BURIAL HISTORY AND SOURCE-ROCK CHARACTERISTICS OF UPPER DEVONIAN THROUGH PENNSYLVANIAN STRATA, BLACK WARRIOR BASIN, ALABAMA

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ECONOMIC GEOLOGY DIVISION

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BURIAL HISTORY AND SOURCE-ROCK CHARACTERISTICS OF UPPER DEVONIAN THROUGH PENNSYLVANIAN STRATA, BLACK WARRIOR BASIN, ALABAMA

By

Richard E. Carroll, Jack C. Pashin,
and Ralph L. Kugler

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1995

GEOLOGICAL SURVEY OF ALABAMA

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ERNEST A. MANCINI
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July 20, 1995

Honorable Fob James
Governor of Alabama
Montgomery, Alabama

Dear Governor James:

I have the honor to transmit herewith a report titled "Burial History and Source-Rock Characteristics of Upper Devonian through Pennsylvanian Strata, Black Warrior Basin, Alabama" by Richard E. Carroll, Jack C. Pashin, and Ralph L. Kugler, which has been prepared and published by the Geological Survey of Alabama as Circular 187.

Alabama's oil and gas resources are the result of several critical geological conditions. Two of these factors include the deposition of a source rock, a rock unit with the potential to generate hydrocarbons, and an appropriate burial history of these source rocks which mature and release the hydrocarbons through time. This report presents preliminary data concerning these conditions for the Upper Devonian through Pennsylvanian rocks of the Black Warrior basin in west-central Alabama. Information contained in this report will serve as a guide for further evaluation and investigation of the state's oil and gas potential.

Respectfully,

Ernest A. Mancini

Ernest A. Mancini
State Geologist

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ABSTRACT

Cuttings from selected wells were collected to study thermal history and to characterize source rocks in the Black Warrior basin. Vitrinite reflectance was measured from whole-rock polished samples at 15 stratigraphic levels in each well to create vitrinite reflectance profiles. Reflectance values ranged from 0.6 to 1.1 percent in the Permit Number (PN) 1780 well and 0.7 to 1.6 percent in the PN2191 well. The profiles show a general increase of vitrinite reflectance with depth. Time/temperature indices calculated from burial history curves for each well indicate that kerogen maturation was rapid and peaked about the same time burial did, between 290 and 200 million years ago (Ma). Also, reburial during Cretaceous time added little, if any, to source-rock thermal maturation of the Paleozoic section. Kerogen type and total organic carbon data from Rock-Eval pyrolysis of cuttings samples from these wells indicate that, although most shale units contain sufficient organic material to be considered oil-prone, shale from the Pottsville and Parkwood Formations tends to be rich in terrestrial, gas-prone, type III kerogen. Isotopic data, gross chemical composition, and gas chromatography indicate that oil in the different Mississippian reservoirs of the Black Warrior basin of Alabama appears to have a common origin, and that Mississippian oils are less mature thermally than those in Jurassic and Cretaceous reservoirs.

INTRODUCTION

The Black Warrior basin is a late Paleozoic foreland basin which encompasses a triangular area in northwest Alabama and northeast Mississippi that is bound on the southeast by the Appalachian orogen, on the southwest by the Ouachita orogen, and on the north by the Nashville Dome. It is economically and strategically important because of conventional oil and gas reserves in Mississippian reservoirs, as well as extensive coal and coalbed-methane resources in the Pennsylvanian Pottsville Formation.

The distribution of oil produced from Mississippian reservoirs in the Black Warrior basin (fig. 1) may be explained partly by variation in the quantity and quality of the source rock and by the burial and thermal evolution of the basin. However, the sources of economic hydrocarbons in the Black Warrior basin remain uncertain. The Devonian Chattanooga Shale, Mississippian Floyd Shale, and shale in the Mississippian-Pennsylvanian Parkwood and Pennsylvanian Pottsville Formations have all been identified as possible sources of oil within Mississippian reservoirs. To provide further constraint on the origin of hydrocarbons in the basin, the quantity, quality, and thermal maturity of organic matter in middle and upper Paleozoic rocks from North Blowhorn Creek oil unit, the most productive oil unit in the basin, and other localities within the Black Warrior basin were investigated. Three general parameters were used to evaluate the hydrocarbon generation potential of each unit: (1) abundance of total organic carbon, (2) source of organic carbon or kerogen type, and (3) degree of maturation of the kerogen.

ACKNOWLEDGMENTS

Dudley D. Rice and Jerry L. Clayton (U.S. Geological Survey) provided geochemical analyses of source rocks and oils. Work for this project was performed under DOE contract number FG22-90BC14448.

ERATHEM	SYSTEM	SERIES		GEOLOGIC UNIT		LITHOLOGY
PALEOZOIC	PENNSYLVANIAN	LOWER	Pottsvile Formation	Coal bed gas	Gas	Coal
PALEOZOIC	PENNSYLVANIAN	LOWER	Pottsvile Formation	"Robertson sandstone"	Gas	Sandstone
PALEOZOIC	PENNSYLVANIAN	LOWER	Pottsvile Formation	"Nason sandstone"	Gas	Sandstone
PALEOZOIC	PENNSYLVANIAN	LOWER	Pottsvile Formation	"Fayette sandstone"	Gas	Sandstone
PALEOZOIC	PENNSYLVANIAN	LOWER	Pottsvile Formation	"Benton sandstone"	Gas	Sandstone
PALEOZOIC	PENNSYLVANIAN	LOWER	Pottsvile Formation	"Robinson sandstone"	Gas	Sandstone
PALEOZOIC	PENNSYLVANIAN	LOWER	Pottsvile Formation	"Chandler sandstone"	Gas	Sandstone
	?	?—?—?				
PALEOZOIC	MISSISSIPPIAN	UPPER	Parkwood Formation	"Coats sandstone"	Oil and Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Parkwood Formation	"Gilmer sandstone"	Oil and Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Parkwood Formation	"Cooper sandstone"	Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Parkwood Formation	"*Millerella* limestone"		Limestone
PALEOZOIC	MISSISSIPPIAN	UPPER	Parkwood Formation	"*Millerella* sandstone"	Oil and Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Parkwood Formation	"Carter sandstone"	Oil and Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Parkwood Formation	"Sanders sandstone"	Oil and Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Floyd Shale	Bangor Limestone	Gas	Limestone
PALEOZOIC	MISSISSIPPIAN	UPPER	Floyd Shale	Hartselle Sandstone	Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Floyd Shale / Pride Mtn.	"Evans sandstone"	Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER	Floyd Shale / Pride Mtn.	"Lewis limestone"	Gas	Limestone
PALEOZOIC	MISSISSIPPIAN	UPPER	Floyd Shale / Pride Mtn.	"Lewis sandstone"	Oil and Gas	Sandstone
PALEOZOIC	MISSISSIPPIAN	UPPER		Tuscumbia Limestone	Gas	Limestone
PALEOZOIC	MISSISSIPPIAN	LOWER		Fort Payne Chert		Chert and cherty limestone
PALEOZOIC	DEVONIAN			Chattanooga Shale		Shale
PALEOZOIC	DEVONIAN			unnamed cherty limestone	Gas	Limestone
PALEOZOIC	SILURIAN			undifferentiated		Limestone
PALEOZOIC	ORDOVICIAN	UPPER & MIDDLE		undifferentiated		Limestone
PALEOZOIC	ORDOVICIAN	MIDDLE		Stones River Group	Gas	Limestone
		?—?—?				
PALEOZOIC	ORDOVICIAN / CAMBRIAN	LOWER / UPPER		Knox Group	Gas	Dolomite and dolomitic limestone
PALEOZOIC	CAMBRIAN	MIDDLE		Ketona Dolomite		Dolomite
PALEOZOIC	CAMBRIAN	MIDDLE		Conasauga Formation		Limestone
PALEOZOIC	CAMBRIAN	LOWER		Rome Formation		Shale and siltstone
PRECAMBRIAN				Basement Complex		Igneous

EXPLANATION

- Oil and Gas (filled symbol)
- Gas (open symbol)

Index Map

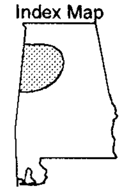

Figure 1.--Stratigraphic column showing oil reservoirs in the Black Warrior basin of Alabama.

METHODS

Two wells, one from near the North Blowhorn Creek oil unit (PN2191) and the other from northern Pickens County (PN1780), were selected for study to assess differences in thermal maturation and thermal history in shallow (PN2191) and deep (PN1780) parts of the Black Warrior Basin. Samples of cuttings from these wells were used to determine vitrinite reflectance and for Rock-Eval pyrolysis. Wells used in this study are identified by State Oil and Gas Board of Alabama permit number (PN).

Whole-rock samples for vitrinite reflectance were crushed to minus-20 mesh size and then embedded in epoxy to make a pellet. After they were polished, the pellets were allowed to dry in a desiccator for at least 24 hours. Reflectance measurements were made with a Nikon Microphot-FX compound microscope. Data were collected using PHOSCAN 3, a PC-compatible program developed by Nikon. Typically, 40 measurements were made for each sample. However, low organic content limited the number of points counted in some samples. Only a few vitrinite particles that could be attributed to either caving or reworking were identified.

Lopatin's method (Lopatin, 1971; Waples, 1982) for computing Time/Temperature Indices (TTI) was used to assess the thermal and burial history for the stratigraphic sequence of the two wells studied. Equations and compaction constants of van Hinte (1978), Sclater and Christie (1980), and Schmoker and Halley (1982) were used to generate decompacted burial curves. Sixteen samples from each well were sent to the U.S. Geological Survey Organic Geochemistry Laboratory in Denver, Colorado, where the samples were analyzed by Rock-Eval pyrolysis for total organic carbon and kerogen type. Twenty-two samples of oil from 18 fields also were analyzed by this laboratory for gross chemical composition.

BURIAL HISTORY

A contour map of vitrinite reflectance in the Mary Lee coal group of the Lower Pennsylvanian Pottsville Formation indicates that thermal maturity generally increases from northwest to southeast (fig. 2). Vitrinite-reflectance values for the Mary Lee group range from 0.6 to more than 1.6 percent, and the highest rank coal is in an elliptical area along the southeast margin of the basin in Jefferson and Tuscaloosa Counties. In Lamar and Pickens Counties, reflectance of the Mary Lee group ranges from 0.6 to 1.0 percent and generally increases from north to south. Most oil in the Black Warrior basin is produced from a linear low-rank anomaly in eastern Lamar and western Fayette Counties that has a distinctive, north-south orientation.

In most parts of the Black Warrior basin of Alabama, patterns of coal rank and structure do not correspond, suggesting that thermal maturation was regulated by regional variations of geothermal gradient as well as local geothermal anomalies (fig. 2). For example, Winston (1990) proposed that irregular reflectance profiles from the high-rank anomaly of Jefferson County are the product of warm water flowing through coal beds. In Lamar and Pickens Counties, where most conventional hydrocarbons in the basin are produced, vitrinite reflectance increases more uniformly with depth, indicating that burial depth and regional variation of geothermal gradient were the most significant determinants of the final rank pattern. Indeed, plots of percent vitrinite reflectance versus depth for the PN2191 and PN1780 wells show an irregular, but distinct, increase in reflectance with increased depth (fig. 3, table B-1). Sample standard deviation ranges between 0.04 and 0.15 percent, with the lowest values in the dominantly terrestrial Pottsville and Parkwood Formations, and the highest in marine Floyd and Chattanooga shale.

Reflectance values from the PN2191 well range from 0.6 to 1.1 percent. These values correspond to high-volatile C bituminous and medium-volatile bituminous in the coal-rank series. The lower value, which is from near the top of the Pottsville Formation, is above the oil window and is thus thermally immature with respect to the generation of oil. The higher value is from the Chattanooga Shale and is near the value associated with peak oil generation. Projection of the regression line to 0.2 percent reflectance (that of peat) gives an estimate of the total depth of burial. Based on this projection, the amount of stratigraphic section removed by erosion is estimated to be about 5,600 feet (±1,700 feet at 95 percent confidence).

Reflectance values for the PN1780 well range from 0.7 percent in the upper part of the Pottsville Formation to 1.6 percent in the Chattanooga Shale. These values correspond to high-volatile bituminous to low-volatile bituminous in the coal-rank series. The lower value is

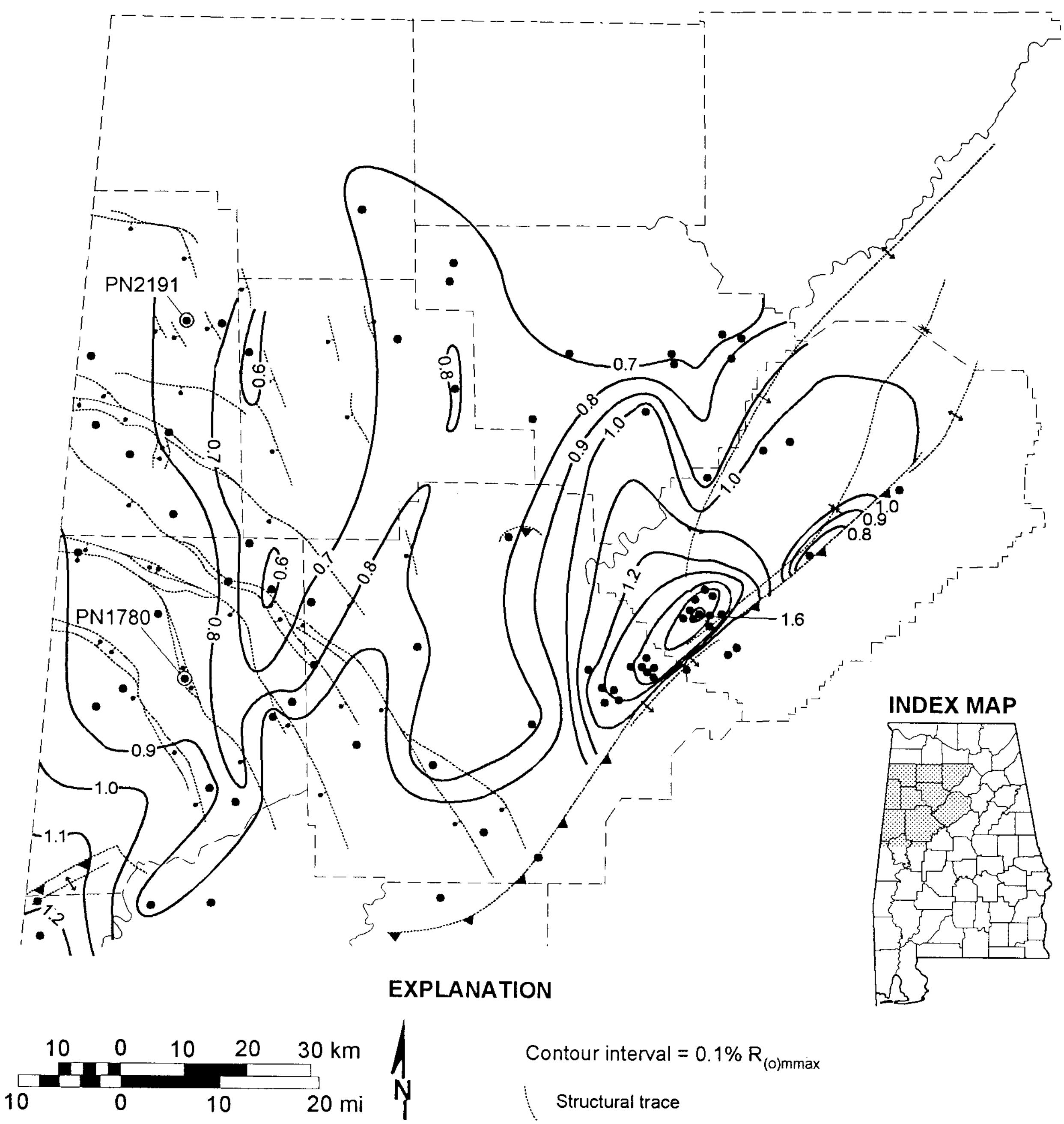

Figure 2.--Vitrinite reflectance map of the Mary Lee coal group in Alabama, showing the location of wells PN2191 and PN1780 (modified from Winston, 1990).

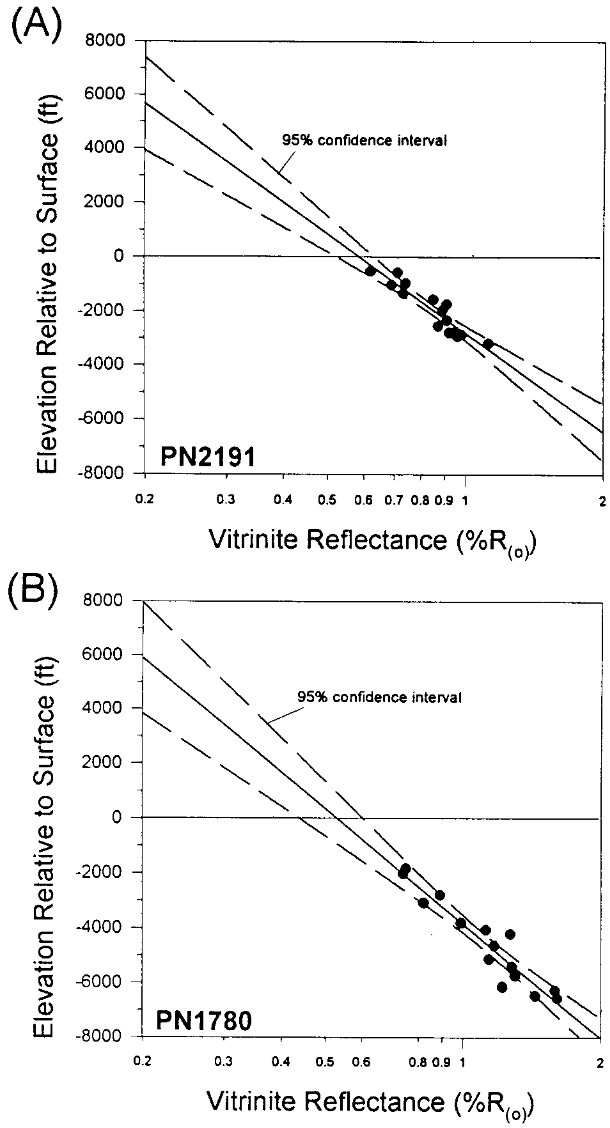

Figure 3.--Vitrinite reflectance versus depth profiles. (A) Well PN2191, (B) Well PN 1780.

within the oil window, whereas the higher value is overmature with respect to oil generation but is still below the upper limit of gas generation. The total stratigraphic section removed by erosion is estimated to be about 6,000 feet (±2,300 feet at 95 percent confidence) in this well. Vitrinite reflectance profiles from three wells in the vicinity of the PN1780 (PN2571, PN3097, and PN4141) show comparable ranges of reflectance (Robertson Research, 1985).

Burial-history curves for the PN2191 and PN1780 wells (fig. 4) are based on rock type and unit thicknesses picked from well logs, ages based on Harland and others (1989), and missing section estimated from vitrinite-reflectance profiles. The burial and tectonic histories of the geologic section represented by the two wells are similar. The main difference is the thick section of Pennsylvanian and Cretaceous rocks in the PN1780 well. To assess the thermal history of kerogen contained within each unit, Lopatin's method for computing Time/Temperature Indices (TTI) was used (Lopatin, 1971; Waples, 1982). The objective was to develop a model for the history of kerogen maturation that would result in TTI values for several horizons in each section equivalent to actual vitrinite-reflectance values observed for these horizons.

The two factors that were varied to produce the most reasonable model were thickness of section lost to erosion and geothermal gradient. The thickness of lost section used in these calculations is based on the vitrinite-reflectance profiles produced during this study (fig. 3). The present geothermal gradient in the area of the wells studied ranges from 1.1 to 2.0°F/100 feet (U.S. Geological Survey and American Association of Petroleum Geologists, 1976). A value of 1.6°F/100 feet was chosen as an average value for the model. Gradients less than this seem unlikely, especially during the time of rapid burial and eventual uplift and erosion of the Pottsville Formation. Geothermal gradients from the analogous western Canadian sedimentary basin range from 1.6 to greater than 2.7°F/100 feet (Majorowicz and Jessop, 1981; Hitchon, 1984). However, using a gradient significantly greater than 1.6°F/100 feet would require that the thickness of lost section be greatly reduced, which seems unlikely based on the reflectance profiles (fig. 3).

Results of the TTI calculations are presented as cumulative TTI-through-time curves for several stratigraphic markers in each well (fig. 5, table B-2). Two apparent trends are that kerogen maturation occurred fairly rapidly, reaching its maximum about the time of deepest burial between 290 and 200 Ma; and that, except for the deepest units in the PN1780 well, reburial of Paleozoic rocks during Cretaceous time added little, if any, to thermal maturation of the Paleozoic section. Liquid-hydrocarbon generation occurs between TTI values of 15 and 160, with peak generation occurring at a TTI of 75 (Waples, 1982). In the PN2191 well, Mississippian rocks above the Tuscumbia Limestone and

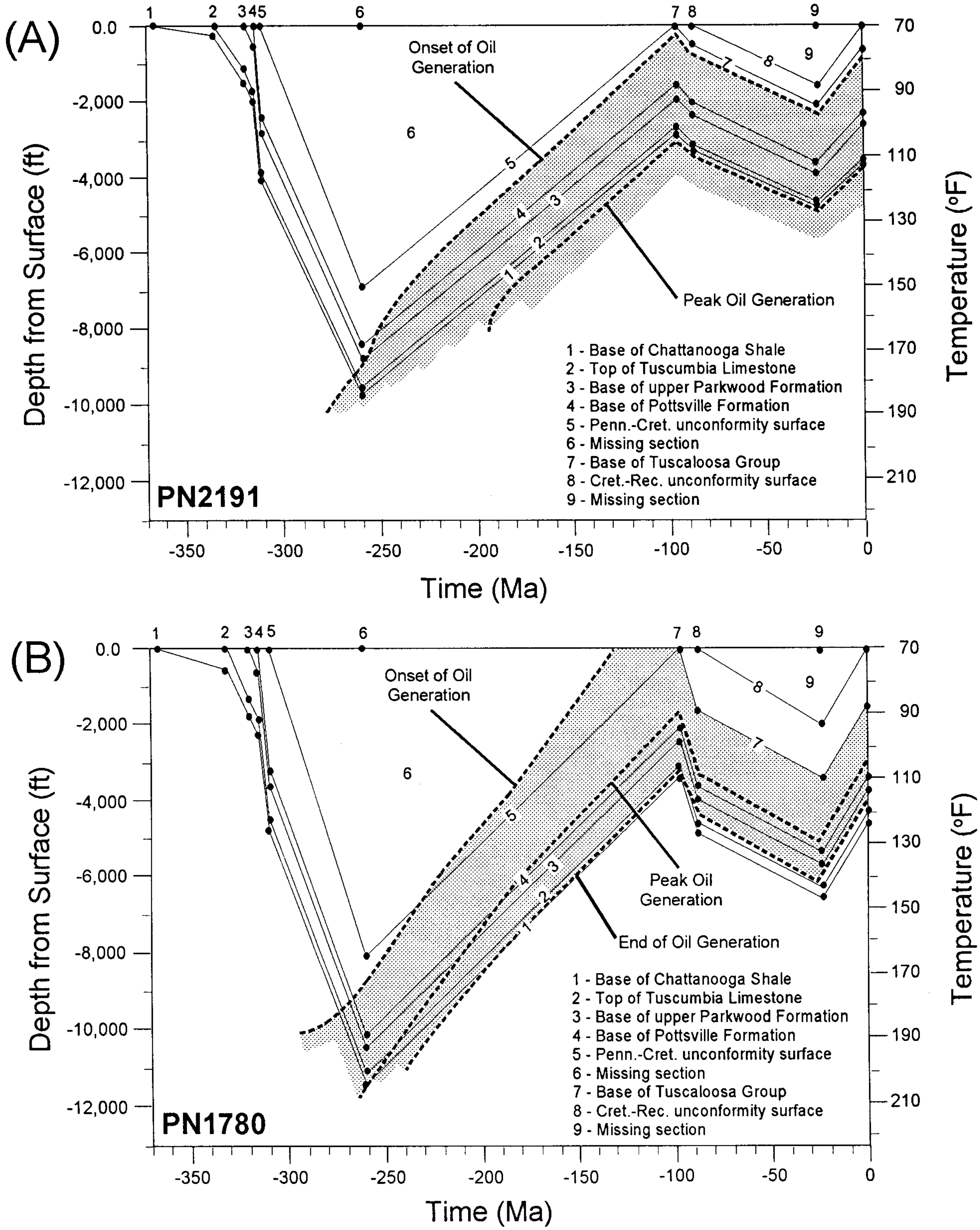

Figure 4.--Burial history curves. (A) Well PN2191, (B) Well PN1780.

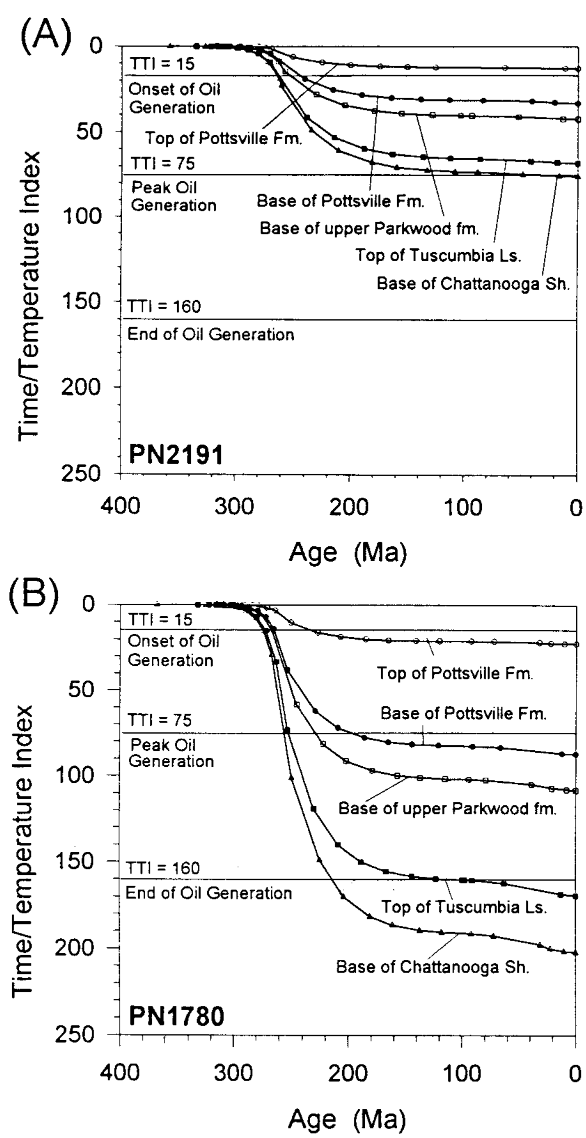

Figure 5.--Time/temperature index versus time cumulative curves. (A) Well PN2191, (B) Well PN1780.

below the upper Parkwood Formation, including the Carter sandstone, attained TTI values from 42 to 68, indicating that these rocks have been heated enough to generate oil, but not to the point of peak generation potential. This same interval in the PN1780 well attained TTI values of between 108 and 169 indicating maturation to the point where they are nearly overmature. Shepard (1985) calculated TTI values for a well in the Plateau region of the Black Warrior basin and found values ranging from 58 for Mississippian rocks to 91 for Ordovician rocks. Data from these three wells show a trend of increasing TTI values for Mississippian rocks from north to south, toward the deepest part of the basin. Hines (1988) calculated TTI values for several stratigraphic horizons in a well in southeastern Pickens County. His TTI values are similar to those for the PN1780 well in this study. However, because he calculated a missing section of 15,000 feet ($\pm$7,500 feet at 95 percent confidence), based on vitrinite reflectance and sandstone porosity, his burial history curve includes extremely high rates of uplift following Pottsville deposition to compensate for the thickness of missing section.

Based on cumulative TTI-through-time curves (fig. 5), the Parkwood Formation entered the oil window (TTI = 15) between 240 and 260 Ma, but never reached peak oil generation (TTI =75) in the PN2191 well. In the PN1780 well, the Parkwood Formation entered the oil window between 260 and 270 Ma and reached peak oil generation between 200 and 250 Ma. Based on these calculated dates, it can be concluded that geothermal maturation of the Parkwood Formation occurred earlier to the south in the deeper part of the basin. In both areas, however, major thermal hydrocarbon generation apparently began just prior to maximum burial and continued during subsequent unroofing.

SOURCE-ROCK CHARACTERISTICS

Sixteen shale samples from the PN2191 well and 16 shale samples from the PN1780 well, in addition to samples from other wells, were submitted to the U.S. Geological Survey organic geochemistry lab for Rock-Eval pyrolysis to determine total organic carbon and kerogen type (table B-3). All samples contain more than 0.5 percent total organic carbon (TOC), indicating that all shale units are potential hydrocarbon source rocks. However, samples from the Floyd and Chattanooga shales are the richest in organic matter with TOC values higher than 2.0 percent.

Results of Rock-Eval pyrolysis are given in plots of Hydrogen Index (HI) versus Oxygen Index (OI) (fig.6). The plot for the PN2191 well shows that organic matter from the Parkwood and Pottsville Formations is dominated by gas-prone type III kerogen. However, kerogen in Floyd and Chattanooga shale is primarily type II, or oil-prone. Subjective visual examination of kerogen from whole-rock polished pellets in

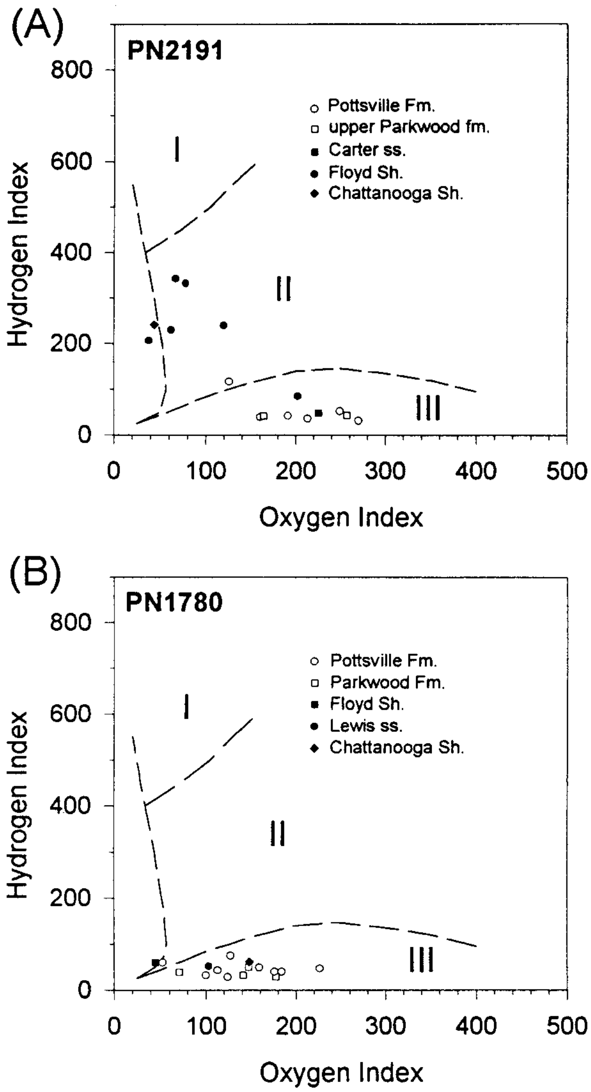

Figure 6.--Plots of hydrogen index versus oxygen index based on Rock-Eval pyrolysis. (A) Well PN2191, (B) Well PN1780. Type I kerogen is oil prone from terrestrial sources, type II kerogen is oil prone from marine sources, and type III kerogen is gas prone.

reflected light and kerogen concentrates in transmitted light verify that the Parkwood and Pottsville samples are dominated by terrestrial plant material, such as vitrinite and similar degraded woody material (type III kerogen). Floyd and Chattanooga samples are dominated by amorphous organic material, mainly matrix bituminite, which has been attributed to degraded marine sources (type II kerogen) but is also mixed with varying amounts of terrestrial plant material. In addition, the alga *Tasmanites* is abundant in Chattanooga Shale, and an unidentified frond-like alga was recognized in Floyd Shale.

The HI versus OI plot for the PN1780 well shows that all units, including those for the Floyd and Chattanooga shales, fall in or very near type III kerogen. Additionally, samples from the Pottsville and Parkwood Formations, which are typically type III, generally have lower OI values than those from the PN2191 well. Lower HI values from samples that typically have type II kerogen and lower OI values from samples that typically have type III kerogen indicate that the rock has matured thermally and that hydrocarbons have been generated.

The potential for the Chattanooga Shale to have generated large amounts of hydrocarbons is limited, however, because the unit is generally less than 10 feet thick where oil is produced from overlying rocks. The Floyd Shale, which typically has lower total organic carbon content than the Chattanooga, is locally thicker than 200 feet. In samples from the PN2191 well, the Floyd Shale had an average TOC value of 2.1 percent, whereas the Chattanooga Shale had a TOC value of 3.1 percent. Given the relative thickness of these two units in the North Blowhorn Creek area, the potential volume of generated hydrocarbons for the Floyd Shale is at least 15 times greater than that of the Chattanooga Shale. However, the Chattanooga Shale thickens northward to more than 40 feet in northern Alabama where economic tar sandstone is present in the Pride Mountain and Hartselle Formations and the Floyd Shale is thin or absent. Additionally, the possibility exists that dark, organic-rich carbonates in the Fort Payne Chert and Bangor Limestone may also have generated hydrocarbons but were not analyzed for this study.

OIL GEOCHEMISTRY

API gravity of oil in Carter sandstone reservoirs from oil and gas fields was mapped relative to structure based on information in Masingill (1989) and State Oil and Gas Board of Alabama files (fig. 7). API gravity of oil in Carter sandstone increases systematically toward the southwest from 22° to 44°. This increase in API gravity parallels an increase in depth of burial of Carter sandstone. API gravity also parallels the rank of coal in the overlying Pottsville Formation

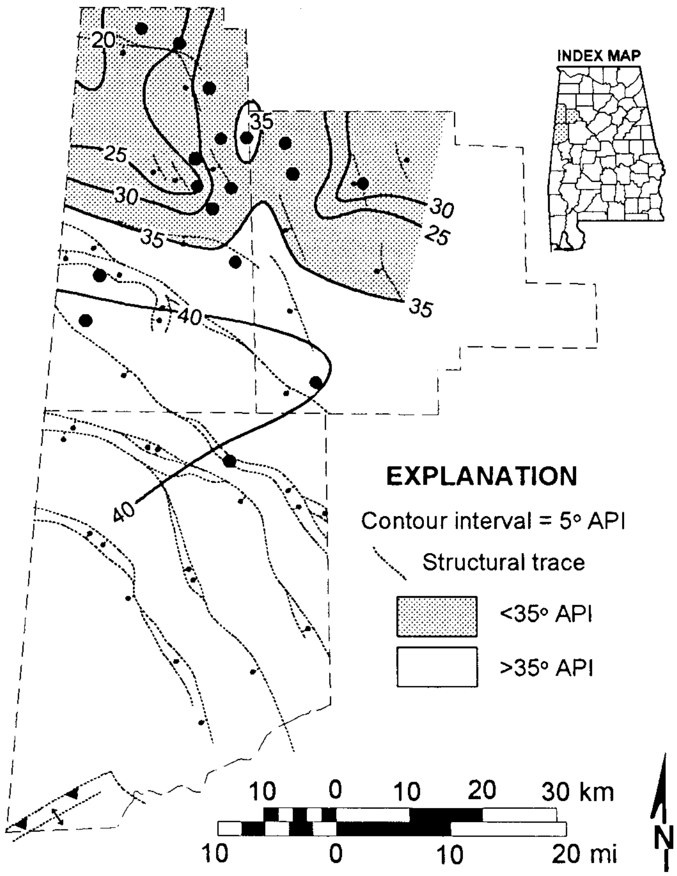

Figure 7.--API gravity distribution of oil from Carter sandstone reservoirs.

(see fig. 2). One exception is the Blakely Creek field which occurs in an area of low coal rank but which has an API gravity of 40°.

The plot of API gravity versus depth (fig. 8) shows a general increase of API gravity with increasing depth. Because API gravity values tend to increase with increasing hydrocarbon maturation, the range of these values can be explained solely on the basis of increasing thermal maturation of the hydrocarbons with increasing depth of the reservoir. This relationship has been confirmed with vitrinite reflectance data. However, API gravity values cluster between 22° and 34° for reservoir depths between 1,500 and 3,000 feet, and between 39° and 41° for reservoir depths greater than 3,000 feet. This clustering may be due to slight differences in timing, rock characteristics, and migrational pathways from source rock to reservoir between the shallower and deeper parts of the basin.

Analysis of the gross chemical composition of oil in Mississippian reservoirs of the Black Warrior basin in Alabama (fig. 9, table B-4) reveals that most of the oil contains a high percentage of saturated hydrocarbons in relation to aromatic hydrocarbons and asphaltenes. This relationship indicates that little biodegradation of the oil has occurred. The gas chromatogram of C_{10+} hydrocarbons in the *Millerella* sandstone, Blowhorn Creek oil unit (PN4510, fig. 10), typical of oils from the Black Warrior basin, does not reveal evidence of extensive biodegradation. However, oil-stained cores from the Carter and Lewis sandstones from several oil units, as well as extensive tar sands in the Hartselle Sandstone along the northern basin margin, indicate a more complex oil history than that of the currently available data. A plot of pristane/n-C_{17} versus heptane (fig. 11, table B-5) compares samples of Mississippian oil from the Black Warrior basin with samples from the Jurassic and Cretaceous of the Gulf Coastal Plain. This plot indicates that Mississippian oils are less mature thermally than those in Jurassic and Cretaceous reservoirs.

Carbon isotope data are consistent among the oil fields (table B-4). Values of $\partial^{13}C$ for the

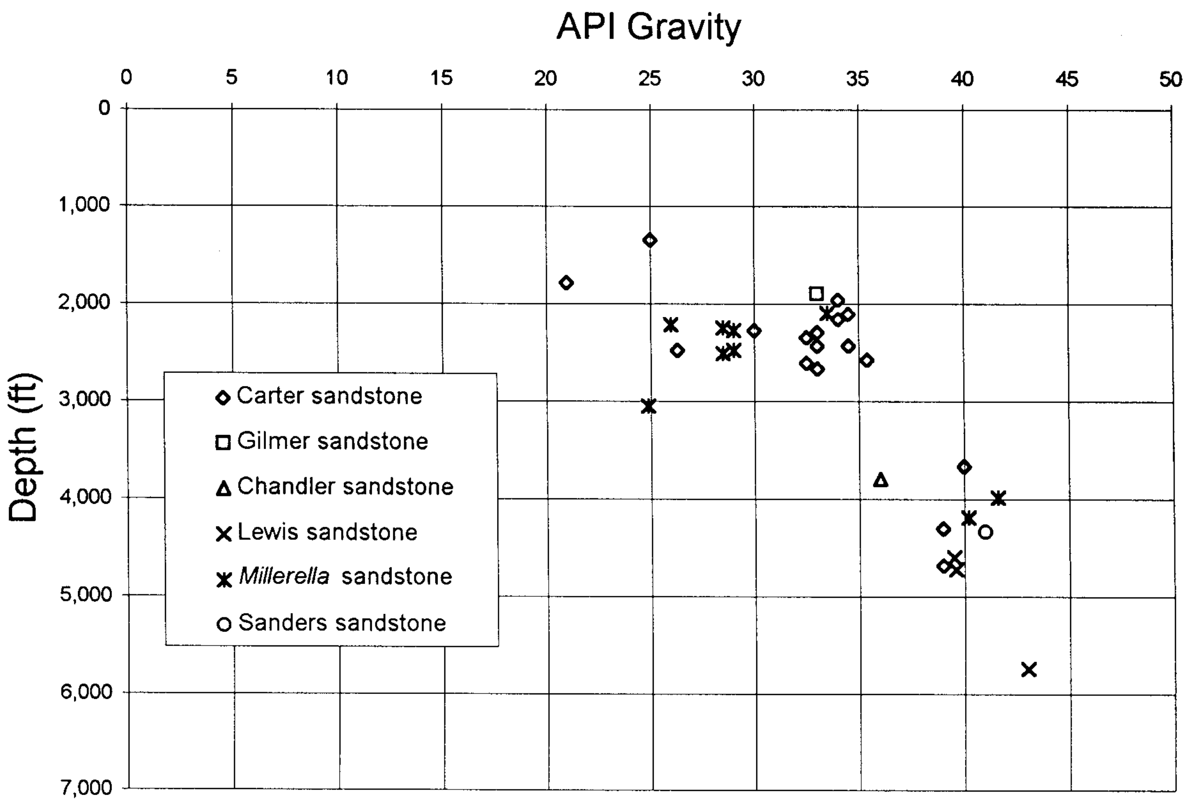

Figure 8.--Plot of API gravity versus depth in Mississippian oils from the Black Warrior basin.

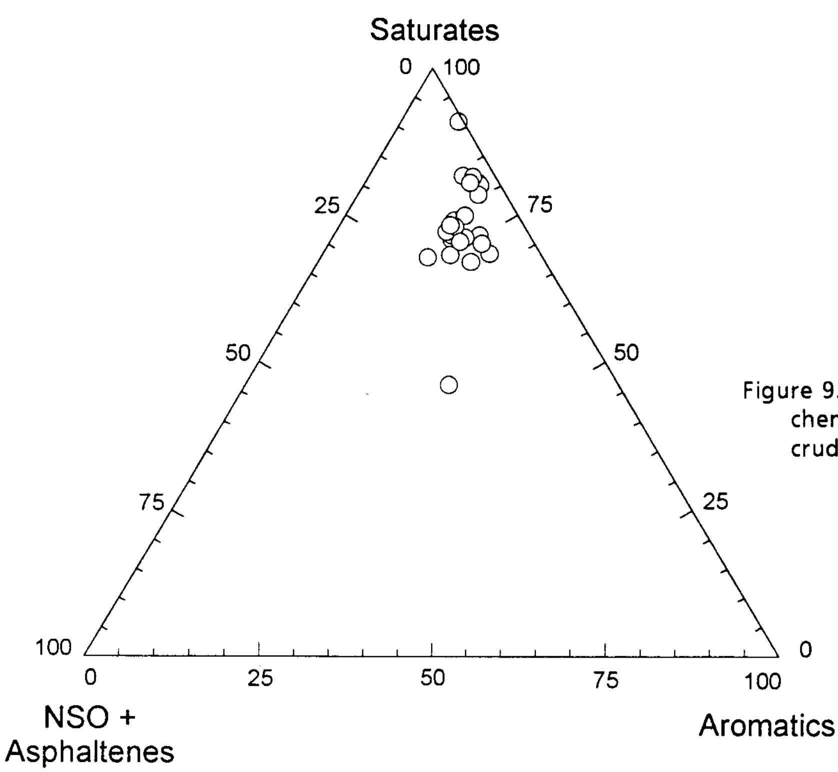

Figure 9.--Ternary diagram illustrating gross chemical composition of C_{15+} fraction of crude oils from the Black Warrior basin.

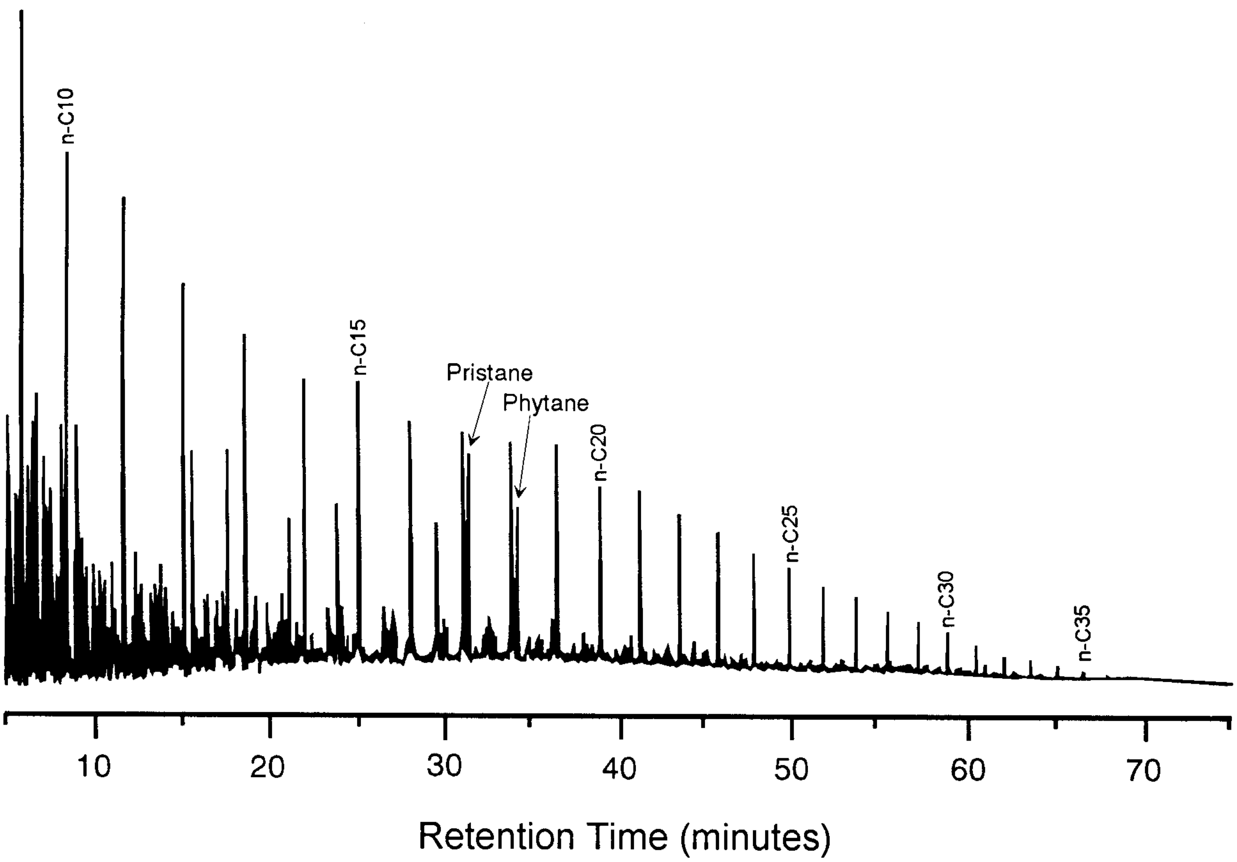

Figure 10.--Gas chromatogram of C_{10+} hydrocarbons in the *Millerella* sandstone, Blowhorn Creek oil unit (PN4510).

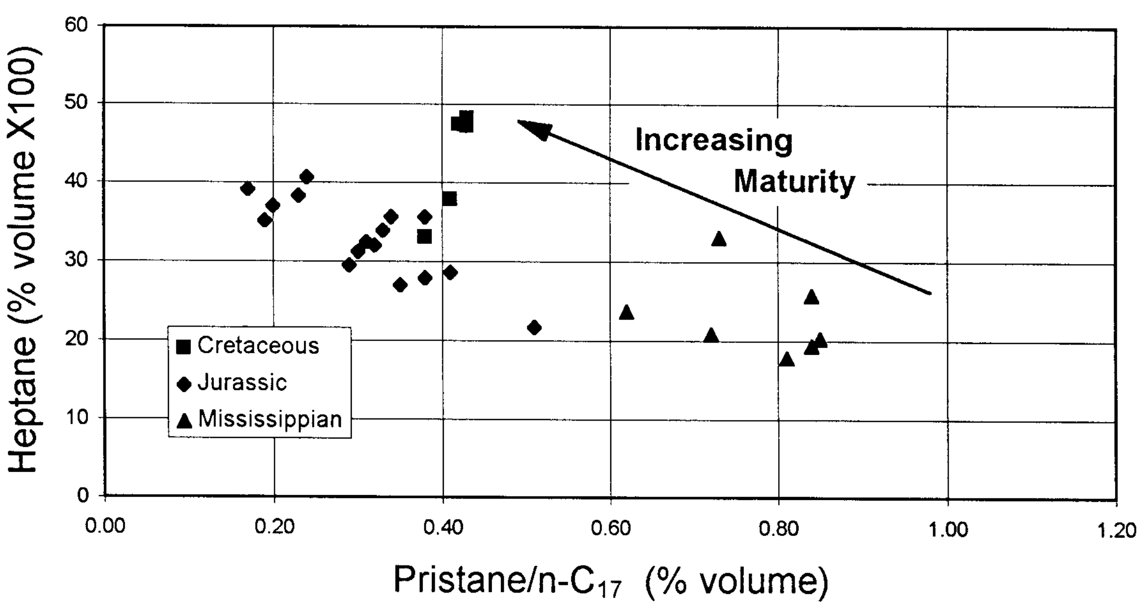

Figure 11.--Plot of pristane/n-C_{17} versus heptane for oils from Mississippian reservoirs in the Black Warrior basin and Jurassic and Cretaceous reservoirs in the Gulf Coastal Plain.

saturate hydrocarbon fraction range from -30.1 to -31.3, a difference of 1.2. Aromatic hydrocarbon fraction $\partial^{13}C$ values range from -29.3 to -30.6 for a difference of 1.3. The differences in these values are within the acceptable range attributable to maturity transformation only (Waples, 1982). Therefore, based on isotopic data and gross chemical composition, it can be concluded that oils in the different Mississippian reservoirs of the Black Warrior basin of Alabama appear to have a common origin.

SUMMARY AND CONCLUSIONS

Investigation of potential source rocks in the middle and upper Paleozoic rocks of the Black Warrior basin in Alabama indicates that most shale of Devonian through Pennsylvanian age has potential for hydrocarbon generation. Burial curves indicate that most units studied are within the liquid hydrocarbon window. Locally, however, the Chattanooga Shale is overmature. In the wells studied, major generation of liquid hydrocarbons began just prior to maximum burial and continued during subsequent unroofing of the basin. Reburial of Paleozoic strata during Cretaceous time apparently had little effect on source-rock maturation in the Black Warrior basin of Alabama.

Kerogen type and total organic carbon data from Rock-Eval pyrolysis indicate that, although most shale units contain sufficient organic material to be considered oil-prone, shale from the Pottsville and Parkwood Formations tends to be rich in terrestrial, gas-prone, type III kerogen. Shale from the Floyd and Chattanooga Formations, by contrast, tends to be rich in marine, oil-prone, type II kerogen. Based on these data, the Floyd and Chattanooga shales are the probable source rocks for oil produced from the Black Warrior basin. The Floyd Shale, because it is thicker and more laterally continuous than the Chattanooga Shale, is more likely the source of oil in the Mississippian reservoirs of the Black Warrior basin. However, the Chattanooga Shale may be the source of hydrocarbons for tar sands in northern Alabama, and all shale units are potential sources of gas.

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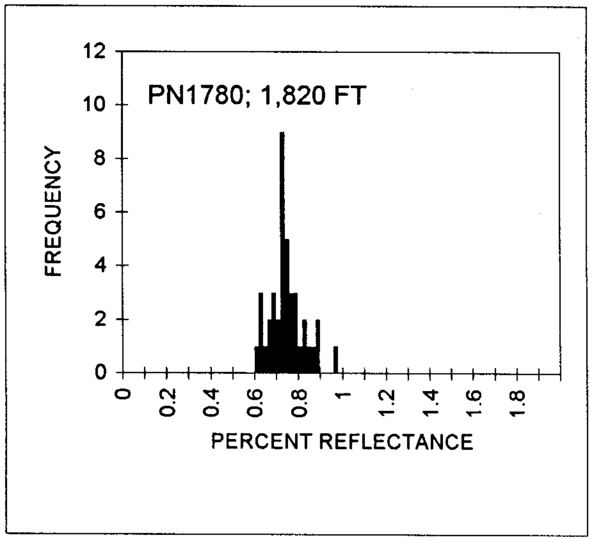
APPENDIX A

VITRINITE-REFLECTANCE HISTOGRAMS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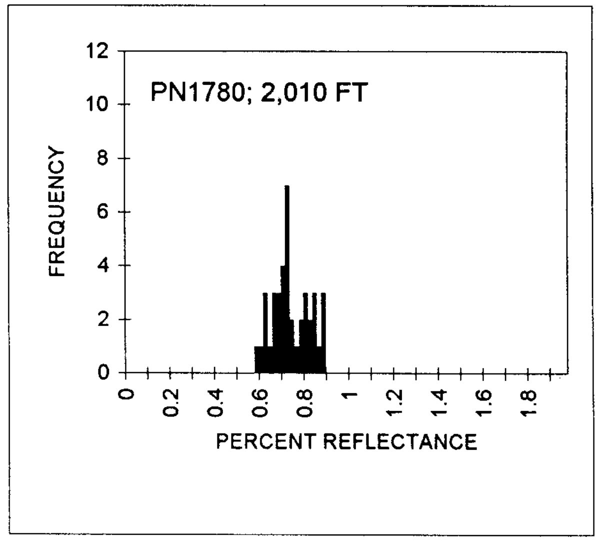
PERCENT REFLECTANCE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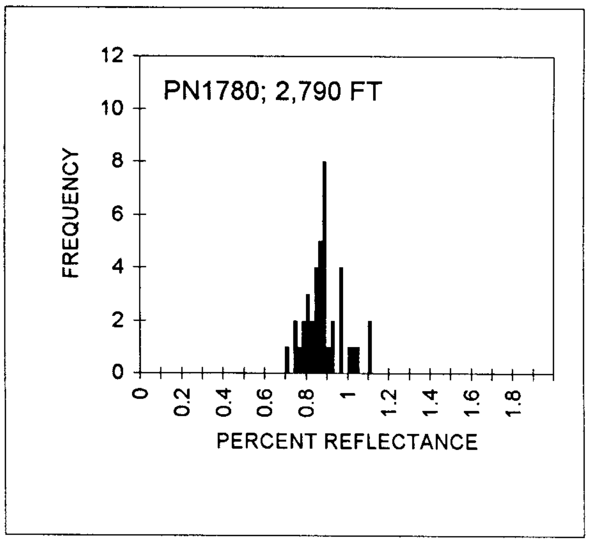
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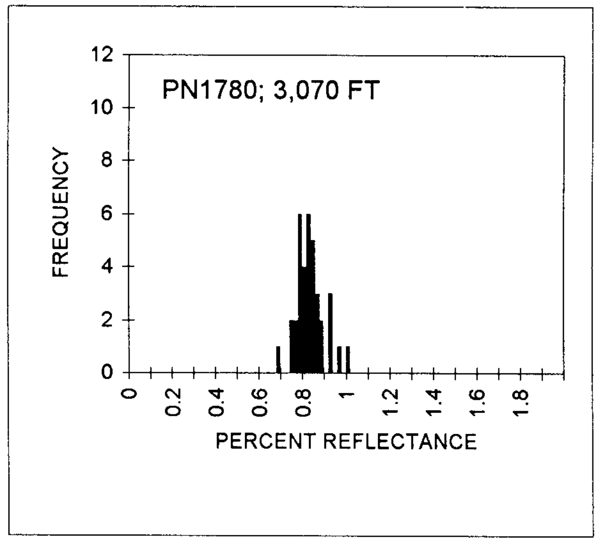
PERCENT REFLECTANCE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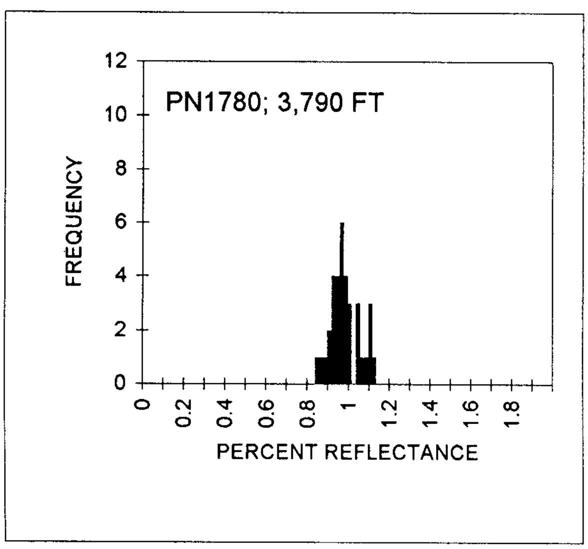
PERCENT REFLECTANCE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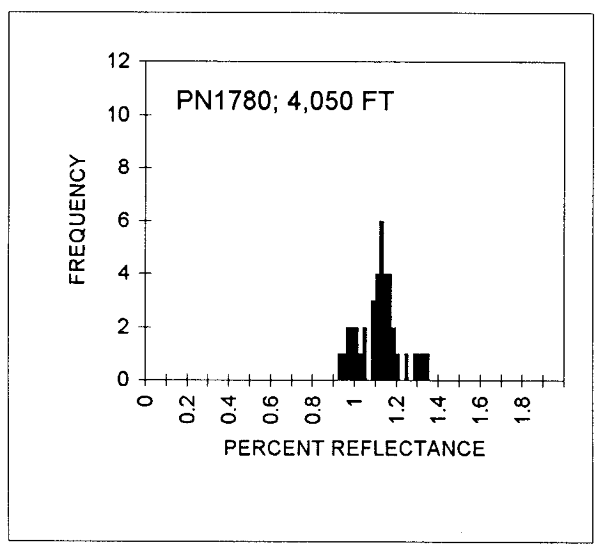
PERCENT REFLECTANCE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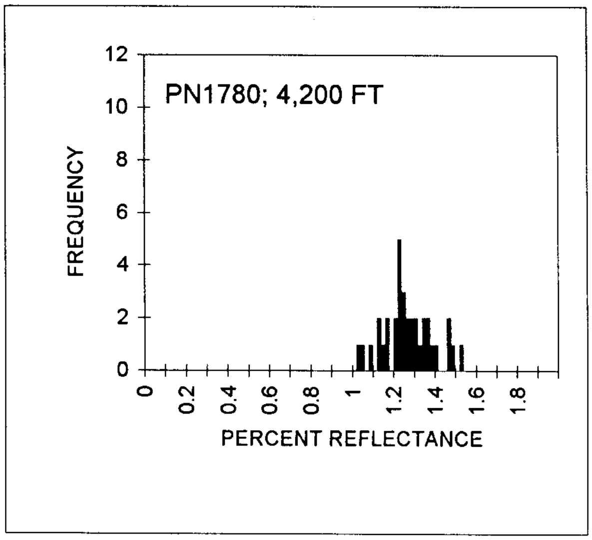
PERCENT REFLECTANCE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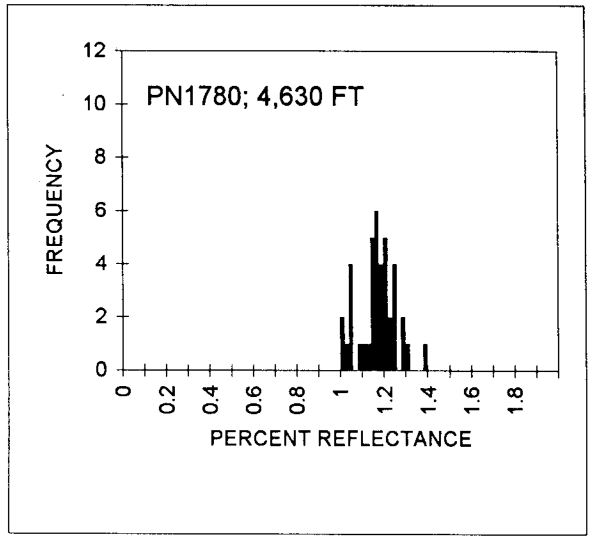
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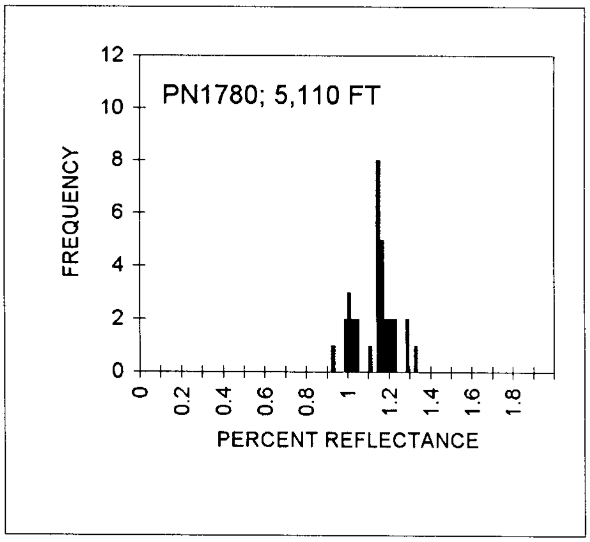
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FREQUENCY
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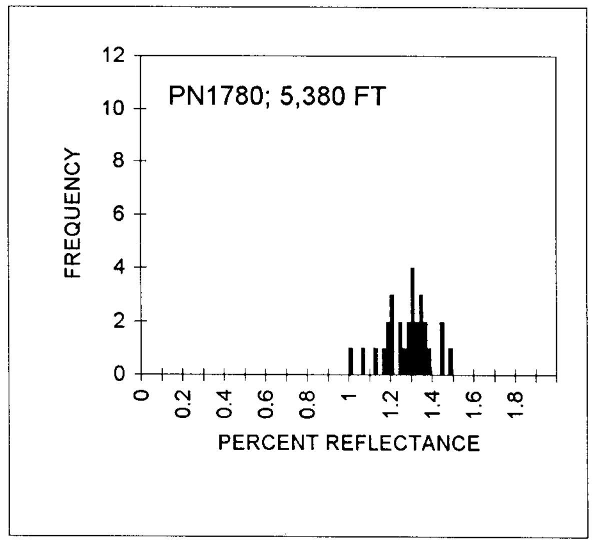
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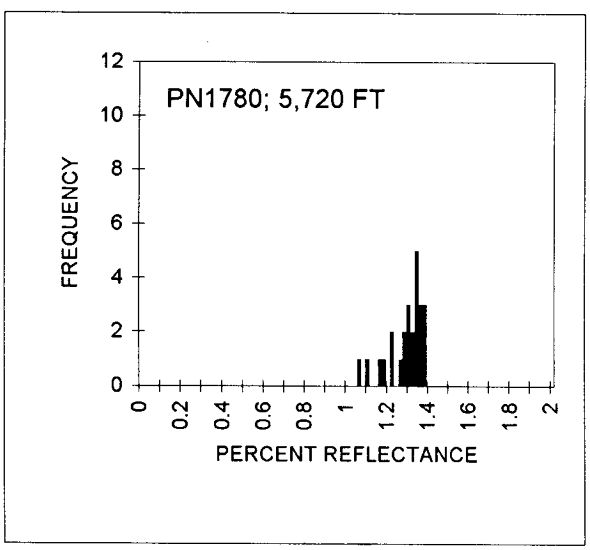
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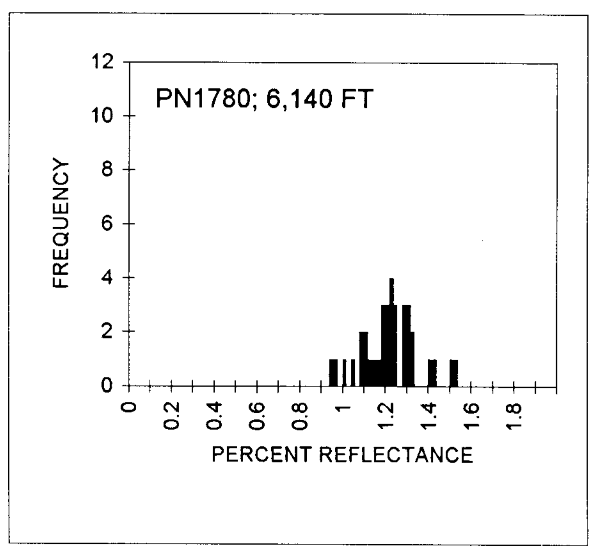
FREQUENCY
PERCENT REFLECTANCE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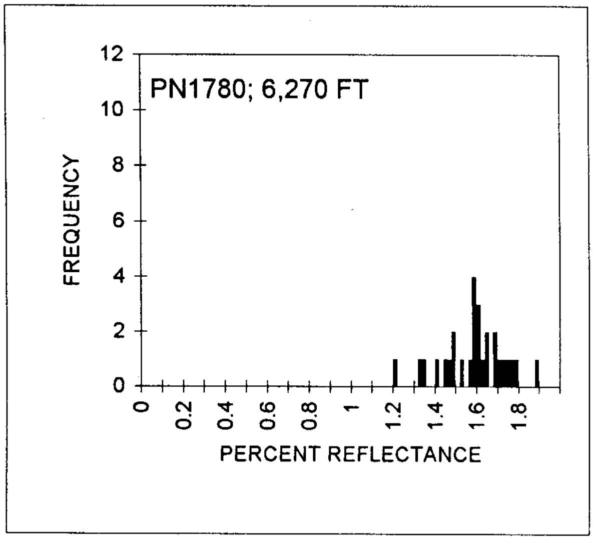
FREQUENCY
PERCENT REFLECTANCE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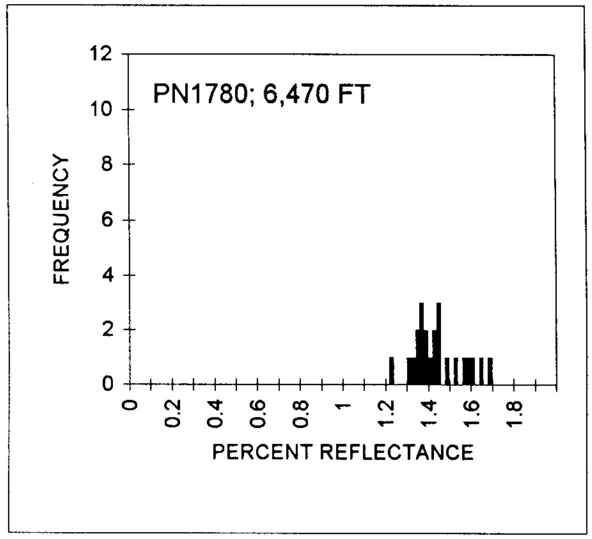
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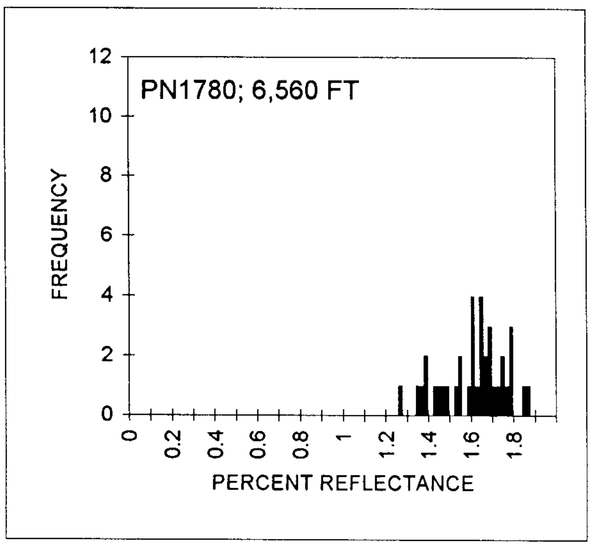
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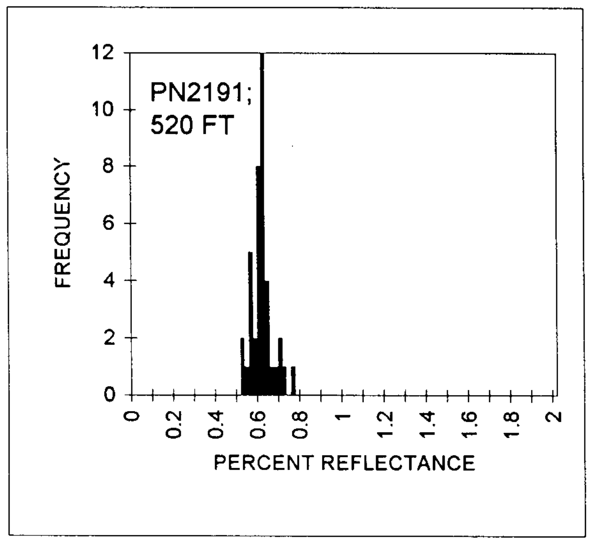
PERCENT REFLECTANCE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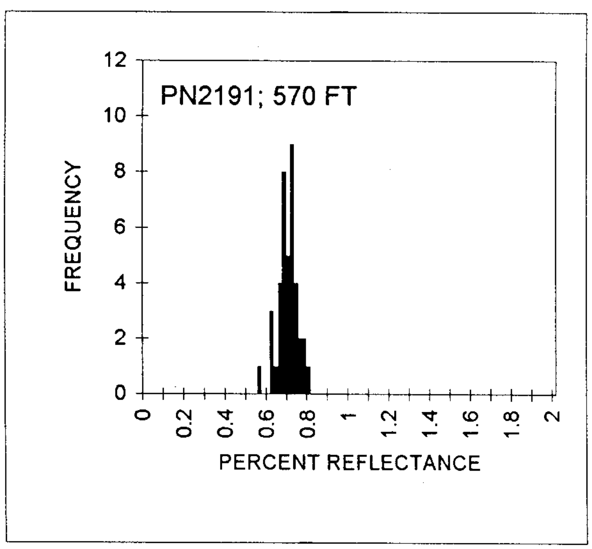
PERCENT REFLECTANCE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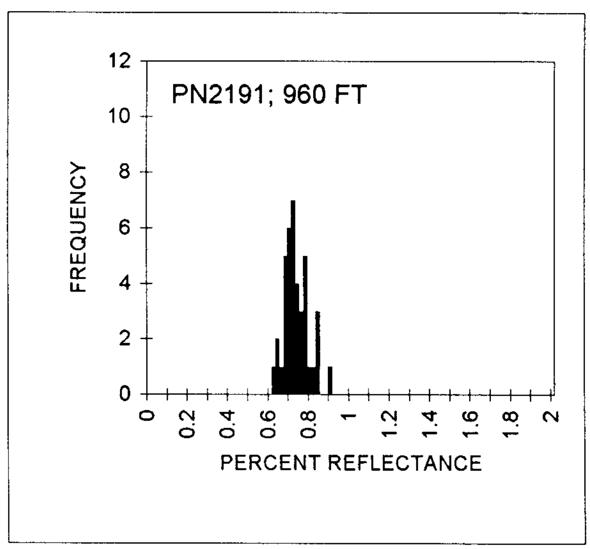
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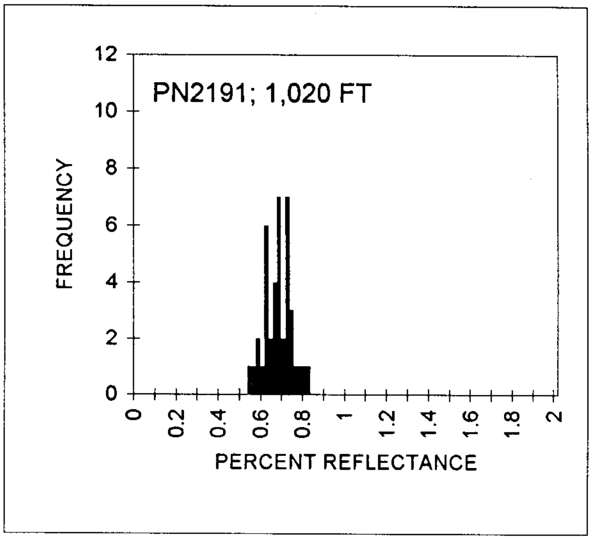
PERCENT REFLECTANCE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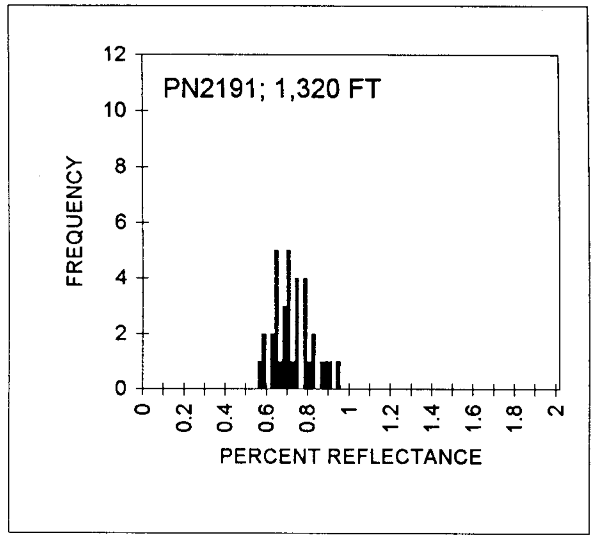
FREQUENCY
PERCENT REFLECTANCE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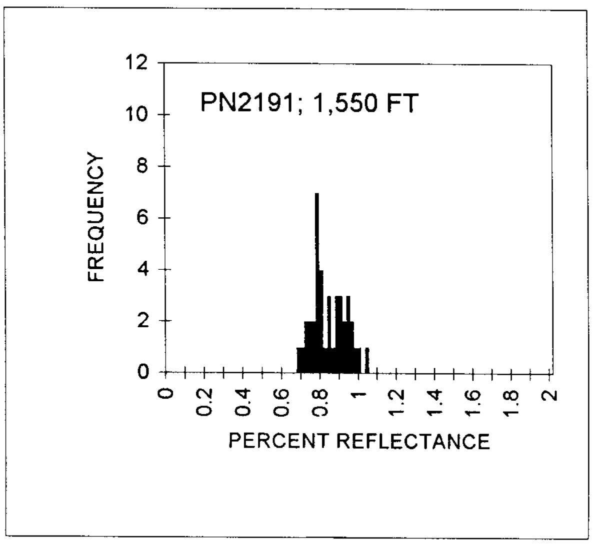
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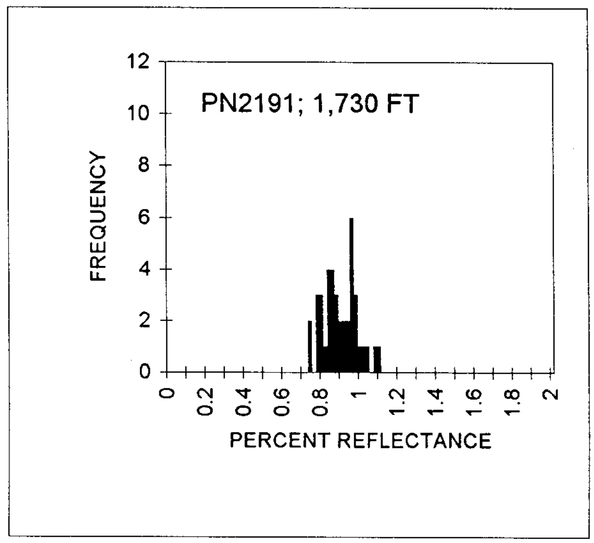
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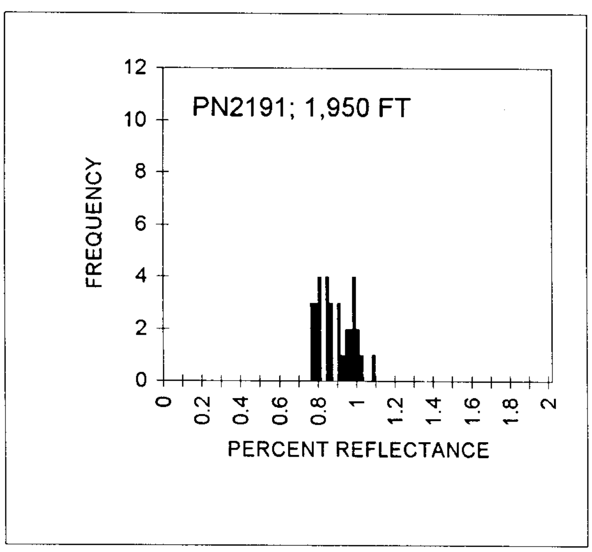
FREQUENCY
PERCENT REFLECTANCE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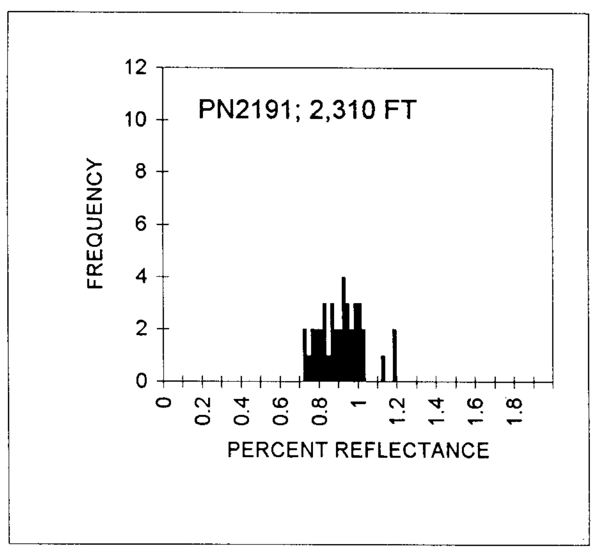
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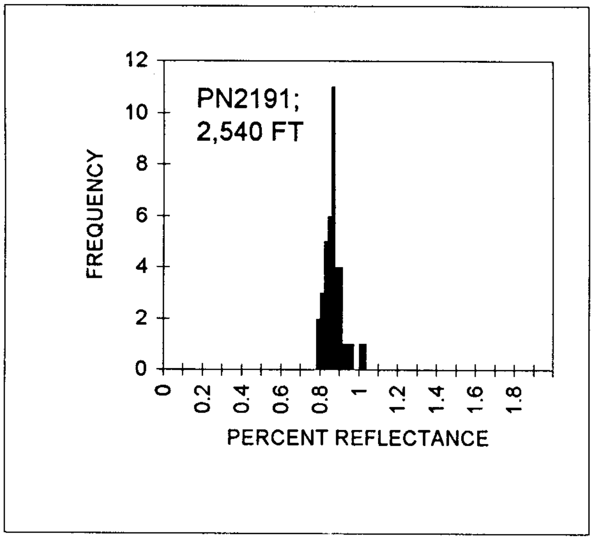
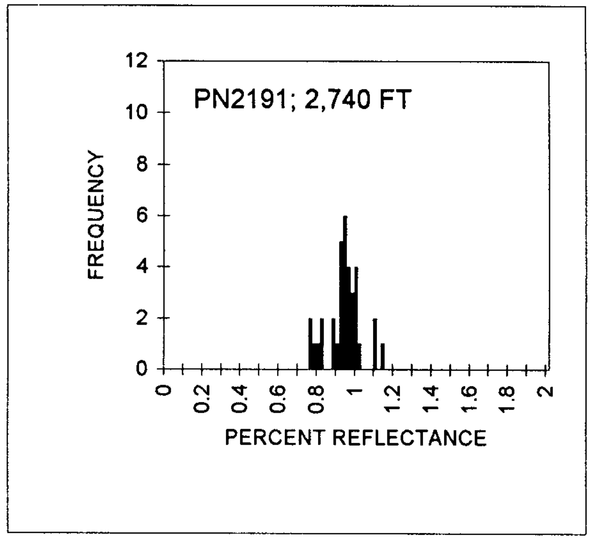

PN2191;
2,540 FT
FREQUENCY
PERCENT REFLECTANCE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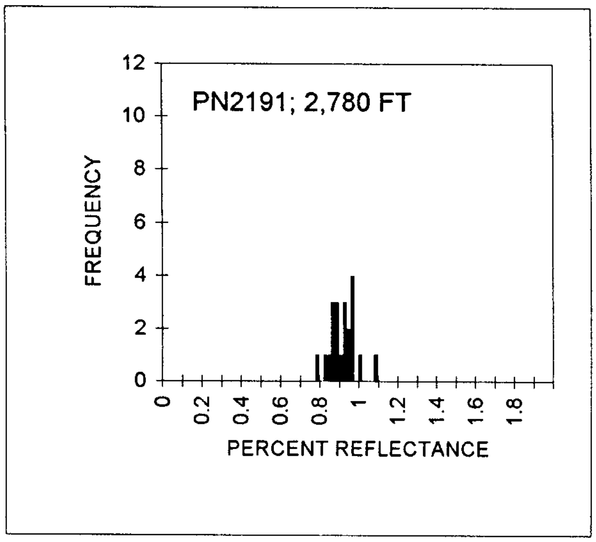
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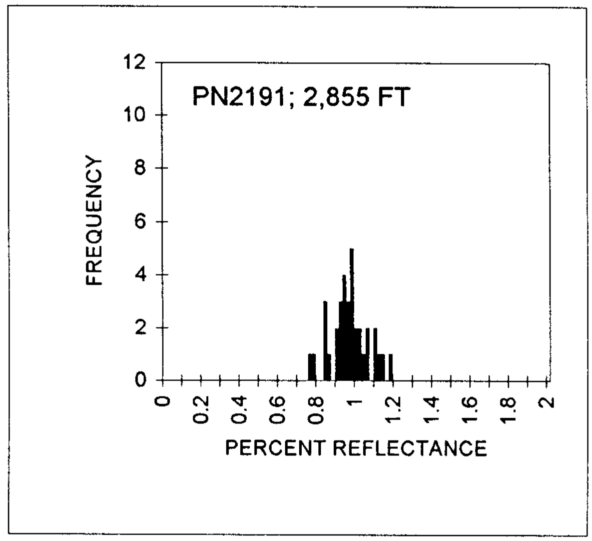
PERCENT REFLECTANCE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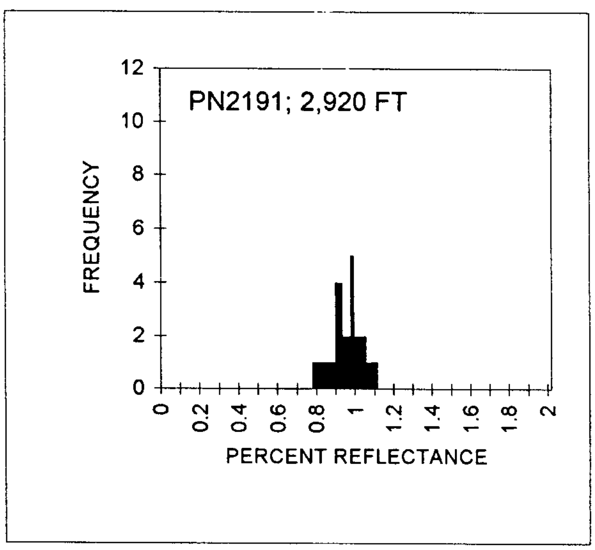
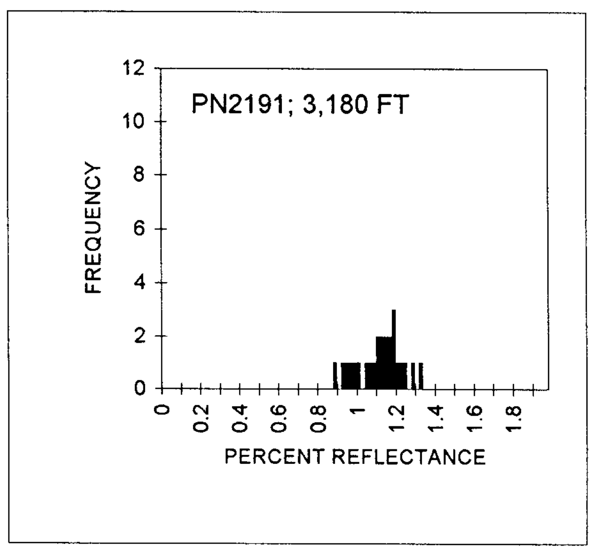
PERCENT REFLECTANCE


PN2191; 2,920 FT
FREQUENCY
PERCENT REFLECTANCE


PN2191; 3,180 FT
FREQUENCY
PERCENT REFLECTANCE

APPENDIX B

SOURCE-ROCK MATURATION AND GEOCHEMICAL DATA

Table B-1.--Vitrinite reflectance data for wells PN1780 and PN2191

Well	Depth (ft)	Unit or formation	Mean % R(o)	Minimum	Maximum	Standard deviation	Count
PN 1780	1,820	Pottsville Fm.	0.75	0.61	0.97	0.078	40
PN 1780	2,010	Pottsville Fm.	.74	.59	.89	.083	40
PN 1780	2,790	Pottsville Fm.	.89	.72	1.11	.086	40
PN 1780	3,070	Pottsville Fm.	.82	.69	1.02	.066	36
PN 1780	3,790	Pottsville Fm.	.99	.84	1.14	.072	35
PN 1780	4,050	Pottsville Fm.	1.12	.93	1.36	.099	40
PN 1780	4,200	Pottsville Fm.	1.27	1.03	1.53	.120	35
PN 1780	4,630	upper Boyles ss.	1.17	1.00	1.40	.084	40
PN 1780	5,110	lower Boyles ss.	1.14	.93	1.33	.096	33
PN 1780	5,380	lower Boyles ss.	1.28	1.01	1.49	.110	29
PN 1780	5,720	upper Parkwood fm.	1.30	1.07	1.40	.089	25
PN 1780	6,140	upper Parkwood fm.	1.22	.95	1.53	.132	36
PN 1780	6,270	Floyd Sh.	1.59	1.20	1.89	.150	28
PN 1780	6,470	Floyd Sh.	1.44	1.22	1.70	.117	23
PN 1780	6,560	Lewis ss.	1.61	1.27	1.86	.148	37
PN 2191	520	Pottsville Fm.	.62	.52	.77	.050	40
PN 2191	570	Pottsville Fm.	.71	.58	.81	.048	40
PN 2191	960	Pottsville Fm.	.74	.62	.91	.061	40
PN 2191	1,020	Pottsville Fm.	.69	.55	.84	.064	40
PN 2191	1,320	Pottsville Fm.	.73	.56	.95	.094	35
PN 2191	1,550	Pottsville Fm.	.85	.69	1.05	.090	40
PN 2191	1,730	Pottsville Fm.	.91	.75	1.10	.088	40
PN 2191	1,950	Pottsville Fm.	.89	.76	1.09	.089	33
PN 2191	2,310	Parkwood Fm.	.91	.72	1.18	.114	40
PN 2191	2,540	Carter ss.	.87	.79	1.02	.051	40
PN 2191	2,740	Floyd Sh.	.95	.76	1.14	.087	35
PN 2191	2,780	Floyd Sh.	.92	.80	1.09	.067	21
PN 2191	2,855	Floyd Sh.	.98	.77	1.19	.097	35
PN 2191	2,920	Lewis ss.	.96	.79	1.10	.080	32
PN 2191	3,180	Chattanooga Sh.	1.12	.88	1.33	.115	25

Table B-2.--Temperature/time index data for wells PN1780 and PN2191

	PN1780		PN2191	
	TTI Value	MA	TTI Value	MA
Top of remaining Cretaceous section				
Initial	0	91	0	91
Onset of oil generation	--	--	--	--
Peak oil generation	--	--	--	--
End of oil generation	--	--	--	--
Final	.5	0	.5	0
Top of remaining Pottsville Formation				
Initial	0	309	0	309
Onset of oil generation	15	231	--	--
Peak oil generation	--	--	--	--
End of oil generation	--	--	--	--
Final	23	0	6	0
Base of Pottsville Formation				
Initial	0	315	0	315
Onset of oil generation	15	266	15	211
Peak oil generation	75	198	--	--
End of oil generation	--	--	--	--
Final	87	0	18	0
Base of upper Parkwood formation				
Initial	0	320	0	320
Onset of oil generation	15	268	15	254
Peak oil generation	75	228	--	--
End of oil generation	--	--	--	--
Final	108	0	23	0
Top of Tuscumbia Limestone				
Initial	0	336	0	336
Onset of oil generation	15	272	15	275
Peak oil generation	75	254	--	--
End of oil generation	160	112	--	--
Final	170	0	39	0
Base of Chattanooga Shale				
Initial	0	267	0	367
Onset of oil generation	15	274	15	281
Peak oil generation	75	256	--	--
End of oil generation	160	214	--	--
Final	202	0	43	0

Table B-3.--Rock-Eval pyrolysis data for wells PN1780 and PN2191

Well	Depth (ft)	Unit or formation	Sample weight	Tmax °C	S1	S2	S3	PI	S2/S3	TOC (wt %)	HI	OI
PN 1780	1,690	Pottsville Fm.	205.1	467	0.04	0.25	1.20	0.14	0.20	0.53	47	226
PN 1780	2,440	Pottsville Fm.	185.9	450	.06	.41	.69	.13	.59	.54	75	127
PN 1780	2,570	Pottsville Fm.	197.5	458	.05	.33	1.07	.13	.30	.67	49	159
PN 1780	3,670	Pottsville Fm.	216.8	454	.03	.28	1.29	.10	.21	.70	40	184
PN 1780	3,680	Pottsville Fm.	212.5	458	.02	.27	1.18	.07	.22	.67	40	176
PN 1780	4,050	Pottsville Fm.	224.1	464	.04	.32	.83	.11	.38	.73	43	113
PN 1780	4,480	Fayette ss.	194.1	471	.02	.31	1.36	.06	.22	1.09	28	124
PN 1780	4,610	upper Boyles ss.	185.2	461	.02	.24	.73	.08	.32	.73	32	100
PN 1780	4,910	lower Boyles ss.	168.9	445	.06	.77	.69	.07	1.11	1.28	60	53
PN 1780	5,430	Parkwood Fm.	190	467	.05	.27	.78	.16	.34	.53	50	147
PN 1780	5,690	Parkwood Fm.	224.9	464	.02	.13	.78	.14	.16	.44	29	177
PN 1780	5,880	Parkwood Fm.	189.2	470	.02	.18	.78	.10	.23	.55	32	141
PN 1780	5,980	Parkwood Fm.	159.3	459	.04	.26	.47	.13	.55	.66	39	71
PN 1780	6,450	Floyd Sh.	214.9	450	.31	1.35	1.00	.19	1.35	2.22	60	45
PN 1780	6,560	Lewis ss.	209.4	459	.07	.59	1.16	.11	.50	1.12	52	103
PN 1780	6,600	Chattanooga Sh.	185.8	454	.07	.31	.74	.18	.41	.50	62	148
PN 2191	570	Pottsville Fm.	182	447	.03	.58	2.72	.05	.21	1.09	53	249
PN 2191	700	Pottsville Fm.	211	438	.07	1.68	1.81	.04	.92	1.43	117	126
PN 2191	1,020	Pottsville Fm.	175.2	456	.02	.34	2.87	.06	.11	1.06	32	270
PN 2191	1,540	lower Boyles ss.	178.6	461	.04	.39	1.76	.10	.22	.92	42	191
PN 2191	1,730	lower Boyles ss.	196.3	445	.03	.39	2.28	.07	.17	1.07	36	213
PN 2191	1,950	lower Boyles ss.	177.6	442	.04	.48	1.98	.08	.24	1.23	39	160
PN 2191	2,140	upper Parkwood fm.	186.6	439	.04	.38	2.27	.10	.16	.88	43	257
PN 2191	2,310	upper Parkwood fm.	211.7	445	.02	.24	.92	.08	.26	.56	42	164
PN 2191	2,490	Carter ss.	238.5	443	.03	.37	1.71	.07	.21	.76	48	225
PN 2191	2,740	Floyd Sh.	145.6	437	.53	3.84	1.92	.12	2.00	1.60	240	120
PN 2191	4,770	Floyd Sh.	230.2	439	.6	8.41	1.66	.07	5.06	2.45	343	67
PN 2191	2,820	Floyd Sh.	210.3	438	.29	5.78	1.36	.05	4.25	1.74	332	78
PN 2191	2,855	Floyd Sh.	23.3	443	.68	4.89	.90	.12	5.43	2.36	207	38
PN 2191	2,920	Floyd Sh.	19.1	446	1.15	9.1	2.46	.11	3.69	3.94	230	62
PN 2191	3,010	Floyd Sh.	239	432	.04	.4	.95	.09	.42	.47	85	202
PN 2191	3,180	Chattanooga Sh.	166.1	433	.54	7.41	1.37	.07	5.40	3.05	242	44

Table B-4.--Gross chemical composition of oils from Mississippian oil fields in the Black Warrior basin

Oil field	County	Permit number	Unit or formation	Depth (ft)	Sat. (%)	Arom. (%)	NSO (%)	Asph. (%)	NSO+ Asph. (%)	API gravity	δ13C
Beaver Creek	Lamar	5030	Carter ss.	1,964	46.1	29.5	9.4	15.1	24.5	34	-30.16
Binyon Creek	Tuscaloosa	3769	Lewis ss.	4,570	--	--	--	--	--	39	--
Blakely Creek	Fayette	6863	Carter ss.	3,666	80.5	16.5	3.0	.0	3.0	40	-31.03
Blowhorn Creek	Lamar	2878	Carter ss.	2,580	--	--	--	--	--	35.4	--
Blowhorn Creek	Lamar	4510	Millerella ss.	2,480	71.5	21.3	6.5	.8	7.3	29	-30.67
Blowhorn Creek	Lamar	2878	Millerella ss.	2,495	68.4	24.3	6.9	.5	7.4	29	-30.65
Bluff	Fayette	4609	Gilmer ss.	1,896	70.8	17.6	9.1	2.5	11.6	33	-30.42
Bluff	Fayette	4517	lower Carter ss.	2,110	68.2	18.7	11.7	1.4	3.1	34	-30.15
Bluff	Fayette	4609	Millerella ss.	2,098	70.1	22.3	7.3	.3	7.6	34	-30.11
Bluff	Fayette	4469	upper Carter ss.	2,348	71.1	19.4	9.3	.2	9.5	33	-30.43
Cains Ridge	Fayette	5941	Millerella ss.	3,190	74.0	16.3	9.7	.0	9.7	--	-31.01
Central Bluff	Fayette	3905	Millerella ss.	2,220	--	--	--	--	--	26	--
Central Fairview	Lamar	1968	Carter ss.	2,435	--	--	--	--	--	34	--
Chicken Swamp Branch	Pickens	6524	Lewis ss.	5,741	90.8	8.5	.7	.0	.7	43	-30.60
Coal Fire Creek	Pickens	5080	Carter ss.	4,615	--	--	--	--	--	39	--
Cooper Creek	Lamar	4775	Millerella ss.	3,984	80.0	17.1	2.6	.2	2.8	41.6	-30.63
East Detroit	Lamar	1565	Carter ss.	1,790	--	--	--	--	--	21	--
Fairview	Lamar	3026	Carter ss.	2,435	71.5	17.3	9.7	1.4	11.1	33	-30.61
Henson Springs	Lamar	1623	Carter ss.	1,345	--	--	--	--	--	25	--
McCracken Mountain	Fayette	4667	Millerella ss.	3,051	74.8	17.5	7.8	.0	7.8	25	-31.02
Mount Zion	Lamar	5454	Lewis ss.	4,719	81.6	13.8	3.3	1.3	4.6	39.8	-31.28
Mud Creek	Lamar	5249	Millerella ss.	4,190	78.4	17.6	3.9	.0	3.9	40.2	-30.57
North Blowhorn Creek	Lamar	2751	Carter ss.	2,297	72.1	16.2	10.8	.9	11.7	33	-30.39
North Bluff	Fayette	4321	Millerella ss.	2,276	67.8	15.6	14.7	1.9	16.6	29	-31.00
North Bluff	Fayette	3777	Millerella ss.	2,278	--	--	--	--	--	29	--
North Fairview	Lamar	3832	Carter ss.	2,275	67.0	22.3	10.2	.5	10.7	30	-30.23
South Brush Creek	Lamar	4322	Carter ss.	2,612	73.0	17.0	9.7	.4	10.1	33	-30.65
South Fairview	Lamar	2337	Carter ss.	2,481	--	--	--	--	--	26.3	--
Star	Lamar	3569	Carter ss.	4,298	81.4	15.3	3.3	.0	3.3	39	-31.08
Star	Lamar	3740	Chandler ss.	3,800	--	--	--	--	--	36	--
Wayside	Fayette	4465	Carter ss.	2,159	73.2	16.2	9.4	1.1	10.5	34	-30.40
West Brush Creek	Lamar	5277	Carter ss.	2,665	70.4	19.0	10.0	.6	10.6	33	-30.76
Yellow Creek	Lamar	3940	Carter and Sanders ss.	4,335	80.4	15.4	3.2	1.0	4.2	41	-31.04

Table B-5.--Pristane/n-C_{17} and heptane values for oil from Mississippian, Jurassic, and Cretaceous oil fields in Alabama

Oil field	Age	Permit number	Unit or formation	Depth (ft)	Pristane/ n-C_{17}	Heptane
Hubbard's Landing	Cretaceous	4675	Washita/Fredericksburg	8,236	0.41	37.89
Latham	Cretaceous	4522	Washita/Fredericksburg	8,046	.38	33.10
Osaka	Cretaceous	6285	Cogle Sand	6,207	.42	47.44
Osaka	Cretaceous	6285	Pilot Sand	6,083	.43	48.28
West Foshee	Cretaceous	5325	Pilot Sand	6,168	.43	47.15
Broken Leg Creek	Jurassic	6153	Smackover Ls.	14,035	.41	28.61
East Barnett	Jurassic	5739	Smackover Ls.	13,600	.34	35.56
Gin Creek	Jurassic	4546	Smackover Ls.	13,582	.19	35.10
Gulf Crest	Jurassic	5226	Smackover Ls.	18,634	.17	39.07
Hanberry Church	Jurassic	5178	Smackover Ls.	13,627	.31	32.45
North Smiths Church	Jurassic	6943	Smackover Ls.	14,238	.38	27.93
Northeast Barnett	Jurassic	6303	Smackover Ls.	13,449	.33	33.91
Pace Creek	Jurassic	5058	Smackover Ls.	11,194	.20	36.97
Palmers Crossroads	Jurassic	5584	Smackover Ls.	14,375	.51	21.75
South Burnt Corn Creek	Jurassic	5272	Smackover Ls.	13,485	.38	35.63
South Vocation	Jurassic	4225	Smackover Ls.	13,456	.24	40.63
South Wild Fork Creek	Jurassic	5869	Smackover Ls.	14,287	.35	26.99
Turnerville	Jurassic	4412	Smackover Ls.	18,407	.23	38.26
Wallace	Jurassic	6752	Smackover Ls.	13,486	.29	29.52
West Falco	Jurassic	6239	Smackover Ls.	13,034	.32	32.03
Wildcat	Jurassic	5930	Smackover Ls.	13,170	.30	31.20
Bluff	Mississippian	4517	lower Carter ss.	2,110	.84	25.73
Bluff	Mississippian	4609	*Millerella* ss.	2,098	.85	20.31
Bluff	Mississippian	4469	upper Carter ss.	2,348	.84	19.40
Chicken Swamp Branch	Mississippian	6524	Lewis ss.	5,741	.62	23.68
Mud Creek	Mississippian	5249	*Millerella* ss.	4,190	.73	32.96
Star	Mississippian	3569	Carter ss.	4,298	.81	17.81
Yellow Creek	Mississippian	3940	Carter and Sanders ss.	4,335	.72	20.80

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