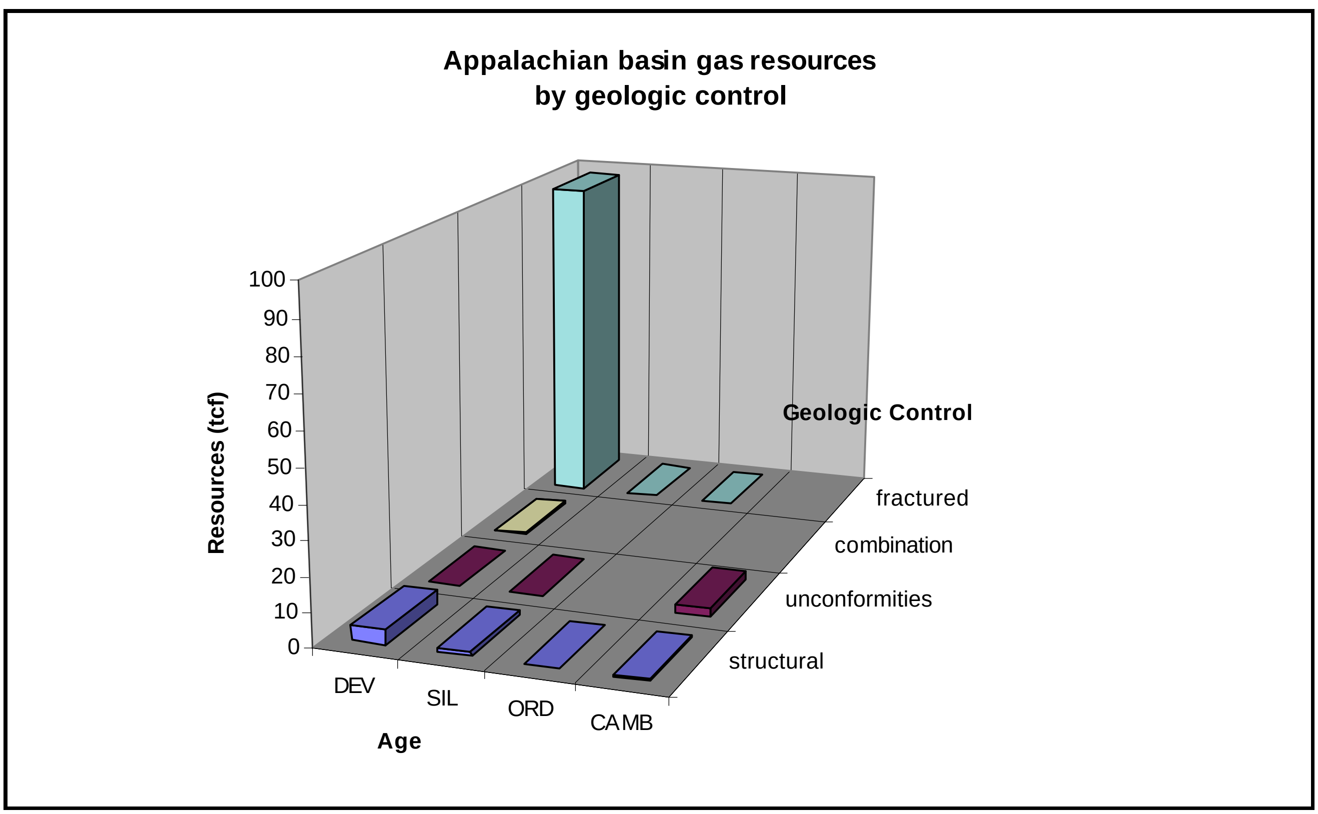

Figure 17. Appalachian basin gas resources by geologic control.

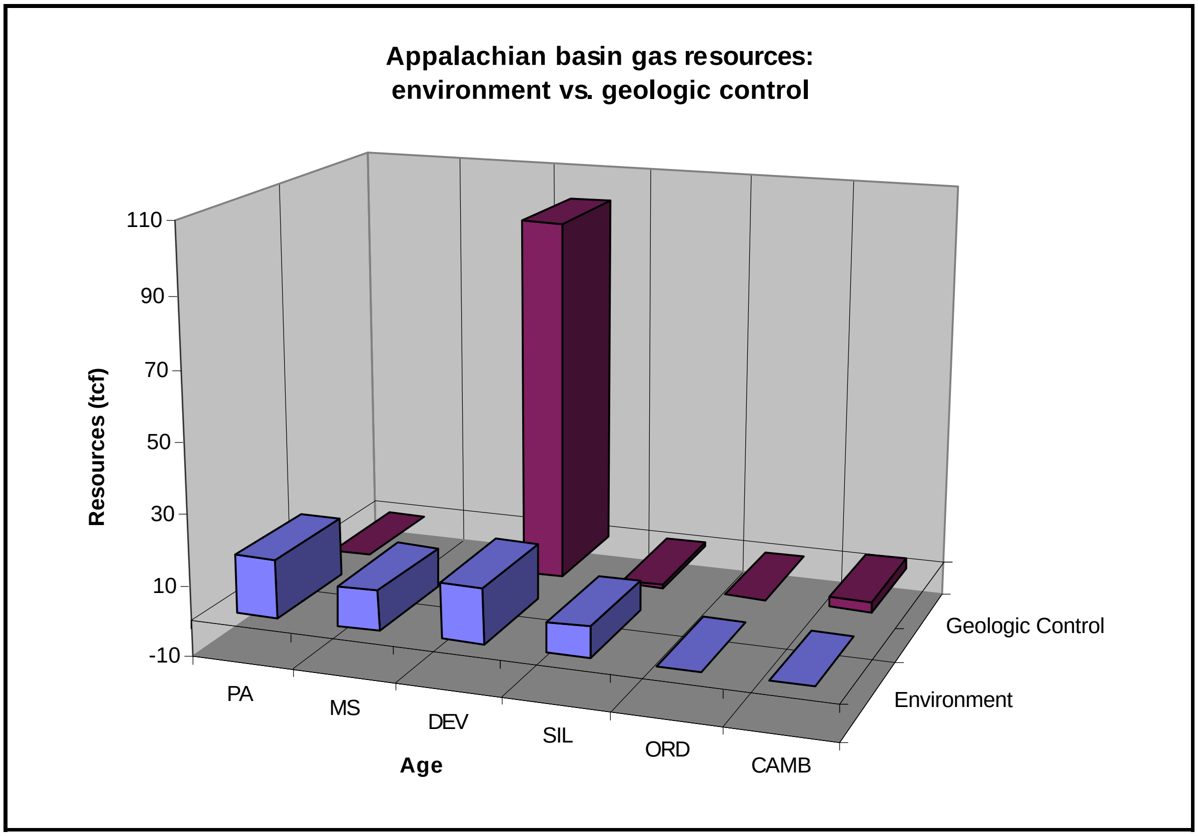

Figure 18. Appalachian basin gas resources: environment versus geologic control.

TOP SEVEN PLAYS (RESOURCES)

Black Shale	89,500 bcf
Pottsville	12,500
Medina/Clinton	8,200
Bradford	7,580
Big Injun	7,073
Berea	5,738
Devonian Sh & Silt	5,600

Figure 19. Top seven plays (resources) in the Appalachian basin.

SECOND SEVEN PLAYS (RESOURCES)	
Oriskany Structure	4,300 bcf
Allegheny	4,100
Weir	3,145
Knox	2,370
Venango	2,300
Huntersville-Oriskany	2,150
Tuscarora	1,074

Figure 20. Second seven plays (resources) in the Appalachian basin.

Small Producers, "Large" Resource (6)			
	Prod (bcf)	Resource (bcf)	R/P
Pre-Knox	5	535	107.0
Trenton	2	127	63.5
Tuscarora	28	1,074	38.4
Allegheny	181	4,100	22.7
Knox	143	2,370	16.5
St. Peter	2	32	16.0
(Stratigraphically older, west side, shallow)			

Figure 21. Small producers, "large" resource

Larger Producers, large Resource (6)			
	Prod (bcf)	Resource (bcf)	R/P
Black Shale	3,000	89,500	29.8
Pottsville	500	12,580	25.2
Shale & Siltst	600	5,600	9.3
Oriskany Structure	900	4,300	4.8
Huntersville-Oriskany	650	2,150	3.3
Berea	1,886	5,738	3.0
(Stratigraphically younger, center, depth varies)			

Figure 22. Larger producers, large resource

Remaining Plays, R/P > 1.0			
	Prod (bcf)	Resource (bcf)	R/P
Mauch Chunk	336	376	1.1
Big Injun	3,965	7,073	1.8
Weir	1,800	3,145	1.7
Oriskany Pinchout	82	133	1.6
Lockport	120	188	1.6
Clinton	6,000	8,200	1.4
Bald Eagle	8	9	1.4
(Wide range in size and age)			

Figure 23. Remaining Plays, R/P > 1.0

Large Plays, R/P < 1.0			
	Prod (bcf)	Resource (bcf)	R/P
Elk	3,000	132	.04
Oriskany Comb	1,300	330	.25
Greenbrier	2,800	800	.29
Venango	7,500	2,300	.31
Bradford	7,700	7,580	.98

Figure 24. Large plays, R/P < 1.0

Smaller Plays, R/P < 1.0			
	Prod (bcf)	Resource (bcf)	R/P
Onondaga Reefs	32	4	.13
Dev-Sil Unconf	110	27	.25
Newburg	290	74	.26
Ordovician Carb	120	42	.35
Ft. Payne	14	6	.43
Bass Islands	16	12	.75
(Proved reserves, probable resources)			

Figure 25. Smaller plays, R/P < 1.0