DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Oil and Gas Resources of the Black Warrior Basin, Alabama and Mississippi

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Open-File Report 87-450X

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INTRODUCTION

Basin location and size

The Black Warrior basin of Alabama and Mississippi is a foreland basin located in the major structural reentrant between the Appalachian and Ouachita fold and thrust belts (fig. 1). The northern margin of the basin is bounded by the Nashville dome. Most of the basin and its thrust faulted margins are concealed beneath Tertiary and Cretaceous rocks of the Gulf coastal plain and the Mississippi embayment (fig. 1). However, in northern Alabama, part of the Black Warrior basin crops out and is identified by a marked broadening of the belt of Pennsylvanian strata between the Nashville dome and the Appalachian fold and thrust belt (King and Beikman, 1974). The Black Warrior basin covers an area of about 23,000 sq mi (59,000 sq km).

Structural setting

Complexly faulted, southwest-dipping Precambrian basement rocks and overlying Paleozoic strata dominate the structure of the Black Warrior basin (figs. 1 and 2). The faults that cut the basement and cover rocks of the basin are extensional in origin and, in general, trend northwestward and exhibit a down-to-the-basin geometry. In the southern part of the basin, Pike (1968) defined a northwest-trending hinge zone across which there is abrupt southwestward thickening of the Pennsylvanian sequence (figs. 1 and 2). Vernon (1971) speculates that this hinge zone is controlled by major southwest-dipping normal faults. The axis of the Black Warrior basin is situated between and subparallel to the northwest-trending hinge zone (Pike, 1968; Vernon, 1971) and the Ouachita fold and thrust belt and may, in part, be overridden by the fold and thrust belt. Judging from the abrupt termination of the northwest-trending structure contours and extension faults in the Black Warrior basin against the northeast-trending thrust faults of the Appalachian fold and thrust belt, Appalachian tectonism appears to have had little influence on the structural fabric of the basin. Thomas (1973) demonstrated that the structures of the Appalachian fold and thrust belt extend beneath the Gulf coastal plain into eastern Mississippi and probably connect with structures of the Ouachita fold and thrust belt.

Stratigraphic framework

The northwest-trending hinge zone of Pennsylvanian age (Pike, 1968; Vernon, 1971) partitioned the Lower and Middle(?) Pennsylvanian Pottsville Formation (fig. 3) into a shelf facies, northeast of and including the hinge zone, and a slope and basin facies, southwest of the hinge zone (Thomas, 1972). The shelf facies consists of sandstone, shale, and coal of deltaic and fluvial origin whereas the slope and basin facies consists of sandstone and shale of offshore marine and turbidite origin. This southwest vergence of the shelf, slope, and basin components of the Pennsylvanian depositional system is consistent with an Appalachian source (Schlee, 1963; Metzger, 1965; Wanless, 1975; Meckel and others, 1985)

Figure 1. Tectonic map of Alabama and Mississippi and adjacent states showing the Black Warrior basin (outlined by heavy line) and major tectonic elements of the region. The map is taken from King (1969). Structure contours, in kilometers below mean sea level, are drawn on top of Precambrian basement rocks. Structure contours of King (1969) are redrawn to conform to data from drill holes 1 and 2. Additional modifications of King's (1969) map are based on the work of Thomas (1973) and Milici (1980). Drill holes are identified as follows: 1. Shenandoah and Occidental No. 1 Smith 26-6, sec. 26, T.9S., R.2W.; 2. Magnolia No. 1 Pierce, Sec. 22, T.13S., R.7E.; 3. Exxon No. 1 Fulgham, sec. 33, T.19N., R.12E.; 4. Sonat No. 1 Lee, sec. 26, T.24N., R.3W. Major tectonic features are identified as follows: AFTB, Appalachian fold and thrust belt; BWB, Black Warrior basin; GCP, Gulf coastal plain; ME, Mississippi embayment; ND, Nashville dome; OFTB, Ouachita fold and thrust belt; PHZ, Paleozoic hinge zone. Exposed rocks in the Appalachian fold and thrust belt are identified as follows: vertical wavy-line pattern, highly metamorphosed rocks of middle and early Paleozoic age; random-dash pattern, granitic plutonic rocks chiefly of middle Paleozoic age; stippled pattern, moderately metamorphosed Paleozoic rocks of the Talladega belt; dash pattern, deformed sedimentary rocks of Cambrian through Pennsylvanian age. Northern and eastern margin of Tertiary and Cretaceous rocks of the Gulf coastal plain are identified by small open circles. XX' is the line of geologic cross section shown in figure 2. Major cities are identified as follows: B, Birmingham; J, Jonesboro; Ja, Jackson; M, Memphis; Mb, Mobile; Mo, Montgomery; N, Nashville; NO, New Orleans.

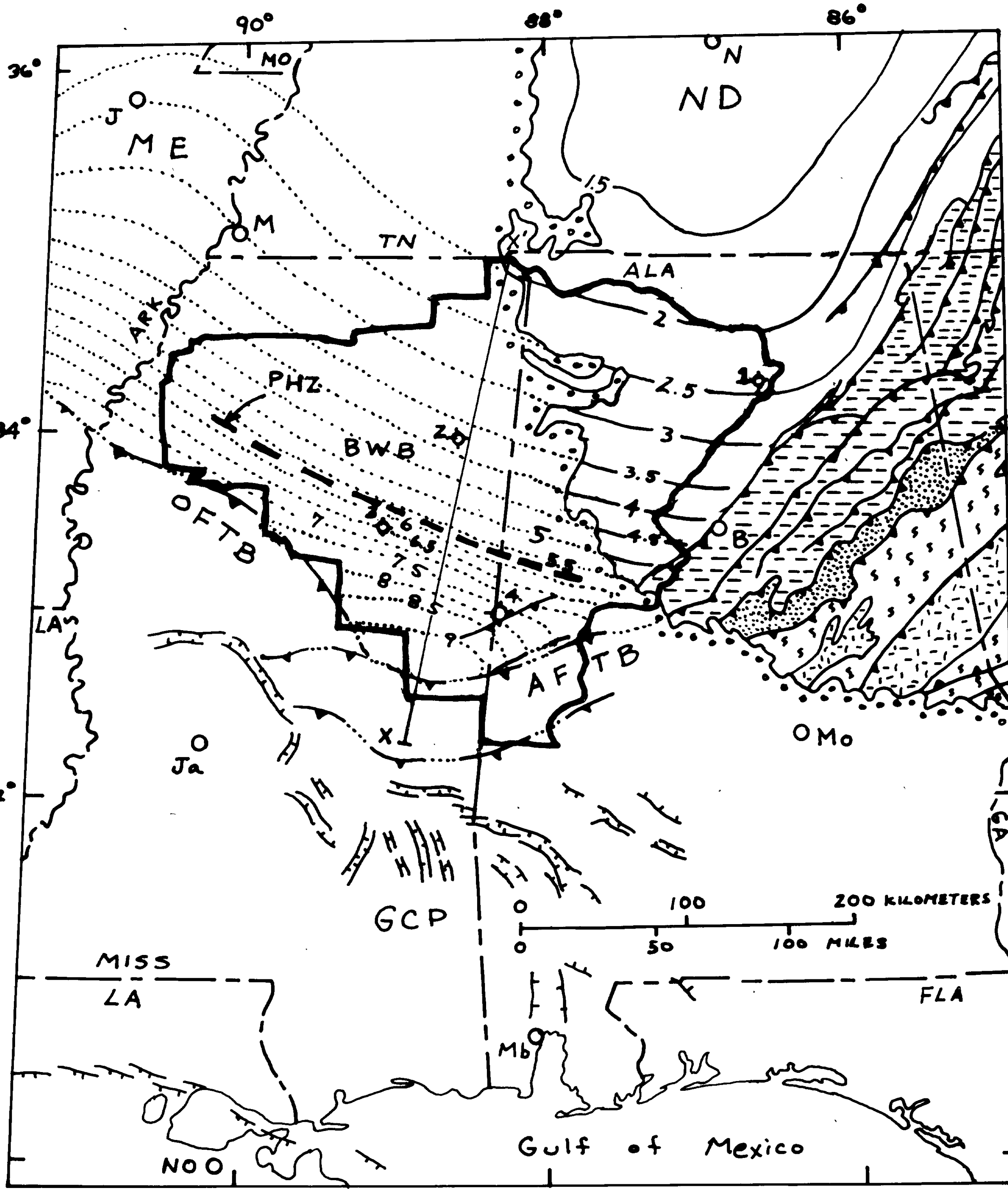
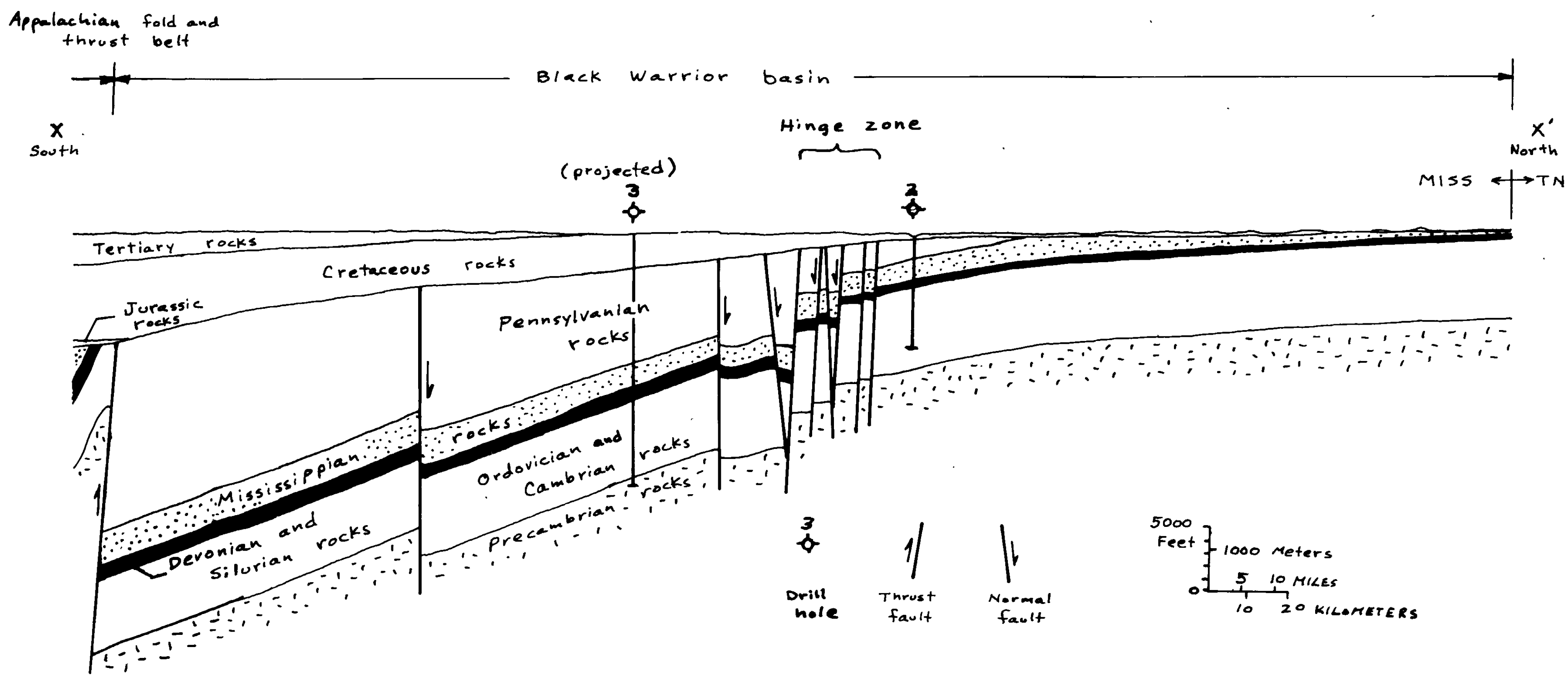

90°
88°
86°
36°
34°
32°
30°
MO
N
ND
J
ME
1.5
M
TN
ALA
ARK
2
PHZ
2.5
BWB
2.0
3
3.5
4
OFTB
7
6
6.5
5
4.5
B
7.5
5.5
8
8.5
4
LA
9
AFTB
X
Ja
Mo
32°
GA
GCP
0
100
200 KILOMETERS
0
50
100 MILES
MISS
LA
FLA
Mb
NOO
Gulf of Mexico

Figure 2. Geologic cross section X-X′ through the Black Warrior basin. Line of section and drill holes 2 and 3 are identified on figure 1. The section is slightly modified from Williams (1969).


Appalachian fold and thrust belt
Black Warrior basin
X
South
Hinge zone
X'
North
(projected)
3
2
MISS
TN
Tertiary rocks
Cretaceous rocks
Jurassic rocks
Pennsylvanian rocks
Mississippian rocks
Devonian and Silurian rocks
Ordovician and Cambrian rocks
Precambrian rocks
3
Drill hole
Thrust fault
Normal fault
5000 Feet
1000 Meters
0
5
10 MILES
10
20 KILOMETERS

rather than an Ouachita source (Ehrlich, 1964; Ferm and Ehrlich, 1967; Horne and others, 1976; Cleaves, 1983) for the detritus of the Pottsville Formation. Thomas (1972) also recognized that deposits of Ordovician, Silurian, and Devonian age in the Black Warrior basin were controlled by a platform edge that had approximately the same orientation and position as the hinge zone of Pennsylvanian age. Moreover, a shelf margin of similar orientation, but located about 30 mi (48 km) northeast of the Pennsylvanian hinge zone, is defined by the Upper Mississippian Bangor Limestone (fig. 3) and the equivalent Neal Shale (Scott, 1978). Southwestward across each of these pre-Pennsylvanian shelf margins (platform edge) strata thicken markedly and become deeper water in origin.

The total thickness of the sedimentary record in the basin ranges from approximately 7,000 ft (2.1 km) along the northern margin to approximately 31,000 ft (9.4 km) in the depocenter in eastern Mississippi (figs. 1 and 2). The Shenandoah and Occidental No. 1 Smith 26-6 drill hole (drill hole No. 1 on fig. 1) was drilled to Precambrian basement rocks in northern Alabama and penetrated 8,200 ft (2.5 km) of Paleozoic strata from the Pennsylvanian Pottsville Formation to the Cambrian Rome Formation (fig. 1). Another drill hole that reached Precambrian basement rocks, the Exxon No. 1 Fulgham in east-central Mississippi (drill hole no. 3 in fig. 1), recorded 21,300 ft (6.5 km) of sedimentary rock, of which the upper 8,000 ft (2.4) was Tertiary and Cretaceous in age and the remainder, Pennsylvanian through Cambrian. The stratigraphy of the Black Warrior basin based largely on the results of the Shenandoah and Occidental and Exxon drill holes, the Magnolia No. 1 Pierce drill hole (drill hole No. 2 in fig. 1), and on published literature, is summarized in figure 3.

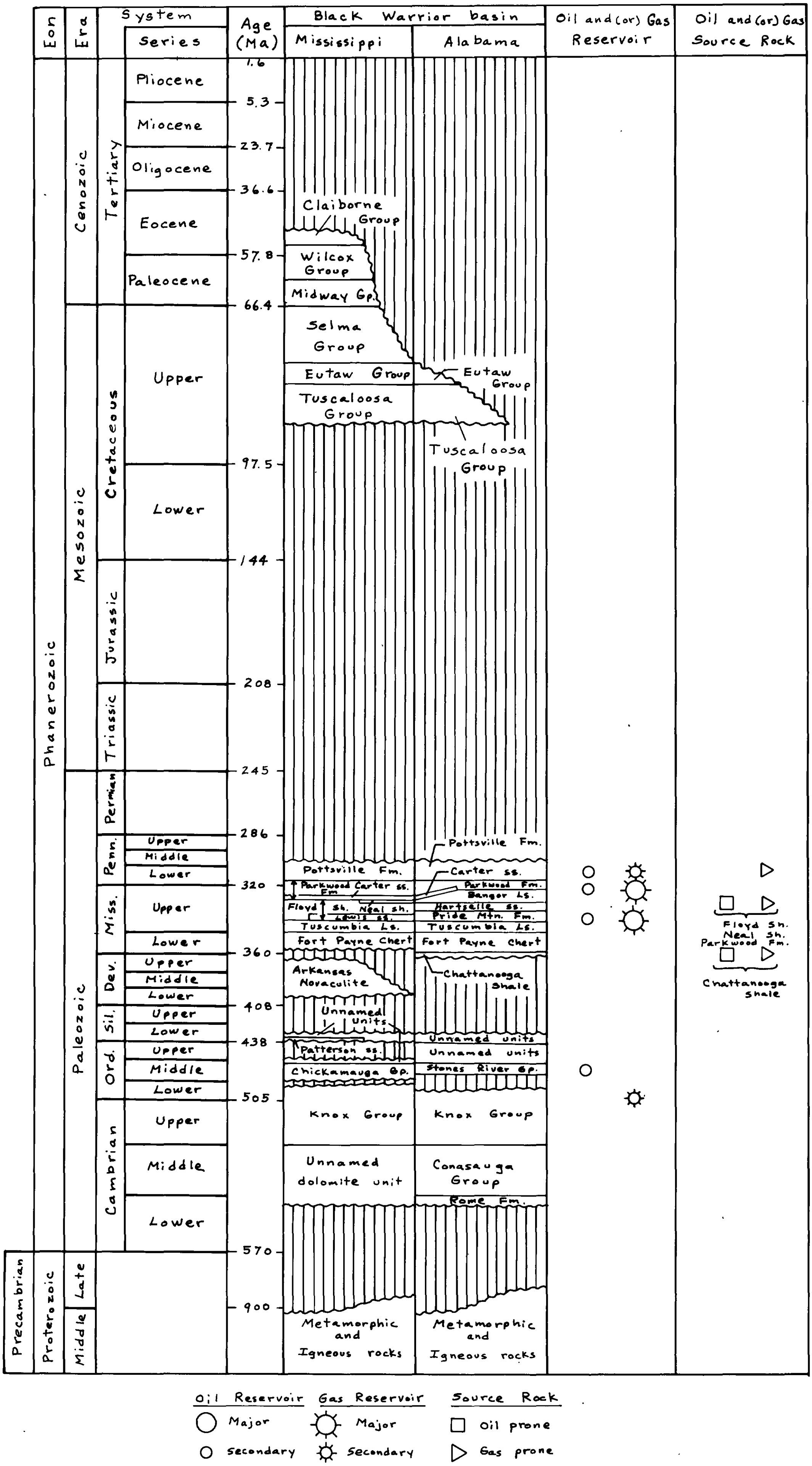
Source rocks

The major oil and gas source rocks identified in the Black Warrior basin are coal beds in the Pennsylvanian Pottsville Formation, dark gray to black marine shale in the Upper Mississippian Floyd Shale, dark gray deltaic shale in the Pennsylvanian and Mississippian Parkwood Formation, and dark gray to black marine shale in the Upper Devonian Chattanooga Shale (fig. 3).

Dark gray to black shale in unnamed units of Silurian and(or) Late Ordovician age (Mellen, 1974a; Thomas, 1972) also could be source rock units in the basin (fig. 3). Additional potential oil and gas source rocks are shale units in nearshore marine facies of the Pottsville Formation, shale units in turbidite and offshore marine facies of the Pottsville Formation, shale units in the Arkansas Novaculite, and shale units in offshore marine facies of the Chickamauga and Knox Groups (Thomas, 1972). However, more data must be collected to determine the regional extent and organic richness of these units before they are considered to be major source rocks.

The Pottsville Formation in the Warrior coal field (southern part of exposed Black Warrior basin in Alabama) consists of seven major coal zones, each of which contains as many as six coal beds from 9- to 38-in (23- to

Figure 3. Stratigraphic correlation chart for Phanerozoic and Precambrian rocks of the Black Warrior basin. Also identified on the chart are the oil and gas reservoirs and source rocks in the basin. The chart is based on the following publications and drill holes: Bearden (1985), Dockery (1981), Exxon No. 1 Fulgham (drill hole no. 3, figure 1), Harris (1975), Kidd (1975), Lott (n.d.), Mellen (1974a), Repetski and Alberstadt (1984), Scott (1978), Shenandoah and Occidental No. Smith 26-6 (drill hole no. 1, figure 1), Thomas (1972), Welch (1959, 1978). Absolute age (in Ma) is taken from the Geological Time Scale compiled by Palmer (1983). The time scale is nonlinear.


Eon
Era
System
Series
Age (Ma)
Black Warrior basin
Mississippi
Alabama
Oil and (or) Gas Reservoir
Oil and (or) Gas Source Rock
Phanerozoic
Cenozoic
Tertiary
Pliocene
Miocene
Oligocene
Eocene
Paleocene
1.6
5.3
23.7
36.6
57.8
66.4
97.5
144
208
245
286
320
360
408
438
505
570
900
Claiborne Group
Wilcox Group
Midway Gp.
Mesozoic
Cretaceous
Upper
Lower
Jurassic
Triassic
Selma Group
Eutaw Group
Tuscaloosa Group
Paleozoic
Permian
Penn.
Miss.
Dev.
Sil.
Ord.
Cambrian
Upper
Middle
Lower
Pottsville Fm.
Parkwood Fm
Carter ss.
Floyd Sh.
Neal sh.
Lewis ss.
Tuscumbia Ls.
Fort Payne Chert
Bangor Ls.
Hartselle ss.
Pride Mtn. Fm.
Arkansas Novaculite
Chattanooga Shale
Unnamed units
Patterson ss.
Chickamauga Gp.
Stones River Gp.
Knox Group
Unnamed dolomite unit
Conasauga Group
Rome Fm.
Precambrian
Proterozoic
Late
Middle
Metamorphic and Igneous rocks
Floyd Sh.
Neal Sh.
Parkwood Fm.
Chattanooga Shale
Oil Reservoir
Major
Secondary
Gas Reservoir
Major
Secondary
Source Rock
Oil prone
Gas prone

96-cm) thick (Musgrove, 1982; Lyons and others, 1985). Many of these coal beds continue into the subsurface of northern Mississippi beneath the Tertiary and Cretaceous sedimentary cover of the Gulf coastal plain (Tarbutton, 1980). By analogy to coal beds in other parts of the United States and the world, the coal beds in the Black Warrior basin are rich in type III kerogen and therefore may be considered as gas prone source rocks (Tissot and Welte, 1978).

Mancini and others (1983) characterize the Floyd Shale as a dark gray shale and note that shale in the overlying Parkwood Formation contains amorphous, herbaceous, and woody organic matter. Moreover, they concluded that prodelta and interdistributary bay shales of the Parkwood Formation and the marine shale of the Floyd Shale contain sufficient amorphous and herbaceous kerogen to have been petroleum source rocks. Sixteen samples of Upper Mississippian shale collected from the subsurface of Alabama by Bearden and Mancini (1985) range in total organic carbon content (TOC) from .07 to 2.36 weight percent with an average TOC of .59 weight percent. According to Scott (1978), the Neal Shale is an organic-rich black shale unit that was deposited in a basinal setting southwest of the depositional limit of the Bangor Limestone.

The Chattanooga Shale is confined to the Alabama part of the basin where it ranges in thickness from 10 to 40 ft (3-12 m) (Glover, 1959; Conant and Swanson, 1961; Thomas, 1972). Samples of the Chattanooga Shale collected several miles north of the basin near the Alabama-Tennessee border have an average TOC of 16.27 weight percent and an average oil yield of 13.9 gallons/ton (Rheams and Neathery, 1984). Rheams and Neathery (1984) also reported that their samples of the Chattanooga Shale appear to follow a maturation trend between type I (oil prone) and type II (oil and gas prone) kerogen.

Burial history, thermal maturation, timing of migration, and entrapment

Three lines of evidence indicate that the source rocks in the Black Warrior basin are thermally mature with respect to oil and(or) gas generation. First, the coal beds in the Pottsville Formation in the Warrior coal field are low-volatile A bituminous in rank (Culbertson, 1964) and contain commercial quantities of methane gas (Graves and others, 1983; Hewitt, 1984). Tissot and Welte (1978) indicated that a coal rank of low-volatile A bituminous corresponds to a thermal maturation level that is capable of generating oil and wet gas. Second, thermal alteration index (TAI) values of 2 and 3 in Upper Mississippian shales in the subsurface of Alabama (Bearden and Mancini, 1985) indicate that they are located in the zone of oil and wet gas generation (Tissot and Welte, 1978). Third, conodont alteration index (CAI) values of 1.5 to 2 for Pennsylvanian rocks exposed in the Warrior coal field indicate that they are located in the zone of oil and wet gas generation (Harris and others, 1978).

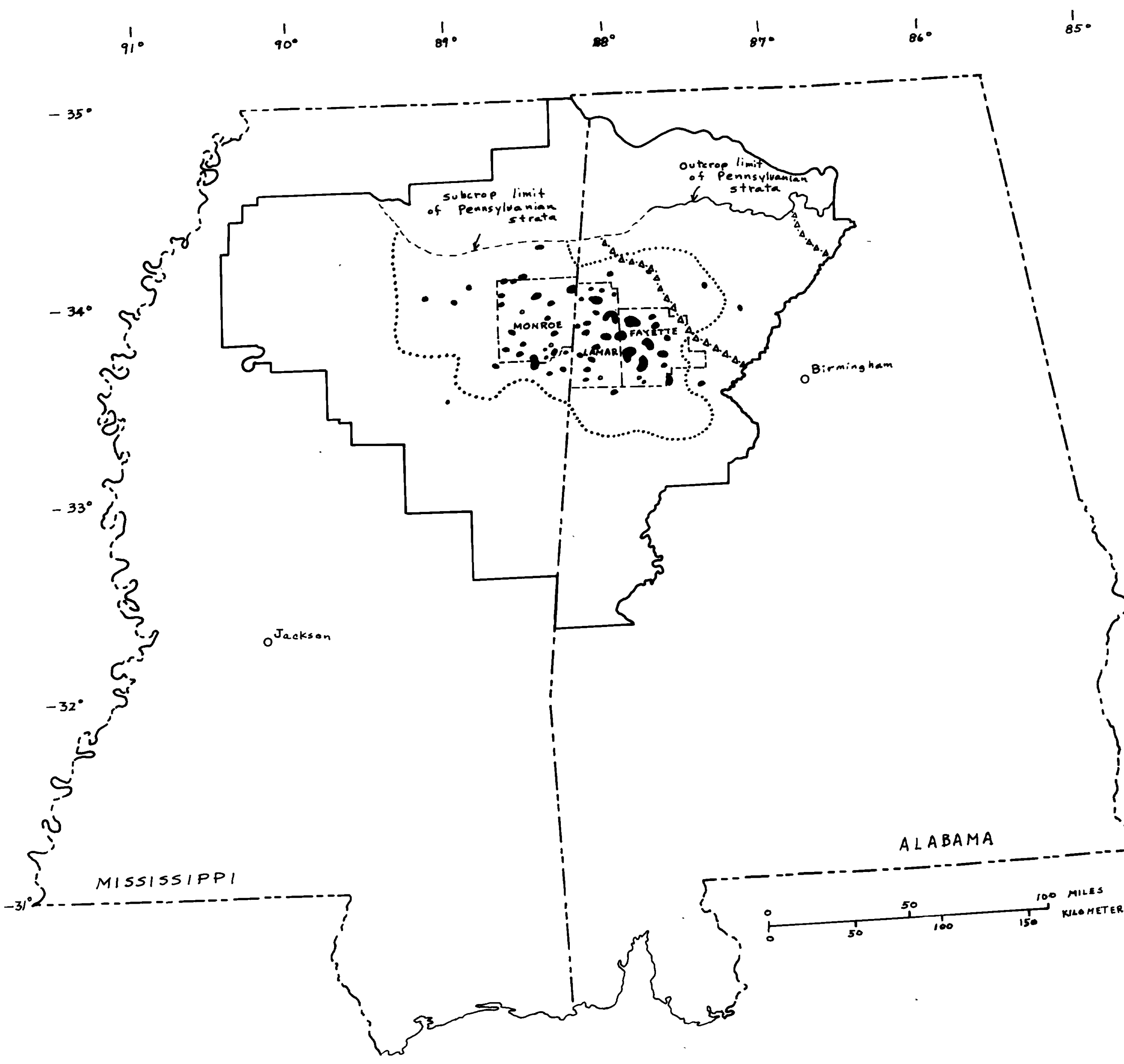
Hydrocarbon generation from the major source rocks probably was initiated in, and continued through, Pennsylvanian time when these rocks were deeply buried beneath a southwestward thickening wedge of terrigenous clastic detritus derived from an Appalachian source. The Pennsylvanian sequence thickens from 400 ft (0.12 km) in the Shenandoah and Occidental No. 1 drill hole on the northern flank of the basin to 7,300 ft (2.2 km) in the Sonat No. 1 Lee drill hole south of the Pennsylvanian hinge zone (fig. 1). Farther south, along the axis of the Black Warrior basin in eastern Mississippi, the Pennsylvanian sequence attains a thickness between 12,000 and 15,000 ft (3.65-4.5 km) (Wanless, 1975). Part of the Pennsylvanian sequence has been removed by pre-Cretaceous erosion and consequently the present-day thickness values for the sequence are a minimum. At least 2,000 ft (0.6 km) of strata of Middle and Late Pennsylvanian and possibly Permian age were eroded from the northern flank of the basin prior to burial beneath Cretaceous and Tertiary strata. The amount of Pennsylvanian strata removed from near the axis of the basin is unknown.

Marked thickness variations in the Pottsville Formation across northwest-trending extension faults (Cleaves, 1983) indicate that Pennsylvanian sedimentation was strongly controlled by penecontemporaneous faulting. Therefore, structural traps created by these growth faults were in place by Pennsylvanian time when major oil and gas generation and migration probably occurred. However, numerous bitumen deposits exposed in Pennsylvanian and Mississippian strata along the northern margin of the basin (Mellen, 1947; Welch, 1959) suggest that significant amounts of oil and gas were never trapped or escaped from the basin after entrapment. Along the northern flank of the basin in Alabama, the total subsurface reserves of bitumen in the Hartselle Sandstone are estimated to be 7.5 billion barrels (Wilson, 1987). Although oil and gas generation and migration seems to have been coincident with the maximum development of structural traps, because of factors such as poor seals, fault rejuvenation, and post-Pennsylvanian uplift and erosion, the amount of oil and gas trapped in the basin is probably a small fraction of what was initially generated. Vernon (1971) implied that a significant part of the petroleum generated in the basin may have escaped because, although structures were present, very few of them had sufficient closure to trap large quantities of hydrocarbons.

Hydrocarbon occurrence

The majority of the oil and gas fields in the Black Warrior basin produce from sandstone reservoirs of Late Mississippian age (figs. 3 and 4). Locally, sandstone units in the Pennsylvanian Pottsville Formation produce small amounts of oil and gas either in combination with, or separate from, Mississippian sandstone reservoirs. Most of these oil and gas accumulations of Mississippian and Pennsylvanian age have been trapped by anticlines associated with normal faults or by lenticular porous sandstones draped across anticlinal noses (Spooner, 1976; Bearden, 1985). Only two wells in the basin have produced hydrocarbons from pre-Mississippian strata. A now-abandoned well located near the Magnolia No. 1 Pierce drill hole (fig. 1) produced 7,813 barrels of oil in one year from a dolomite zone of Ordovician age (Mellen, 1974b). Originally, this dolomite zone was assigned to the Knox Group (Frascogna, 1957; Pike, 1968; Mellen, 1974b; Vernon, 1971), but conodont studies by Repetski and Alberstadt

Figure 4. Map of Alabama and Mississippi showing the outline of the Black Warrior basin, selected counties, and the distribution of existing oil and(or) gas fields. Heavy dots show the known subsurface limits of the known Upper Mississippian deltaic sandstone reservoirs in the basin, with the exception of the Hartselle Sandstone (Bearden, 1985; Cleaves, 1983; Welch, 1978). Triangles show the subsurface limits of the Hartselle Sandstone (Cleaves, 1983).



91°
90°
89°
88°
87°
86°
85°
35°
34°
33°
32°
31°
30°
Subcrop limit of Pennsylvanian strata
Outcrop limit of Pennsylvanian strata
MONROE
LAMAR
FAYETTE
Birmingham
Jackson
ALABAMA
MISSISSIPPI
0
50
100 MILES
0
50
100
150
KILOMETERS

(1984) indicated that the dolomite zone is early Middle Ordovician in age. Therefore, the oil productive dolomite zone in the Magnolia No. 1 Pierce well is younger than the Knox Group. The second well, located in eastern Mississippi near the Exxon No. 1 Fulgham drill hole (fig. 1), initially flowed gas at a rate of 200 thousand cubic feet per day (MCFPD) from a carbonate reservoir in the Knox Group (McCaslin, 1976). From September, 1971 through June, 1973 this well produced 123,752 MCF of gas (Mellen, 1974b).

PRINCIPAL PLAYS

Play identification

According to Proctor and others (1982) a play consists of a group of prospects, with or without nearby discovered fields, having common geologic characteristics such as source rock, trapping mechanism, and structural history which may contain oil and(or) gas. In the recent U.S. Geological Survey assessment of undiscovered oil and gas resources, only those plays that are believed to have at least one undiscovered accumulation equal to or greater than 1 million barrels of oil (BO) or 6 billion cubic feet (BCF) of gas are evaluated.

The Upper Mississippian (Chesterian) sandstones constitute the only play identified in the basin. Attributes of this play are 1. several thermally mature source rocks, 2. potential structural and stratigraphic traps, 3. favorable timing regarding the age of trap formation and hydrocarbon migration, 4. adequate sandstone reservoirs, and 5. known commercial oil and gas accumulations. Numerous holes drilled into or through the Upper Mississippian strata of the basin provide a substantial data base.

Prospective stratigraphic intervals in the basin not considered to be plays include the Pennsylvanian Pottsville Formation, the Chickamauga Group (Middle Ordovician) and equivalent strata, and the Knox Group (Lower Ordovician and Cambrian). At present, too little is known about one or more aspects of these intervals to assign them to plays. In the case of the Pottsville Formation, the reservoir quality of the sandstone is fair to poor (Beard and Maylan, 1987) southwest of the hinge zone, where the opportunity for undiscovered resources is most favorable, and little is known about the organic richness of the intervening shale beds. Overpressuring, another factor that would increase the desirability of this interval as an exploration target, particularly if the sandstones have very low permeability, has not been identified in the basin. Porous, vuggy, and fractured dolomite zones present in the Knox and Chickamauga Groups (Mellen, 1974b) may be difficult to predict. Moreover, although a few hydrocarbon shows and limited production exist in these rocks, the source of the hydrocarbons have yet to be attributed to known, widespread, organic-rich strata.

Coalbed methane from coal beds in the Pottsville Formation has been identified as an unconventional resource in the Black Warrior basin (Graves and others, 1983; Hewitt, 1984). As of 1982, severl coal degasification fields and research areas, with as many as 38 producing wells per site, have been established in the Alabama part of the basin and the adjoining Appalachian fold and thrust belt (Bolin and Masingill, 1983). In place coalbed methane resources in the basin are estimated to range from 5 to 10 trillion cubic feet (Hewitt, 1984; Shirley, 1986).

Upper Mississippian (Chesterian) sandstone play

The play derives its name from Upper Mississippian (Chesterian) deltaic sandstone reservoirs that have produced the majority of the oil and gas discovered to date in the Black Warrior basin. Informal and formal names assigned to these sandstone reservoir units include the Lewis, Evans, Abernathy, Rea, Sanders, Carter, and Gilmer sandstones and the Hartselle Sandstone. The stratigraphic position of several of these sandstones is identified in figure 3. The sandstones were derived from the craton to the north and northwest (Welch, 1978; Cleaves, 1983). Anticlines in association with northwest trending normal faults or lenticular sandstones draped across anticlinal noses are expected to be the primary traps. The northern limit of the play is bounded by the outcrop limit of Pennsylvanian strata in Alabama and by the adjoining subcrop limit of these rocks beneath the Tertiary and Cretaceous sequence in Mississippi (fig. 4). At present, oil and gas exploration in this sequence has been confined to the lobe of deltaic sandstones that is centered in Monroe County, Mississippi and Lamar and Fayette Counties, Alabama (fig. 4; Welch, 1978; Cleaves, 1983; Bearden, 1985). However, as drilling expands into deeper parts of the basin and into the northwest part of the basin, new deltaic systems and(or) deep-water sandstone systems may be recognized. Based on the possibility that sandstone reservoirs may extend beyond the presently defined deltaic lobe, the southern, western, and eastern limits of the play are drawn at the corresponding borders of the Black Warrior basin province (fig. 4).

In general, the thickness of the deltaic sandstone reservoirs range from 30 to 50 ft (9-15 m), but locally individual sandstone units may be as thick as 150 ft (45 m) (Welch, 1978; Cleaves, 1983; Bearden, 1985). The sandstone reservoirs are either linear-shaped bodies of distributary channel and distributary mouth bar origin or sheet-like bodies that originated by the reworking of distributary mouth bar deposits by marine currents (Welch, 1978; Cleaves and Broussard, 1980; Cleaves, 1983; Bearden, 1985).

The Chesterian sandstones are fine- to medium-grained quartz arenites (Spooner, 1976; Mancini and others, 1983; Bearden, 1985; Bearden and Mancini, 1985). Average porosity values of the Carter sandstone, measured in cores from five fields, range from 10 to 17.8 percent (Spooner, 1976; Bearden, 1985; Bearden and Mancini, 1985). Average permeability values of the Carter sandstone, based on measurements from 2 fields, range from 10 to 67 millidarcies (md) (Spooner, 1976; Bearden, 1985; Bearden and Mancini, 1985). Porosity and permeability values of other producing Upper Mississippian sandstones in the basin are commonly within these ranges of values (Frascogna, 1957; Davis and Lambert, 1963). Most of the sandstones have primary, intergranular porosity that has been modified by quartz overgrowths and calcite cementation (Bearden and Mancini, 1985). Dissolution porosity is also present as a result of leached carbonate allochems, calcite cement, and(or) matrix (Bearden and Mancini, 1985). Although not documented, tectonic fractures very possibly could enhance the porosity of the Chesterian sandstones in highly faulted regions of the basin such as along the hinge zone.

An extensive network of northwest-trending normal faults and derivative anticlinal structures have trapped most of the oil and gas in the Upper Mississippian (Chesterian) sandstones. Stratigraphically controlled accumulations resulting from sandstone pinchouts and(or) diagenetic alterations in combination with anticlinal structures have also been documented (Frascogna, 1957; Davis and Lambert, 1963; Spooner, 1976; Bearden, 1985). Lateral and top seals for the hydrocarbon accumulations are prodeltaic and offshore marine gray shale and siltstone units up to 50 ft (15 m) thick. Locally, impermeable pelitic units in either the foot wall or hanging wall of normal faults may act as lateral seals.

Abundant oil and gas production and shows in the Upper Mississippian sequence in the subsurface and bitumen deposits in equivalent rocks in the outcrop indicate that large quantities of oil and gas were available for entrapment in this play.

Dark gray to black shale units in the Parkwood Formation, Floyd Shale, Neal Shale, and possibly the Chattanooga Shale are the source of the oil and gas (fig. 3). Bearden and Mancini (1985) describe the shales in the Parkwood Formation and Floyd Shale as excellent source rocks and Scott (1978) describes the Neal Shale as being rich in organic matter. Studies by Rheams and Neathery (1984) indicate that the Chattanooga Shale is an excellent oil- and gas-prone source rock. The low volatile-A bituminous rank of Pennsylvanian coal beds, TAI values between 2 and 3 in Upper Mississippian shale beds, and CAI values between 1.5 and 2 in Pennsylvanian strata indicate that the Upper Mississippian and Upper Devonian source rocks in the basin are mature with respect to oil and gas generation. Maximum hydrocarbon generation and migration from the Upper Mississippian and Devonian source rocks probably occurred during Pennsylvanian time when they were buried beneath a southwestward thickening wedge of terrigenous clastic sediments derived from the Appalachian fold and thrust belt. The marked influence of northwest-trending, down-to-the-basin normal faults on Pennsylvanian sedimentation (Cleaves, 1983) suggests that structural traps were available in the Upper Mississippian sequence by Pennsylvanian time, when peak oil and gas generation and migration occurred.

Drilling in this play has been largely concentrated in the northern part of the basin where the depth to the reservoir sandstones ranges from 1000 to 6000 ft (0.3-1.8 km). In contrast, drilling has been sparse in the northwest part of the basin where the depth to the reservoir sandstones is relatively shallow and in the southwest part of the basin where the depth to the reservoir sandstones ranges from 10,000 to 18,000 ft (3.0-5.5 km).

According to Pike (1968), the first gas production in the Black Warrior basin was established in 1909 from a Pennsylvanian sandstone in Fayette County, Alabama (fig. 4) at a depth of 1400 ft (0.4 km). In 1926 gas was discovered in Monroe County, Mississippi (fig. 4) from an Upper Mississippian sandstone at a depth of 2,400 ft (0.7 km) (Pike, 1968). Exploration in the 1950's and early 1960's in the basin was concentrated in and around Monroe County and resulted in the discovery of several small gas fields and two noncommercial oil accumulations in Upper Mississippian sandstone reservoirs (Welch, 1971). The largest field discovered during this phase of exploration, Muldon field, produced gas from the Upper Mississippian Sanders sandstone at about 5500 ft (1.67 km) (Frascogna, 1957). The discovery of the East Detroit field in Lamar County, Alabama (fig. 4) in 1970 is attributed by Bearden and Mancini (1985) to have been the catalyst for the upswing in drilling activity in the 1970's and 1980's (McCaslin, 1978, 1979, 1980, 1984, 1985). Through 1982, 57 gas fields and 9 oil fields had been discovered in Upper Mississippian sandstone reservoirs in the Alabama part of the basin and all but two of these fields have been discovered since 1970 (Bolin and Masingill, 1983).

The majority of the gas discovered in the basin is dry and nonassociated (Spooner, 1976; Bolin and Masingill, 1983), but locally, small amounts of oil, wet gas, and condensate have been produced with the dry gas. Of the 155 billion cubic feet (BCF) of gas that was produced from Upper Mississippian sandstone reservoirs through 1982 in the Alabama part of the basin, 141 BCF was produced from the Carter sandstone (Bolin and Masingill, 1983; Bearden and Mancini, 1985). Cumulative gas production from these reservoirs through 1984 was about 225 BCF (White, 1986). Cumulative oil production from Upper Mississippian reservoirs in Alabama was about 1.2 million barrels through 1982 (Bolin and Masingill, 1983; Bearden and Mancini, 1985) and about 2.2 million barrels through 1984 (White, 1986). Cumulative gas production from Mississippian and Pennsylvanian reservoirs in the Mississippi part of the basin was about 358 BCF and 46 BCF, respectively, through 1987 (Mississippi State Oil and Gas Board, 1987). Ultimate recoverable gas resources for the Aberdeen, Splunge, Muldon, and Corrine fields in Mississippi are estimated to be 18 BCF, 35 BCF, 80 BCF, and 200 BCF, respectively (Frascogna, 1957; Welch, 1971; Spooner, 1976; Oil and Gas Journal, 1977). Cumulative oil production from Mississippian and Pennsylvanian reservoirs in Mississippi was about 1.9 million barrels through 1987 (Mississippi State Oil and Gas Board, 1987).

Based on qualitative resource assessment techniques developed by Miller (1983) and Taylor and Steven (1983), the potential for undiscovered oil and gas resources in the Upper Mississippian (Chesterian) sandstone play is rated high. The level of certainty of the estimated resource is D, meaning that the available information clearly defines the level of resource potential (Taylor and Steven, 1983).

Several factors may limit the volume of undiscovered resources in the play. First, reservoir-quality sandstone units have not been identified in the area south and west of the major exploration activity centered in Monroe County, Mississippi and Lamar and Fayette Counties, Alabama (fig. 4). However, drilling in these areas is still sparse and thus the possibility is good that at least some reservoir-quality sandstones exist there. Second, the quality of the seals is unknown. Downy (1984) suggests that the sealing capacity of fault planes is poor, so that hydrocarbon entrapment along fault zones must rely on impervious lithologic units in the adjoining block. If the lateral seals are thin and(or) have low capillary pressure, hydrocarbons may have been trapped only temporarily if at all. Third, the amount of pre-Cretaceous uplift and erosion in the basin is unknown. Major uplift of the basin then may have been accompanied by the rejuvenation of Pennsylvanian-age faults and by the creation of an extensive network of dilation fractures, both of which may have permitted the redistribution and(or) escape of oil and gas along vertical pathways.

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