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# ESTIMATES OF UNCONVENTIONAL NATURAL-GAS RESOURCES OF THE DEVONIAN SHALE OF THE APPALACHIAN BASIN

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## INTRODUCTION

The organic-rich Devonian shales of the Eastern United States are an important unconventional source of natural gas. In order to define, assess, and stimulate development of this resource the Department of Energy initiated the Eastern Gas Shales Project. As part of this program, this report presents an assessment of the in-place natural gas resources from the Devonian shales of the Appalachian basin.

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## GEOLOGIC SETTING

The Devonian gas shales, a sequence of predominantly Middle to Late Devonian age black, dark-brown, and dark-gray shaly rocks rich in organic matter, underlie more than 160,000 square miles of the Appalachian basin. Along the north edge of the basin, the shale sequence is exposed at many localities from Albany, New York, to Norwalk, Ohio, particularly along the south shore of Lake Erie, as well as along the east flank of the Cincinnati arch from Norwalk southward to Pickwick Dam, Hardin County, Tennessee. The shale sequence dips to the east and south into the basin and lies more than 12,000 feet below sea level in the vicinity of the anthracite fields of eastern Pennsylvania in the deeper part of the Appalachian basin. On the east side of the basin some of the shales, particularly those of Middle Devonian age, are well exposed in folds in the Valley and Ridge from southeastern New York to southwestern Virginia. To the southwest in Tennessee, Georgia, and Alabama, Late Devonian organic-rich dark shales crop out at numerous localities in the Valley and Ridge and in the Cumberland Plateau segment of the Appalachian Plateau.

The Middle and Upper Devonian gas shales are dark, tough, laminar-bedded rocks. Alternating light and dark laminae are commonly a few hundredths of an inch thick and have great lateral continuity. The dark Devonian shales may contain as much as 20 percent by volume of organic detritus, which is the source of the gas in the shale sequence. In addition to the organic matter, the shales are composed largely of clay minerals and much clay- and silt-sized detrital silica. Illite is the principal clay mineral present, whereas mixed-layer expandable clays, chlorite, and kaolinite occur locally (Hosterman and Whitlow, 1981B). Mixed-layer illite-smectite occurs sparingly in some of the thin ash-fall beds intercalated in the shale sequence. Calcite and dolomite occur as concretions and nodules or in thin layers, beds, and laminae. Pyrite is ubiquitous in euhedral crystals, masses of crystals, nodules, framboids, laminae, or replacing fossils. Locally pyrite may make up as much as 10 percent of the shale by weight. A number of metallic elements including barium, cadmium, calcium, cobalt, copper, lead, manganese, mercury, molybdenum, nickel, potassium, thorium, titanium, uranium, vanadium, and zinc are present in trace amounts. Of the trace elements, uranium is of special interest to geologists because it is generally associated with the organic matter of the gas shales, and its radioactive response on the gamma-ray log permits geologists to map the extent and thickness of the gas shales. Although relatively widely dispersed in amounts ranging from 5 to 100 parts per million, the quantity of uranium present in the more than 12,600 cubic miles of the Devonian gas shales makes up the country's largest low-grade uranium resource.

Generally the darker laminae contain a greater amount of organic matter and less detrital silica. In contrast, the lighter colored laminae contain much clay and silica but little or no organic matter. In addition to the laminae, the gas shales commonly show a crude cyclic layering in 0.5- to 4-foot intervals marked by differences in color and resistance to erosion. The tough black shales weather in relief, whereas the lighter brown shales form reentrants between the more resistant black beds.

The freshly exposed unweathered rock of the shale sequence appears massive although some lighter gray laminae or partings may suggest the shaly nature of the strata. The rock is tough and weathers slowly to thin sharp-edged discoidal chips, which are commonly stained reddish brown by iron oxides produced by the weathering of pyrite. The black and brown shales of the shale sequence are commonly more resistent to weathering than the associated light-gray shale and mudrock. At many places where the rocks are nearly horizontal, the black shales cap small waterfalls or crop out in cliffed gullies, gorges, glens, and canyons.

The Devonian gas-shale sequence underlies more than 160,000 square miles of the Appalachian Plateau segment of the Appalachian basin and has a volume in excess of 12,600 cubic miles. Surface and subsurface data are insufficient to accurately determine the area and thickness of the gas-shale sequence in the Valley and Ridge segment of the basin. The thickness of the gas-shale sequence varies considerably in the Appalachian basin as the result of interfingering both laterally and vertically of the dark shales rich in organic detritus with gray shale, siltstone, and mudrock low in organic matter; depositional thinning of shale away from source areas or local centers of accumulation; faulting, subsidence, and tectonic warping during deposition of the shaly sequence; and extensive erosion of part of the sequence in the western part of the basin. Thickness of the Devonian black shale facies ranges from zero in parts of Alabama, Tennessee, and Georgia to more than 1,400 feet in northeastern Pennsylvania (de Witt, and others, 1975).

Recent stratigraphic studies show that the gas-shale sequence contains several regionally extensive units of black shale, each of which has a discrete center of accumulation. Some units of black shale may contain several local areas of thick shale within a thinner widespread sheet of black and dark brown rock. In general, the black shales interfinger to the east with eastward-thickening tongues of light-gray shale, mudrock, and turbidite siltstone. (For an explanation of the paleogeographic and paleotectonic settings see Ettensohn and Barron, 1981.)

The rocks of the black Devonian shale sequence do not contain typical clastic-reservoir strata with abundant intergranular porosity. The shales are tight rocks of very low permeability (0.005 millidarcy to less than 1 microdarcy) and small porosity (1 to 3 percent). Locally, siltstone and very fine grained quartzose turbidites are intercalated in the shaly sequence; however, these beds also have low porosity values that are comparable to the black shales. Their thin, brittle nature relative to the enclosing organic-rich shales would more easily facilitate fracturing under tectonic stress thus creating needed porosity, permeability, and better reservoir conditions.

Commonly joints and fractures of the natural-fracture systems cutting the shale sequence serve as reservoirs for gas evolved from organic matter in the shale. A large volume of gas is contained in matrix porosity or is adsorbed by the organic matter in the shale. Much of this gas is held tightly within the matrix of the shale, and because of the very low permeability of the gas shales, only a small volume moves along permeability pathways from the matrix to microfractures and macrofractures. The volume of matrix and adsorbed gas greatly exceeds the volume contained in the joint and fracture system (Brown, 1976). The long productive life, 50 years or more, and the relatively flat decline curves typical of shale-gas wells have been attributed to the slow release of matrix and adsorbed gas and its slow movement along congested permeability pathways to the well bore.

The organic matter in the shale sequence is the most important component of these rocks because it is the source from which the gas was generated. Some methane was produced by bacterial action during the early stages of accumulation of the muds containing organic matter. Later during the diagenetic transformation stage, the organic material was converted to kerogen at a relatively low temperature (less than 80$^{\circ}$C) within 100 or so meters below the water-sediment boundary. Through continued thermal maturation, resulting from deeper burial at an approximate temperature range of $80^{o}$-$150^{o}C$, the kerogen passes to the catagenic stage and is transformed into liquid and gaseous hydrocarbons.

During thermal maturation, terrestrial kerogen yields mainly methane or dry gas. Marine kerogen yields wet gas and oil during part of the maturation process at temperatures between about $80^{o}C$ and $150^{o}C$. Beyond the catagenic stage, at temperatures in excess of $150^{o}C$, the oil phase is progressively altered to the end products, dry methane and fixed carbon. Thus during the later stages of thermal maturation (between $150^{o}$ and $300^{o}C$) only dry methane is generated from both types of kerogens in the Devonian gas-shale sequence.

In the Appalachian basin, the degree of thermal maturation increases to the east and southeast from the western outcrop belt (Harris and others, 1978) as the Devonian black shales are buried under an increasing thickness of younger rocks. This maturation pattern is also reflected in the systematic change of the amount, composition, and $\delta^{13}C$ of the light hydrocarbons ($C_1$ and $C_4$) generated from the organic matter in the shales. In the western part of the basin, the gas composition is isotopically light and somewhat drier with a $\delta^{13}C$ value of about -53 per mil. In the central part, the hydrocarbon composition is comparatively wet and the $\delta^{13}C$ value ranges from about -51 to -42 per mil. Here the Devonian black shales are buried beneath 2,000 to 4,000 feet of younger rock. Farther east and buried below 6,000 to 9,000 feet of rock, the gas generated is low in the content of wet, heavier hydrocarbons and has $\delta^{13}C$ values in the range of -41 to -26 per mil. Thus, in the Appalachian basin, the shale sequence exhibits a full range of natural gas from mixed early biogenic-thermal through mid-range wet methane to upper-maturation level dry methane, and ultimately, in the easternmost metamorphosed segment of the basin, to black, supermature, carbonaceous slates devoid of methane.

Drilling histories and production data from the Appalachian basin indicate that Devonian shales will yield gas abundantly only in areas where extensive natural fracture systems are well developed in the sequence. The first domestic and commercial production of natural gas in the United States was obtained from the Devonian gas shales in Chautauqua County, New York, along the south shore of Lake Erie in the 1820's and 1830's. Some of the wells in this area produced gas at low pressures and small volumes from the shale sequence for more than 100 years. The area is undergoing rebound from loading by Pleistocene glacial ice, and the near-surface joint system has been enhanced and sprung open by the release of weight, which permits gas to escape more readily from the shale sequence. The reservoir is only partly sealed by accumulations of glacial debris and recent lacustrine deposits. As a result of incomplete seals, gas escapes from the fractured reservoir at many places, and gas wells rarely show normal relationships of rock pressure to depth.

The Big Sandy gas field of eastern Kentucky and western West Virginia is associated with an extensive fracture system produced by repeated reactivation of basement faults of the Rome Trough segment of the Eastern Interior aulacogen (Harris, L. D., 1978). Apparently subsidence and normal faulting along the aulacogen generated the widespread and pervasive system of fractures and joints that make up the Big Sandy reservoir system. Some shale-gas wells have been productive for more than 50 years in the Big Sandy area, and several of the more productive have yielded several billion cubic feet each. The first wells were drilled in the Kentucky part of the field in the 1920's, and to date (1982) more than 9,600 wells have produced more than 2.5 trillion cubic feet of gas, mainly from the Devonian-shale sequence (Brown, 1976).

In the Big Sandy field, as elsewhere in the Appalachian basin, where the gas-shale sequence is naturally fractured it is both source bed and reservoir rock.

In some parts of the Appalachian basin the Devonian shales may be present, but apparently an extensive natural fracture system is not. In these areas, wells drilled to the shale sequence may yield gas but not in commercially extractible volumes with existing stimulation and production techniques.

## DEFINITIONS

Natural gas is a mixture of gaseous hydrocarbons divided, for the purpose of this study, into three categories: macrofracture gas, microporosity gas, and sorbed gas.

Macrofracture gas is free gas filling the major fracture and joint systems. It is assumed here that the gas which leaks from core samples before they were canned at the surface is mainly macrofracture gas.

Microporosity gas is gas which fills "small" fractures and other "small" matrix porosity. "Small" here means, in the practical sense, small enough that the gas does not leak out before canning.

Sorbed gas is gas either absorbed or adsorbed by the organic matter in the shale.

The gas resource is that amount of gas considered to be in the shales. The term in-place resource is synonymous with the term resource and indicates the total amount of gas present as distinguished from the amount that could be actually recovered.

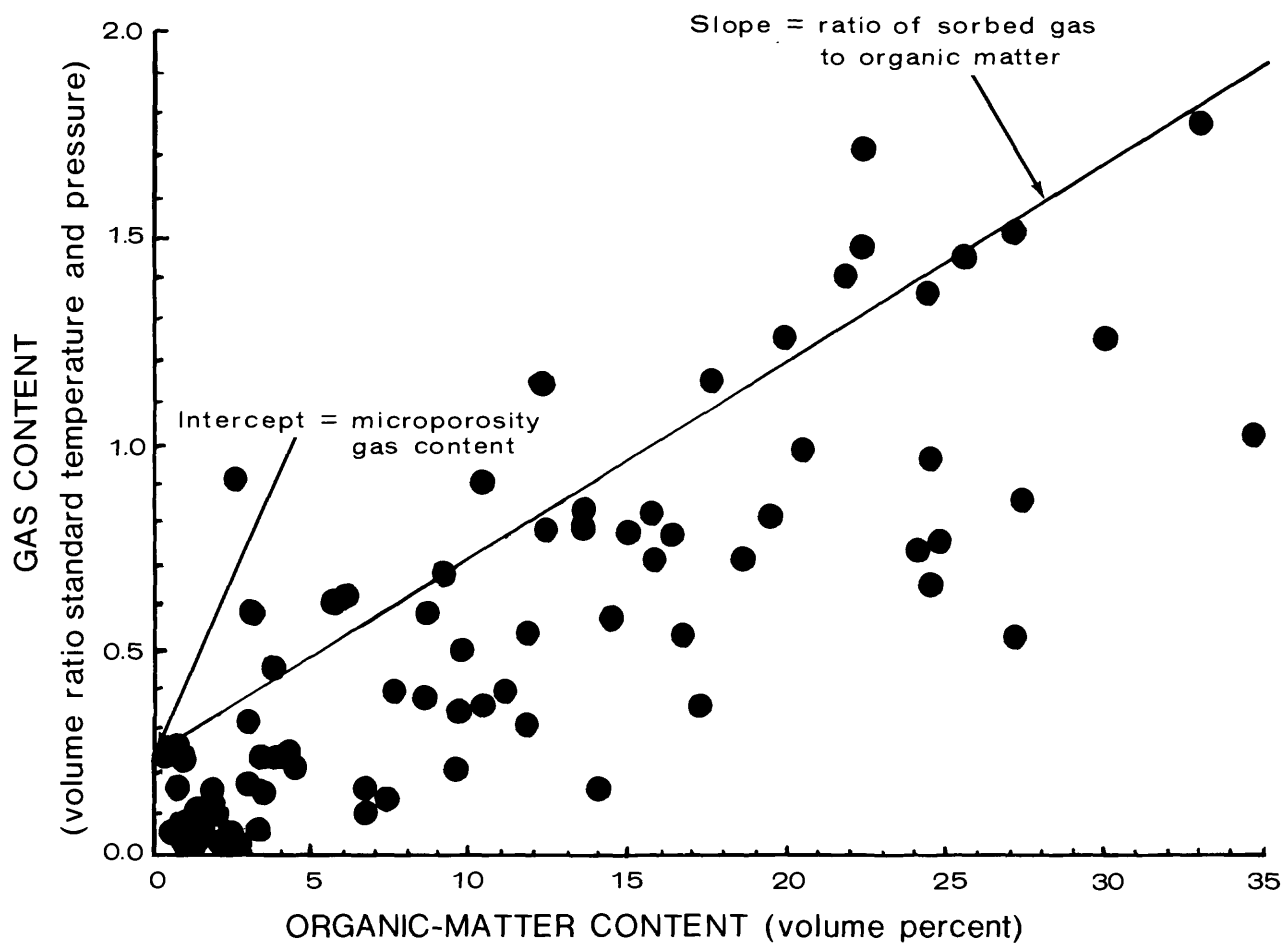
## BASIS FOR APPRAISAL

A number of major assumptions had to be made for this appraisal. Foremost of these is that because the Devonian shale is an unconventional reservoir, the standard engineering equations for conventional porous-medium reservoirs are not strictly applicable.

The gas of the Devonian shale is considered to be in three categories: macrofracture gas, microporosity gas, and sorbed gas. Some studies (for example, Lewin and Associates, 1979) have suggested that most or all gas produced from the shale was contained in the fracture system. In contrast, Smith and others (1979) suggested that much higher fracture porosities than are seen in core examinations would be needed to contain the volume of produced gas. Core examinations probably exaggerate the amount of fracture porosity because the cores include fractures induced by the coring process as well as open fractures which would be closed under reservoir pressures. In this study, large fractures are assumed to contain only a small amount of the total volume of gas-in-place, not enough to explain most or all of the production. Most of the gas is in the microporosity and sorbed on organic matter in the shale matrix. Large fractures are assumed to act mainly as permeability pathways, rather than as reservoirs.

Estimates of microporosity and the ratio of sorbed gas to organic matter have been mainly based on graphs of gas content versus organic-matter content from canned-core samples (fig. 1). We assumed that data from off-gassing experiments of canned cores can be used to establish a relationship between amount of gas and amount of organic matter. We further assumed that on a plot of gas versus organic content a line can be fit subjectively to that data and that the slope of the line will be an estimate of the ratio of sorbed gas to organic matter while the intercept will be an estimate of the effective

Figure 1.--Typical plot of gas volume versus organic-matter content based on data from off-gassing experiments. Because a small but unmeasured volume of gas escapes from the microfractures during coring and canning of the core samples, the line defining the ratio of gas content to organic-matter content in the shales has been migrated in favor of the higher gas content values in an attempt to evaluate the gas content of the microporosity in the core samples. The line has been subjectively fit to the data points and intercepts the gas content ordinate at a positive value equivalent to the gas content present in the microporosity.


Slope = ratio of sorbed gas
to organic matter
Intercept = microporosity
gas content
GAS CONTENT
(volume ratio standard temperature and pressure)
ORGANIC-MATTER CONTENT (volume percent)
0.0
0.5
1.0
1.5
2.0
0
5
10
15
20
25
30
35

microporosity. The problem of gas leakage from microfractures is partially addressed by giving more weight to measurements showing higher gas contents for given organic-matter contents. The line subjectively fit to the data, as illustrated in fig. 1, thus tends to pass through the higher gas-content values of the data set and does not pass through the origin. Most leakage from samples before canning is assumed to be macrofracture gas.

Shales with very low organic contents usually have little or no gas. In this study, shale with an organic-matter content of less than 2 percent by volume is considered to have only a negligible amount of gas.

Certain areas of the basin have been assessed as having only negligible resource potential and were not included in this estimate. They include Tennessee and Alabama where organic-rich shale occurs, but the sequence is considered too thin to provide sufficient potential. Negligible potential was assigned to the area east of the 4 Conodont Color Alteration Index (CAI) isograd (Harris and others, 1978) because of supermaturity. Some potential may exist in some of the deep synclines of Virginia, but information is insufficient for a quantitative appraisal.

The estimate of most practical significance would be one of the amount of economically recoverable gas from the shale. However, the authors of this report feel that an estimate of recoverability is beyond the scope of a geological appraisal such as this. One major problem is lack of knowledge of the drainage volume of a single well. Because of the non-simple drainage pattern and the unconventional nature of the reservoir, it is probably inappropriate to assume a standard well spacing (as was done by Lewin and Associates, 1979) as sufficient for drainage. Another major problem is economics. This requires many further assumptions on use, costs, completion techniques, and many other factors beyond the scope of this report.

## METHOD OF ASSESSMENT

### Play Area Delineation

In resource appraisal by the play-analysis method, a play is defined as an area in which the main geologic and geochemical attributes are relatively consistent but differ significantly from some of the attributes in adjacent plays. Basically a play is an areal unit around which an exploration program may be generated.

For this appraisal, we subdivided the main part of the Appalachian Plateau province and a small segment of the adjacent Valley and Ridge province into 19 plays. Our separation was based on both structural and stratigraphic criteria (table 1). The plays (fig. 2) and some of their critical attributes are discussed sequentially.

1. The North-Central Ohio play is the area adjacent to the outcrop of the Devonian shale sequence from Lake Erie south to the vicinity of Chillicothe, Ohio. The black Ohio Shale underlies the area in thicknesses ranging from 350 to 600 feet (Wallace, and others, 1977). The organic content of the shale is high for the Appalachian basin, in the range of 10 to 15 percent of the shale by volume. However the maturation level of the shale as determined by the CAI is low, about 1.0 to 1.5, which indicates that the shales have not attained maturation temperatures in the range for maximum oil or gas generation. The area is structurally simple and lacks either large-scale normal or thrust faults. Locally, the regional joint pattern has been enhanced by rebound from loading of the area by Pleistocene glacial ice.

Figure 2.--Natural gas plays in the Appalachian basin.

1. North-Central Ohio
2. Western Lake Erie
3. Eastern Lake Erie
4. Plateau Ohio
5. Eastern Ohio
6. Western Penn-York
7. Southern Ohio Valley
8. Western Rome Trough
9. Tug Fork
10. Pine Mountain
11. Plateau Virginia
12. Pittsburgh Basin
13. Eastern Rome Trough
14. New River
15. Portage Escarpment
16. Cattaraugus Valley
17. Penn-York Plateau
18. Western Susquehanna
19. Catskill

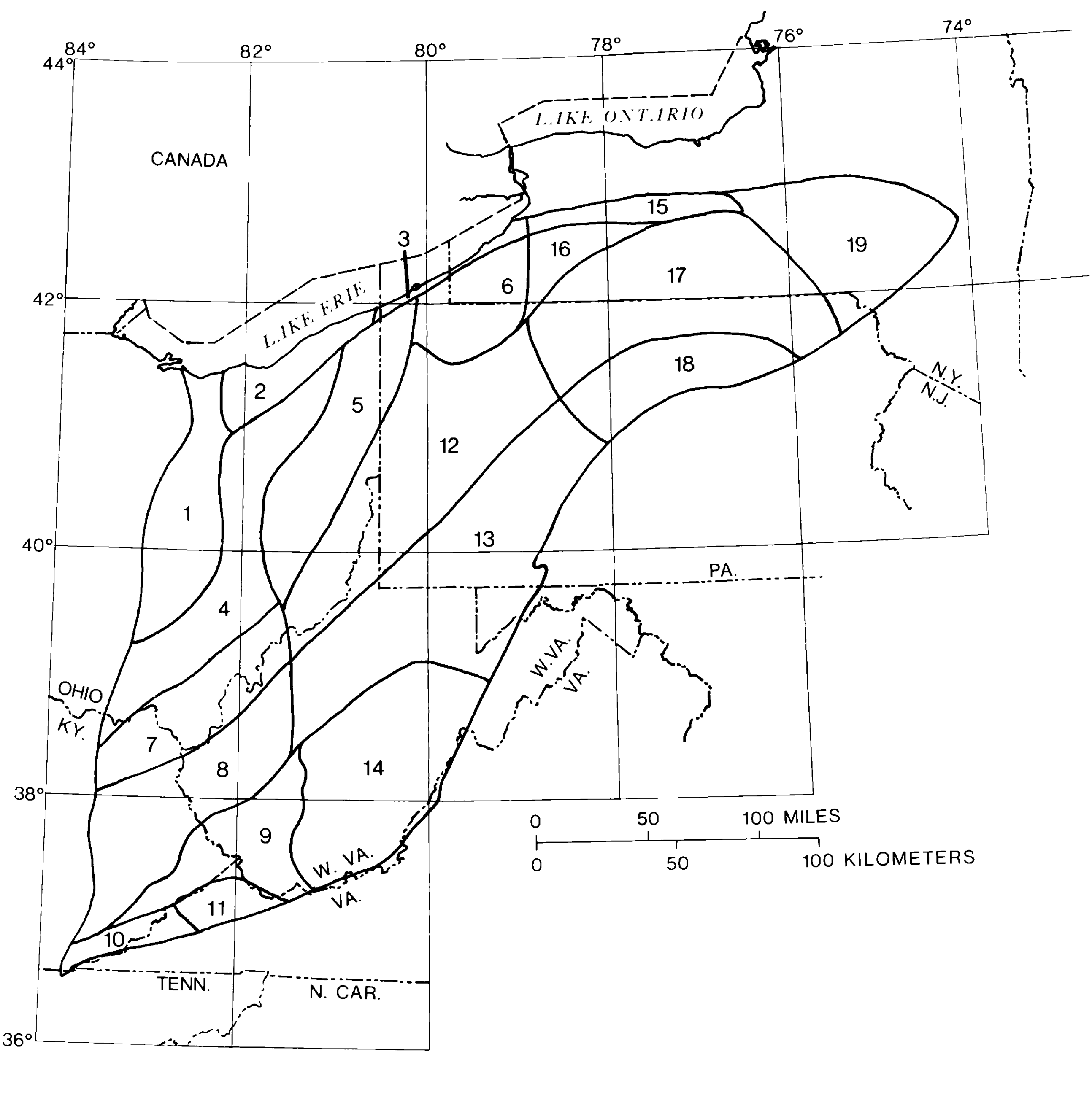

84°
82°
80°
78°
76°
74°
44°
42°
40°
38°
36°
CANADA
LAKE ONTARIO
LAKE ERIE
OHIO
KY.
PA.
W. VA.
VA.
N.Y.
N.J.
TENN.
N. CAR.
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
0 50 100 MILES
0 50 100 KILOMETERS

Table 1.--Structural and stratigraphic features of plays for the Appalachian basin

| Plays | Structural | | | | | Stratigraphic | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Glacial rebound | Vertical tectonics | Horizontal tectonics: thrust | Horizontal tectonics: salt flow | None | Thick lobe | Brittle beds | High organic content | Aggregate thickness of black shale in feet |
| 1 | X | | | | | | | X | 350 to 600 |
| 2 | X | | | | | X | | X | 600 ± |
| 3 | X | | | | | | X | | 300 to 400 |
| 4 | | X? | X? | | | X | | X | 450 to 800 |
| 5 | | | X? | X | | | X | | 500 to 900 |
| 6 | | | | X | | | X | | 400 to 600 |
| 7 | | X | | | | | X | X | 200 to 600 |
| 8 | | X | | | | X | X | X | 500 to 1,000 |
| 9 | | X | | | | | X | X? | 400 to 900 |
| 10 | | | X | | | | X | X | 100 to 400 |
| 11 | | | X | | | | X | X | 400 to 600 |
| 12 | | | X | | | | X | | 300 to 600 |
| 13 | | X | X | X? | | | X | | 400 to 900 |
| 14 | | | X | | | | X | | 400 to 1,000 |
| 15 | X | | | X | | | X | | 400 to 1,000 |
| 16 | | | | | X | | X | | 300 to 500 |
| 17 | | | X | X | | X | X | | 600 to 1,000 |
| 18 | | X | X | X | | | | | 600 to 1,400 |
| 19 | | | | | X | | | | 400 to 800 |

Gas in quantitites sufficient for domestic use has been obtained from the gas-shale sequence, particularly in the northern part of the North-Central Ohio play area. Shallow depths to the Devonian shale sequence indicate low reservoir pressures for gas in the shales. This play thus appears to have a moderate potential for shale-gas production.

2. The Western Lake Erie play is the area adjacent to Lake Erie from the vicinity of Norwalk, Huron County, Ohio, east to the Ohio-Pennsylvania border. The Huron Member of the Ohio Shale and the older Rhinestreet Shale Member of the West Falls Formation are present with an aggregate thickness of about 600 feet (Wallace and others, 1977). The Middle Devonian Marcellus Shale is present locally in the eastern part of the play area. The organic content of the shales is moderate, ranging from about 11 percent by volume in the western part of the play to about 5 percent to the east near the State line. The maturation level by the CAI index is below 1.5, which indicates that black shales have not attained temperatures sufficient to release gas or oil in large volumes. The area is structurally simple because it lies north and west of the western limit of the thin-skinned thrusting in the Appalachian basin. The Western Lake Erie play area has been and is rebounding from loading by Pleistocene glacial ice, and the near-surface joints have been accentuated as permeability pathways permitting matrix gas to migrate into the joint system. The effective depth to which the joints have been sprung appears to be about 1,000 to 1,500 feet. The Western Lake Erie play is an area that has produced Devonian shale gas in domestic and small commercial volumes for about 100 years. It is a play area of good potential for additional shale-gas production.

3. The Eastern Lake Erie play is the area along Lake Erie in northwestern Pennsylvania and adjacent to southwestern New York in a belt about 10 miles wide. The Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Shale Member of the West Falls Formation, and the Marcellus Shale are the principal black shales underlying the play (Wallace and others, 1977). Their aggregate thickness is 300 to 400 feet. The organic content of the gas shales is moderate for the Appalachian basin, ranging from 6 to 7 percent of the shale by volume. The maturation level is relatively low, in the CAI 1.5 to 2.0 range, which indicates that much of the organic carbon in the shales remains to be converted to oil and gas. Similar to the Western Lake Erie play, the Eastern Lake Erie play area is also undergoing isostatic rebound from glacial loading, which is enhancing the surface joint system and opening permeability pathways in the shale sequence to depths of 1,000 to 1,500 feet. Gas seeps are common in the play area. The Eastern Lake Erie play differs from the western one in that the eastern one has many beds of siltstone intercalated in the upper part of the Dunkirk Shale Member and in the overlying gray-shale sequence. These hard, brittle beds have been jointed and broken to a greater degree than the softer shales during the loading and unloading of ice during the Pleistocene and Holocene. Fracturing of the hard beds produced a more extensive fracture reservoir system which made the eastern area a slightly better play than its western counterpart. Shale gas has been produced in domestic and commercial quantities from the Devonian shales of the Eastern Lake Erie play area for about 160 years. Several wells drilled into the Devonian-shale sequence in the vicinity of Erie, Pennsylvania, have produced as much as 300 MCF per day after stimulation, which demonstrates a good potential for the gas-shale sequence in the play area.

4. The Plateau Ohio play is an elongate area extending from the Ohio River near Portsmouth, Ohio, northeast to the highlands of Geauga County on the south side of the Lake Erie West play. The Cleveland and Huron Members of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation are the principal black shale units present under the play area (Wallace and others, 1977). Their aggregate thickness ranges from 450 to 800 feet. The organic carbon content is high to moderate, ranging from 11 percent to 7 percent northeastward across the play. The maturation level is relatively low, in the CAI 1.0 to 1.5 range. Much of the organic carbon in the shales remains to be converted to oil or gas or both. The play area is structurally simple. Large faults are not known, although several small gas fields associated with marked surface lineations suggest that fracture porosity has been developed locally, particularly in the southern part of the play area. Although the Plateau Ohio play has a good thickness of shale source beds, the low level of maturation and the absence of extensive structures indicate a low potential for the play.

5. The Eastern Ohio play is an elongate area extending from the southern boundary of the Lake Erie plays south to the northwest corner of Washington County, about 20 miles northwest of Marietta, Ohio. The Huron Member of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation are the main black shales under the Eastern Ohio play area (Wallace and others, 1978; Roen and others, 1978A). The aggregate thickness of the two shales ranges from 500 to 900 feet, although locally some gray shale and siltstone are intercalated in the upper part of the Rhinestreet Shale Member. The organic carbon content of the black shales is moderate, ranging from more than 7 to less than 5 percent by volume. The maturation level is about CAI 1.5 and is slightly greater than in the Plateau Ohio play. The increase in maturation

level is the result of deeper burial of the gas-shale sequence. Although the shales lie in the maturation range in which kerogens are converted into both gas and oil, these beds have not been heated to the range of maximum gas and oil yield. The Eastern Ohio play area lies along the western edge of thin-skinned folding in the Salina salt beds and in adjacent carbonate rocks a short distance below the Devonian gas-shale sequence. Faulting and folding of the gas-shale sequence has produced zones of fracture porosity in the shales and in the brittle, silty-gray shale and siltstone sequence above the black gas shales. Consequently the Eastern Ohio play area appears to have moderate potential for shale gas, particularly close to the western pinch-out of the salt beds where small-scale splay faults may ramp up to the shale sequence.

6. The Western Penn-York play is a semicircular area including part of northwestern Pennsylvania and adjacent southwestern New York, south of the Eastern Lake Erie play. It includes much of the plateau country south of Lake Erie in the upper part of the Allegheny River basin. The Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Shale Member of the West Falls Formation, and the Marcellus Shale of the Hamilton Group are the principal black gas-shales underlying the Western Penn-York play. The shales have an aggregate thickness of 400 to 600 feet. Their organic carbon content is moderate to low, ranging from 4 to 6 percent by volume. The maturation level is moderate, in the CAI 1.5 to 2.0 range. The maturation temperatures have been sufficiently high to generate both gas and oil from the gas shales, but much unconverted organic carbon remains in the source beds. Beds of siltstone are intercalated with, or closely overlie, the black-shale sequence, and locally where the sequence has been broken by minor faulting and folding, considerable fracture porosity has been developed in the sequence of brittle beds. The Western Penn-York play area is structurally simple. A few small

folds and some small-scale faults, which may be associated with the west edge of the thin-skinned tectonic belt, interrupt the southeast regional dip into the Appalachian basin. Considering the thickness of black shale and the presence of brittle-bed fracture-porosity reservoirs, the Western Penn-York play has a moderate potential for shale gas.

7. The Southern Ohio Valley play encompasses the main valley of the Ohio River from the vicinity of Marietta, Washington County, Ohio, southwest to the vicinity of Portsmouth, Ohio, at the mouth of the Scioto River and into northeastern Kentucky to outcrops of the Ohio Shale in Fleming and Rowan Counties. The Cleveland and Huron Members of the Ohio Shale are the principal black shales in the western part of the play; whereas the Cleveland Member of the Ohio Shale is absent by facies change in the eastern part of the play and the Rhinestreet Shale Member of the West Falls Formation is present above the mid-Devonian unconformity at the base of the gas-shale sequence (Roen and others, 1978B). The aggregate thickness of black shale ranges from about 200 feet in the west to about 600 feet in the eastern part of the play. The maturation level is relatively low, ranging from slightly more than CAI 1.0 in the west to slightly more than CAI 1.5 near Marietta at the east end of the play. The increase in maturation to the east is a reflection of increased depth of burial of the gas-shale sequence and the loss of the Cleveland Member of the Ohio Shale at the top of the sequence. The organic content of the black shales ranges from a high of 16 percent by volume eastward to a moderate value of 5 percent at the east end of the play. Throughout most of the play area, laminae and thin beds of siltstone are intercalated in the black-shale sequence; locally the brittle beds are shattered to form fracture-porosity reservoirs. Structurally the area is relatively simple. The regional dip to the east is locally interrupted by small faults and low-amplitude folds,

particularly along the south edge of the play adjacent to the Rome Trough and at the east end of the play area contiguous to the Burning Springs anticline. The presence of an adequate thickness of black and brown shales rich in organic matter and of brittle-bed fracture reservoirs indicates that the Southern Ohio Valley play has a moderate to good potential for shale gas.

8. The Western Rome Trough play is the area containing most of the Big Sandy Gas field of eastern Kentucky and contiguous western West Virginia. The Ohio Shale and the older Rhinestreet Shale Member of the West Falls Formation or their lateral equivalents, the Gassaway and Dowelltown Members of the Chattanooga Shale, are the principal black shales underlying the Western Rome Trough play (Kepferle and others, 1978). The aggregate thickness of the black shales ranges from 500 to 1,000 feet in the play area. The organic content of the black shales is moderate to high for the Appalachian basin, ranging from 5 to 16 percent by volume. The maturation level is low to moderate, ranging from CAI 1.4 to about CAI 1.8. Maturation temperatures were sufficient to generate both oil and gas from organic matter in the gas-shale sequence, particularly in the central and eastern parts of the play area. Vertical tectonics, repeated rejuvenation of the normal faults of the Rome Trough fault system in the late Paleozoic, shattered the gas shale and produced the extensive fracture reservoir system of the Big Sandy gas field. Without the extensive natural fracture system the gas shales are not capable of yielding gas in commercial quantities. The Western Rome Trough play contains thick beds of black shale rich in organic detritus, an extensive natural fracture system, and maturation levels sufficiently advanced to generate much gas from the organic matter in the shale. These conditions are most ideal for the production of shale gas. Commercial volumes of Devonian shale gas have been recovered from the Western Rome Trough play area for the past 60 years, and

the Big Sandy gas field has produced more than 2 trillion cubic feet of gas mainly from the Devonian shale sequence. The play area has a good potential for the production of shale gas.

9. The Tug Fork play area is south of the Western Rome Trough play and underlies much of the high Appalachian Plateau from Harlan County, Kentucky, northeast to the vicinity of Charleston, Kanawha County, West Virginia. The play area centers in the drainage area of the Tug Fork of the Big Sandy River along the Kentucky-West Virginia border. The Huron Member of the Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation are the principal black shales in the Tug Fork play area. The aggregate thickness of the black shales ranges from about 400 to 900 feet and the organic content of the sequence is moderate, ranging from a maximum of about 10 percent in Harlan County eastward to a minimum of 5 percent in Kanawha County. The maturation level is moderate, ranging from CAI 1.5 to slightly more than CAI 2.0. The rocks of the gas-shale sequence are in the oil-and-gas-generating maturation range. In most of the Tug Fork play area, a 120- to 150-foot sequence of siltstones and sandstones of the Bedford Shale and Berea Sandstone of Late Devonian and Early Mississippian age directly overlies the gas-shale sequence. These brittle beds have been fractured in part by the effects of subsidence along the Rome Trough and in part by thrusting during the Alleghenian orogeny at the close of the Paleozoic Era. Locally they form fracture reservoirs that contain gas, which migrated from the subjacent gas-shale sequence. The upper part of the Huron Member of the Ohio Shale grades eastward into a sequence of siltstone and shale. Where fractured in the vicinity of small-scale faults, the brittle beds in the sequence form local fracture-porosity reservoirs. The shale sequence is also fractured but not as greatly as in the Rome Trough plays. However, the combination of fracture

reservoirs in the shale sequence and in the associated brittle beds suggest that the Tug Fork play area has a moderate to good potential for producing shale gas.

10. The Pine Mountain play is confined to the Pine Mountain thrust block of southwestern Virginia, southeastern Kentucky, and adjacent Tennessee. The Ohio Shale and the Rhinestreet Shale Member of the West Falls Formation or their equivalents, the Gassaway and Dowelltown Members of the Chattanooga Shale, are the main black shales underlying the Pine Mountain play. The aggregate thickness of black shales ranges from 100 to 400 feet, and the organic content is high for the Appalachian basin, ranging from 9 to 15 percent by volume. The degree of maturation is moderate in the range of CAI 1.5 to CAI 2.0. The rocks of the gas-shale sequence are within the temperature range for generating both gas and oil from their contained organic matter. The Pine Mountain play area is dominated by thin-skinned tectonics. A large near-bedding décollement moved the Pine Mountain thrust block 4 to 12 miles to the northwest. The master fault is near the base of the Devonian gas-shale sequence, and many small faults splay upward to shatter and fracture the shales above the décollement. The faulting produced many pockets of fracture porosity charged with gas. Gas flows freely from the reservoir when it is opened by a well, but the volume of gas is small. The well may cease producing in a few hours or a few days. However, the Berea Sandstone overlies the gas-shale sequence in the eastern part of the play area and forms an excellent fracture reservoir because it was extensively broken during Alleghenian thrusting. The Mississippian age shale above the Berea seals the gas in the fracture-reservoir rock. Because the individual fracture-porosity reservoirs appear to be small and not interconnected to any great extent in the area where the Berea Sandstone is absent, the Pine Mountain play appears to have only moderate potential for producing shale gas.

11. The Plateau Virginia play area underlies most of the coal-bearing high plateau of southwest Virginia contiguous to the east side of the Pine Mountain play area. The Russell Fork fault separates the two play areas. The main black shales in the Plateau Virginia play are the Cleveland and Huron Members of the Ohio Shale and the older Rhinestreet Shale Member of the West Falls Formation. The aggregate thickness of the black shales ranges from 400 to 600 feet. The organic content is moderate, ranging from 4 to 7 percent of the shale by volume. The maturation level is moderate for the Appalachian basin, ranging from CAI 1.5 to CAI 2.0. The rocks are within the maturation range to yield both gas and oil from their contained organic matter. The gas-shale sequence is overlain by about 100 feet of siltstone and sandstone of the Berea. These hard rocks, which were considerably fractured by thrusting and folding associated with the Alleghenian orogeny, are an extensive fracture reservoir which traps and holds gas migrating from the fractured black-shale sequence below. The Lower Mississippian shales above the Berea Sandstone seal the gas within the Berea reservoir. Because of the extensive fracture-porosity reservoir closely associated with good source rocks in the gas-shale sequence, the Plateau Virginia play appears to have a good potential for producing shale gas. It seems to be better than the potential of the Pine Mountain play area.

12. The Pittsburgh basin play underlies much of western Pennsylvania north of the Eastern Rome Trough play and extends south along the Ohio River Valley to the north end of the Burning Springs anticline near Marietta, Ohio. The gas-shale sequence is buried to depths of 5,000 to 7,500 feet in the Pittsburgh basin play. The older black shales, the Rhinestreet Shale Member of the West Falls Formation, the Geneseo Shale Member of the Genesee Formation, and the Marcellus Shale of the Hamilton Group, are the main gas

shales in the play area (Roen and others, 1978B). Their aggregate thickness ranges from 300 to 600 feet. The organic content is relatively low for the gas-shale sequence, in the range of 4 to 6 percent of the shale by volume. The maturation level is moderate to moderately high, about CAI 2.0. The play is near the west edge of the area dominated by thin-skinned thrusting. Zones of fracture porosity have developed locally in the black shales and associated silty shale and thin siltstone sequences. Because the faulting and folding in the Pittsburgh basin play are relatively small scale, fracture porosity has not developed as extensively in this play as it has to the east and south. Vertical tectonics of the Rome Trough do not appear to have affected the Pittsburgh basin play area. As a result of the absence of extensive fracture reservoirs in the gas-shale sequence, the Pittsburgh basin play area has a poor potential for producing shale gas.

13. The Eastern Rome Trough play covers the extension of the Rome Trough east of the Burning Springs anticline in northern West Virginia and the contiguous parts of western Pennsylvania. The principal black shales in the play area are the Rhinestreet Shale Member of the West Falls Formation, the Geneseo Shale Member of the Genesee Formation, and the Marcellus Shale of the Hamilton Group. The aggregate thickness of the black shales ranges from about 400 to more than 900 feet. The organic content of the black shales is low for the Appalachian basin, in the range of 3 to 5 percent by volume. Because the gas shales are buried to depths of 5,000 to 8,000 feet below sea level, their level of maturation is moderate to high for gas shales, in the range of CAI 1.5 to CAI 3.0. As in the Western Rome Trough play, vertical tectonics produced an extensive fracture system in the black shales and associated hard beds. In the Eastern Rome Trough play thin-skinned thrusting of the Alleghenian orogeny has been superimposed upon the vertical tectonics.

Extensive fracture porosity has been developed associated with splay faults and anticlinal folds produced by thin-skinned thrusting. Although the organic content of the gas shales is relatively low, the greater level of maturation and the abundance of fracture-porosity reservoirs in both the gas shales and associated hard-bed sequences suggest that the Eastern Rome Trough play has a good potential for producing shale gas.

14. The New River play area underlies the Appalachian Plateau of southern West Virginia east of the Tug Fork play and south of the Eastern Rome Trough play. The Geneseo Shale Member of the Genesee Formation and the Marcellus Shale of the Hamilton Group are the main black shales in the play. They have an aggregate thickness of 400 to 1,000 feet and a relatively low organic content, in the range of 3 to 5 percent of the shale by volume. Their maturation level is relatively high for gas shales, in the range of CAI 2.0 to CAI 3.0 which is beyond the temperature for the maximum generation of oil. Structurally the New River play is dominated by thin-skinned thrusting which has formed extensive zones of fracture porosity in the gas shales and associated brittle-bed sequences in the vicinity of splay faults, ramps, and anticlines. Locally small splay faults may also be associated with the troughs of synclines. The depth to the gas shale sequence, the greater degree of maturation, and the relatively low organic content of the Devonian shales indicate that the New River play has a low potential for shale gas production.

15. The Portage Escarpment play underlies the Portage Escarpment and adjacent highland from the meridian of Buffalo east across the Genesee Valley and the Finger Lakes district to the meridian of Syracuse and Tully. The Dunkirk Shale Member of the Perrysburg Formation, the Rhinestreet Shale Member of the West Falls Formation, the Middlesex Shale Member of the Sonyea Formation, the Renwick and Geneseo Shale Members of the Genesee Formation, and

the Marcellus Shale of the Hamilton Group are the main black shales underlying the play area (Wallace and others, 1977). The aggregate thickness of these several black shales ranges from 400 to 1,000 feet. The organic content is relatively low, ranging from 3 to 6 percent. The maturation level is moderate, in the CAI 2.0 to CAI 2.5 range, indicating that maturation temperatures were near the upper level for the generation of oil but well within the limits for generation of natural gas. The area has been depressed by the weight of a thick sheet of Pleistocene glacial ice and is now isostatically rebounding from the release of the weight. Consequently, the regional joint system is being sprung or enhanced which increases the permeability pathways by which matrix gas escapes. In the area of the larger Finger Lakes, the rocks of the Portage Escarpment play have also been affected by thin-skinned thrusting in the salt beds of the Salina Formation. Splay faults rising through the Lower and Middle Devonian rocks have formed extensive zones of fracture porosity in the gas shales and in the associated sequences of brittle beds. Consequently, although the quantity of organic matter in the Devonian gas shales is relatively low and the maturation moderately high, the gas shales of the Portage Escarpment play appear to have a good potential for the production of shale gas.

16. The Cattaraugus Valley play underlies much of the drainage basin of Cattaraugus Creek in western New York. It lies south of the western part of the Portage Escarpment play and east of the Western Penn-York play. The Dunkirk Shale Member of the Perrysburg Formation and the Rhinestreet Shale Member of the West Falls Formation are the principal black shales underlying the play area. The aggregate thickness of the black shales ranges from 300 to 500 feet and the organic content of the shales is moderate to low in the range of 3 to 6 percent. The maturation level is moderate in the range of CAI 1.5

to CAI 2.2. The gas shales are more deeply buried in the Cattaraugus Valley play than in the Portage Escarpment play. The near-surface effects of rebound from glacial loading do not appear to have enhanced the joint systems in the Cattaraugus Valley play. The play also lies north and west of the area of thin-skinned tectonics in the Appalachians. Consequently, the Cattaraugus Valley play lacks the tectonics needed to form much fracture porosity. In the absence of extensive fracture porosity, the Cattaraugus Valley play has a poor potential for the production of shale gas.

17. The Penn-York Plateau play is the area underlying much of the high plateau of south-central New York and adjacent north-central Pennsylvania from the meridian of Olean, New York, and Bradford, Pennsylvania, east to the meridian of Scranton, Pennsylvania. The Geneseo Shale Member of the Genesee Formation and its lateral equivalent, the Burket Member of the Harrell Shale of Late Devonian age, and the Marcellus Shale of the Hamilton Group of Middle Devonian age are the main black shales in the Penn-York Plateau play. Locally in south-central New York, the Middlesex Shale Member of the Sonyea Formation may be sufficiently thick to be a source bed. The aggregate thickness of the black shales ranges from 600 to 1,000 feet. The organic content of the shales is generally low, in the range of 3 to 5 percent by volume. The maturation level is moderate to high for the gas shales, ranging from about CAI 2.0 in the west to CAI 3.0 in the east. Maturation temperatures were mainly in the dry-gas range. Structurally most of the Penn-York Plateau play is dominated by thin-skinned tectonics. Décollements occur mainly in the Silurian salt sequence, and splay faults ramp into the Lower, Middle, and Upper Devonian rocks to develop extensive zones of fracture porosity in the gas shales and associated sequences of brittle beds. Normal faults associated with several of the larger of the Finger Lakes, which project into the play area from the

adjacent Portage Escarpment play, suggest that vertical as well as compressive forces have locally produced fracture porosity. Although the organic content of the shales is relatively low and the maturation level is moderately high, the abundance of fracture porosity suggests that the Penn-York Plateau play has a moderate potential for shale gas production.

18. The Western Susquehanna play underlies much of the West Branch and a smaller segment of the East Branch of the Susquehanna River in north-central Pennsylvania. The Burket Member of the Harrell Shale and the Marcellus Shale of the Hamilton Group are the main gas shales of the play. The aggregate thickness of the black shales ranges from 600 to more than 1,400 feet. The organic content of the shales is low, ranging from 3 to 5 percent by volume. Because the Devonian gas shales are relatively deeply buried adjacent to the Allegheny Front, the maturation level is high for gas, in the range of CAI 2.5 to CAI 3.5. The Western Susquehanna play area has been subjected to vertical tectonics along the eastern extension of the Rome Trough as well as to the compressive stresses of thin-skinned tectonics of the Alleghenian orogeny. The rocks have been greatly fractured, particularly in the vicinity of splay faults and antithetic faults rising from décollements in the evaporites of the Silurian salt sequence. However, because of the low organic content of the gas shales and the relatively high degree of maturation of the shales, the Western Susquehanna play has only a poor potential for producing shale gas.

19. The Catskill play area underlies the Catskill Mountains of southeastern New York and the peripheral highlands in extreme northeastern Pennsylvania. The Marcellus Shale of the Hamilton Group is the only Devonian gas shale in the play. The black shales in the Hamilton Group have an

aggregate thickness of 400 to 800 feet. Their organic content is relatively low, in the range of 3 to 5 percent by volume. The maturation level is high, in the range of CAI 3.0 to CAI 4.0. Structurally the Catskill play is relatively simple. Normal faults which cut the Ordovician rocks south of the Adirondack Mountains do not appear to have broken the Devonian rocks, and the thin-skinned faults and folds of the Penn-York Plateau and the eastern part of the Portage Escarpment plays are not present in the Catskill play. Consequently, the Catskill play has only a poor potential for producing shale gas because the shales have a relatively low organic content and a relatively high thermal maturatity, and they lack extensive fracture porosity systems.

## Method of Calculation

The amount of gas in each play was calculated using the equation:

$$G = \underbrace{\left[ \phi\text{macro} \times TH_s \times \frac{P_r}{P_s} \times \frac{T_s}{T_r} \times \frac{1}{z} \times \text{area} \times (5280 \text{ ft/mi})^2 \right]}_{\text{macrofracture gas}}$$

$$+ \underbrace{\left[ \phi\text{micro} \times TH_s \times \text{area} \times (5280 \text{ ft/mi})^2 \right]}_{\text{microporosity gas}}$$

$$+ \underbrace{\left[ \text{SOR} \times \text{Org} \times TH_s \times \text{area} \times (5280 \text{ ft/mi})^2 \right]}_{\text{sorbed gas}}$$

where:

$G$ = volume of gas in the area (in cubic feet)

$\phi$macro = average macrofracture porosity as a fraction of the total volume (at reservoir conditions)

$TH_s$ = average thickness of organic-rich shale (in feet)

$P_r$ = average reservoir pressure (in psia)

$P_s$ = standard pressure (14.73 psia)

$T_r$ = average reservoir temperature (in degrees Rankine)

$T_s$ = standard temperature (520° R)

$z$ = gas deviation factor (0.9)

area = area (in square miles)

$\phi$micro = average content of microporosity gas at standard temperature and pressure as a fraction of rock volume

SOR = average volume ratio of sorbed gas to organic content (gas volume at standard temperature and pressure)

Org = average organic content as a fraction of rock volume

The equation can be broken down into three parts for separate calculation of each of the three types of gas.

Two major factors affect the use of point-estimate input to the equation:

1. there is only very limited data for most of the assessed area, especially in the eastern part of the basin, and
2. what limited data that does exist is subject to large sampling errors and differences in interpretation.

These two factors make a deterministic point-estimate of very limited value. The approach chosen for this analysis was a probabilistic Monte Carlo technique. The Monte Carlo technique allows the analyst to recognize and estimate variations or ranges of potential values for the variables.

Using the Monte Carlo technique, each variable from the equation is entered in the form of a probability distribution. Each of these distributions is randomly sampled and the equation is solved to give a value for volume of gas. This procedure is repeated many (in this study, one thousand) times and the resulting gas-volume values are used to construct an empirical probability distribution for amount of gas. Because the equation can be broken into three parts according to categories of gas, the procedure can provide probability distributions for each category as well as for the total amount of gas.

The result of this approach is a probability distribution or interval estimate for the three components and for the total equation. This allows an analysis of sensitivity and of variability of the potential amounts of gas.

In an area of sparse data, the probability distribution of a Monte Carlo approach yields much more potential insight than a deterministic point estimate.

## Derivation of Input

The main published sources of information used in estimating the input distributions are listed in the Selected References. In order to better estimate the uncertainty in each variable, the input distributions were subjectively synthesized from various published and unpublished materials.

The basic configuration of gas shales in the basin was taken from published cross sections (Kepferle and others, 1978; Roen and others, 1978a, 1978b; Wallace and others, 1977, 1978; West, 1978) as well as unpublished isopach and structure maps by Roen. These maps and cross sections were used to estimate average depths which, when combined with subjective pressure and temperature gradients, yielded average reservoir pressures and temperatures. The thickness of organic-rich shale was based on maps by de Witt and others (1975), Schmoker (1980, 1981), and Roen (unpub. mapping).

The organic content of the shale was estimated for the western part of the basin using mainly the map by Schmoker (1981). For the eastern part of the basin, data were taken from Claypool and others (1980), Claypool and Stone (1979), and other unpublished data.

The microporosity- and sorbed-gas contents were estimated, as previously explained, using data from off-gassing experiments. Unpublished data from the U.S. Geological Survey, the Battelle Columbus Laboratories, and the Mound Facility were used for this purpose. Because of sparse data, the estimate of macrofracture porosity was very subjective. Sources such as Smith and others (1979) provided some help.

The gas deviation factor (z) was calculated using 60 U.S. Geological Survey gas analyses. Gas deviation factors were calculated for each, using the pseudocritical method, and then one average figure was used for the entire basin.

This information was subjectively synthesized by members of the appraisal team who then each made separate estimates of the input distributions. The uncertainty in the estimate for each variable was assumed to be approximately normally distributed. The normal distributions estimated by the individual team members were then averaged to give one set of normal distributions to be used as input to the program.

Within the program, these normal distributions were approximated by linear interpolation between seven fractiles (.01, .10, .25, .50, .75, .90, and .99). The normal distribution was truncated at each tail by treating the .01 and .99 fractiles as minima and maxima. Negative values were excluded by changing any negative values of the seven mentioned fractiles to zero.

## RESULTS OF STUDY

Table 2 presents estimates of the in-place natural gas resources of the Appalachian Devonian shale. For each of the nineteen plays, the probability distribution for amount of gas in the play is represented by the 95th fractile ($F_{95}$), the 5th fractile ($F_5$), and the mean estimate. The 95th fractile is a low estimate with a corresponding 95 percent chance of there being greater than that amount. The 5th fractile is a high estimate with only a 5 percent chance of there being greater than that amount.

Similarly, the 95th fractile, 5th fractile, and mean estimate are given for the entire basin. In many other studies (for example, Miller and others, 1975, and Dolton and others, 1981) subunits are fairly independent. In <u>those</u>

cases the columns of fractiles are not additive. In the present study, however, the individual plays are strongly dependent. The simplest (linear) relationship between distributions was assumed. In this case, unlike the other cases, the columns of fractiles are additive.

Figure 3 presents the qualitative assessments of potential reported in the "Play Area Delineation" section (pages 12 to 29). Unlike the estimates of in-place resources in table 2, the assessments in figure 3 do take into account recoverability and economics. Thus, for example, play 12 is estimated to have a very large amount of gas in-place, but because of probably low recoverability, the play has been assessed as having poor potential for shale-gas production.

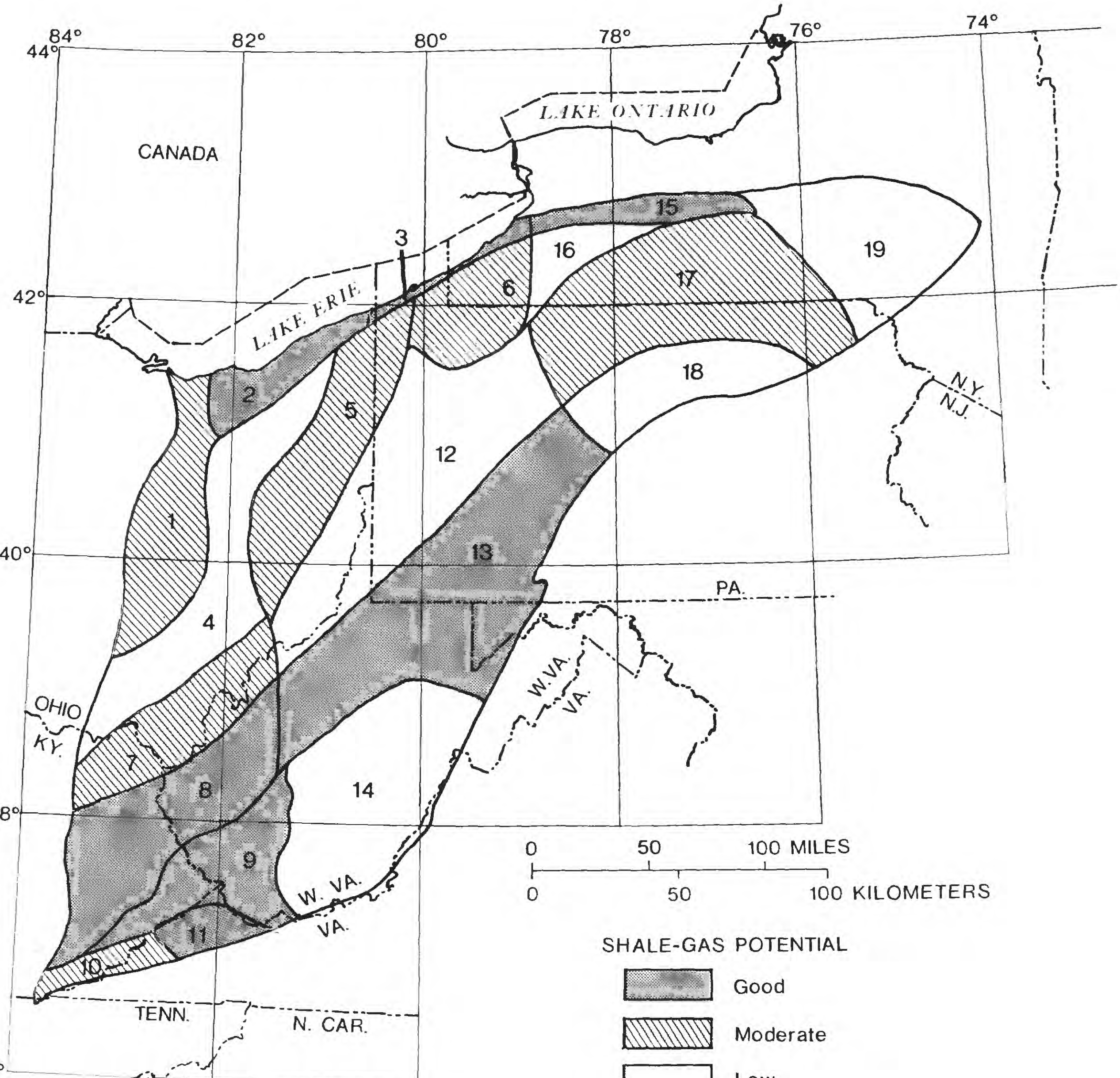
Table 2.--Estimates of in-place natural gas resources in the Devonian shale of the Appalachian basin.
[All tabulated values were rounded from original numbers. Therefore, totals may not be precisely additive]

| Play | Natural Gas Resources (trillions of cubic feet) low $F_{95}$ 1/ | high $F_5$ 1/ | mean |
|---|---|---|---|
| 1. North-Central Ohio | 17.9 | 34.2 | 25.9 |
| 2. Western Lake Erie | 21.7 | 31.3 | 26.5 |
| 3. Eastern Lake Erie | 2.1 | 3.3 | 2.7 |
| 4. Plateau Ohio | 44.4 | 76.2 | 59.9 |
| 5. Eastern Ohio | 35.2 | 55.1 | 44.7 |
| 6. Western Penn-York | 20.4 | 28.2 | 24.3 |
| 7. Southern Ohio Valley | 19.7 | 36.2 | 27.7 |
| 8. Western Rome Trough | 38.0 | 74.0 | 56.0 |
| 9. Tug Fork | 13.7 | 25.9 | 19.7 |
| 10. Pine Mountain | 10.7 | 18.7 | 14.6 |
| 11. Plateau Virginia | 3.9 | 10.2 | 7.1 |
| 12. Pittsburgh Basin | 76.8 | 129.9 | 102.1 |
| 13. Eastern Rome Trough | 70.7 | 132.5 | 100.3 |
| 14. New River | 38.5 | 91.7 | 63.1 |
| 15. Portage Escarpment | 8.5 | 21.3 | 14.6 |
| 16. Cattaraugus Valley | 10.4 | 23.2 | 16.6 |
| 17. Penn-York Plateau | 98.1 | 195.2 | 146.0 |
| 18. Western Susquehanna | 24.1 | 67.7 | 44.9 |
| 19. Catskill | 22.1 | 75.8 | 47.6 |
| Entire basin | 577.1 | 1130.8 | 844.2 |

1/ $F_{95}$ denotes the 95th fractile; the probability of more than the amount $F_{95}$ is 95 percent. $F_5$ is defined similarly. Because of dependency between plays, these fractiles (unlike those in many other studies) are additive.

Figure 3.--Qualitative assessment of production potential from Devonian Shales of the Appalachian basin.

1. North-Central Ohio
2. Western Lake Erie
3. Eastern Lake Erie
4. Plateau Ohio
5. Eastern Ohio
6. Western Penn-York
7. Southern Ohio Valley
8. Western Rome Trough
9. Tug Fork
10. Pine Mountain
11. Plateau Virginia
12. Pittsburgh Basin
13. Eastern Rome Trough
14. New River
15. Portage Escarpment
16. Cattaraugus Valley
17. Penn-York Plateau
18. Western Susquehanna
19. Catskill


84°
82°
80°
78°
76°
74°
44°
42°
40°
38°
36°
CANADA
LAKE ONTARIO
LAKE ERIE
OHIO
KY.
PA.
N.Y.
N.J.
W.VA.
VA.
W. VA.
VA.
TENN.
N. CAR.
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
0
50
100 MILES
0
50
100 KILOMETERS
SHALE-GAS POTENTIAL
Good
Moderate
Low

## COMPARISON WITH OTHER STUDIES

Some recent estimates of gas resources of the Devonian shale in the Appalachian basin are presented in table 3. Except for the estimate of the Federal Energy Regulatory Commission (1978), there is substantial agreement among the estimates in spite of the fact that very different assumptions and methods were used in the various studies.

Table 3.--Comparison of estimates of in-place natural gas resources in the Devonian shale of the Appalachian basin (in trillions of cubic feet).

| | |
|---|---|
| Smith (1978) | 206-903 |
| Federal Energy Regulatory Commission (1978) | 285 |
| Kuuskraa and Meyer (1980) | 400-2,000 |
| National Petroleum Council (1980) | 225-1861 |
| This report | 577-1131 (844 mean) |

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