

Chapter 3

Petroleum Assessment of the Chattanooga Shale/Floyd Shale— Paleozoic Total Petroleum System, Black Warrior Basin, Alabama and Mississippi



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Volume Title Page*

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Chapter 3 of

Geologic Assessment of Undiscovered Oil and Gas Resources of the Black Warrior Basin Province, Alabama and Mississippi

Compiled by Joseph R. Hatch and Mark J. Pawlewicz

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Petroleum Assessment of the Chattanooga Shale/ Floyd Shale–Paleozoic Total Petroleum System, Black Warrior Basin, Alabama and Mississippi

By Mark J. Pawlewicz and Joseph R. Hatch

Overview

The total petroleum system approach was used to estimate the undiscovered petroleum resources of the Chattanooga Shale/ Floyd Shale–Paleozoic Total Petroleum System (TPS) in the Black Warrior Basin Province in Alabama and Mississippi. The TPS was defined geologically, and two conventional assessment units (AU), the Pre-Mississippian Carbonate AU and Carboniferous Sandstones Assessment Unit, were evaluated formally. Based on the numerical code system established to identify individual provinces, petroleum systems, and assessment units (Klett and others, 1997), the Black Warrior Basin Province is numbered 5065, the Chattanooga Shale/Floyd Shale–Paleozoic TPS is numbered 506501, and the Pre-Mississippian Carbonates AU and Carboniferous Sandstones AU are numbered 50650101 and 50650102, respectively. Geologic data considered in defining TPS and AU boundaries included source-rock distribution and thickness, overburden thickness, faulting intensity, and organic-matter thermal maturity. Historical production data were used to estimate volumes of gas in undrilled areas.

Geologic Setting

The Chattanooga Shale/Floyd Shale–Paleozoic TPS (fig. 1) extends approximately from the Appalachian fold and thrust belt on the southeast side of the Black Warrior Basin to the Nashville dome on the north and to the buried Ouachita structural front to the southwest in central Mississippi. Regarding the two conventional AUs defined within the TPS: (1) the Pre-Mississippian Carbonates AU consists of platform carbonate reservoirs in the Cambrian and Lower Ordovician Knox Group and the Middle Ordovician Stones River Group, with gas trapped by basement-controlled fault blocks and possible ramp anticlines associated with frontal thrust faults and facies changes; and (2) the Carboniferous Sandstones AU consists of fluvial, deltaic, and shallow-marine sandstone reservoirs in the Upper Mississippian Floyd Shale and Parkwood Formation (including the informally named

“Lewis,” “Evans,” “Sanders,” “Carter,” and “Millerella” sandstones) and the Lower-Middle Pennsylvanian Pottsville Formation (including the informally named “Fayette” and “Nason” sandstones), with gas and oil trapped by a variety of basement-involved fault blocks, stratigraphic traps, and a combination of structural and stratigraphic traps (fig. 2).

Stratigraphic Framework

As described by Thomas (1972), the Upper Mississippian Floyd Shale is primarily dark gray shale that constitutes the lower part of the clastic sequence overlying the Upper Mississippian Tuscumbia Limestone and the Lower Mississippian Fort Payne Chert in the Black Warrior Basin (fig. 2). The shale is believed to be primarily the prodelta facies of a major regressive wedge that grades upward into the Upper Mississippian Bangor Limestone and Parkwood Formations and includes beds equivalent to the Hartselle Sandstone and “Evans” and “Lewis” sandstones and shales. The Floyd Shale includes back-barrier marine, lagoonal, and marginal marine clays and is believed to have been derived from the southwest and transported toward the northeast. The unit thickens to the northeast, reaching a maximum of 600 ft in depocenters along the Appalachian downwarps (fig. 3) (Thomas, 1972). Sandstone beds as much as 80 ft thick, siderite nodules, shaly argillaceous limestone, and calcareous shale and chert are included in the formation.

In the eastern part of the Black Warrior Basin, in northern Alabama, the Upper Devonian Chattanooga Shale and the Lower Mississippian Maury Shale have a combined thickness of less than 50 ft. These two shales thin and pinch out to the west and south, and in Mississippi they form discontinuous black shale units. The Chattanooga Shale rests unconformably on Silurian and Ordovician strata in the eastern part of the basin, whereas the shale oversteps the eastward-thinning Lower Mississippian Fort Payne Chert in the western part of the basin (Thomas, 1988).

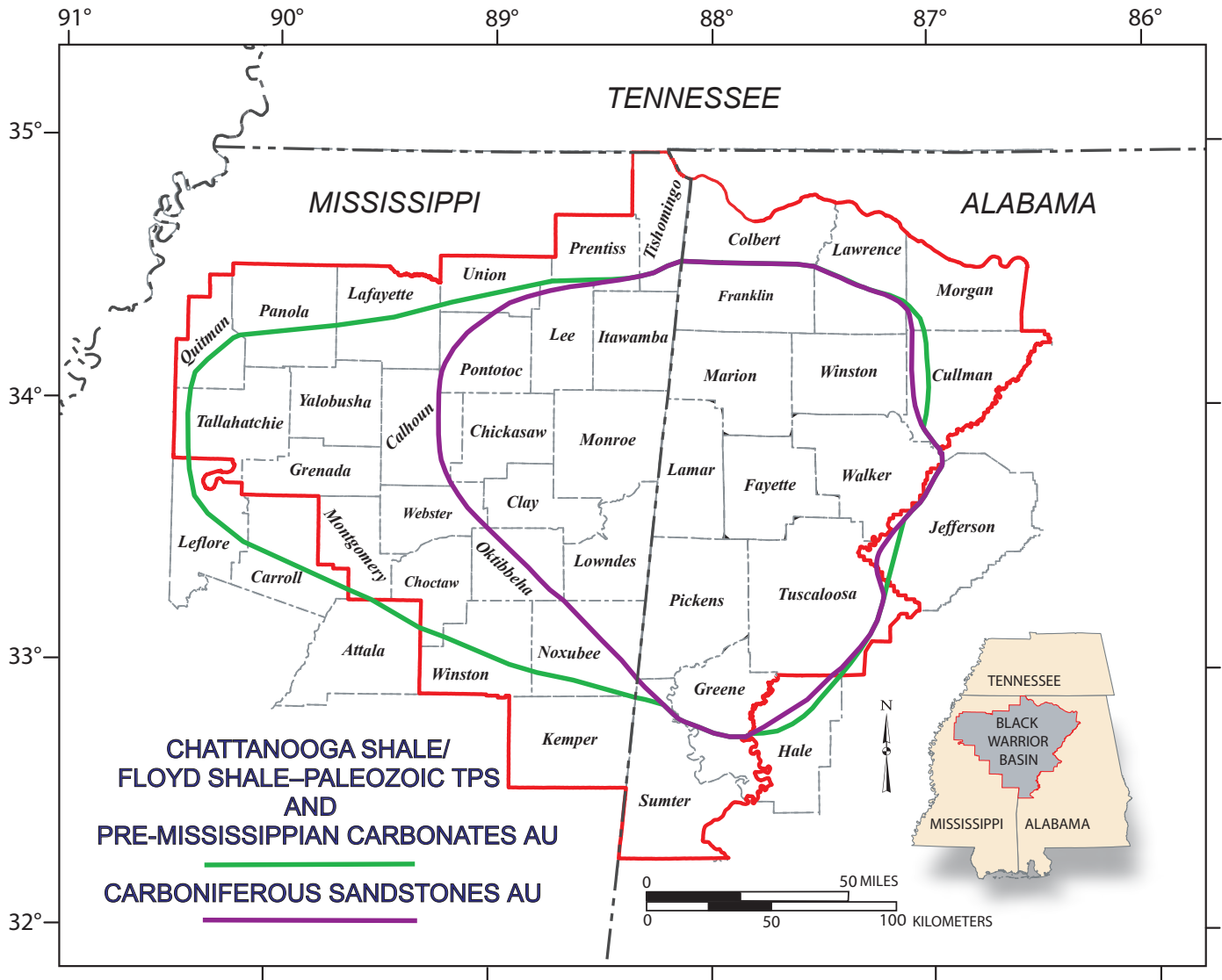


Figure 1. Areal distribution of the Chattanooga Shale/Floyd Shale–Paleozoic Total Petroleum System (TPS), Pre-Mississippian Carbonate Assessment Unit (AU), and Carboniferous Sandstones AU in the Black Warrior Basin Province, northwestern Alabama, and northeastern Mississippi.

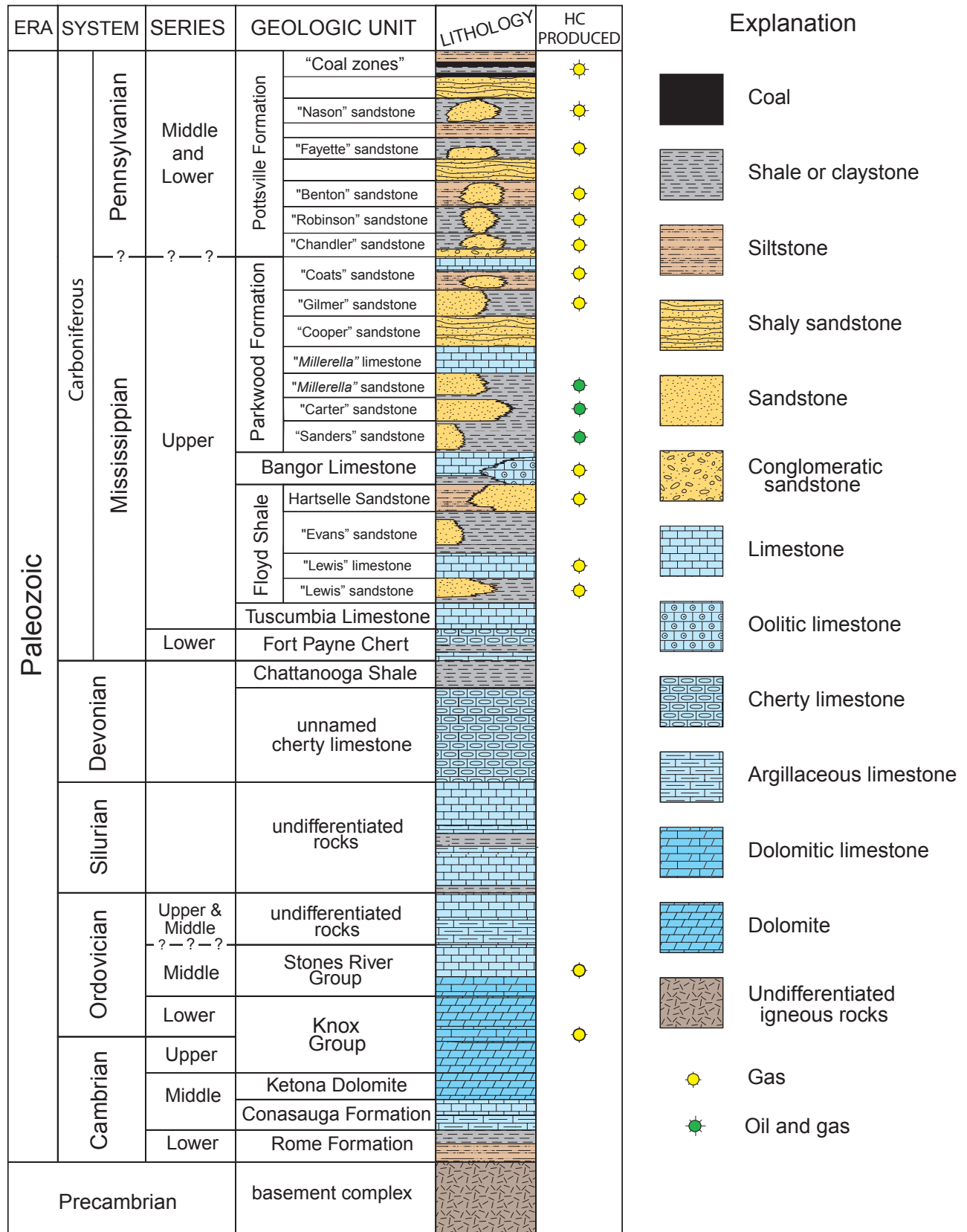


Figure 2. Generalized stratigraphic column for the Black Warrior Basin, Alabama and Mississippi. Unit names in quotes are informal names of local usage. After Montgomery 1986; also modified in part from Popov and others (2001, their fig. 13).

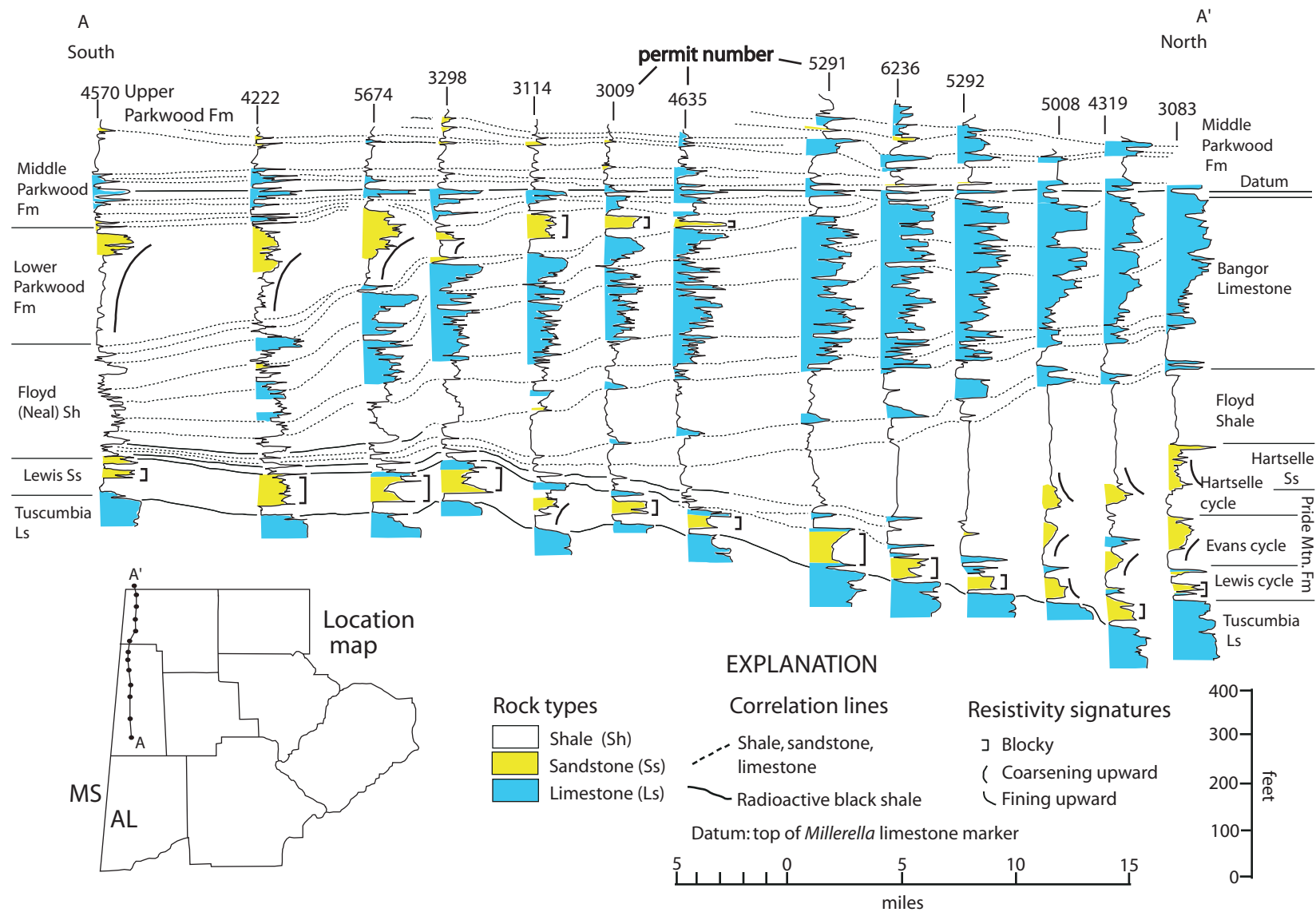


Figure 3. Floyd Shale depositional cycles. Modified from Pashin and Rindsberg (1993). County names for location map given in figure 1.

Structural Framework

As described by Thomas (1988), the structural framework of the Black Warrior Basin can be broadly characterized as a homocline that dips southwest toward the Ouachita orogenic belt and contains numerous superimposed folds and faults (fig. 4). On the southeast margin of the basin, folds of the Appalachian thrust belt are superimposed on the homocline. The Paleozoic strata are complexly faulted (fig. 5). Major faults trend northwest, and normal faults have dips of 60–70° (Pike, 1968). In southeastern Mississippi, normal and thrust

faults, apparently of Early Pennsylvanian age, have placed Carboniferous rocks in fault contact with Lower Ordovician and Cambrian strata (Thomas, 1988). Seismic data from the southwestern part of the basin indicate as much as 9,800 ft of displacement on down-to-the-southwest faults.

During the Mesozoic and Cenozoic, the Black Warrior Basin began to tilt to the southwest toward the axis of the Mississippi embayment. Fault systems originating during this time period, which were associated with the opening of the Gulf of Mexico, crosscut Paleozoic structures.

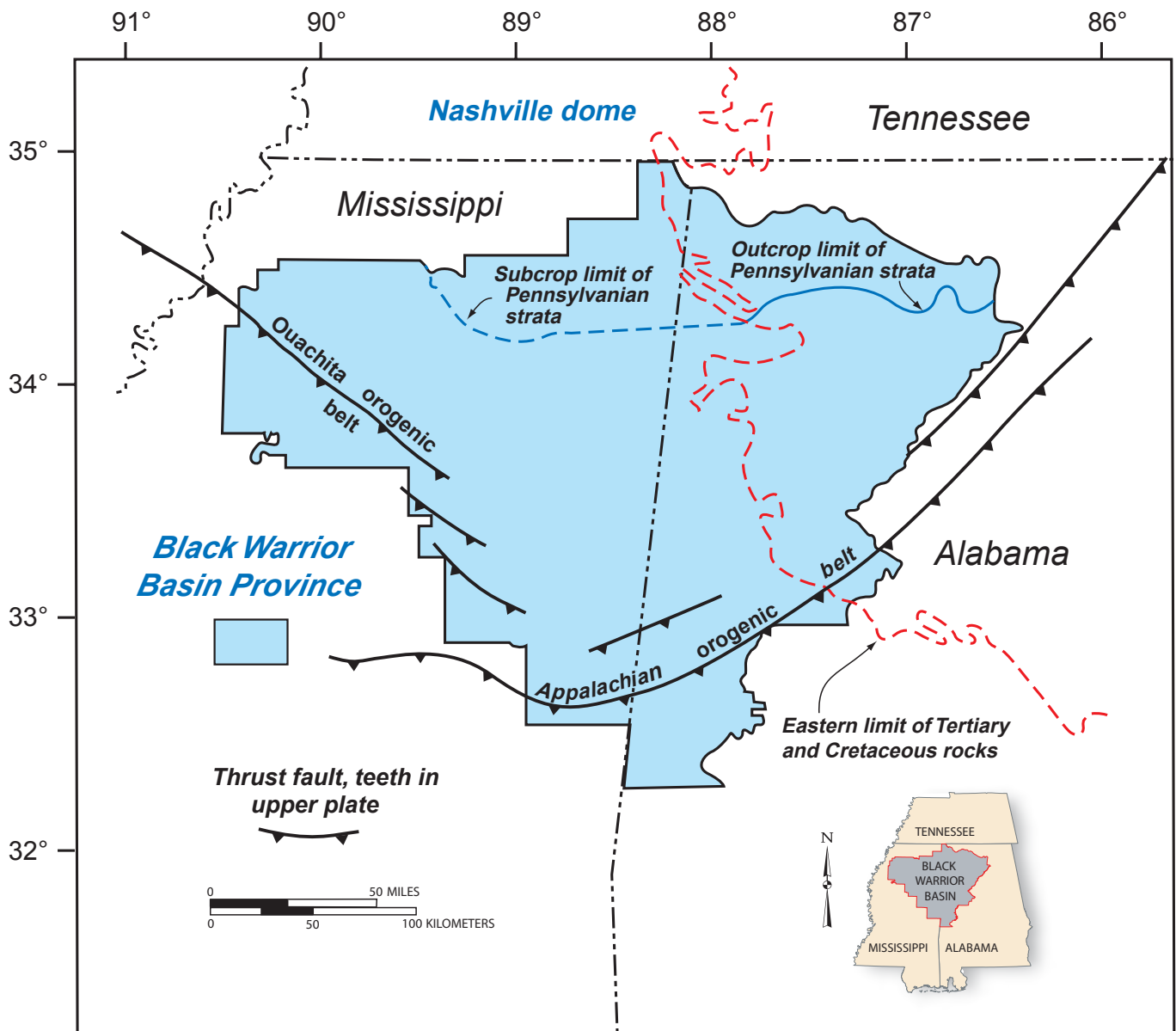


Figure 4. Tectonic setting of the Black Warrior Basin, Alabama and Mississippi. Modified from Thomas (1988), Ryder (1994), and Popov and others (2001, their fig. 11).

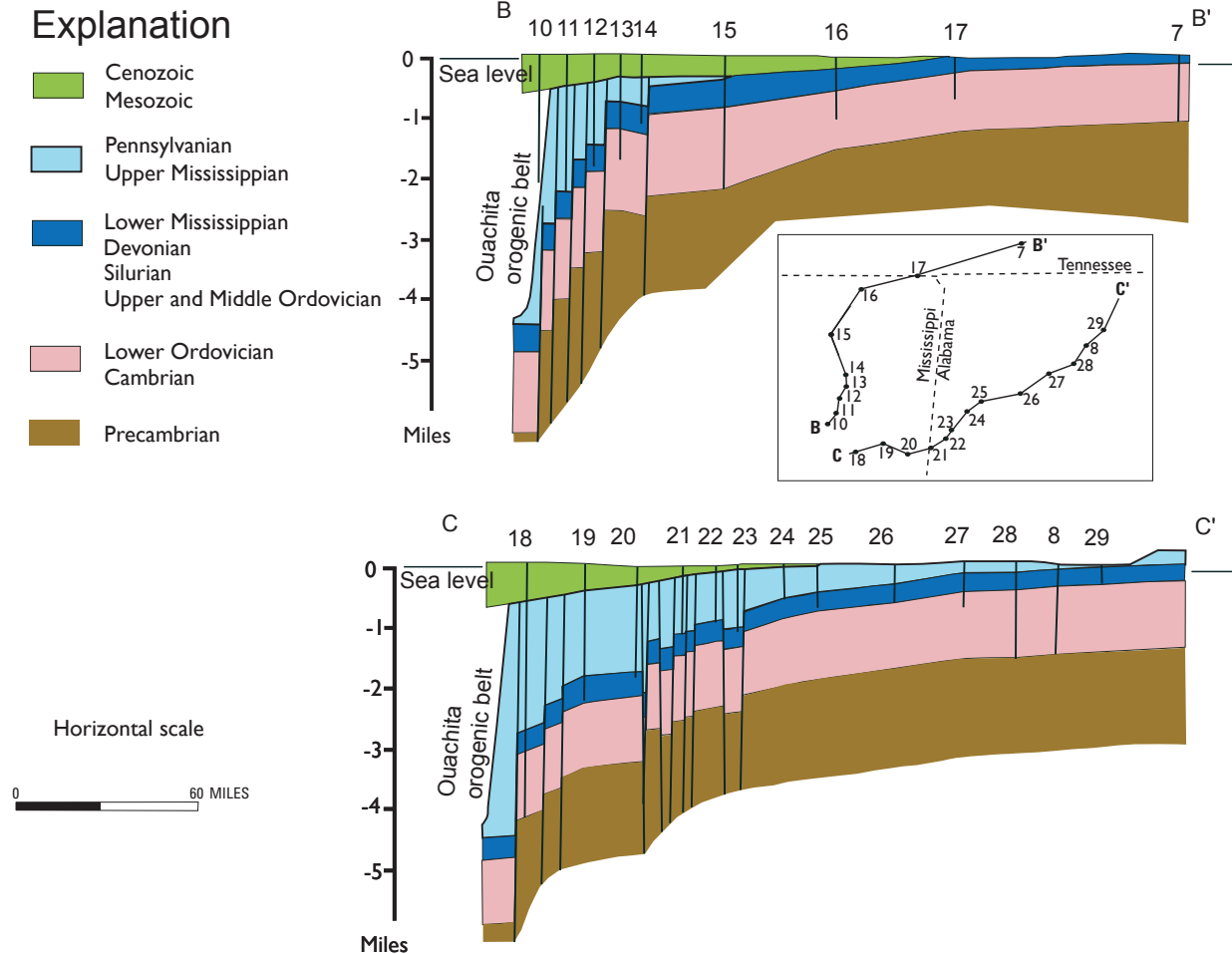


Figure 5. Cross sections showing structural relations of Paleozoic rocks across the Black Warrior Basin, Alabama and Mississippi. From Thomas (1988).

Hydrocarbon Source-Rock Characterization

Hydrocarbon source-rock potential is dependent on the amount, composition, and thermal maturity of organic matter in the rock. The amount of organic matter is measured by the total organic carbon (TOC) content, the relative hydrogen richness (hydrogen index, HI) of the organic matter, the Rock-Eval[®] hydrogen index (S_2/TOC , in milligrams per gram [mg/g]), the Rock-Eval[®] Tmax (°C) thermal maturity, and the vitrinite reflectance (% R_o) thermal maturity. Median values and ranges for TOC and HI for 19 Floyd Shale and eight Chattanooga Shale core samples are summarized in table 1. The distributions of TOC and HI for these samples are shown in figures 6, and 7, respectively.

Organic Carbon

As indicated in table 1, TOC ranges from 0.5 to 10.2 weight percent (wt %) (mean 1.8 wt %) for the Floyd Shale

and 2.4 to 12.7 wt % (mean 4.6 wt %) for the Chattanooga Shale. Ronov (1958) estimated a critical minimum TOC of 0.5 wt % for shale to be an effective hydrocarbon source rock; so, on that basis, most intervals within the two formations qualify as potential hydrocarbon source rocks. Even though the Floyd

Table 1. Ranges and median values of total organic carbon and hydrogen index for core samples from the Floyd Shale and Chattanooga Shale in the Black Warrior Basin, Alabama, and Mississippi. Data are for samples where Rock-Eval[®] Tmax ≤ 450° and total organic carbon ≥ 0.5 percent.

[TOC, total organic carbon; wt %, weight percent; HI, hydrogen index; mg HC/g TOC, milligrams of hydrocarbons per gram of TOC. Data listed in Carroll and others (1995, their table 8-3)].

Unit	Number of samples	TOC (wt %)	HI (mg HC/gTOC)
Floyd Shale	19	Range 0.5–10.2 Mean 1.8	Range 42–345 Mean 145
Chattanooga Shale	8	Range 2.4–12.7 Mean 4.6	Range 140–350 Mean 260

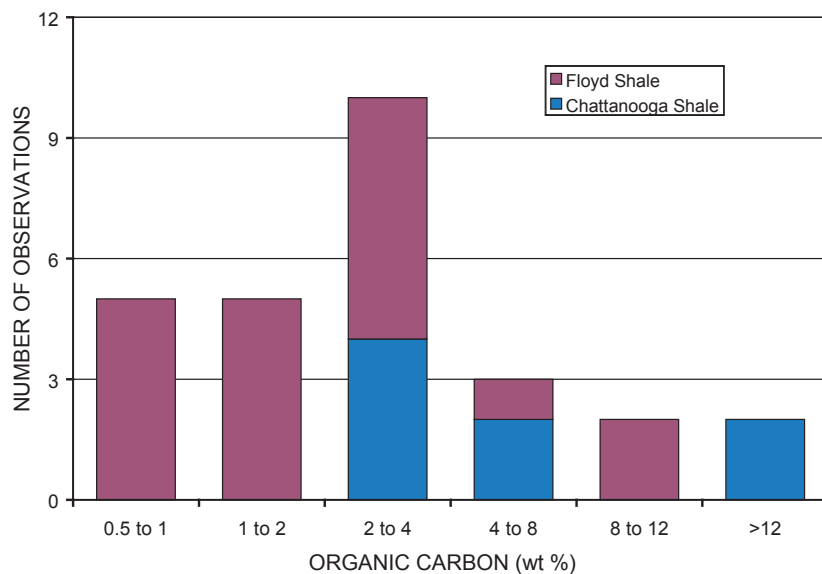


Figure 6. Stacked bar histogram of organic carbon contents for 19 Floyd Shale samples and 8 Chattanooga Shale samples from the Black Warrior Basin, Alabama and Mississippi. Samples are those where Rock-Eval® Tmax ≤ 450°C and total organic carbon ≥ 0.5 percent. Wt %, weight percent.

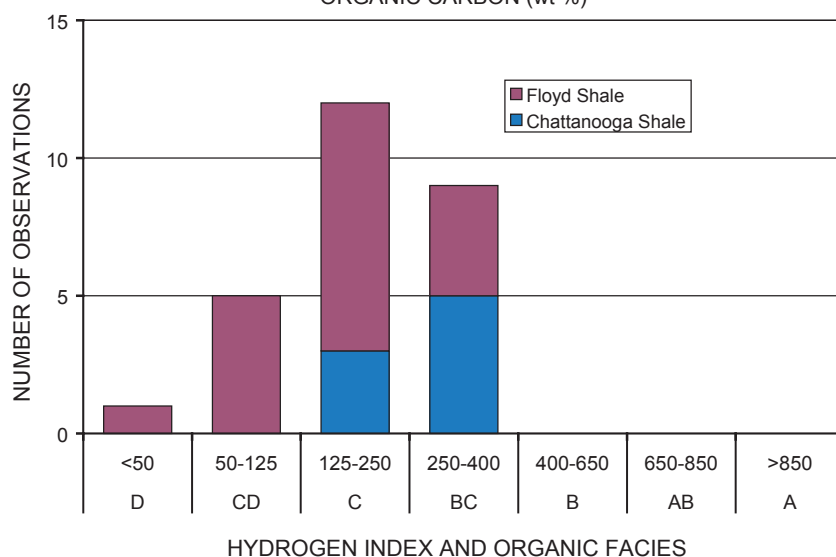


Figure 7. Stacked bar histogram of hydrogen indices (mg S₂/gTOC) for 19 Floyd Shale samples and 8 Chattanooga Shale samples from the Black Warrior Basin, Alabama and Mississippi. Samples are those where Rock-Eval® Tmax ≤ 450°C and total organic carbon content ≥ 0.5 percent; boundaries for organic facies D through A from Jones (1987). <, less than; >, greater than.

Shale has less organic matter, it probably is the primary contributor of hydrocarbons to the TPS because of its much greater thickness — as much as 200 ft locally — compared to the average thickness of only 10 ft for the Chattanooga Shale.

Hydrogen Index – Organic Facies

Hydrogen indices for the Floyd Shale samples range from 42 to 345 mg/g, whereas HI for the Chattanooga Shale samples range from 135 to 350 mg/g. Nevertheless, the median HI is lower for the Floyd Shale (150 mg/g) than for the Chattanooga Shale (260 mg/g).

Jones (1987) defined a series of organic facies (labeled A–D) for rocks based on microscopic and chemical characteristics (HI, H/C ratios) of organic matter that is marginally mature with respect to petroleum generation (Ro about 0.50). Organic facies A has the highest potential for oil generation, and facies AB also has high potential for oil. Organic facies B, however, is the source of most of the world’s oil. Organic facies BC has capacity to generate both oil and

gas, and hydrocarbons generated from organic facies C are nearly always condensate and gas. Organic facies CD has a moderate capacity for dry gas generation, whereas organic facies D is essentially nongenerative (Jones, 1987).

As summarized in table 1 and shown in figure 7, organic matter in the Floyd Shale primarily represents organic facies C (median HI = 150, with the range in compositions from organic facies BC to D). Organic matter in the Chattanooga Shale is primarily organic facies BC and C (median HI = 260). Under thermally mature conditions, organic matter in the Floyd Shale should primarily generate gas and gas condensate with some oil, whereas organic matter in the Chattanooga Shale should generate both oil and gas according to data on organic-facies types published by Tissot and Welte (1978).

Organic Matter Thermal Maturity

Rock-Eval® Tmax measurements of organic matter in 29 Floyd Shale samples and 9 Chattanooga Shale samples from northwestern Alabama are listed in Carroll and others (1995,

their table 8–3). T_{max} for the Floyd Shale samples ranges from 432° to 497°C, and T_{max} for the Chattanooga Shale samples ranges from 433° to 454°C; these values indicate that the organic matter is thermally mature with respect to hydrocarbon generation (Espitalié and others, 1977).

Vitrinite reflectance measurements for seven Floyd Shale samples and one Chattanooga Shale sample from northwestern Alabama, as listed in Carroll and others (1995, their table 8–1), show R_o values that range from 0.92 percent to 1.6 percent, confirming that organic matter in the samples is thermally mature with respect to hydrocarbon generation.

In their study of the thermal maturity of Devonian through Pennsylvanian strata in the Black Warrior Basin in northwestern Alabama, Carroll and others (1995) observed a general increase of thermal maturity with depth based on R_o values derived from whole-rock preparations of borehole cuttings. Additionally, their results indicated a general increase of thermal maturity from the northwestern part of the basin in Alabama toward the south, corresponding to the increased depth of burial shown on a regional cross section by Thomas (1988).

Thermal Maturity Modeling

Lopatin modeling (fig. 8) of the stratigraphic interval from the Devonian Chattanooga Shale through the Upper Mississippian Parkwood Formation in Pickens County, west-central Alabama, provides evidence for a complex burial and thermal history and enables some generalizations to be made about burial and hydrocarbon generation (Telle and others, 1987; Hines, 1988; Carroll and others, 1995). Major thermal maturation apparently took place during rapid burial of the foreland basin that was associated with Appalachian-Ouachita orogenesis. For example, coal in the Lower Pennsylvanian Pottsville Formation, which overlies the Parkwood Formation, attained a high-volatile-A bituminous rank during maximum burial at the end of the Paleozoic (251 Ma). It is noteworthy that major thermogenic oil and gas generation is thought to have occurred at that time. According to the Lopatin models, however, minor thermogenic gas generation may have continued during post-orogenic unroofing, but generation was effectively completed

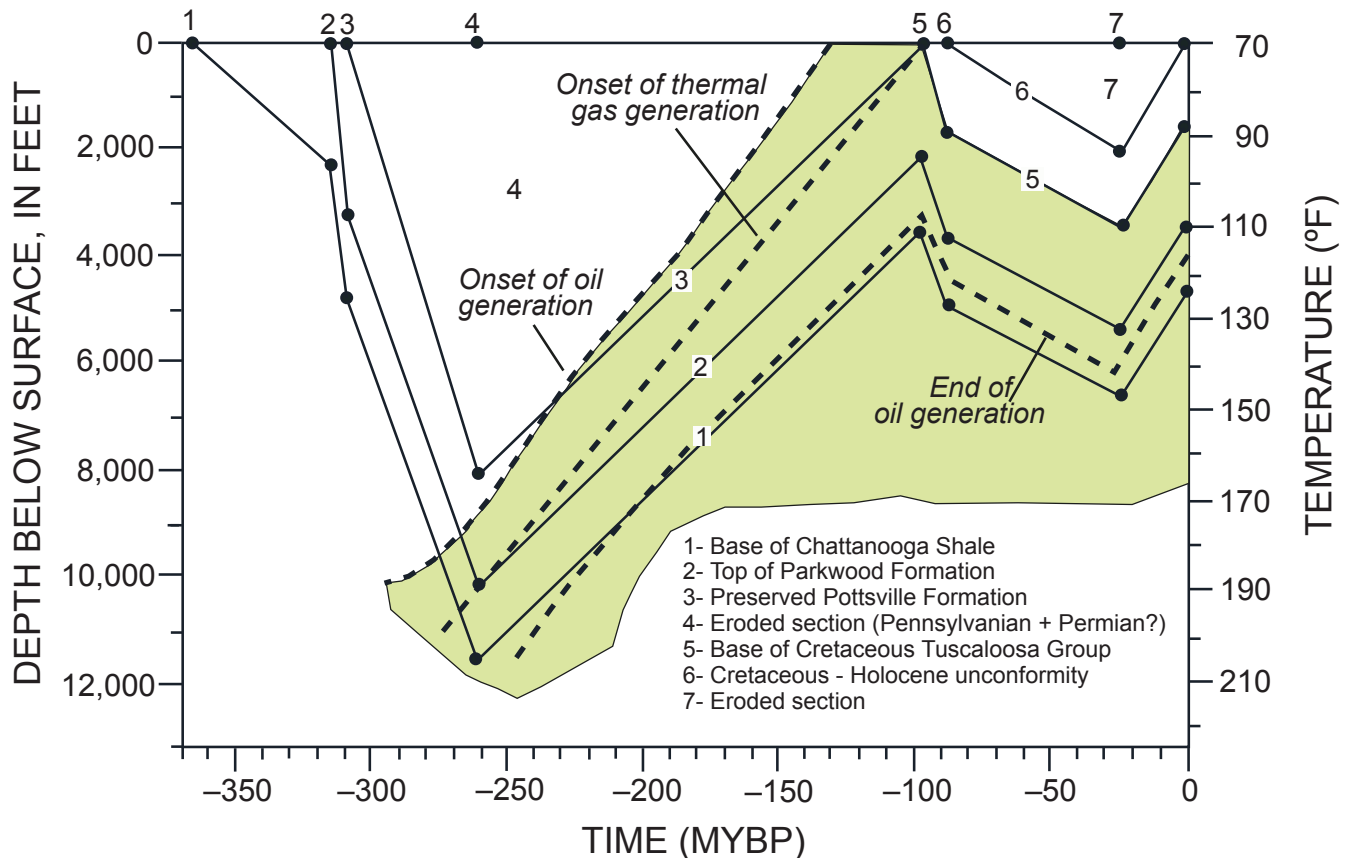


Figure 8. Relation between burial history and thermal conditions with respect to oil and gas generation in the Chattanooga Shale-Parkwood Formation stratigraphic interval in Pickens County, Alabama. Modified from Carroll and others (1995, their fig. 4), and Pashin and Hinkle (1997, their fig. 26). MYBP, million years before present.

and unaffected by Late Cretaceous reburial by Gulf Coastal Plain and Mississippi Embayment strata.

Hydrocarbon Chemistry

Natural Gas Chemistry

Chemical analyses of produced gases from the Chattanooga Shale/Floyd Shale–Paleozoic TPS (mainly a dry gas system due to its composition of organic matter with low hydrogen content) are summarized in table 2. The analyses, from Moore and Sigler (1987) and Hamak and Sigler (1991), represent gas samples from Mississippian and Pennsylvanian sandstone reservoirs of the Carboniferous Sandstones AU and demonstrate a wide range of compositions. Median gas wetness is 3.7 percent (range 0.1 to 28.5 percent), with a general increase from north to the south (fig. 9). The increase in gas wetness from north to south is related to an increase in depth (fig. 10) that is likely caused by increased thermal maturity to the south (as shown by Carroll and others, 1995). Median contents of CO₂ (0.10 percent) and N₂ (1.3 percent) are low, with neither showing any systematic changes within the basin (for example, the distribution of CO₂ contents shown in fig. 11). These produced gases contain no measurable H₂S. No gas analyses are available from reservoirs of the Pre-Mississippian Carbonate AU.

Table 2. Ranges and median values of gas wetness, N₂ content, CO₂ content and δ¹³C, for produced gases from the Carboniferous Sandstone Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

[Gas wetness %, 100 times (1-[C₁, mole %/ΣC₁-C₃ mole %]); PDB, Pee Dee belemnite standard. Analyses from Moore and Sigler (1987) and Hamak and Sigler (1991). %, percent; ‰ parts per thousand]

Measured component	Number of samples	Range	Median
Gas wetness	88	0.1 to 28.5	3.7
CO ₂ content (mole %)	88	<0.01 to 27.7	0.1
N ₂ content (mole %)	88	<0.01 to 9.8	1.3
δ ¹³ C ₁ (‰ PDB)	6	-47.2 to -49.8	-49.2

Oil Chemistry

Chemical analyses of oils produced from Mississippian and Pennsylvanian sandstone reservoirs of the Carboniferous Sandstones AU are summarized in table 3. The analyses, including oil gravity (°API), pristane/phytane ratios, and δ¹³C for the saturated and aromatic hydrocarbon fractions, are compiled from Carroll and others (1995).

A representative saturated hydrocarbon distribution of an oil sample is shown in figure 12. This oil, from the Blowhorn Creek field in Lamar County, Alabama, is characterized by a gradual decrease in the amounts of *n*-alkanes between C₁₀ and C₃₀, no significant odd-even numbered *n*-alkanes, and relatively abundant pristane and phytane with a pristane/phytane ratio near 1.3. This saturated hydrocarbon distribution is similar to that of oils derived from Upper Devonian–Mississippian shales in other eastern Paleozoic-age basins (for example, see saturated hydrocarbon distribution for oil from the Mississippian Aux Vases Sandstone in the Illinois Basin in Hatch and others, 1991, their fig. 24–8).

A plot of oil gravity relative to reservoir depth for 31 oil samples from the Mississippian and Pennsylvanian sandstone reservoirs (fig. 13) shows an increase in °API gravity with depth of the reservoir, indicating an increase in thermal maturity with increasing depth (Carroll and others, 1995). This increase in oil gravity with depth parallels the increase in gas wetness with depth shown in figure 10.

Carboniferous Sandstones Assessment Unit

The geologic model for the Carboniferous Sandstones AU is characterized by gas and oil being trapped in Upper Mississippian and Lower Pennsylvanian fluvial, deltaic, and shallow-marine sandstone reservoirs by a variety of basement-involved fault blocks as well as in stratigraphic traps and combined structural-stratigraphic traps. Source rocks are the Upper Devonian Chattanooga Shale and the Upper Mississippian Floyd Shale (figs. 2, 3, 14).

Reservoir Rocks

The reservoir rocks of the Carboniferous Sandstones AU include various sandstones in the Upper Mississippian Parkwood Formation and the Lower-Middle Pennsylvanian Pottsville Formation (figs. 2, 3). These sandstones are part of a clastic wedge that was deposited in a variety of terrestrial to open-marine environments (Kugler and Pashin, 1994). The “Carter” sandstone of the Parkwood Formation, the most prolific oil producer in the basin, for example, originated as deltaic, beach barrier, and shelf-bar deposits (Bearden and Mancini, 1985).

Hydrocarbon Exploration and Production History

Hydrocarbon exploration and production history of the Carboniferous Sandstones AU are summarized as follows:

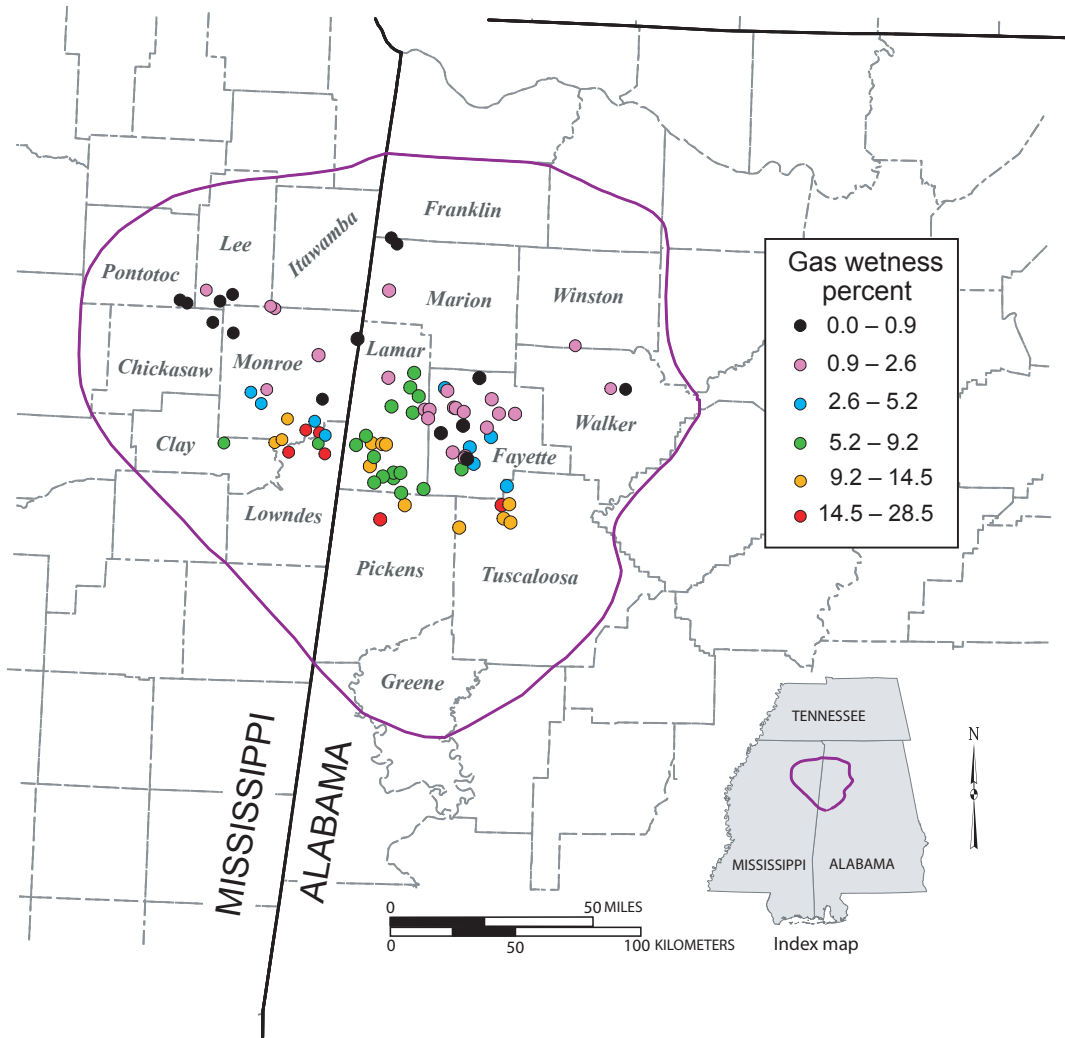


Figure 9. Distribution of gas wetness for samples from reservoirs of the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi (gas wetness percent = $100 \times (1 - [C_1 \text{ mole percent} / \sum C_1 - C_5 \text{ mole percent}])$).

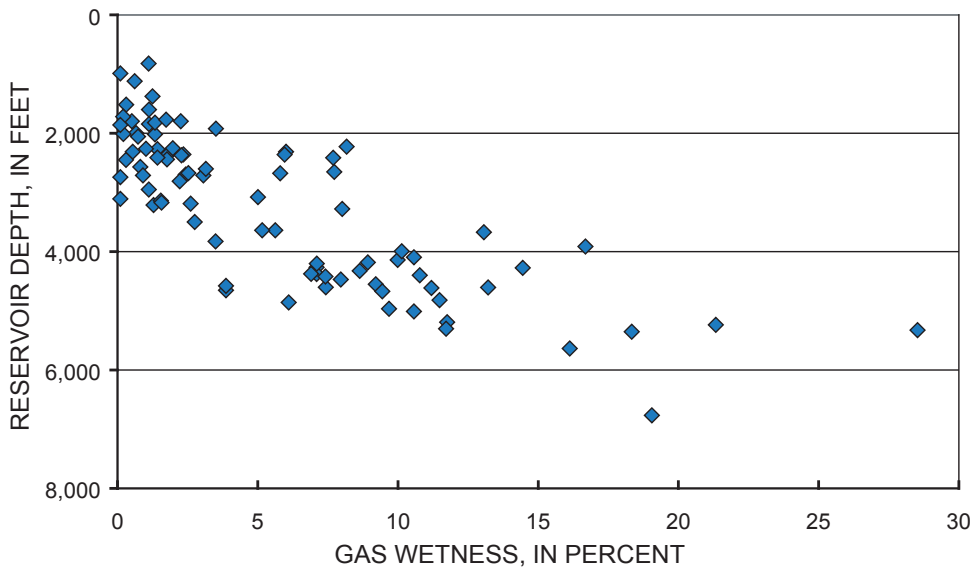


Figure 10. Gas wetness relative to depth for samples from reservoirs of the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi. Gas wetness percent = $100 \times (1 - [C_1 \text{ mole percent} / \sum C_1 - C_5 \text{ mole percent}])$.

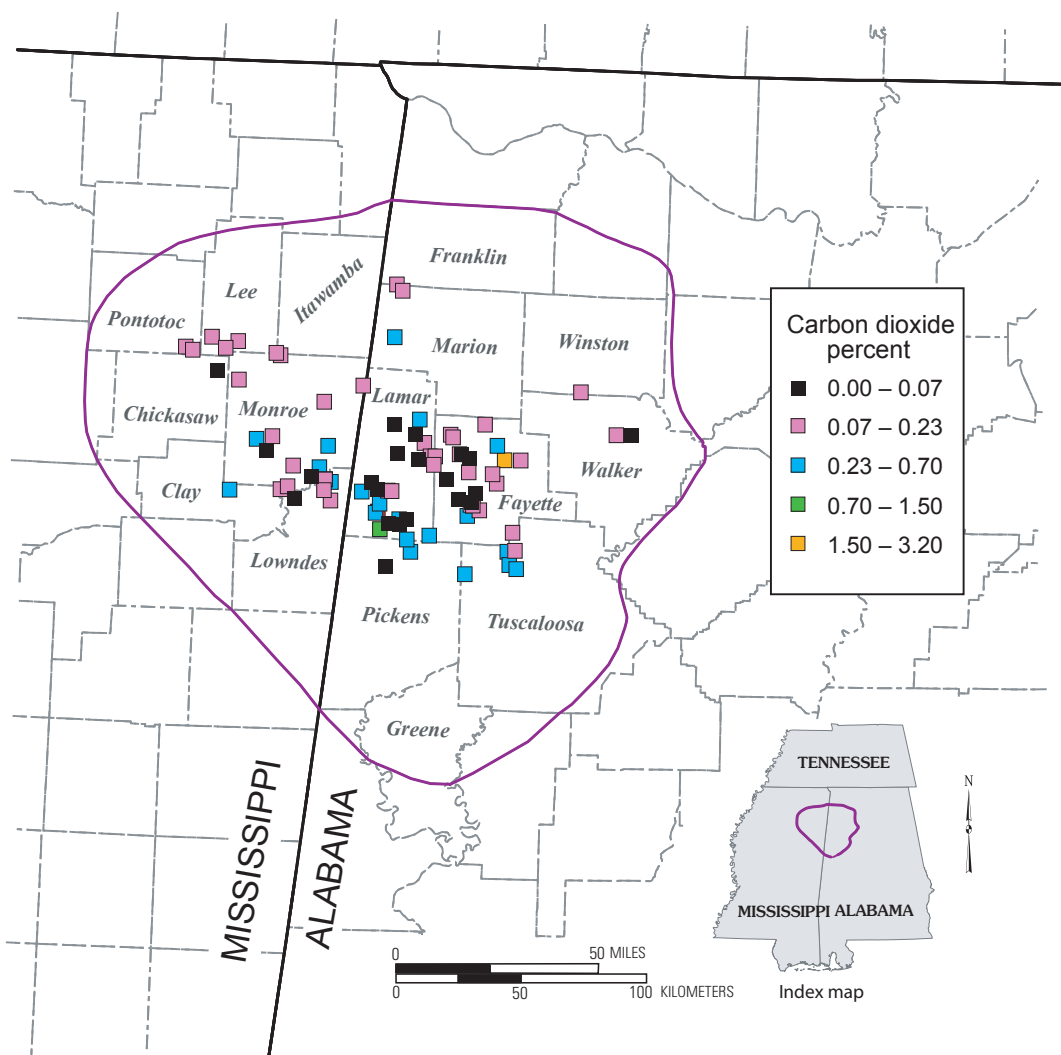


Figure 11. Distribution of carbon dioxide contents (mole percent) for gas samples from reservoirs of the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

Table 3. Ranges and median values of oil gravity ($^{\circ}$ API), pristane/phytane ratios, and $\delta^{13}\text{C}$ of saturated and aromatic hydrocarbon fractions of oils from the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama, and Mississippi.

[PDB, Pee Dee belemnite standard; ‰, parts per thousand; oil gravity measurements and $\delta^{13}\text{C}$ analyses of saturated (sat.) and aromatic (arom.) hydrocarbons fraction listed in Carroll and others (1995, their table 8–4); pristane/phytane ratios and isotope analyses available from <http://energy.cr.usgs.gov/other/index.htm>]

Measured component	Number of samples	Range	Median
Gravity ($^{\circ}$ API)	31	21 to 43	34
Pristane/Phytane	24	1.13 to 1.55	1.28
$\delta^{13}\text{C}$ sat. (‰ PDB)	23	-31.3 to -30.1	-30.64
$\delta^{13}\text{C}$ arom. (‰ PDB)	23	-30.6 to -29.3	-29.87

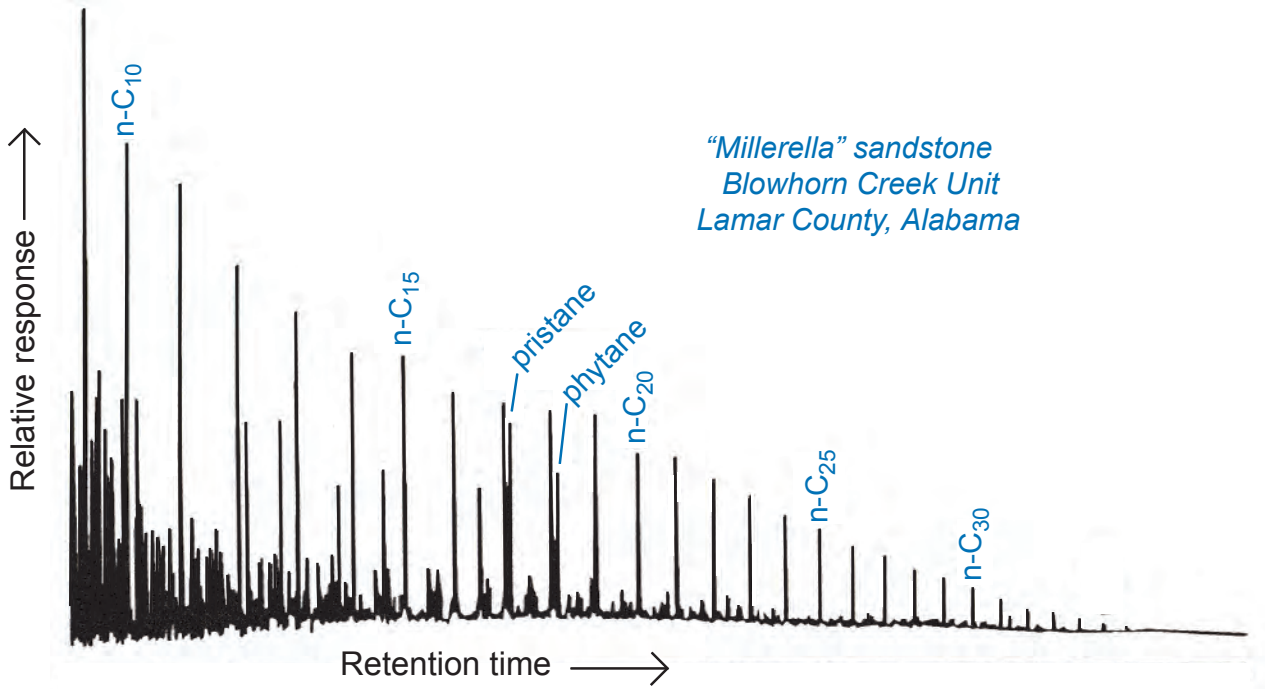


Figure 12. Plot showing C₁₀+ saturated hydrocarbon distribution for oil produced from the "Millerella" sandstone, Blowhorn Creek oil unit, Lamar County, Alabama. After Carroll and others (1995, their fig.10).

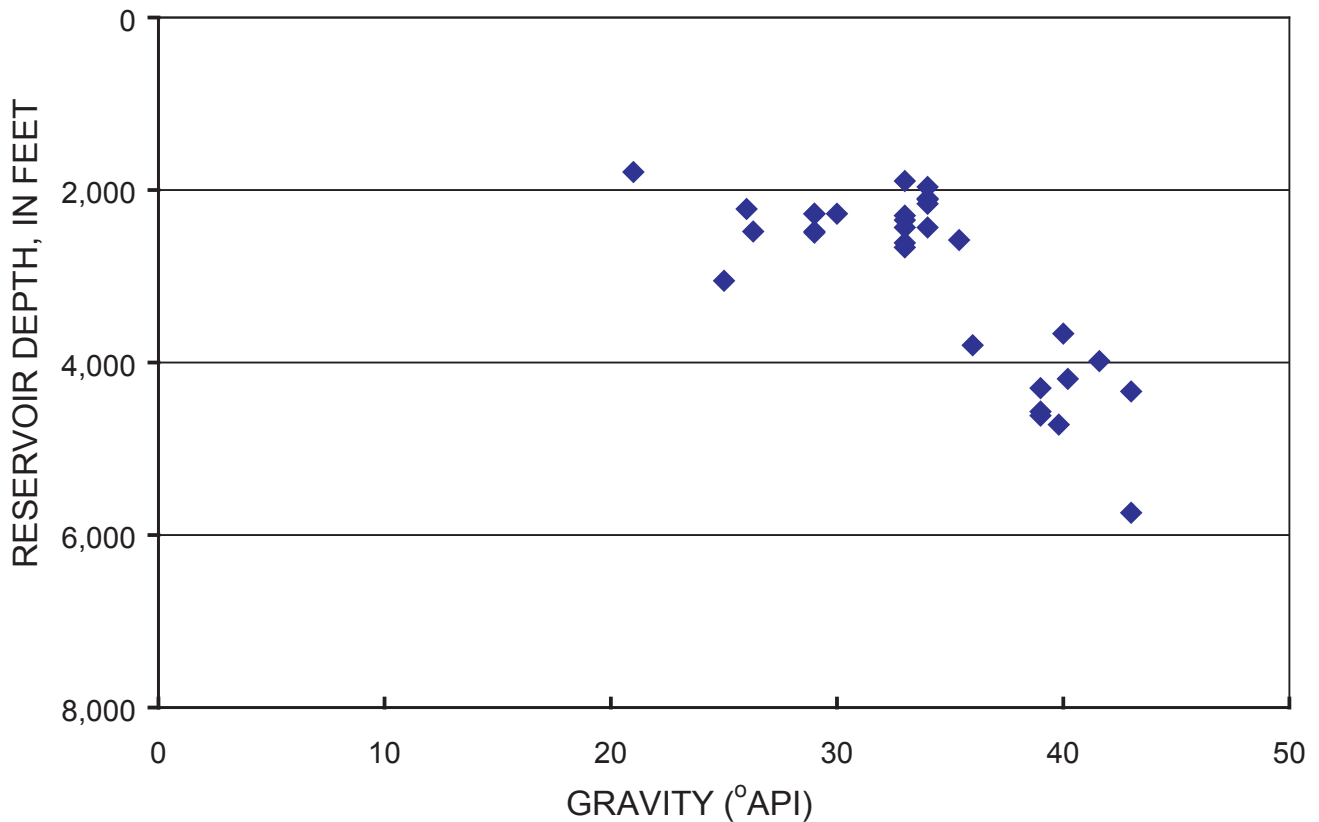


Figure 13. Plot of gravity (°API) relative to reservoir depth for 31 oil samples from the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi. Modified from Carroll and others (1995, their fig. 8).

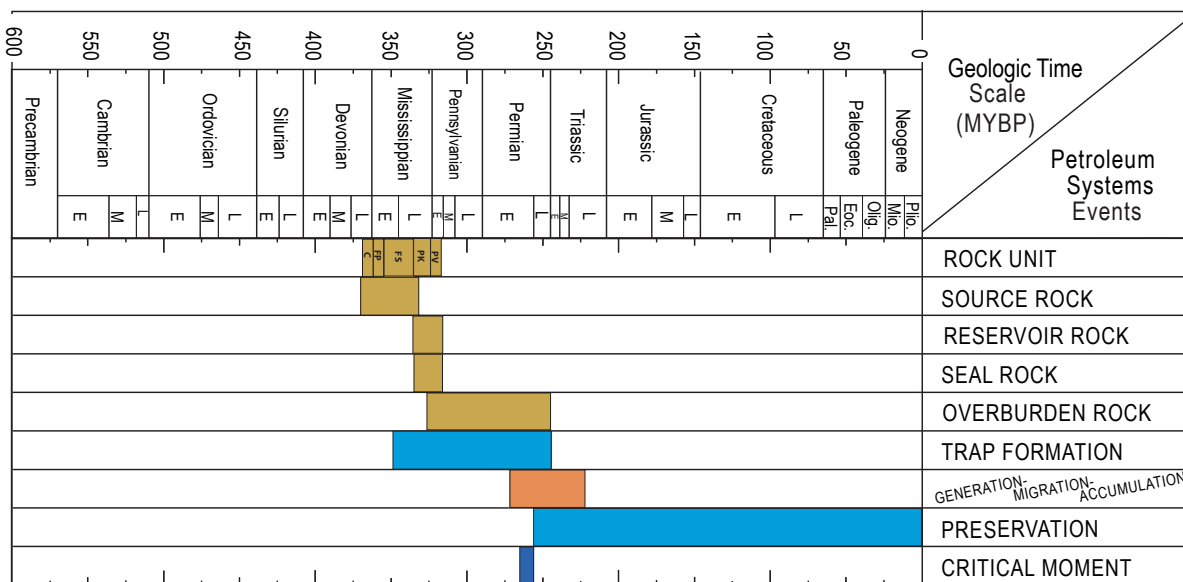


Figure 14. Events chart for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi. All features in the events chart are required to have a viable total petroleum system. PV, Pottsville Formation; PK, Parkwood Formation; FS, Floyd Shale; FP, Fort Payne Chert; C, Chattanooga Shale.

- Gas production in the Black Warrior Basin was first established in 1909 from Pennsylvanian sandstone in Fayette County, Alabama, at a depth of 1,400 ft. In 1926, gas was discovered in Monroe County, Mississippi, in Upper Mississippian sandstone at a depth of 2,400 ft. Exploration in the 1950s and early 1960s 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. The largest field discovered during this phase of exploration was the Muldon field (Monroe County, Mississippi), which produced gas from the Upper Mississippian “Sanders” sandstone at about 5,500 ft.
- Renewed exploration activity in the 1970s and 1980s was initiated by the discovery of the East Detroit field (Lamar County, Alabama) in 1971. Ninety-five gas, gas-associated oil, and oil fields were discovered during these two decades, including the two largest gas fields — Corinne field in Monroe, Lowndes, and Clay Counties, Mississippi (discovered in 1972), and Blooming Grove field in Fayette and Lamar Counties, Alabama (discovered in 1975), and the two largest oil fields — North Blowhorn Creek field in Lamar County, Alabama (discovered in 1979), and South Brush Creek field in Lamar County, Alabama (discovered in 1985). The 10 most productive gas fields are listed in table 4, and the 5 most productive oil fields are listed in table 5.
- Through May 2002, 137 conventional nonassociated gas fields and oil-associated gas fields were discovered in the Alabama part of the Black Warrior Basin, the dominant reservoir being the Upper Mississippian “Carter” sandstone. The three largest nonassociated gas fields are the (a) Blooming Grove field in Fayette and Lamar Counties (cumulative production, 68.8 billion cubic feet of gas [BCFG]; discovered in 1975), (b) Musgrove Creek field in Fayette County (cumulative production, 44.0 BCFG; discovered in 1974), and (c) McGee Lake field in Lamar County (cumulative production, 39.1 BCFG; discovered in 1979).
- Through December 2003, 84 conventional non associated gas fields, oil-associated gas fields, and oil fields were discovered in the Mississippi part of the basin, predominantly in Upper Mississippian “Carter” and “Sanders” sandstone reservoirs. The three largest nonassociated gas fields are the (a) Corinne field in Monroe, Lowndes, and Clay Counties (cumulative production, 152 BCFG; discovered in 1972), (b) the Muldon field in Monroe County (cumulative production, 64.9 BCFG; discovered in 1952), and (c) Splunge field in Monroe County (cumulative production 35.8 BCFG; discovered in 1973).
- Most oil fields have cumulative production less than 0.5 million barrels of oil (MMBO). Exceptions are the (a) North Blowhorn Creek field in Lamar County, Alabama (cumulative production, 6.2 MMBO), (b) South Brush Creek field in Lamar County, Alabama (cumulative production, 1.7 MMBO), (c) Blowhorn Creek field in Lamar County, Alabama (cumulative production, 0.67 MMBO), (d) Bluff field in Lamar County, Alabama, (cumulative production 0.57 MMBO), and (e) Maple Branch field in Monroe County, Mississippi (cumulative production, 0.94 MMBO).

6. A substantial deposit of asphalt, estimated to contain 7.5 billion barrels of oil (BBO) (Wilson, 1987), exists within the Upper Mississippian Hartselle Sandstone and the Pride Mountain Formation in north-central and northwest Alabama. This deposit, the result of biodegradation or oxidation due to subsequent subaerial exposure, was not evaluated in this assessment primarily because of its physical nature. The solid nature of the asphalt lends itself to surface mining, and use of the material has been mostly for roadbuilding, though the deposit has the potential to be refined into liquid hydrocarbon.

Assessment Data

Details on assessment-data sheets and the assessment model are described in Schmoker and Klett (2000). For the Black Warrior Basin assessment, the minimum undiscovered field sizes were set at 0.5 MMBO and 3.0 BCFG.

Drilling data in the Carboniferous Sandstones AU show an appreciable decline (more than half) in the number of new-field wildcat wells during the 15-year period between 1985 and 2000 (fig. 15). Field size, in terms of gas accumulations, also decreased during this period, as shown in figure 16, and this trend is further evidenced by a plot showing grown gas-field size compared to accumulation-rank size during the first-, second-, and third-thirds segments of the exploratory history of the AU (fig. 17). Similar plots for oil-field discoveries are shown in figures 18 and 19; although the plot of oil-field size relative to accumulation-size rank for the first and second halves of the exploratory history shows a decrease in field size, not enough information is available to indicate a specific trend. It should be noted, however, that the sizes of oil and gas fields are expected to decrease with time in any given AU, as larger fields generally are found early in the exploration history of a petroleum province.

Reservoir depths for most gas and oil fields discovered in the Carboniferous Sandstones AU during the 1970s and 1980s remained between 1,500 and 5,000 ft (figs. 20, 21).

Table 4. Ten most productive gas fields in the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

[BCFG, billion cubic feet of gas; ss., sandstone; Fm., formation; MS, Mississippi; AL, Alabama. Mississippi data at <http://www.ogb.state.ms.us/whatsnew.htm>, accessed May 2004]

Field (State)	County	Discovery year	Productive units (s)	Cumulative production (BCFG)
Corrine (MS)	Clay, Lowndes, Monroe	1972	Nason ss., ¹ Parkwood Fm. Lewis ss. ¹	152.0
Blooming Grove (AL)	Fayette, Lamar	1977	Parkwood Fm.	68.8
Muldon (MS)	Monroe	1952	Sanders ss. ¹	² 64.9
Beaverton (AL)	Lamar	1973	Parkwood ss., ¹ Lewis ss. ¹	45.4
Musgrove Creek (AL)	Fayette	1974	Carter ss. ¹	44.0
Buttahatchie River (MS)	Monroe	1977	Carter ss., ¹ Lewis ss. ¹	28.7
McGee Lake (AL)	Lamar	1979	Carter ss., ¹ Lewis ss. ¹	39.1
Splunge (MS)	Monroe	1973	Carter ss. ¹	35.8
Star (AL)	Lamar	1974	Parkwood Fm. Lewis ss. ¹	38.8
McCracken Mountain (AL)	Fayette	1974	Lewis ss., ¹ Parkwood Fm., Pottsville Fm.	36.2

¹ Informal name or local usage.

² Gas storage.

Table 5. Five most productive oil fields in the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

[MMBO, million barrels of oil; AL, Alabama; MS, Mississippi; ss., sandstone; Fm., formation. Mississippi data at <http://www.ogb.state.ms.us/whatsnew.htm> accessed May 2004]

Field (State)	County	Discovery year	Productive unit(s)	Cumulative production (MMBO)
North Blowhorn Creek (AL)	Lamar	1979	Carter ss. ¹	6.21
South Brush Creek (AL)	Lamar	1985	Carter ss. ¹	1.73
Maple Branch (MS)	Monroe	1976	Lewis ss. ¹	0.94
Blowhorn Creek (AL)	Lamar	1978	Parkwood Fm.	0.67
Bluff (AL)	Fayette	1977	Parkwood Fm.	0.57

¹ Informal name of local usage.

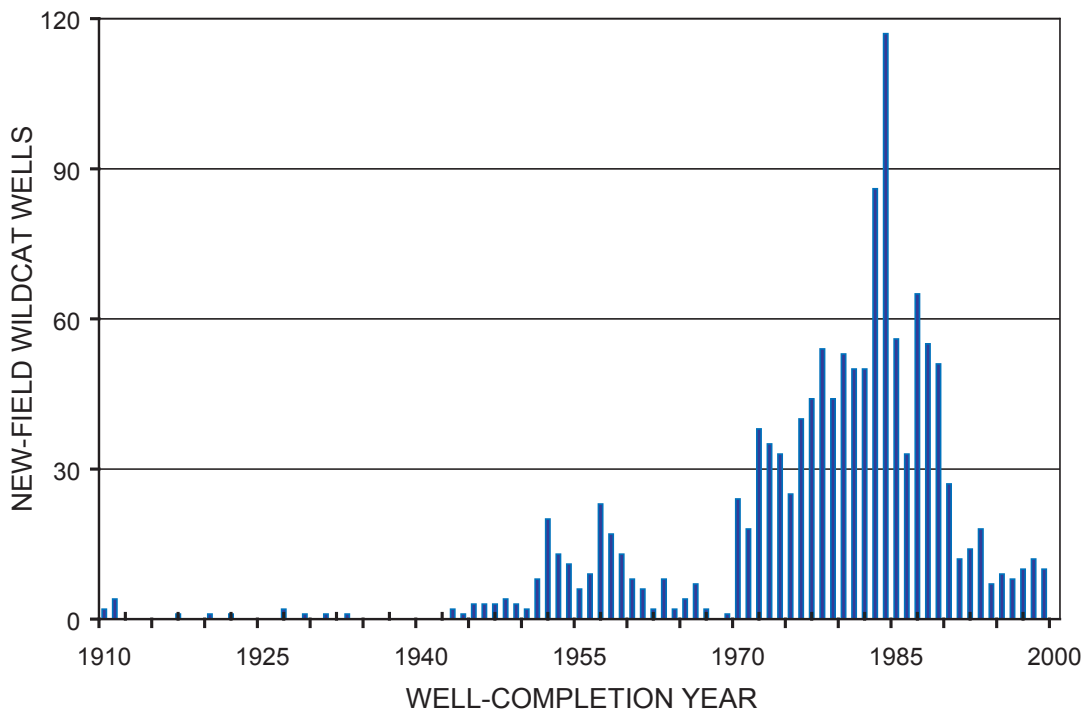


Figure 15. New-field wildcat oil and gas wells relative to well-completion year for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

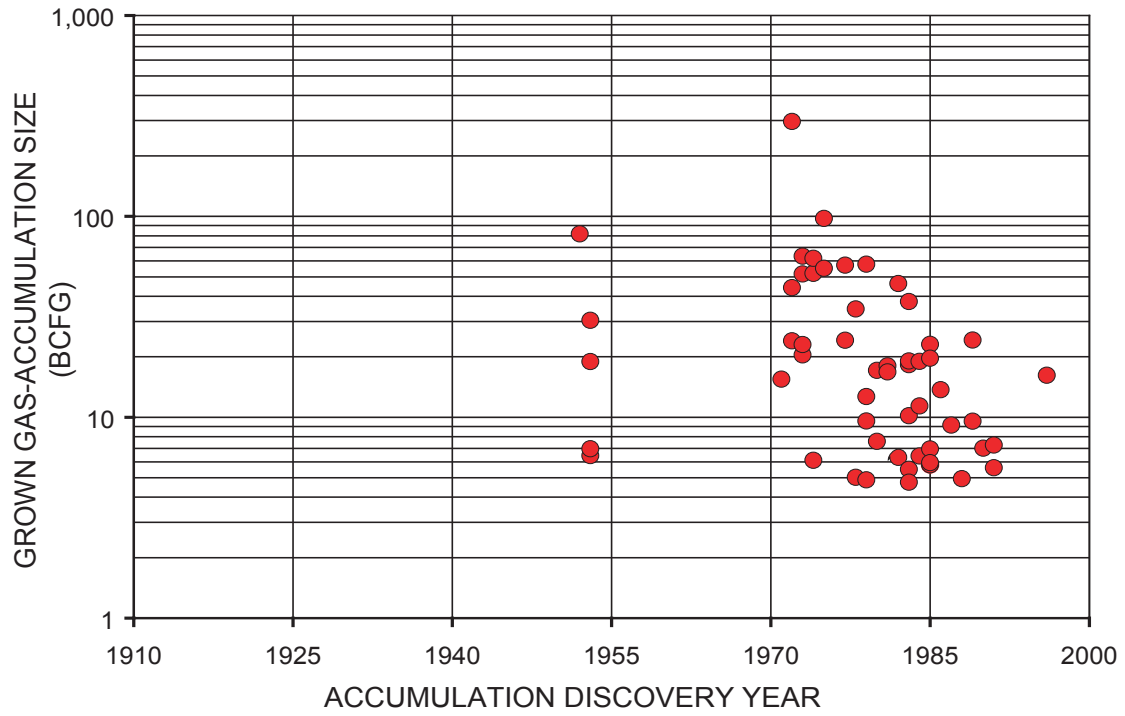


Figure 16. Grown gas-accumulation size relative to accumulation-discovery year for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi. BCFG, billion cubic feet of gas.

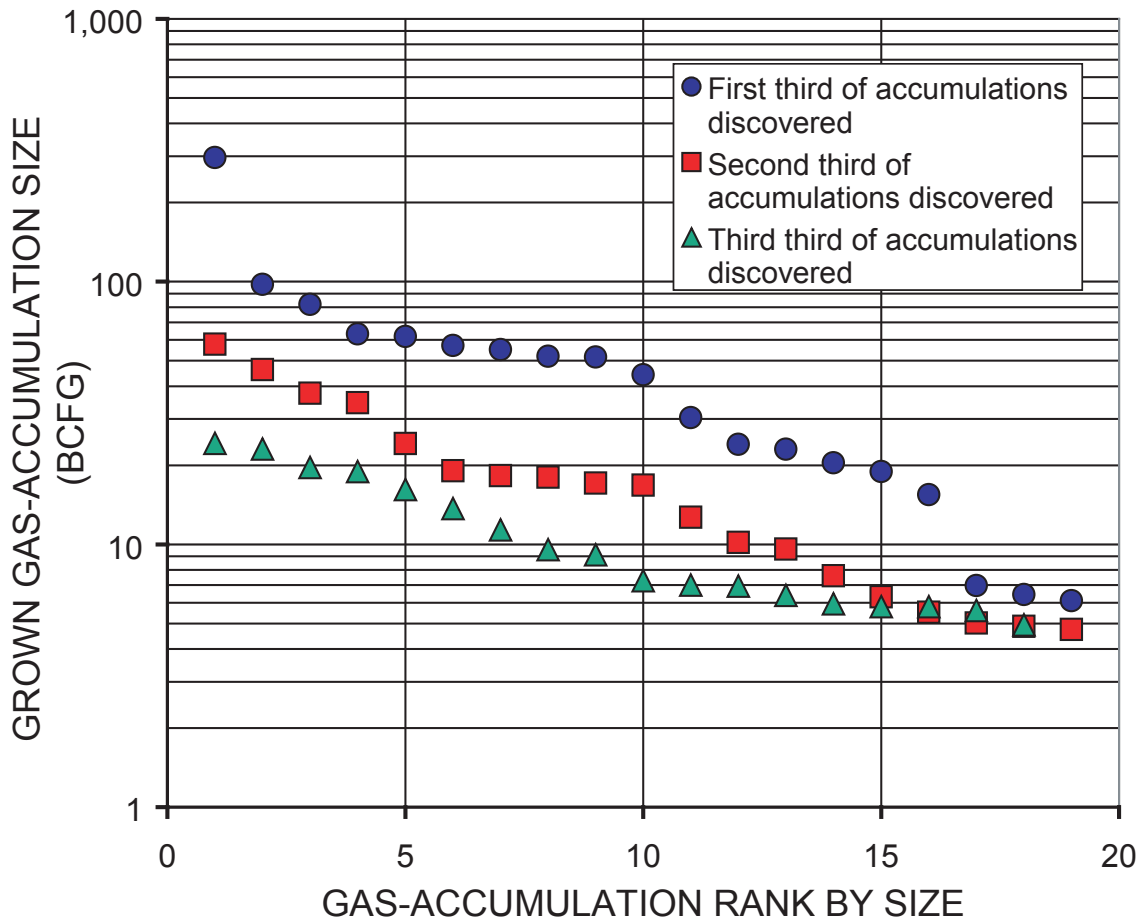


Figure 17. Grown gas-accumulation size relative to accumulation rank by size for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi. BCFG, billion cubic feet of gas.

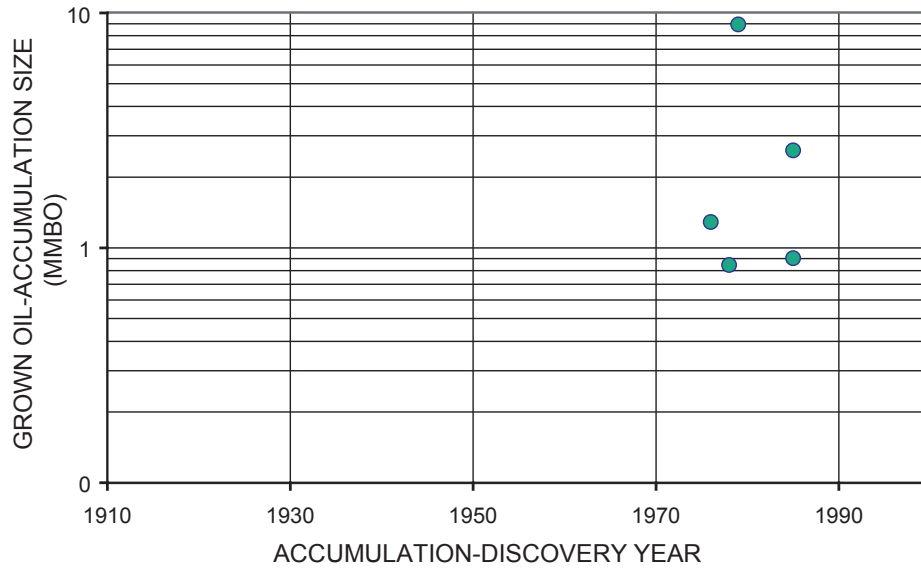


Figure 18. Grown oil-accumulation size relative to accumulation-discovery year for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi. MMBO, million barrels of oil.

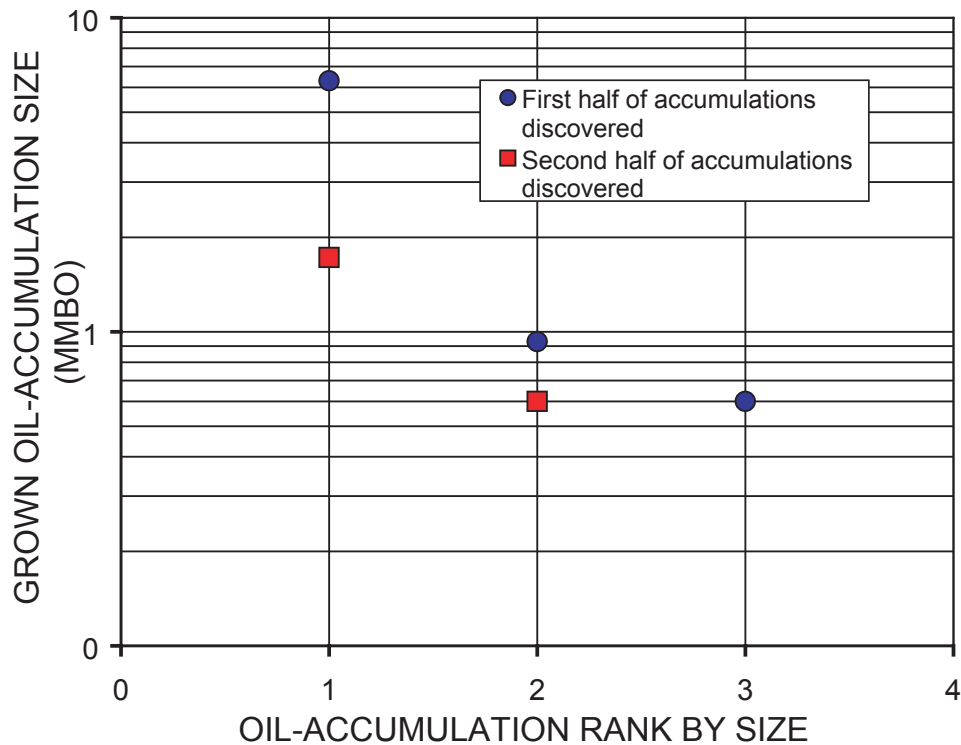


Figure 19. Grown oil-field size relative to accumulation rank by size for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi. MMBO, million barrels of oil.

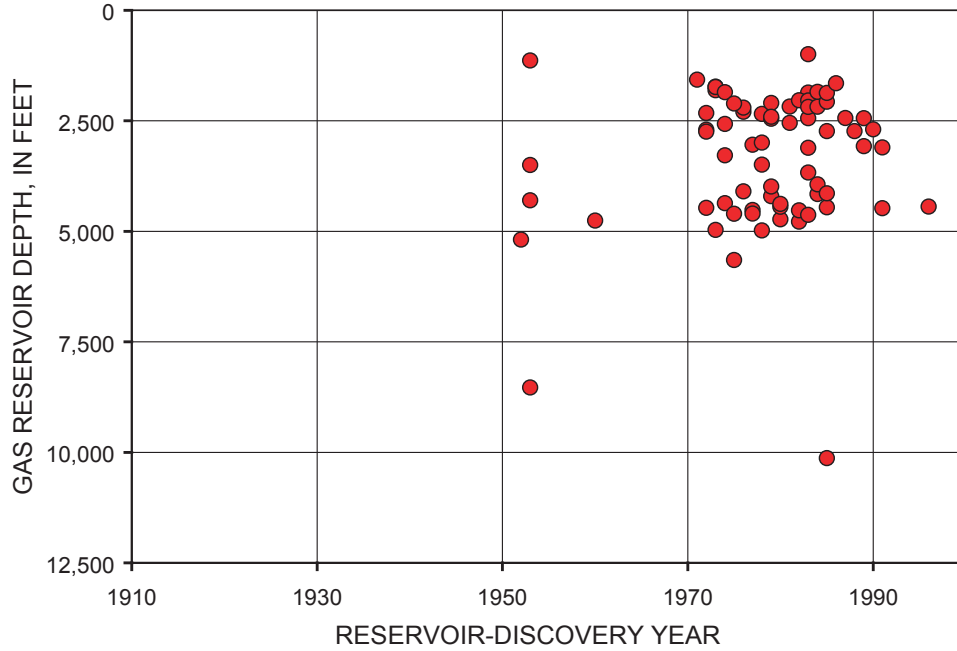


Figure 20. Gas reservoir depth relative to reservoir-discovery year for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

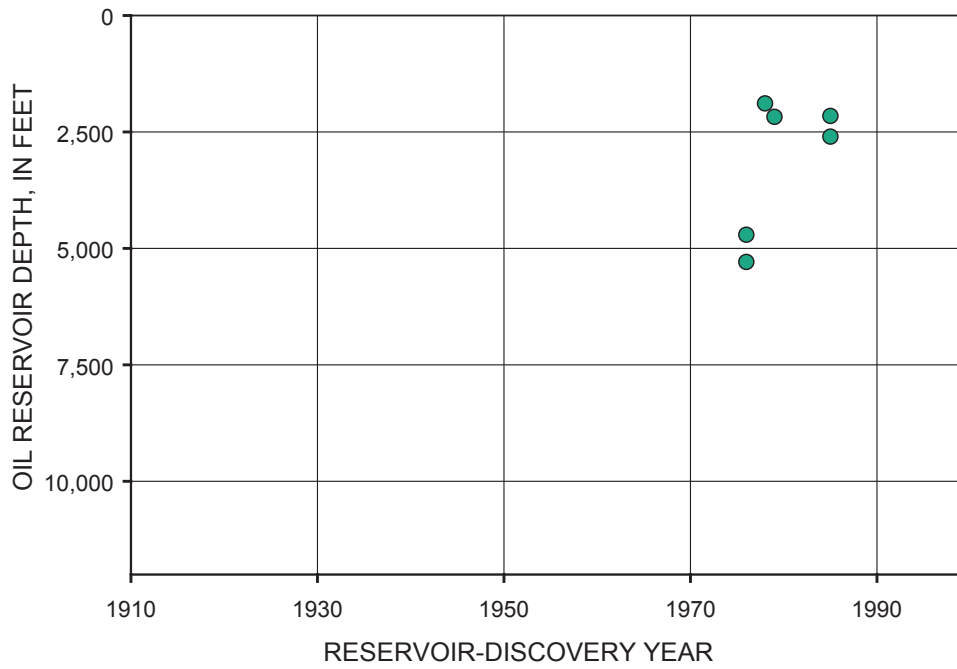


Figure 21. Oil reservoir depth relative to reservoir-discovery year for the Carboniferous Sandstones Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

Assessment Results

Estimated undiscovered resources in the Carboniferous Sandstones AU include means of (1) 359.55 BCFG and 1.89 million barrels of natural gas liquids (MMBNGL) for gas reserves, and (2) 5.91 MMBO, 8.26 BCFG, and 0.05 MMBNGL for oil reservoirs (U.S. Geological Survey, 2003, their table 1).

Pre-Mississippian Carbonates Assessment Unit

The Pre-Mississippian Carbonates AU consists of Cambrian and Ordovician platform-carbonate reservoirs (fig. 22), with gas having accumulated primarily in basement-controlled fault block traps and possibly in traps formed by frontal thrust faults and facies changes. Encompassing a substantial portion of the Black Warrior Basin, this AU extends from the Appalachian fold-thrust front in Alabama west to the edge of the Ouachita orogenic belt in Mississippi (fig. 4). The Upper Mississippian Floyd Shale is the likely source rock; commonly, this shale sequence is in fault contact with the carbonate reservoirs.

Reservoir Rocks

The Pre-Mississippian Carbonates AU is largely composed of carbonate rocks of the Upper Cambrian-Lower Ordovician Knox Group and the Middle Ordovician Stones

River Group (fig. 2). This carbonate sequence represents the maximum transgression of a persistent shallow marine shelf (Thomas, 1988). In Alabama, the sequence is as much as 4,200 ft thick in the Appalachian fold belt, and 5,700 ft were penetrated in a well on the south flank of the Nashville dome, where the strata overlie Precambrian granite (Pike, 1968). The lower Knox Group consists primarily of cherty dolomite, whereas the upper several hundred feet is interbedded limestone and dolomite, with the limestone content increasing to the southwest and the dolomite content increasing to the north (Kidd, 1975). The top of the Knox Group is at the top of the upper dolomite, generally referred to as the “Snow zone,” which has vuggy porosity that is probably the result of subaerial exposure and karst development.

The Middle Ordovician Stones River Group unconformably overlies the Knox Group. This carbonate sequence (fig. 2) is 800 ft thick in the southern part of the Black Warrior Basin in Alabama and as much as 1,150 ft thick in northern Alabama (Kidd, 1975).

Extensional and possibly thrust faulting during the late Paleozoic placed Mississippian source rocks in contact with the Cambrian-Ordovician carbonate strata (fig. 23). Gas generated from the organic-rich Floyd Shale migrated along faults into the karstic reservoirs. Geologic mapping indicates that extensional faults are widespread in the Black Warrior Basin.

Assessment Unit Analog

Hydrocarbon exploration and production in the Black Warrior Basin has primarily involved Mississippian and younger strata. As a result, there is a general lack of basin-wide information pertaining to the older rocks, as well

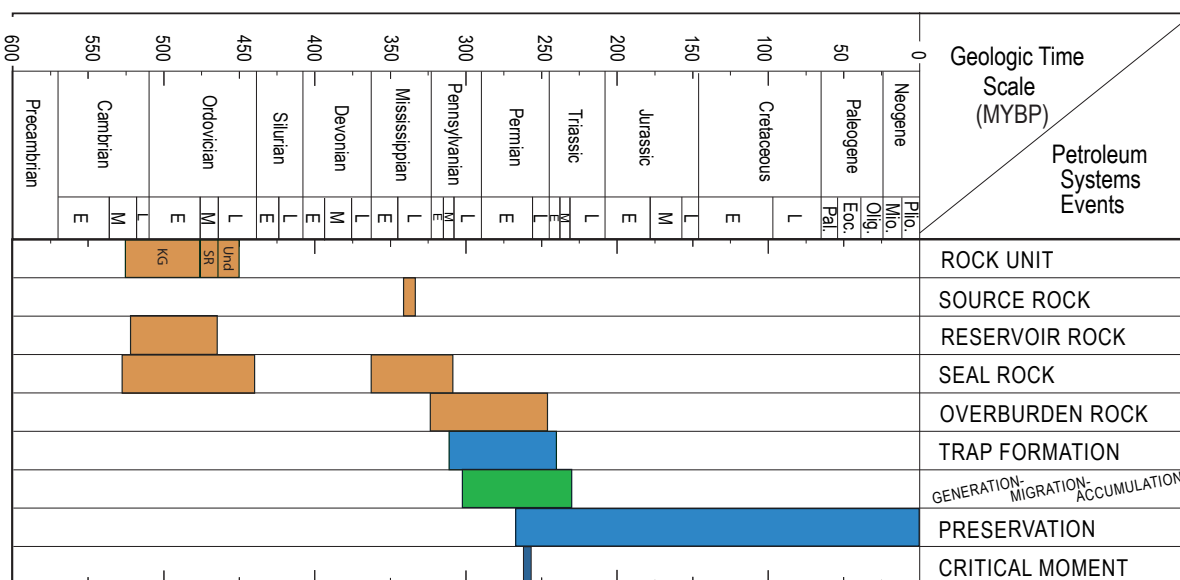


Figure 22. Total petroleum system events chart for the Pre-Mississippian Carbonates Assessment Unit in the Black Warrior Basin, Alabama and Mississippi, showing relative timing of geologic features. All features in the events chart are required to have a viable total petroleum system. Und, undifferentiated Upper and Middle Ordovician rocks; SR, Stones River Group; KG, Knox Group.

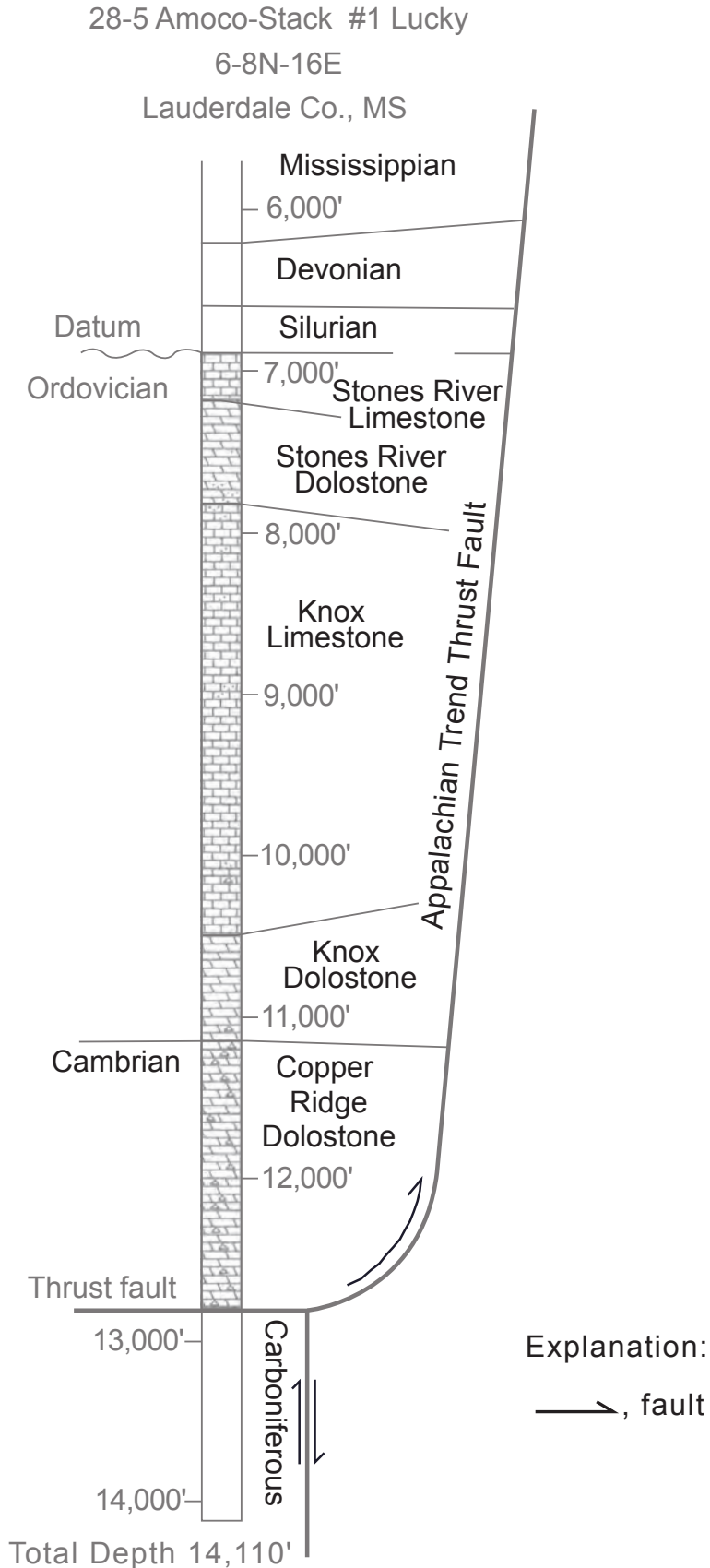


Figure 23. Borehole profile showing Cambrian-Ordovician source rocks in fault contact with Carboniferous source rocks. Borehole is located in Lauderdale County, Mississippi. From Henderson (1991). Depth below land surface, in feet.

as uncertainty regarding detailed fault relations between the Cambrian/Ordovician reservoir rocks and the upper Paleozoic source rocks. For these reasons, an analog of the Arkoma Basin in Arkansas and Oklahoma was used to provide a better understanding of the geologic setting and the conditions leading to hydrocarbon generation, migration, and accumulation with respect to the Pre-Mississippian Carbonates AU in the Black Warrior Basin. Both basins are foreland basins created during Ouachita/Appalachian orogenesis, when Paleozoic rocks were thrust over the south and east margins of the North American craton.

The Cambrian-Ordovician Knox Group of the Black Warrior Basin is equivalent in age to the Arbuckle Group of Oklahoma and Arkansas. Perry (1995) described the Arbuckle Group through the Devonian “Misener Sandstone” basement-fault and shelf-gas play in the Arkoma Basin, which closely resembles the Pre-Mississippian Carbonates AU in the Black Warrior Basin. Each of these (play or AU) share features such as deeply buried carbonate rocks capped by an erosional unconformity and an associated thick zone of karstic porosity. Also, extensional basement faulting brought younger source rocks into contact with the carbonate rocks, providing fault-block structural traps.

Each basin has had a single deep gas discovery, with limited if any additional discoveries. In the Arkoma Basin, the deep discovery well was in the Wilburton field, and the corresponding deep discovery well in the Black Warrior Basin was in the Maben field.

Production History

Through December 2003, cumulative gas production from the Cambrian and Lower Ordovician Knox Group in the Maben field in Oktibbeha County, Mississippi (discovery date, 1970), was 31.2 BCFG, of which 95 percent (29.5 BCFG) was produced after 1998. The production numbers show considerable variability within the last 3 years — 5.9 BCFG in 2001, 9.14 BCFG in 2002, and 7.71 BCFG in 2003.

Well data for the Pre-Mississippian Carbonates AU show a substantial decline in the number of new-field wildcat completions in the 10-year period between 1955 and 1965, and that completions were intermittent from 1965 to the late 1990s (fig. 24). These data, as well as data for discovered field sizes and new-field wildcats, also demonstrate that the sizes of oil and gas fields decrease with time, following the trend discussed previously with respect to the Carboniferous Sandstones AU. A small upswing in the drilling of new-field wildcat wells in the mid-to-late 1990s may be a reflection of economic conditions, such as the price of natural gas.

Assessment Data

Because the Pre-Mississippian Carbonates AU has only one producing field (Maben), comparisons of field-size distributions through time and determining changes in depths to newly discovered reservoirs through time were not possible.

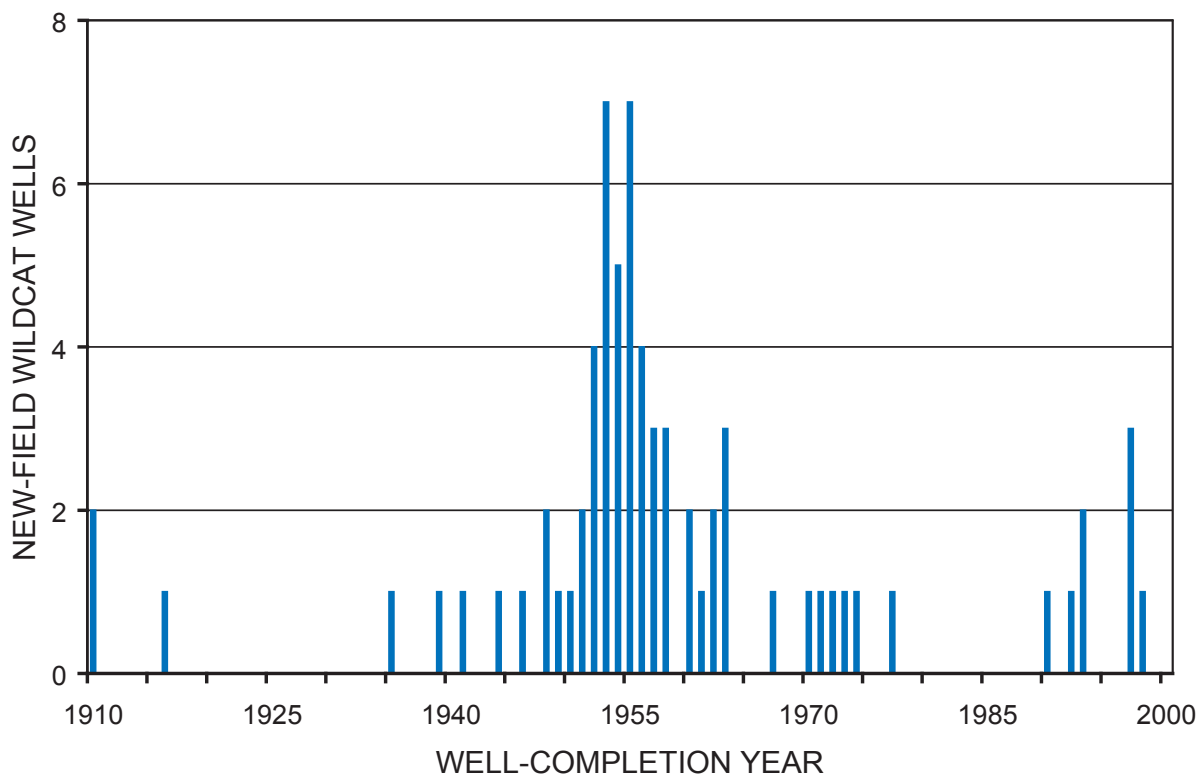


Figure 24. New-field wildcat gas wells relative to well-completion year for the Pre-Mississippian Carbonates Assessment Unit in the Black Warrior Basin, Alabama and Mississippi.

Assessment Results

Based on the analogy with the Wilburton field in the Arkoma Basin, estimated means of undiscovered resources in Pre-Mississippian Carbonates AU are 1,087 BCFG and 5.7 MMBNGL (U.S. Geological Survey, 2003, their table 1). The largest expected gas field is estimated to be 218 BCFG.

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