PLAY MOf: MIDDLE ORDOVICIAN FRACTURED CARBONATES

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Location

Porosity development along faults and fractures characterize the Middle Ordovician fractured carbonate play. Reservoirs of this play are found predominantly associated with large structural features. Fields of this play have been identified along the faulted northwestern and western margin of the Appalachian basin (particularly south-central Ontario, northwestern through central-eastern Ohio, north-central Tennessee, and central Kentucky), in eastern Kentucky within the Rome trough, and in western Virginia associated with the Pine Mountain fault system (Figures MOf-1, MOf-2).

A number of fields are located just west of the crest of the Cincinnati arch and, therefore, are not in the Appalachian basin proper. These include Albany Consolidated, Ashburn Creek South, Chicken Gizzard, Flat Creek, Ida Consolidated, and Mason Consolidated. These fields are included on the maps and in the discussion of this play for completeness; however, they were not included in the calculations for the resources and reserves.

Production History

The Appalachian basin has had a long history of oil and gas production from fractured Ordovician carbonate reservoirs. In 1829, the first gusher of record in North America, the "American Oil Well," was drilled in Cumberland County, Kentucky. This well, not intended to be an oil well, caught fire and flowed into the Cumberland River, setting the river on fire for several miles (Jillson, 1919a). Commercial production of gas from the Middle Ordovician Trenton Limestone began in 1884 in northwestern Ohio near the city of Findlay in Hancock County. The discovery well was drilled by the Findlay Natural Gas Company on the farm of Dr. Charles Oesterlin. The drilling of a well to the Trenton was encouraged by surface seepages of gas in the area. This discovery set off a major drilling boom in northwestern Ohio that spread to eastern Indiana and resulted in the successful giant Lima-Indiana trend (Wickstrom, Gray, and Stieglitz, 1992). This boom resulted in the drilling of an estimated 100,000 wells and production of approximately 485 million barrels of oil and more than 1 tcfg. Most of this giant field is not considered to be in the Appalachian basin, so will not be discussed at length in this volume (for more, see Keith and Wickstrom, 1992). However, the success which Findlay, Ohio, had in luring industry there with cheap fuel provided the impetus for many other discoveries to the east in the Appalachian basin.

From 1885 through the 1930s, exploratory drilling continued on the northwesternmost flank of the Appalachian basin, east of the Lima-Indiana trend. This era of drilling resulted in the discovery of 12 gas fields that produced from fractured Trenton and Black River limestones (some of which produced both oil and gas) in the Appalachian basin. Most of this production was intended for residential and small industrial use, and was distributed by small companies formed by local citizens. Because of this type of development, very few individual wells were gauged, nor was much of the end-use volume measured. Drillers produced as much as they could from the wells, depleting the pressure. Gas from the wells was piped directly to customers, who were charged by the month depending upon the type and number of devices using the gas (Bownocker, 1906). Therefore, gas production figures for these early fields are mostly nonexistent.

Beginning in August 1941 and continuing through the end of 1943, four gas wells were drilled on the "Concord Anticline" in Clinton County, Kentucky. The best producing of these wells, the No. 1 S.F. Stockton, completed in 1943, initially produced 3 MMcfg/d from the Sunnybrook (Lexington Limestone). These wells were subsequently shut-in with hope that a pipeline would be constructed to the area (Diamond, 1944). This hope was not fulfilled and these wells were eventually plugged.

The Rose Hill and Ben Hur fields of Lee County, Virginia, (Figure MOf-2) were discovered in 1942 and 1963, respectively. These fields produce from the Ordovician Trenton Limestone. Although these fields have produced mostly oil, there is associated gas in the wells that is often flared because of a lack of pipelines. The Stonewall Gas Co. No.1 Cope well in the Rose Hill field tested at 4,500 Mcfg/d (Miller and Fuller, 1954; Bartlett, 1988).

In September 1945, the No. 1 Luther Hay (Clinton County, Kentucky) began producing an estimated 3,000 to 4,000 barrels of oil per day and a considerable amount of gas out of a fractured zone within the High Bridge Group (Jillson, 1946). Although it caught fire, the success of this oil well set off a drilling boom that lasted several years in southern Kentucky and northern Tennessee, resulting in the discovery of several additional small pools that have subsequently been combined into the Concord Consolidated field (Figure MOf-2).

In the 1950s, gas production was established from two pools (Acton and Hornby) in Halton County, Ontario, Canada. A little over 500 MMcfg was produced from these pools before being abandoned in the early 1970s (Bailey Geological Services, Ltd. and Cochrane, 1984).

Beginning in the early 1960s, another drilling boom took place in north-central Ohio, spurred on by the discovery of oil in the Cambrian "Copper Ridge" dolomite in the Morrow Consolidated field (see M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas). This drilling activity led to the discovery of three additional Trenton/Black River fracture-controlled fields and re-ignited interest in some of the older producing areas. The main emphasis during this period of drilling was on oil production; therefore, some gas-prone areas of Trenton/Black River production were ignored or downplayed.

In 1965, production was discovered from the Cambrian Rose Run Sandstone in Holmes County, Ohio. While drilling to the Rose Run and other Knox prospects, a number of discoveries within the lower Black River ("Gull River") and Wells Creek Formation occurred. These discoveries are typically small one-well pools, are commingled with Knox Dolomite production, and appear to be

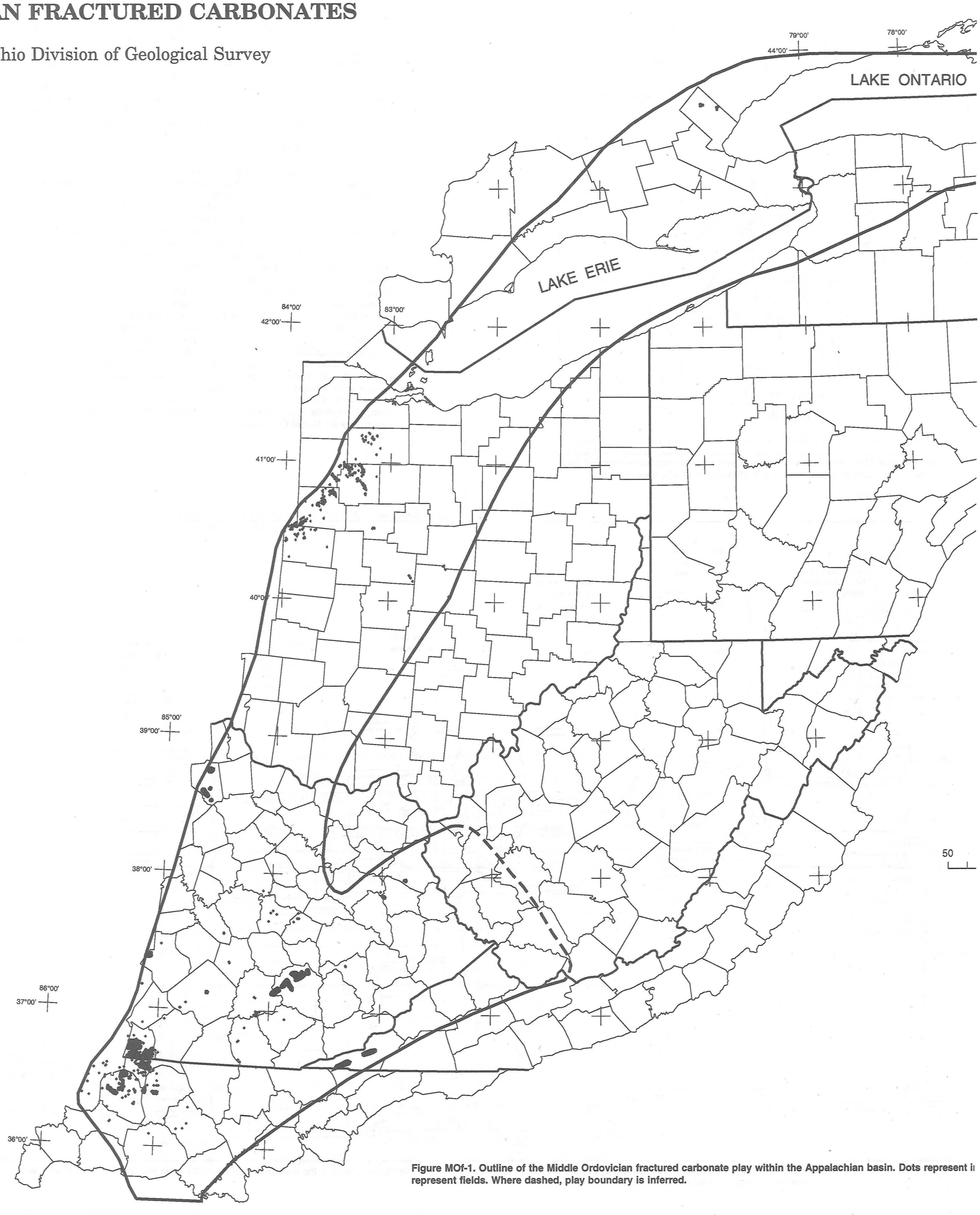

Figure MOf-1. Outline of the Middle Ordovician fractured carbonate play within the Appalachian basin. Dots represent i represent fields. Where dashed, play boundary is inferred.

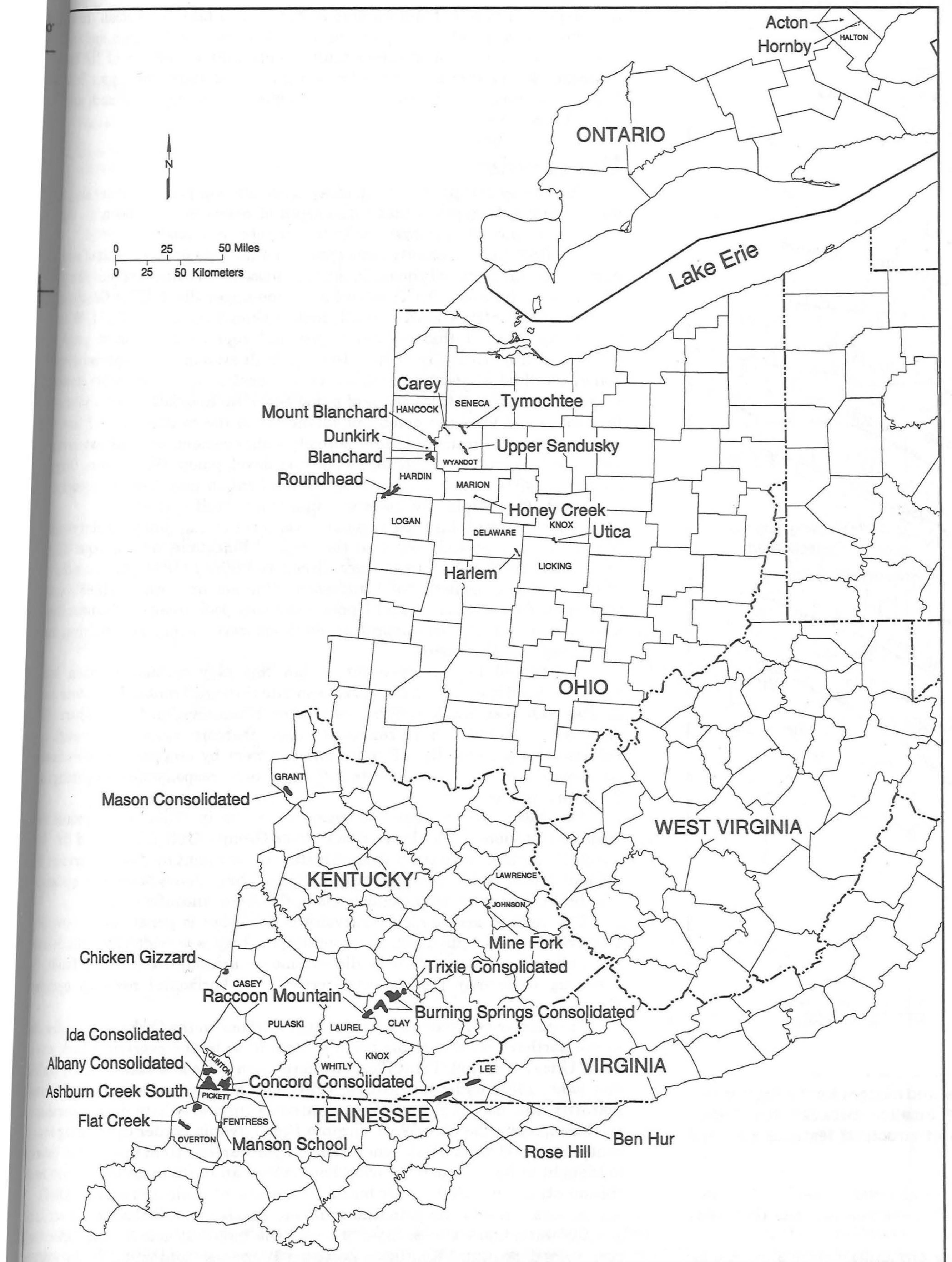

Figure MOf-2. Location of Middle Ordovician fractured carbonate fields mentioned in text or listed in Table MOf-1. Other areas of production illustrated in Figure MOf-1 are not shown.

located along similar fault structures that control the Knox Group production (see M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas). Although there has been production found from this interval in a wide region, only one area to date, the Utica pool of Ohio, has a sufficient number of wells to be classified separately.

During the early to mid-1980s, when prices for both oil and gas were high, drilling activity returned once again to the Trenton/Black River fracture plays of northwestern Ohio. Although a number of prospects were drilled, no new field discoveries were found. However, the Harlem and Honey Creek fields (Figure MOf-2), both mid-1960s discoveries, were developed for their gas potential during this time.

In September 1990, another Ordovician fracture-system discovery occurred in Clinton County, Kentucky (Hamilton-Smith and others, 1990). This well, the Syndicated Options Limited of Austria, No. 9372, Ferguson Brothers, initially produced as much as 400 barrels of oil per hour and recently has begun producing only gas. The large production from this well has set off another drilling campaign in Clinton, Cumberland, and Wayne counties in southern Kentucky and Clay, Fentress, Overton, and Pickett counties in northern Tennessee that still continues. Despite these successes and a large amount of oil production from the area, a reliable market for the produced gas has never been developed. Most gas wells have been allowed to blow down for several days in the hopes that they would begin producing oil. A failure to produce oil resulted in their plugging. Gas produced along with oil is usually flared.

Reliable production figures for this play are generally lacking. However, available figures indicate a cumulative production from this play of at least 44 bcf. Using the analogous production figures from the Albion-Scipio field (Hurley and Budros, 1990) as discussed below yields a cumulative production total of about 120 bcf from this play.

Stratigraphy

The producing units comprising the Middle Ordovician fractured carbonates play are the Utica Shale/Point Pleasant interval, the Trenton Limestone, the Black River Group, and the Wells Creek Formation. Figure MOf-3 illustrates the generalized stratigraphy relevant to this play's discussion, from the Cambrian

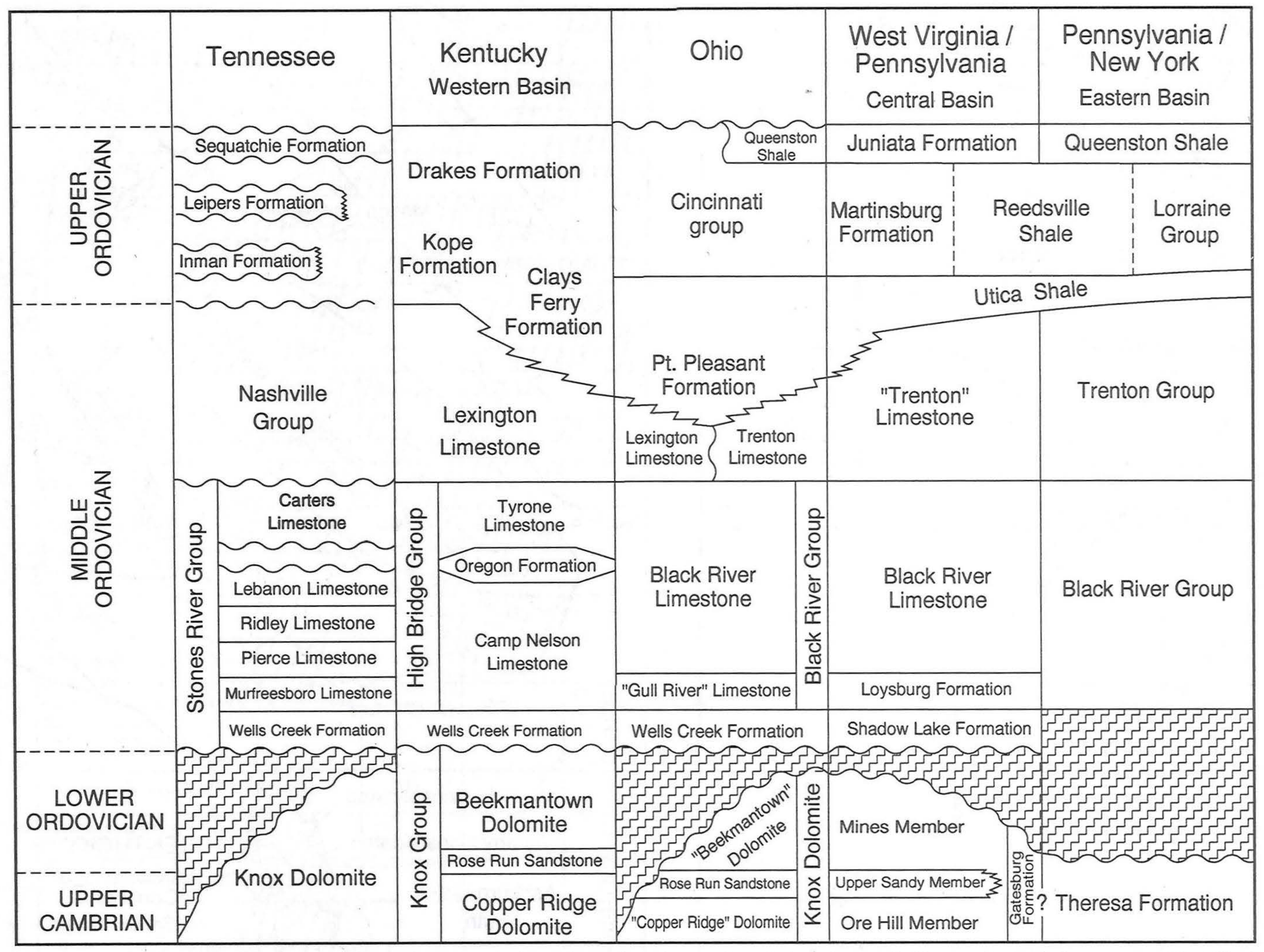

Figure MOf-3. Generalized stratigraphic correlation chart for Upper Cambrian through Upper Ordovician strata. Modified from Janssens (1973; 1977), Rickard (1973), Kentucky Geological Survey (1983), Shaver (1985), Ryder (1992a; 1992b), Wickstrom, Gray, and Stieglitz (1992), Bergstrom and Mitchell (1992), and Riley and others (1993).

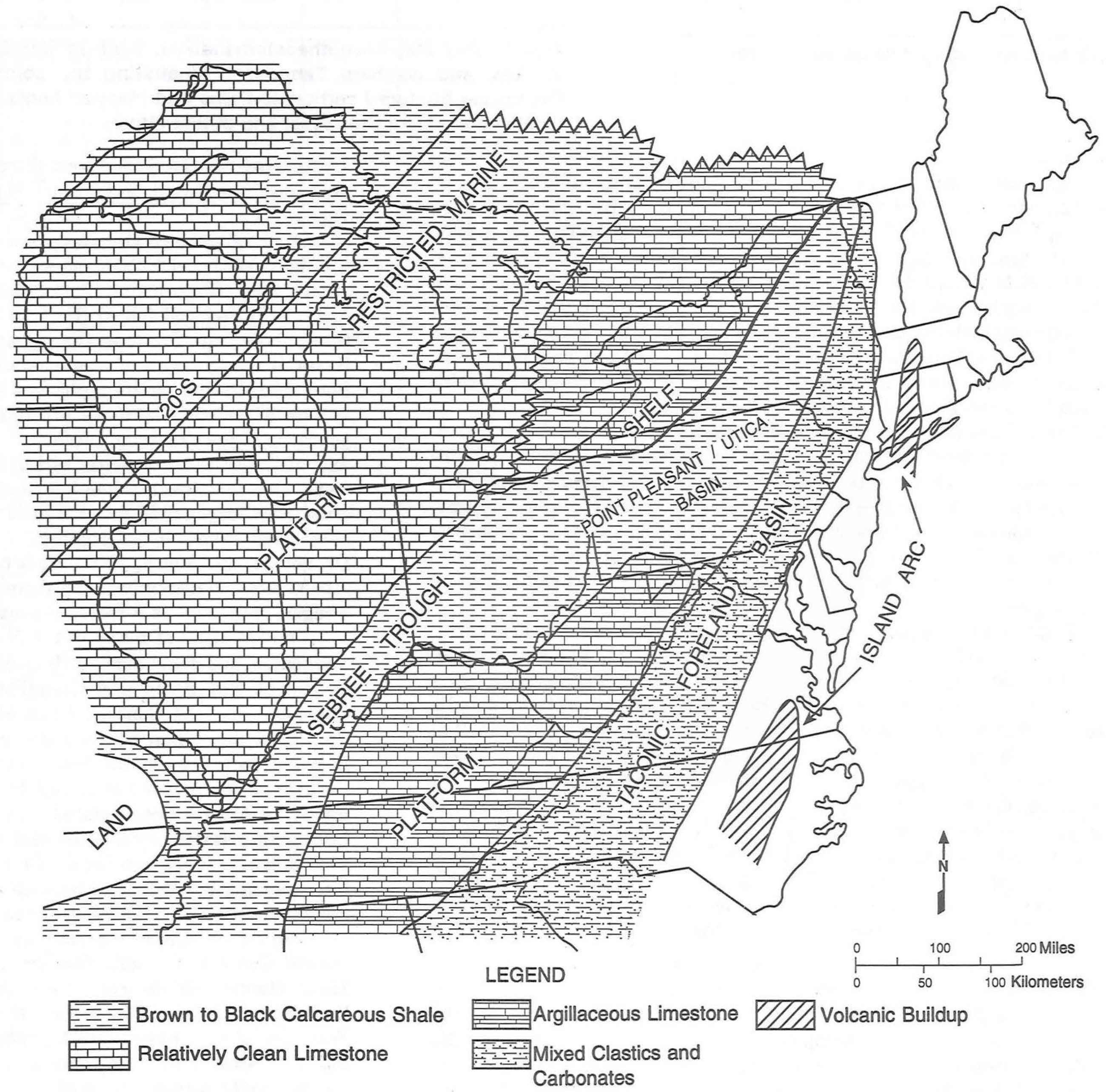

Figure MOf-5. Regional reconstruction of major depositional and tectonic elements present toward the end of Trenton depositional time. The eastern United States was undergoing a compressive pulse of the Taconic orogeny, causing differing water depths and amounts of terrigenous input across the region. Modified from Keith (1988) and Wickstrom, Gray, and Stieglitz (1992).

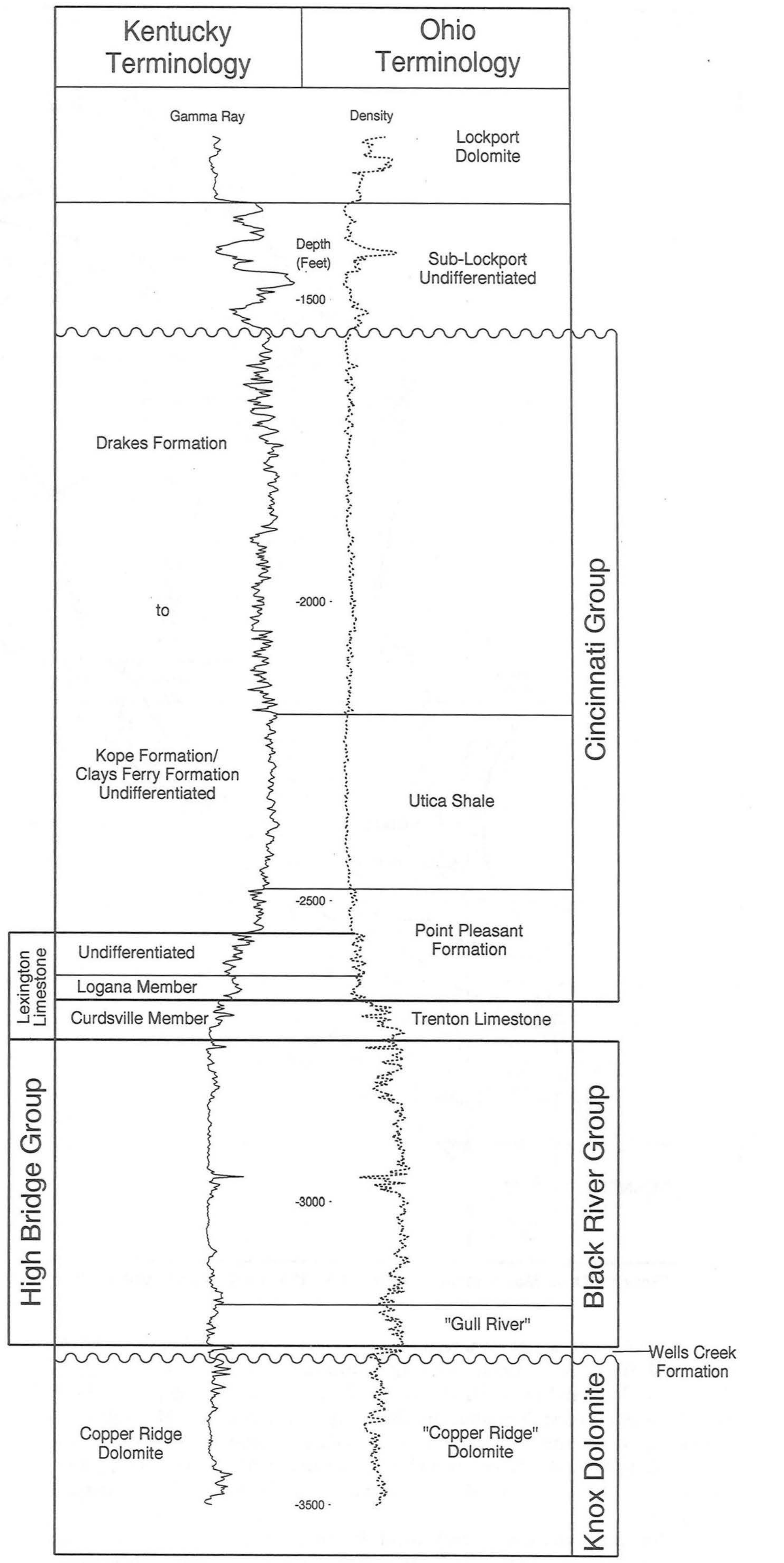

Figure MOf-4. Representative geophysical log curves from a well in Delaware County, Harlem Township, Ohio (permit number 251) illustrating Ohio stratigraphic terminology (right) versus Kentucky stratigraphic terminology (left). Stratigraphic nomenclature from Janssens (1973; 1977), Kentucky Geological Survey (1983), Wickstrom, Gray, and Stieglitz (1992), and Bergstrom and Mitchell (1992).

"Copper Ridge" dolomite through the Upper Ordovician Queenston Shale and their equivalent units across the Appalachian basin. For a more detailed review of the Cambrian and Ordovician stratigraphic framework of the Appalachian basin, refer to Ryder (1991; 1992a; 1992b) and Ryder, Harris, and Repetski (1992).

Overlying and intertonguing with the Utica/Point Pleasant units is a relatively thick sequence of interlayered gray to green calcareous shale, limestone, siltstone, and sandstone of the "Cincinnati" group and its equivalents (Figures MOf-3, MOf-4). This sequence is approximately 1,800 feet thick in central Pennsylvania and thins to about 900 feet on the northwest edge of the basin.

The Utica Shale consists of gray to black and brown shales, finely crystalline dark limestone, and locally, fossiliferous shale and limestone. The Utica represents a major transgression across the eastern United States, but the shales indicate a large influx of organic material, restricted circulation, and low-energy conditions (Bergstrom and Mitchell, 1992). Although the term Utica has been used basinwide for more than a hundred years, only recently have studies been undertaken to demonstrate lithologic and biostratigraphic equivalency of this unit regionally (Bergstrom and Mitchell, 1992; Ryder, 1991, 1992a, 1992b; Ryder, Harris, and Repetski, 1992).

The Utica Shale/Point Pleasant interval was deposited on top of the Trenton and thickens between the Trenton platform areas (Figure MOf-5) (Keith, 1988; Ryder, Harris, and Repetski, 1992; Wickstrom, Gray, and Stieglitz, 1992). The Utica Shale/Point Pleasant interval in northwestern Ohio, at the northwestern flank of the basin, thins to about 100 feet thick, whereas in parts of central Pennsylvania this interval reaches more than 700 feet in thickness (Wallace and Roen, 1989; Wickstrom, Gray, and Stieglitz, 1992). Considerable debate has taken

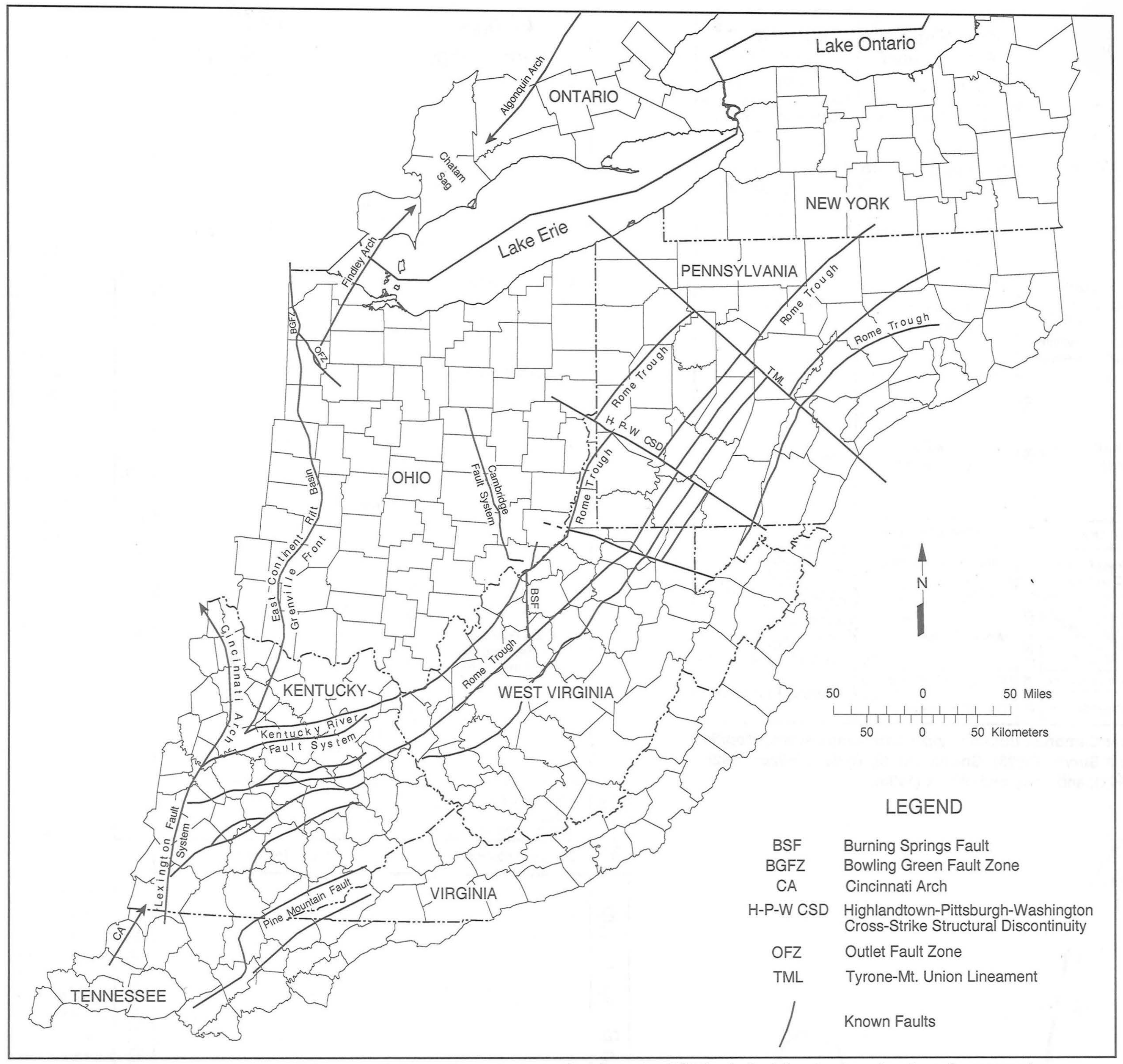

Figure MOf-6. Major structural features that may impact production from the Middle Ordovician fractured carbonate reservoirs.

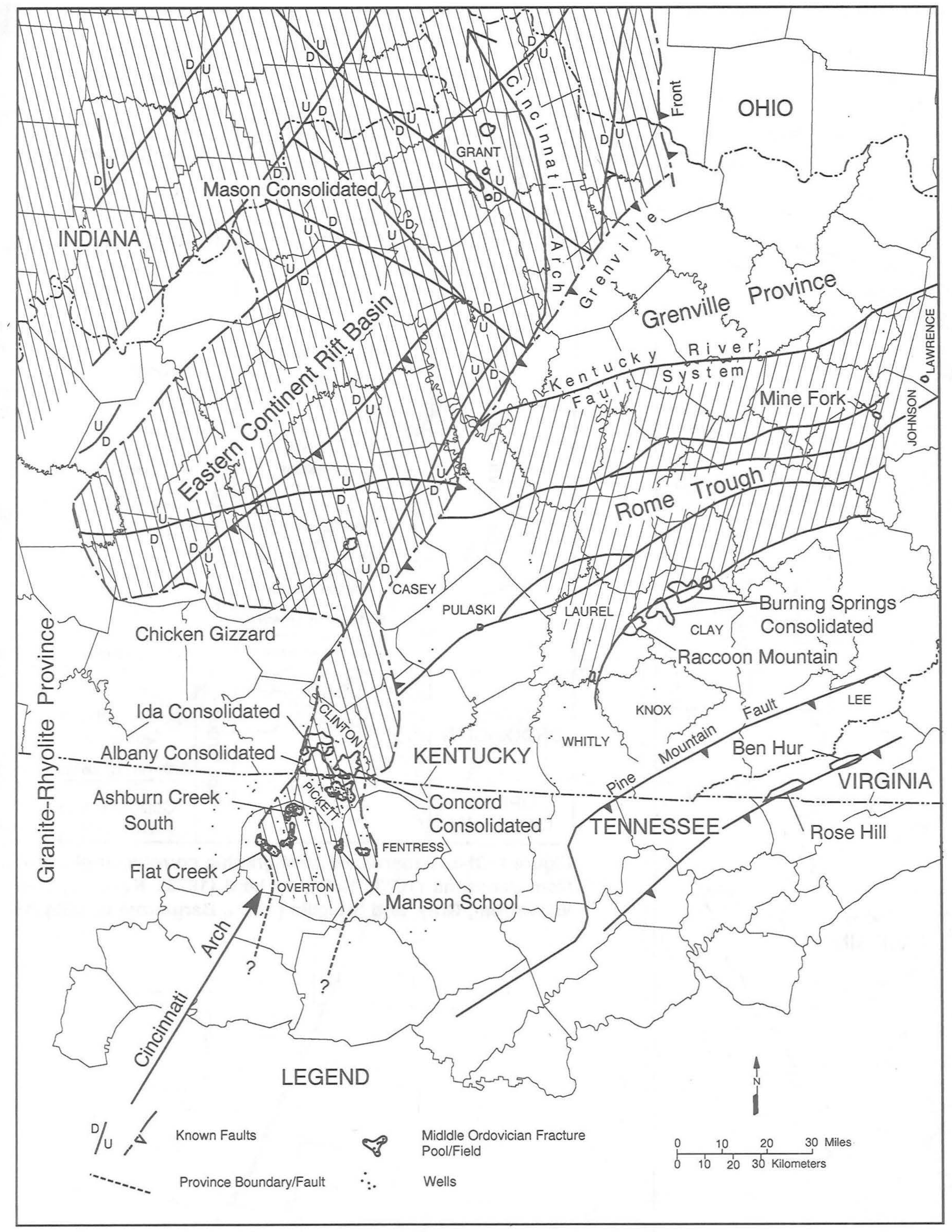

Figure MOf-7. Map of southeastern Indiana, southwestern Ohio, central and eastern Kentucky, western Virginia, and northern Tennessee illustrating the coincidence of location between the Middle Ordovician fractured carbonate fields and mapped faults. Locations of structural features and fault locations are from Drahovzal and others (1992).

place as to whether or not an unconformity exists at the top of the Trenton (see Keith and Wickstrom, 1993), although most modern researchers, including Wickstrom, Gray, and Stielglitz (1992) and Fara and Keith (1989), conclude that the surface is a minor disconformity. Recently, Bergstrom and Mitchell (1992), based on conodont biostratigraphy, have stated that this contact represents a gap corresponding to lower Edenian and possibly upper Mohawkian time, and it represents a period of very slow, or interrupted, deposition in a submarine environment.

The Trenton Limestone overlies the Black River Group within the entire basin. Generally the Trenton consists of light-brown to dark-gray bioclastic to argillaceous micritic limestone with common shale partings and well-defined metabentonite intervals. The thickness of the Trenton Limestone ranges from 220 feet on the northwestern flank of the basin, to less than 40 feet in central Ohio, to 800 feet in north-central New York (Rickard, 1973; Wickstrom, Gray, and Stieglitz, 1992). The Lexington Limestone, a facies equivalent of the Trenton in central Kentucky, outcrops around the Lexington area. The limestone is fossiliferous and phosphatic. The thickness of the limestone ranges from a minimum of 180 feet in the north to a maximum in excess of 320 feet in the north-central part of the state (Cressman, 1973).

The Black River Group is composed mainly of light brown to gray micritic to finely crystalline limestone. Its thickness ranges from approximately 1,100 feet in the Rome trough to about 100 feet on the eastern side of the basin and about 500 feet on the west (Ryder, Harris, and Repetski, 1992; Wickstrom, Gray, and Stieglitz, 1992). The Black River rocks are equivalent to the High Bridge Group of Kentucky usage and are included in the Stones River Group as used in Tennessee (Figure MOf-3).

At the base of the Black River Group is a relatively clean micritic limestone interval bounded below by the Wells Creek Formation and above by an argillaceous zone in the lower Black River (Figure MOf-4). This interval has been called the "Gull River" limestone by Ohio drillers. The name "Gull River" was originally used in Ontario for a unit stratigraphically higher in the Black River Group and has been erroneously applied by drillers to a lower unit at the base of the Black River in Ohio. Currently, use of the term is very prevalent, and production from this interval, primarily from dolomitized zones, continues to be discovered; therefore, the term is used in this discussion.

The Wells Creek Formation varies in composition across the basin and includes waxy, dolomitic, pyritic green shales; argillaceous limestones and dolomites; minor dark shales; and small amounts of sandstone and siltstone. The thickness of the Wells Creek Formation is highly variable because of the relief on the Knox unconformity. Regionally, the Wells Creek ranges in thickness from 0 to 150 feet, thickening to the east. Where the Wells Creek is absent, the Black River Group rests directly on the Knox unconformity or on the Beekmantown Group farther to the east (Ryder, 1992a; Wickstrom, Gray, and Stieglitz, 1992). The Wells Creek is equivalent to the Shadow Lake Formation of western Pennsylvania.

The age relationships between the Utica/Point Pleasant interval and the Trenton Limestone are not fully understood at this time. However, it appears likely that a partial time equivalence exists between the upper Trenton and the lower Point Pleasant units. Using conodont and graptolite biostratigraphy, Bergstrom and Mitchell (1992) have shown a late Middle Ordovician through mid-Late Ordovician age (Maysvillian through Shermanian) for the Utica/Point Pleasant interval. A Middle Ordovician age is assigned to the Trenton Limestone through Wells Creek Formation (Shermanian through Middle Chazyan). Ryder, Harris, and Repetski (1992) presented a thorough synopsis of the faunal work used to establish the Trenton through Wells Creek ages.

The Utica Shale and "Point Pleasant" formation represent a deeper basin, inter-platform, restricted-circulation, anoxic depositional environment (Figure MOf-5). Deposition of these units probably began contemporaneously with the Trenton carbonate buildups in response to compression from the Taconic orogeny, which altered the basin shape and water depths (Wickstrom, Gray, and Stieglitz, 1992). Deposition of these units ceased with complete inundation of the region by deeper water and more normal, open-marine conditions represented by the "Cincinnati" group.

The Trenton was deposited in a wide range of depositional environments across the Appalachian basin because of its contemporaneity with a compressional pulse of the Taconic orogeny. The Trenton was deposited in a clastic-rich shelf environment to the east, a relatively argillaceous platform to the southwest, and a cleaner carbonate platform to the northwest (Figure MOf-5) (Keith, 1988; Wickstrom, Gray, and Stieglitz, 1992). Therefore, thicker accumulations of the Trenton are found on the shelf and platform areas.

The Black River was deposited in shallow epeiric seas in environments ranging from shallow subtidal to tidal flat (Cressman and Noger, 1976; Stith, 1979). The Wells Creek represents a brief interval of mixed clastic and carbonate sedimentation deposited as shallow seas once again covered the previously emergent Knox unconformity surface. The contact between the Wells Creek and the overlying Black River is generally fairly sharp.

Structure

Figure MOf-6 illustrates some of the major structural features affecting the Appalachian basin. Those of prime importance to this play include the Grenville front, East Continent Rift Basin, Rome trough, Bowling Green fault zone, Findlay arch, Cincinnati arch, Lexington fault system, and the Pine Mountain fault.

Much of the fracturing associated with the Middle Ordovician carbonate reservoirs is thought to be due to reactivation of deeper structures (Wickstrom, Drahovzal, and Keith, 1992; Wickstrom, Gray, and Stieglitz, 1992). The exceptions to this are the Rose Hill and Ben Hur fields of Virginia. These fields are located on the folded and fractured upper and lower plates of the Pine Mountain overthrust fault, which is a result of thin skinned tectonics (Bartlett, 1988).

Much of western Ohio and central Kentucky are underlain by a portion of the East Continent Rift Basin, a Proterozoic extensional feature (Drahovzal and others, 1992) (Figure MOf-5). Compression associated with the Grenville orogeny further faulted and folded the East Continent Rift Basin rocks. The Grenville front, the suture between the Grenville province and the East Continent Rift Basin, is a major zone of crustal weakness that has been repeatedly reactivated. Both the Bowling Green fault zone of northwest Ohio and the Lexington fault system of central Kentucky are thought to lie along the Grenville front. The positions of the Cincinnati arch and the Jessamine dome are coincident with the axis of the thickest deposits within the East Continent Rift Basin (over 20,000 feet). This relationship has led to speculation that this extra thickness of the crust was responsible for this area remaining largely unaffected by the later subsidence events in the adjoining Appalachian and Illinois basins (Wickstrom, Drahovzal, and Keith, 1992). East of the Grenville front, Beardsley and Cable (1983) have characterized the Grenville strata as large, thrusted accretionary wedges, emplaced as a result of continental collision.

The locations of many of the fractured reservoirs of central Kentucky and Tennessee are coincident with subsurface features associated with the East Continent Rift Basin and Grenville front. For example, the Flat Creek, Ida Consolidated, and Concord Consolidated fields overlie a portion of the East Continent Rift Basin where it narrows between blocks of the Granite-Rhyolite Province to the west and the Grenville Province to the east (Figure MOf-7). Farther north in central Kentucky, a number of fractured carbonate fields, including Mason Consolidated and Chicken Gizzard, again overlie the East Continent Rift Basin within areas of expected faulting within the rift assemblage. This coincidence of location leads to speculation that the increased density of fractures in these Paleozoic carbonate fields may be due to reactivation of deeper fault systems in the East Continent Rift Basin.

The Rome trough is a large Cambrian extensional feature extending from central Kentucky through West Virginia and Pennsylvania (McGuire and Howell, 1963; Harris, 1978). The Ordovician fractured carbonate fields of eastern Kentucky—Raccoon Mountain, Burning Springs Consolidated, and Mine Fork—lie along mapped faults associated with the Rome trough (Figure MOf-7). This relationship suggests another example of reactivation of older structures.

In northwestern and central Ohio, Wickstrom, Gray, and Stieglitz (1992) proposed a number of northwest-oriented wrench faults that were activated under compressional forces related to the Taconic orogeny; they have also shown a set of northeast-trending fault zones that are postulated to have been extensional in nature in the Cambrian and reactivated by the same compressional forces of the Taconic in the mid to late Ordovician. These fault systems are situated on or near the East Continent Rift Basin and Grenville front. It is along these mapped fault trends that a number of the fracture-controlled fields of this play are located (Figure MOf-8). The Upper Sandusky, Carey, and Roundhead fields (Figure MOf-8) are examples of such structure-related reservoirs.

Reservoir

The primary trap type within this play consists of porosity zones along faults and fractures. It appears that three types of reservoir have been developed in these carbonate fracture systems in the Appalachian basin.

The first type of porosity development/enhancement is a result of secondary mineralization (primarily dolomitization) caused by circulating fluids along faults and fracture systems. The Trenton Limestone-upper Black River Group fields in northwest to central Ohio and south-central Ontario (Figures MOf-1, MOf-2) are prime examples of this reservoir type and represent the most prolific gas production from this play to date. In large fault systems with appreciable gouge zones, the fluid interaction with the gouge resulted in considerable amounts of vugular porosity and thick zones of mineralization. In smaller fault systems with less volume of fluid movement, or farther from the central area of large fault systems, the mineralization and porosity enhancement are less extensive and may result in good intercrystalline porosity development (Wickstrom, Gray, and Stieglitz, 1992). In some cases, later mineralization may have proceeded so far as to seal off multiple pay zones within a single fault system.

In reservoirs of this type, it is not uncommon to find that secondary dolomite has partially to entirely replaced the original limestone, and baroque dolomite crystals typically line vug openings. Gregg and Sibley (1984) attribute this type of dolomite to epigenetic fluid migration. Haefner and others (1988), working with cores from the Carey and Upper Sandusky pool areas of Wyandot County, Ohio, concluded that the mineralization fluids were warm, gravity-driven brines from deeper in the basin.

The second type of reservoir within this play consists of open, largely unmineralized fractures in the Knox Dolomite through Trenton Limestone. In the central Kentucky and Tennessee reservoirs, Hamilton-Smith and others (1990) assume the production is related to open fracture systems, although they acknowledge a possibility of minor enhancement by secondary mineralization. Reactivation of deep-seated faults is thought to be responsible for opening these fracture systems.

The third type is found in scattered wells in Ohio that produce from fractured portions of the lower Black River Group ("Gull River") and the Wells Creek Formation. Secondary dolomitization is prevalent in these reservoirs. The dolomitization fluids probably travelled into these zones from the underlying Cambrian fracture systems and/or along the Knox unconformity.

The vertical seal for all reservoirs of this play is generally the overlying Utica Shale or its equivalent. Horizontally, the trap is provided by tight dolomite or unaltered limestone. Where displacements are sufficient along faults, the overlying shale may provide both vertical and horizontal seals on upthrown blocks.

The primary source rocks for the hydrocarbons in the Ordovician carbonates in the northern portion of the basin is thought to be the overlying dark gray to black Utica Shale and "Point Pleasant" formation (Cole and others, 1987; Wallace and Roen, 1989; Ryder and others, 1991). On the basis of estimates of thermal maturity, the most prolific generating areas were probably in deeper portions of the basin, along the Ohio/West Virginia/Pennsylvania border continuing toward central Pennsylvania. Peak generation of hydrocarbons from this source interval is thought to have occurred during Pennsylvanian to Permian time when much thicker strata provided higher burial temperatures (Cole and others, 1987).

Analyses of oils and potential source intervals from Kentucky indicate that the Devonian black shales have provided the hydrocarbons for the Ordovician reservoirs of southern Kentucky, northern Tennessee, and probably the western Virginia pools (J. A. Drahovzal, written commun., 1994). For both the north and south areas, migration from the deeper portions of the basin was pressure driven and probably occurred by way of interformational flow, faults and fractures, and unconformities.

Depth and pressure of the reservoirs vary widely across the basin (Table MOf-1). In general, the depth to the top of the Middle Ordovician carbonate reservoirs ranges from 100 feet in Tennessee to 4,518 feet in eastern Kentucky with an overall average of 1,258 feet. As with production records, it is difficult to obtain reliable measurements of reservoir pressures and flow rates from the fields of this play. The available data indicate that pressures in this play range from 90 psi at 395 feet to 1,450 psi at 4,518 feet with an average pressure of 365 psi. Most of the fields of this play are underpressured.

Recorded initial open flow values range from 2 Mcf/d to 2,063 Mcf/d with an average of 465 Mcf/d. Final open flow values range from 5 Mcf/d to 4,795 Mcf/d with an average of 368 Mcf/d. Judging from written accounts of early wells, many probably had higher initial production but were not gauged or reported. It should also be noted that it was common practice in the older fields to use nitroglycerine charges for stimulation of wells; while this usually increased, or started, production of oil, the records indicate that it commonly decreased gas production.

Heterogeneity within the reservoirs of this play is a result of two main factors: a dual porosity system may be present, consisting of macrovugs or open fracture cavities and intercrystalline porosity (Keith and Wickstrom, 1992); and pay zones may be very discontinuous both horizontally and vertically because of the nature of porosity development/enhancement and secondary mineralization by circulating brines along fracture systems. Single or multiple pay zones may develop within a reservoir system. The individual pay zones may or may not be well connected to others (Keith and Wickstrom, 1992)

The dominant drive mechanism in the northern fields of this play is solution gas (Table MOf-1). Water encroachment is also more common in the north, indicating a possible contribution from a water-drive system. The fields of central Kentucky and northern Tennessee appear to be dominated by a gas drive system, with some instances of water encroachment reported.

Completion strategies vary widely across the basin and with time. Most of the older wells were completed open hole and were stimulated by shooting with liquid nitroglycerin. The amount of nitroglycerin used differed by operator, from as little as 30 quarts to as much as 400 quarts. In modern wells, both open hole and perforations through casing have been used with success. Likewise, many different types of stimulation treatments have been tried on these carbonate

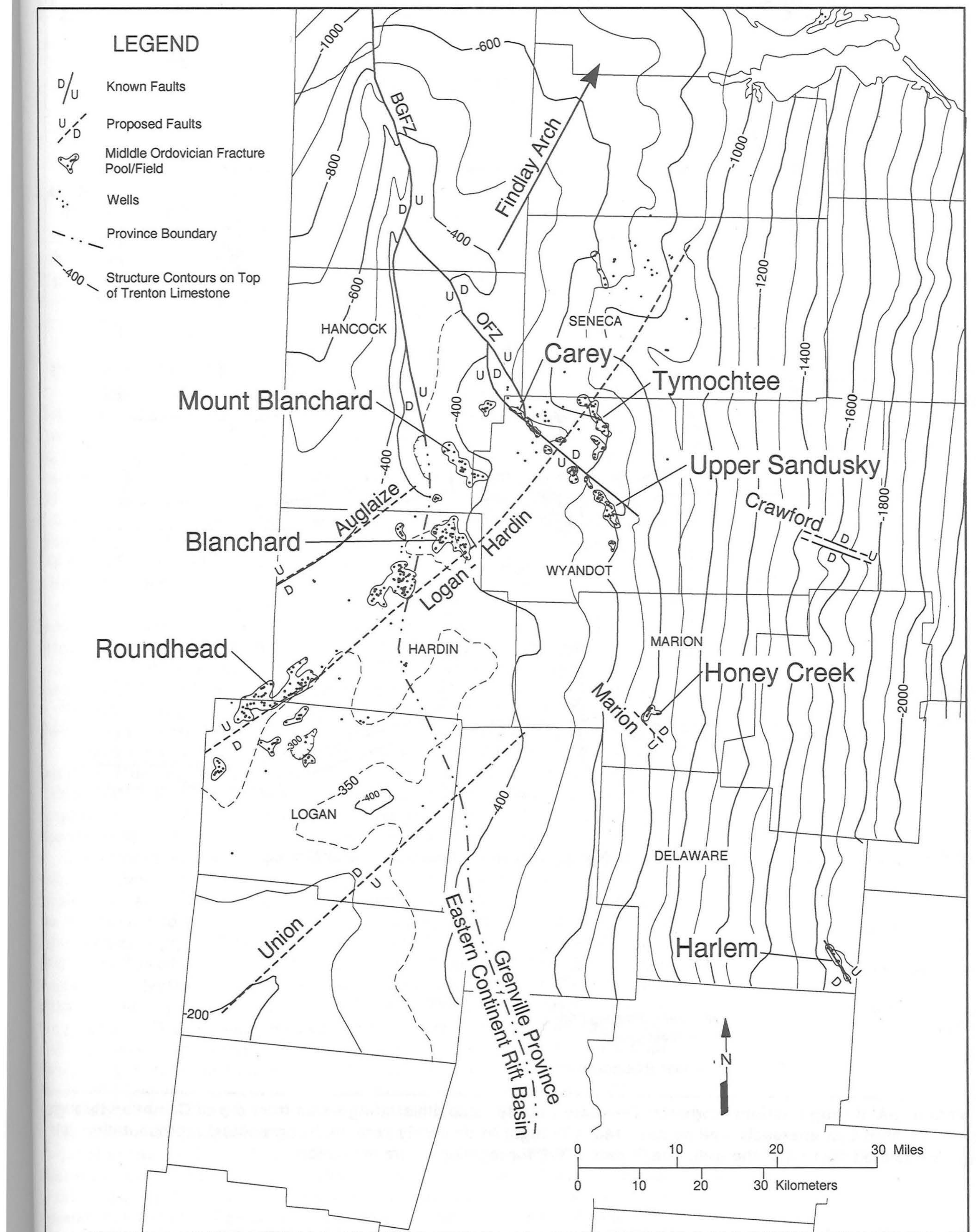

Figure MOf-8. Map of a portion of northwestern Ohio illustrating the relation between mapped structure and faults with the location of Middle Ordovician fractured carbonate gas reservoirs. See Figure MOf-2 for location. Structure contours drawn on top of the Trenton Limestone. Contour interval = 100 feet; where dashed, contour interval = 50 feet. Structure contours and faults are from Wickstrom, Gray, and Stieglitz (1992). Grenville province boundary is from Drahovzal and others (1992).

rocks, including warm acid treatments, acid fracs (with and without nitrogen assists), foam fracs, water with sand proppant, and oil fracs. Schrider and others (1984) published the results of an evaluation program run to test various completion and production practices within the Trenton of northwest Ohio and, in general, found that non-water-based stimulants provide the best results because of less swelling of clays and fewer fines released.

A number of reservoir irregularities have been noted locally within this play. High paraffin content of oils (which may block reservoir pore throats during degassing) appears to be more common in the deeper reservoirs of the play. Sour gas is found in the Honey Creek field and probably occurred in some of the older fields, but records are incomplete. High amounts of mobile fines that may further block pore spaces are also encountered throughout the play and are most notable where the reservoir rock is more argillaceous.

Description of Key Field

Harlem gas field: The Harlem gas field, located in Harlem Township, Delaware County, Ohio (Figures MOf-2, MOf-9), provides an opportunity for detailed examination because it was developed relatively recently and is fairly typical of the fractured carbonate reservoirs. Hydrocarbons have been produced from the Trenton Limestone, Black River Group, and the "Copper Ridge" dolomite in this field, although the "Copper Ridge" production could not be sustained. The discovery well, the Federal Oil and Gas, No. 1 Jenobel Fronk (Ohio county permit number, Delaware 146), was drilled in 1964 in search of additional "Copper Ridge" production to extend the boom from neighboring Morrow County. During drilling, a fault zone was encountered in the well at the approximate position of the Trenton Limestone. Drilling continued to a depth of 3,609 feet in the "Copper Ridge." After acidizing the "Copper Ridge" without result, a plug was set and the "Trenton" zone was tested (the actual Trenton interval is missing in this well). This zone produced 795 Mcfg natural with a pressure of 985 psi on a 12-hour test. After treatment with 5,000 gallons of acid, the well flowed at a rate of 4,435 Mcfg/d on a five-hour test. Other companies unsuccessfully attempted to offset this success over the next couple of years and finally abandoned the area. The Fronk well was sold to the landowner because a pipeline to the township could not be justified for one well. Reportedly, the landowner used this well to start his own mini-utility and sold the gas to surrounding farms.

In the early 1980s, Industrial Natural Gas Company (ING) began evaluating this area, baited by the success of the Fronk well. After acquiring and analyzing both seismic and detailed aeromagnetic surveys over the area, in 1982 they drilled the No.1 Jackson (Delaware 300) well, which had an initial production of 225 Mcfg/d. ING's subsequent drilling program successfully proved the northwest trend of the fault system. After ING demonstrated additional gas reserves in the area, Columbia Gas built a 10-mile pipeline to gather gas from this field. While defining the northern segment of this fault with six gas wells and two dry holes, ING also tried to locate the southern extension of this system. After three dry holes (Delaware 299 is shown on Figure MOf-9 as a gas well, although its productive life was very short), two in Harlem Township and one in neighboring Monroe Township of Licking County, the company abandoned its efforts on this field. The program was acquired by a partnership called Sunbury-Trenton, Inc., who ran additional seismic lines and drilled another four productive wells and three dry holes before also abandoning efforts in this field.

Eleven gas wells, two combination wells, and 18 dry holes have been drilled in and around this field. Cumulative production is 2.1 bcf, of which approximately 1.5 bcf has been produced from the Fronk discovery well.

The main producing units of this field are dolomitized sections of the Trenton Limestone and Black River Group. In some wells, the entire Trenton-Black River sequence has been dolomitized; in others, the dolomite and original limestone are interlayered. The dolomitization and reservoir development have occurred along a northwest-oriented fault with approximately 20 feet of vertical displacement. The fault cuts across a northeast-trending anticline (Figures MOf-9, MOf-10).

The discovery well (Delaware 146) apparently is the only well that has cut the fault plane (Figure MOf-10). Close correlation of the geophysical logs and sample examination reveals that the basal "Point Pleasant" formation, the entire Trenton Limestone, and the upper portion of the Black River Group are not recognized in this well. In their place is a section of dark shale and white calcite rubble. Production from this well is from the fault zone and fractured and dolomitized Black River located directly below the fault zone. In this field, trapping is apparently the result of porous dolomite sections being surrounded by tight dolomite and unaltered limestone sections.

	TABLE MOf-1	Blanchard OH	Carey OH	Dunkirk OH	Harlem OH	Honey Creek OH	Mt. Blanchard OH	Roundhead OH	Tymochtec OH	Upper Sandusky OH
BASIC RESERVOIR DATA	POOL NUMBER	3406500802	3417500777	3406500801	3404100968	3410100976	3406500800	3406500805	3417500778	3417500776
	DISCOVERED	1885	1880	1888	1964	1964	1886	1922	1890	1889
	DEPTH TO TOP RESERVOIR	1,320	1,216	1,225	2,808	1,710	1,295	1,366	1,339	1,328
	AGE OF RESERVOIR	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician
	FORMATION	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton
	PRODUCING RESERVOIR	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton
	LITHOLOGY	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite
	TRAP TYPE	fractured	fractured	fractured	fractured	fractured	fractured	fractured	fractured	fractured
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
	DISCOVERY WELL IP (Mcf)		1,500		4,435	1,500				1,889
	DRIVE MECHANISM	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas
	NO. PRODUCING WELLS	0	0	0	0	0	0	0	0	0
	NO. ABANDONED WELLS	70	63	43	13	7	> 25	79	50	51
	AREA (acreage)									
	OLDEST FORMATION PENETRATED	Trempealeau	solution gas	Trenton	Knox	Kerbel	Knox	Trempealeau	Trempealeau	Black River
	EXPECTED HETEROGENEITY DUE TO:	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	10	12	2	25	16	25	15	7	16
	AVERAGE COMPLETION THICKNESS (ft.)									
	AVERAGE POROSITY–LOG (%)					10				
	MINIMUM POROSITY–LOG (%)					10				
	MAXIMUM POROSITY–LOG (%)					19				
	NO. DATA POINTS	0	0	0	0	8	0	0	0	0
	POROSITY FEET									
	RESERVOIR TEMPERATURE (°F)				94	70				
	INITIAL RESERVOIR PRESSURE (psi)	315	420	460	985	550	452	331	400	350
	PRODUCING INTERVAL DEPTHS (ft.)	1,320-1,423	1,276-1,443	1,225-1,367	2,808-2,976	1,710-1,820	1,295-1,436	1,366-1,430	1,339-1,572	1,328-1,482
	PRESENT RESERVOIR PRESSURE (psi) / DATE	61/1947				515/1985	29/1952	185/1955		
FLUID & GAS PROPERTIES	Rw (Ωm)									
	GAS GRAVITY (g/cc)									
	GAS SATURATION (%)					70				
	WATER SATURATION (%)					30				
	COMMINGLED	no	no	no	yes	no	no	no	no	no
	ASSOCIATED OR NONASSOCIATED	associated	associated	nonassociated	nonassociated	associated	nonassociated	associated	associated	associated
	Btu/scf									
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned
	ORIGINAL GAS IN PLACE (Mcf)	8,074,000	6,190,000	4,225,000	2,668,000	1,250,000	1,522,000	3,717,000	4,913,000	5,011,000
	ORIGINAL GAS RESERVES (Mcf)	6,460,000	4,950,000	3,380,000	2,135,000	1,000,000	1,217,518	2,974,000	39,300,000	4,001,000
	PRODUCTION YEARS	1885-	1880-1957	1888-1951	1964-1993	1964-1992	1886-1952	1922-	1980-	1889-
	REPORTED CUMULATIVE PRODUCTION (Mcf)	184,559			2,029,000	500,000	194,803	225,834		
	NO. WELLS REPORTED	2	0	0	11	5	4	6	0	0
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	6,460,000	4,950,000	3,380,000	2,135,000	1,000,000	1,217,518	2,974,000	3,930,000	4,001,000
	REMAINING GAS IN PLACE (Mcf)/DATE	1,615,000	1,240,000	845,000	533,000	750,000	304,000	743,000	983,000	1,010,000
	REMAINING GAS RESERVES (Mcf)/DATE	0	0	0	0	0	0	0	0	0
	RECOVERY FACTOR (%)	80	80	80	80	80	80	80	80	80
	INITIAL OPEN FLOW (Mcf/d)	124	177	700		2,063		272	190	840
	FINAL OPEN FLOW (Mcf/d)	247	370		612	582	379	904	157	728

	TABLE MOf-1	Burning Springs Consolidated KY	Concord Consolidated KY	Mine Fork KY	Raccoon Mountain KY	Trixie Consolidated KY	Manson School TN	Ben Hur VA	Rose Hill VA	Acton Ontario, Canada	Hornby Ontario, Canada
BASIC RESERVOIR DATA	POOL NUMBER	1600320365	1600459365	1601319368	1601600368	1602002368	4104900163				
	DISCOVERED	1966	1941	1984	1955	1983	1979	1963	1942	1954	1959
	DEPTH TO TOP RESERVOIR	2,000	447	4,518	2,720	2,634	500	1,600	1,100	280	1,532
	AGE OF RESERVOIR	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician
	FORMATION	Trenton	Trenton	Knox	Knox	Trenton	Nashville	Trenton	Trenton	Black River	Black River
	PRODUCING RESERVOIR	Trenton	Trenton	Knox/ Stones River	Knox/ Stones River	Knox/ Stones River	Trenton	Trenton	Trenton	Trenton	Trenton
	LITHOLOGY	dolomite	limestone	limestone	limestone	limestone	limestone	limestone	limestone	limestone	limestone
	TRAP TYPE	fractured	structural	structural	structural	structural	fractured	structural	structural	structural	structural
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	Ds	Ds
	DISCOVERY WELL IP (Mcf)				488	90	45		211	100	2
	DRIVE MECHANISM	gas	gas	gas	gas	gas	gas				
	NO. PRODUCING WELLS	8	19	2	2	3	7		1	15	3
	NO. ABANDONED WELLS	2	6	0	0		0			15	3
	AREA (acreage)	1,750	3,850	350	245	4,200					
	OLDEST FORMATION PENETRATED	Knox	Knox	Rome	Knox	Knox	Knox		Black River	Precambrian	Precambrian
	EXPECTED HETEROGENEITY DUE TO:	fractures	fractures	fractures	fractures	fractures	fractures	fractures diagenesis	fractures diagenesis	fractures	fractures
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	20	6	32	17	19					
	AVERAGE COMPLETION THICKNESS (ft.)										
	AVERAGE POROSITY–LOG (%)	9	4	7	9	8					
	MINIMUM POROSITY–LOG (%)	4	1	1	4	2					
	MAXIMUM POROSITY–LOG (%)	20	7	16	15	17					
	NO. DATA POINTS	5	7	4	6	22	0			0	0
	POROSITY FEET										
	RESERVOIR TEMPERATURE (°F)	82	73		83					82	62
	INITIAL RESERVOIR PRESSURE (psi)	750		1,450	800	125	185			415	2,586
	PRODUCING INTERVAL DEPTHS (ft.)	2,000-3,645	447-1,510	4,518-4,642	2,720-3,558	2,634-3,875	500-700		1,100-2,150	280-374	1,532-1,615
	PRESENT RESERVOIR PRESSURE (psi) / DATE	350/1987		235/1986	245/1991	600/1991				94/1973	
FLUID & GAS PROPERTIES	Rw (Ωm)			0.06	0.06	0.06					
	GAS GRAVITY (g/cc)				0.068	0.656					0.628
	GAS SATURATION (%)	80		56	74	62					
	WATER SATURATION (%)	20		44	26	38					
	COMMINGLED	no	no	yes	yes	yes	no			no	no
	ASSOCIATED OR NONASSOCIATED	associated	nonassociated	nonassociated	associated	associated				nonassociated	nonassociated
	Btu/scf				1,076	1,118				1,046	1,336
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing				abandoned	abandoned
	ORIGINAL GAS IN PLACE (Mcf)	2,400,000	550,000	300,000	540,000	590,000					115,000
	ORIGINAL GAS RESERVES (Mcf)	2,000,000	480,000	230,000	440,000	490,000					92,000
	PRODUCTION YEARS		1941-	1984-present	1955-	1984-1991				1954-1973	1959-1972
	REPORTED CUMULATIVE PRODUCTION (Mcf)					454,000				490	
	NO. WELLS REPORTED	0	0	0	0		0			15	
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)										
	REMAINING GAS IN PLACE (Mcf)/DATE										
	REMAINING GAS RESERVES (Mcf)/DATE										
	RECOVERY FACTOR (%)	90	90	90	90	90	80				
	INITIAL OPEN FLOW (Mcf/d)						32				
	FINAL OPEN FLOW (Mcf/d)	138	29	364	207	848					

Resources and Reserves

Much of the drilling and production from fields of this play occurred before modern permitting regulations and tax collections. Also, many of the southern fields of this play have not had markets for the produced gas. Therefore, production figures for these gas wells are not available. For these reasons as well as a total lack of gauging in some of the oldest fields, it is nearly impossible to obtain reliable production figures to use for reserve calculations and in constructing representative decline curves. While many of the larger fields in Ohio produced their largest amount of gas from the late 1880s through 1910, the earliest production figures available started in the late 1920s. Of the 42 fields examined as part of this investigation, production from wells within portions of only eight fields was obtained (some of this data is proprietary). Therefore, the following figures are conservative estimates at best. The author believes that a significant sampling of accurate production records for this play would easily double the reserves reported here and may alter some areas by an order of magnitude.

THE ATLAS OF MAJOR APPALACHIAN GAS PLAYS

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Funded by
U.S. Department of Energy, Morgantown Energy Technology Center
Cooperative Agreement DE-FC21-91-MC28176

Compiled by
The Appalachian Oil and Natural Gas Research Consortium

With Contributions by
Kentucky Geological Survey
Ohio Department of Natural Resources, Division of Geological Survey
Pennsylvania Bureau of Topographic and Geologic Survey
West Virginia Geological and Economic Survey
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