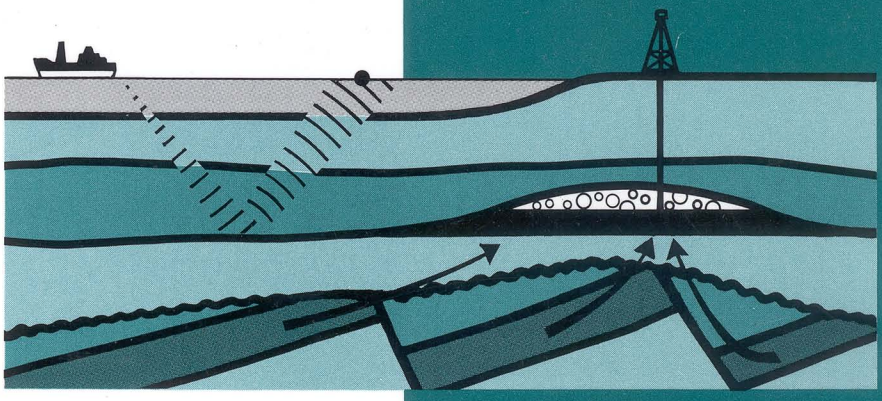
IFP EXPLORATION RESEARCH CONFERENCES

MIGRATION OF HYDROCARBONS IN SEDIMENTARY BASINS



ÉDITIONS TECHNIP

M.D. LEWAN[1]

PETROGRAPHIC STUDY OF PRIMARY PETROLEUM MIGRATION IN THE WOODFORD SHALE AND RELATED ROCK UNITS

ABSTRACT The Woodford Shale (Devonian-Mississippian) of Oklahoma and some of its age-equivalent rock units are significant sources of Paleozoic oil in several basins within North America. Petrographic examination of thin sections of Woodford Shale samples that were thermally matured both in nature and in hydrous pyrolysis experiments provides useful insights on primary migration of petroleum. Shales in the pre-oil generation stage contain amorphous masses of kerogen dispersed within a translucent groundmass. As thermal stress increases, a viscous bitumen generated from the degradation of the dispersed kerogen masses impregnates the planar bedding fabric of the shale. If the amount and distribution of organic matter are favorable, a continuous bitumen network eventually develops within the groundmass. Increasing thermal stress results in the generation of oil from the bitumen network. This oil impregnates micropores within the groundmass and excess oil is expelled into adjacent fractures. Following this primary-oil generation stage, the bitumens and retained oil are carbonized to a pyrobitumen with increasing thermal stress, which results in an opaque groundmass. Bitumen migration and oil expulsion are considered to be the result of a net volume increase of the organic matter within the confined inorganic matrix. The increase in volume is attributed to the overall decrease in density of the reaction products and thermal expansion of the generated liquid organic phases.

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PETROGRAPHIC STUDY OF PRIMARY PETROLEUM MIGRATION

1. INTRODUCTION

Petrographic examination of source rocks in thin section at different maturity levels provides some insights into understanding primary migration of petroleum. This study uses such an approach on Upper Devonian - Lower Mississippian black shales that have naturally and artificially gone through the different stages of petroleum generation. The naturally matured samples are from the Mid-Continent states (Fig. 1) where these black shales are considered to be a major source of petroleum. Names assigned to these black shales change regionally with Woodford Shale occurring in southern Oklahoma, Arkansas Novaculite occurring in southeastern Oklahoma and west-central Arkansas, and Chattanooga Shale occurring in northeastern Oklahoma, southwestern Missouri, and northwestern Arkansas. Orogenic uplifts and subsequent erosion have allowed these black shales to be exposed in outcrop along road and river cuts. The three uplift areas from which the samples were collected each represent a different stage of petroleum generation. Woodford Shale samples from the Arbuckle Mountains are in the pre-oil generation stage, Chattanooga Shale samples from the Ozark Uplift are in the primary-oil generation stage, and Arkansas Novaculite samples from the Ouachita Mountains are in the post-oil generation stage.

The artificial maturation experiments were conducted on Woodford Shale in the pre-oil generation stage. The experimental approach employed is referred to as hydrous pyrolysis and involves heating rocks in a closed system with liquid water at subcritical temperatures [1]. If the proper time and temperature conditions (300 to 360°C for 72 hours) are employed in these experiments, free-flowing liquid oil generated within the source rock is expelled into the surrounding liquid water. This expelled oil is compositionally similar to natural crude oils [1] and may be quantitatively collected off the water surface in the reactor at the end of the experiment. As noted by Lewan and others [1], the major advantage of hydrous pyrolysis over anhydrous pyrolysis (i.e., without liquid water) is its ability to generate an expelled oil from a source rock, without employing vacuum cryogenic trapping, carrier gas flushing, or solvent refluxing. This is particularly important in the study of primary migration where expulsion of generated oil is intuitively a vital part of the process.

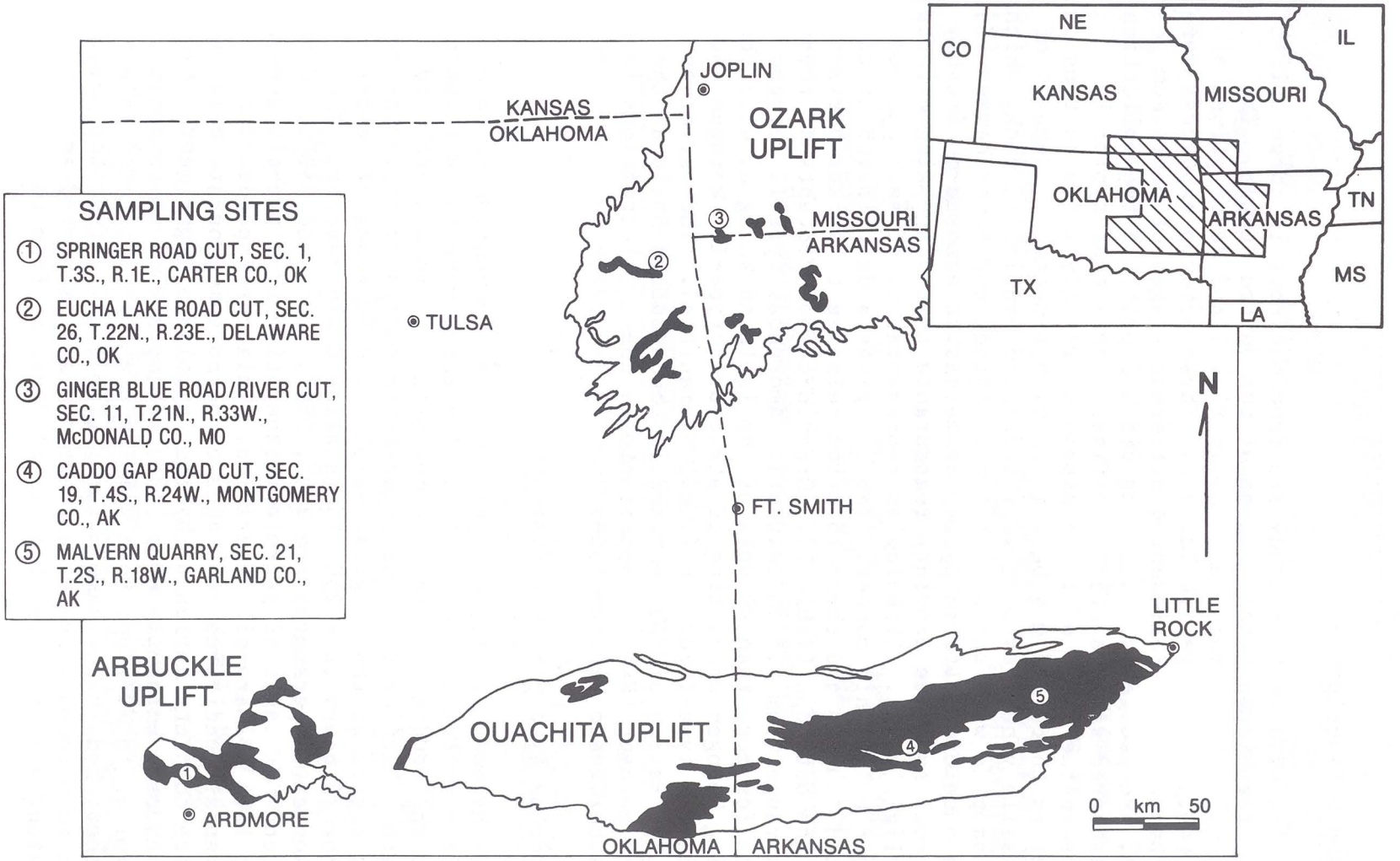


Fig. 1. Generalized map showing the sites where Devonian– Mississippian black shales were sampled in three uplift areas of the Mid–Continent region in the United States. The blackened areas represent sedimentary rocks of early Mississippian to late Ordovician age.

2. MATERIALS AND PROCEDURES

2.1 Sample Description

Samples used in this study are from outcrops in three uplift areas in the Mid-Continent region of the United States. The sampling-site locations are given in Fig. 1 and descriptions of the exposures are given in Table 1. These outcrop exposures were chosen because they represented different stages of petroleum generation, and pedogenic weathering did not prohibit the collection of unweathered samples [2]. The fissile zone that typically develops on the faces of these exposures is only a few to tens of centimeters thick and may be removed with a mattock. Removal of this fissile veneer exposes well indurated nonfissile rock, which may be sampled with the use of a rock chisel and crack hammer [3]. The presence of unaltered pyrite or marcasite exposed on freshly broken rock surfaces provides reassurance that weathering effects are negligible [2]. Lithologies representative of each outcrop were sampled in this manner. Table 2 gives a description of the collected samples and their location relative to marker horizons within the outcrops (Table 1). Organic-carbon contents of these samples range from 1.5 to 14.0 wt%. Amorphous type-II kerogen accounts for more than 80 vol% of the isolated kerogen, with the remaining kerogen consisting of structured type-III kerogen and palyniferous type-I kerogen (i.e., Tasmanites). The variation in atomic H/C ratios of the kerogens in the Woodford Shale at the Springer outcrop (Fig. 1) appears to be due to fluctuations in these subordinate kerogen types.

2.2 Hydrous Pyrolysis Experiments

Four hydrous pyrolysis experiments were conducted on cores taken from a slab of sample WD-7. The cores were taken perpendicular to the bedding fabric, and measured 5 cm in diameter and 3 cm in length. Each of the four experiments consisted of isothermally heating a core of the original sample with 50 grams of deionized water for 72 hours in a 250-ml Hastelloy C-276 reactor. The experimental temperatures are 200°, 250°, 300°, and 352°C, which correspond to stages of petroleum generation from pre-oil generation to late primary-oil generation. This correspondence of experimental conditions to stages of petroleum generation is based on a more complete series of hydrous pyrolysis experiments that were conducted on sample WD-5 [4,5]. Sample WD-5 is compositionally similar to WD-7 and both samples are only separated by a 4-cm thick chert bed in the same outcrop (Table 2). After the reactors cool to room temperature, the generated gas is vented and the water along with any expelled oil is decanted from the reactor.

TABLE 1
DESCRIPTION OF SAMPLING SITES

SAMPLING SITE NO.	FORMATION NAME	EXPOSURE THICKNESS (m)	MARKER HORIZON	GENERAL DESCRIPTION
1	WOODFORD SHALE	23	CONTACT WITH OVERLYING GREENISH-GRAY SHALE	ALTERNATING BEDS OF CHERT AND SHALE WITH SOME PHOSPHATE NODULES IN THE UPPER PORTION.
2	CHATTANOOGA SHALE	9	BENCH SURFACE AT THE TOP OF THE EXPOSURE	UNIFORM BLACK SHALE WITH CONE-IN-CONE LIMESTONE IN CENTRAL PORTION.
3	CHATTANOOGA SHALE	8	CONTACT WITH OVERLYING BOONE LIMESTONE	UNIFORM BLACK SHALES WITH SOME DIFFUSION BANDING.
4	ARKANSAS NOVACULITE (MIDDLE MEMBER)	~30*	BASAL CONTACT WITH LOWER MEMBER	ALTERNATING BEDS OF SHALE AND CHERT.
5	ARKANSAS NOVACULITE (MIDDLE MEMBER)	15	BASAL CONTACT WITH LOWER MEMBER	GRAPHITIC BLACK SHALES AND MINOR INTERCALATED KAOLINITIC SHALES.

*THIS IS ONLY AN APPROXIMATION DUE TO INTERNAL COMPRESSIONAL FAULTING.

TABLE 2
LOCATION AND DESCRIPTION OF SAMPLES

SAMPLING SITE NO.	SAMPLE NO.	SAMPLE INTERVAL THICKNESS (cm)	LOCATION OF SAMPLE INTERVAL (m)*	ROCK TYPE+		
				NOMINAL	PRIMARY	ROOT
1	WD-27	5	-3.28	CHERTY	QUARTZOSE	CLAYSTONE
	WD-4	6	-12.82		QUARTZOSE	CHERT
	WD-5	7	-12.88	CHERTY	QUARTZOSE	CLAYSTONE
	WD-7	3	-12.84	CHERTY	QUARTZOSE	CLAYSTONE
2	CH-58	6	-0.60	SILTY	ARGILLACEOUS	CLAYSTONE
	CH-57	7	-3.26		ARGILLACEOUS	CLAYSTONE
	CH-55	7	-6.13		ARGILLACEOUS	CLAYSTONE
	CH-54	6	-7.61	SILTY	ARGILLACEOUS	CLAYSTONE
3	CH-36	8	-0.15		ARGILLACEOUS	CLAYSTONE
	CH-38	11	-4.25		ARGILLACEOUS	CLAYSTONE
	CH-37	5	-8.16	SILTY	ARGILLACEOUS	CLAYSTONE
4	NO-14	3	+35.00		QUARTZOSE	CLAYSTONE
	NO-15	7	+34.93		QUARTZOSE	CHERT
5	NO-10	8	+3.50	KAOLINITIC	ARGILLACEOUS	CLAYSTONE
	NO-11	6	+8.37		QUARTZOSE	CLAYSTONE

* LOCATIONS ARE GIVEN IN REFERENCE TO MARKER HORIZONS NOTED IN TABLE 1. PLUS SIGNS DENOTE DISTANCE ABOVE MARKER HORIZON TO BASE OF SAMPLE INTERVAL, AND MINUS SIGNS DENOTE DISTANCE BELOW MARKER HORIZON TO TOP OF SAMPLE INTERVAL.

+ ROCK TYPES ARE IN ACCORDANCE WITH THE CLASSIFICATION PROPOSED BY LEWAN (1978) AND ARE BASED ON EXAMINATION OF THIN SECTIONS AND SEMI-QUANTITATIVE X-RAY DIFFRACTION DATA. THE ROOT-NAME CHERT IS USED HERE TO DESCRIBE HARD, MICROCRYSTALLINE, SILICA-RICH (SiO_2 >90 wt.%) ROCKS WITH SPLINTERY OR CONCHOIDAL FRACTURES.

PLATE 1
HYDROUS PYROLYSIS MATURATION SERIES

PHOTO 1. – ORIGINAL WOODFORD SHALE (WD–27) BEFORE HYDROUS PYROLYSIS: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

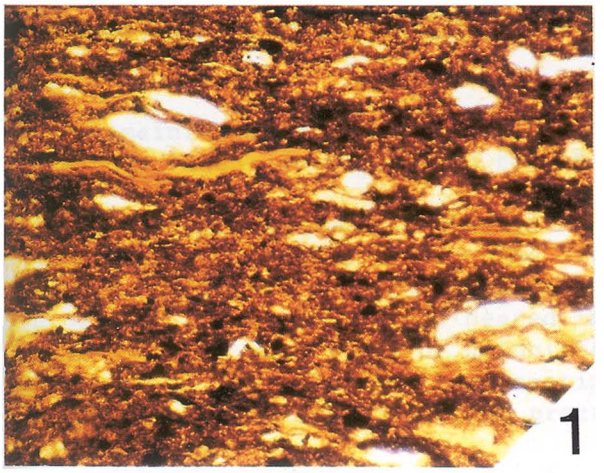
PHOTO 2. – ORIGINAL WOODFORD SHALE (WD–27) BEFORE HYDROUS PYROLYSIS: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.22 mm.

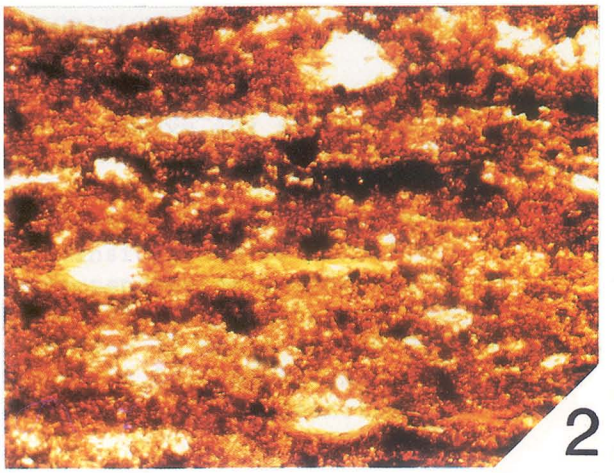
PHOTO 3. – WOODFORD SHALE (WD–27) AFTER HYDROUS PYROLYSIS AT 300 ° C FOR 72 HOURS: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

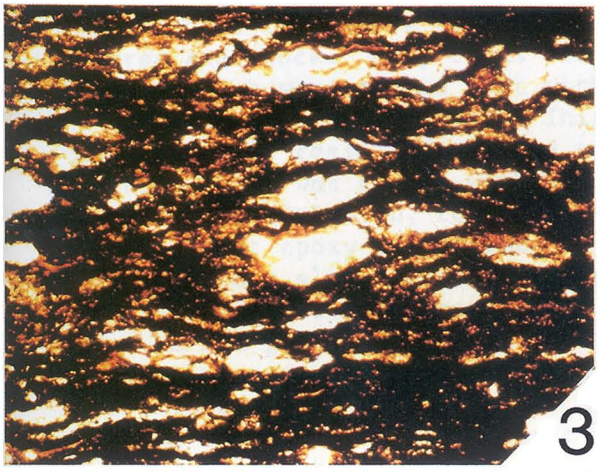
PHOTO 4. – WOODFORD SHALE (WD–27) AFTER HYDROUS PYROLYSIS AT 300 ° C FOR 72 HOURS: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.22 mm.

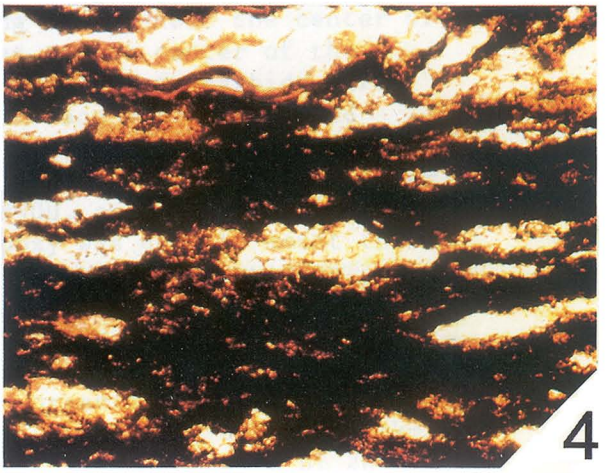
PHOTO 5. – WOODFORD SHALE (WD–27) AFTER HYDROUS PYROLYSIS AT 352 ° C FOR 72 HOURS: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

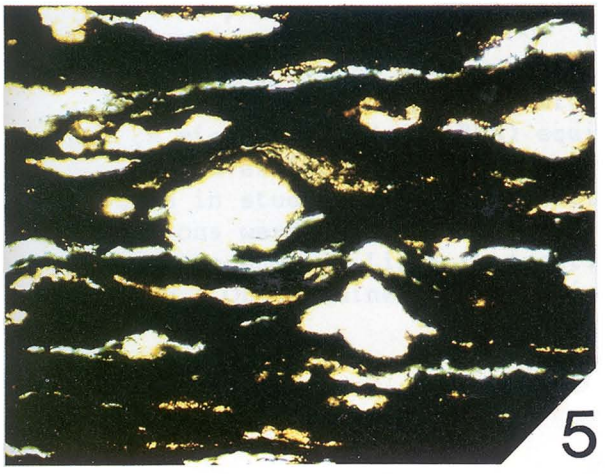
PHOTO 6. – WOODFORD SHALE (WD–27) AFTER HYDROUS PYROLYSIS AT 352 ° C FOR 72 HOURS: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.22 mm.











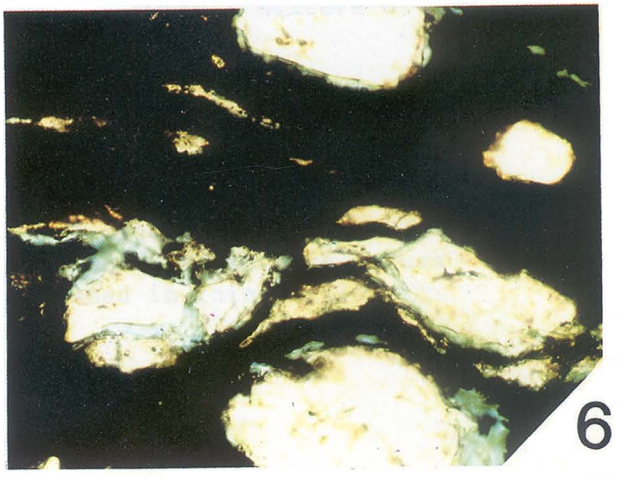


PLATE 1

The remaining core is rinsed with benzene to remove any sorbed oil and then vacuum dried at 50°C for 18 hours.

An additional hydrous pyrolysis experiment was conducted on a sawed block of sample WD-27. The block dimensions are 6.3 x 3.2 x 2.8 cm, with the longest dimension being perpendicular to the bedding fabric. The block was heated in a one-liter 316-stainless steel reactor with 375 g of deionized water for 72 hours at 340°C, which is in the primary-oil generation stage [4,5]. After the experiment, the same collection procedures were used as described for the cores.

2.3 Thin Section Preparation and Examination

The cores and sawed block were impregnated with an epoxy resin (Dow Epoxy Resin-331 or Epo-Tek-301) containing blue dye and allowed to harden for 18 hours. Five- to eight-millimeter thick chips were cut transverse to the bedding fabric near the center of the cores and block. Chip faces closest to the center of the cores and block were ground flat with #180 silicon carbide abrasive on a rotating lap or belt. This surface was impregnated again with epoxy resin and allowed to harden for 18 hours. The impregnated face was ground with a series of silicon carbide abrasives starting with #180, followed by #400, and finished with #600. Hilquest epoxy or Epo-Tek-301 epoxy was used to mount the ground face to a glass slide (~1200 μm thick) and allowed to harden for 18 hours. The mounted chip was cut to a thickness of about 1 mm and ground down with #600 aluminum oxide grit to the desired thickness. Typical thicknesses of 30 μm for thin sections [6] were found to be too thick for most organic shales because of the opaque character of the organic matter. A more useful thickness for organic shales was found to be within the range of 20 to 25 μm. Thicknesses were determined optically by the maximum interference color (200-250 nm) of quartz grains within the rocks. The only procedural difference in preparing the naturally matured samples was that the 5- to 8-mm thick chips were first cut from the samples and then impregnated with epoxy. Cover slips (180 μm thick) were placed on all of the thin sections with a mixture of elvacite and xylene.

Thin sections were examined with an Olympus polarizing research microscope (Model BHS) equipped with a spindle stage and four objectives (10X, 20X, 40X, and 63X). All of the objectives were used in studying the thin sections, but the most informative observations were made with the 20X and 40X objectives using a substage condenser. Light intensities ranged from exposure values of 5 to 6. Opaque minerals were distinguished in thin section

from organic matter with the use of reflected light from a fiber optic illuminator. Photomicrographs were taken with the Olympus automatic exposure camera system (Model PM-10AD), equipped with a color temperature module (Model PM-CTR). Scales were determined with a Leitz 2-mm micrometer.

3. RESULTS AND DISCUSSION

3.1 Artificial Maturation Series

All of the cores were recovered from the reactor intact. Cores pyrolyzed at 200° and 250°C for 72 hours showed no obvious differences from the original rock, while cores heated at 300° and 352°C for 72 hours showed en echelon parting separations that are not in the original rock. These parting separations are parallel to the bedding fabric and tend to pinch out laterally. Although these parting separations render the cores more fragile, their en echelon character allows the cores to remain coherent if handled carefully. After 300°C for 72 hours, the parting separations occur at 2.5- to 5-mm intervals with maximum thicknesses between 100 and 150 μm. Bitumen films and globules line many of the parting separations and suggest that bitumen may have been removed from them during the benzene rinse procedure before recovering the cores. In addition to these partings, the core heated at 352°C for 72 hours developed a series of shorter, thinner, and more frequent parting separations. These are typically 100 to 300 μm long, with maximum thicknesses of 5 to 10 μm, and occur at 100 to 200 μm intervals. No bitumen films or globules line any of the parting separations under these experimental conditions.

Photomicrographs of the original rock in thin section are shown in Photos 1 and 2 of Plate 1. The original rock has a translucent light- to medium-brown groundmass composed of cryptocrystalline quartz, illite, and kaolinite on the basis of X-ray powder diffraction patterns. Medium-brown amorphous masses of organic matter are dispersed throughout the groundmass. These organic masses are equant to slightly elongate in shape and range from 1 to 3 μm in diameter. Subrounded to subangular microcrystalline quartz grains are supported by the groundmass and comprise between 10 and 15 vol% of the rock. These grains are elongate in shape with their shortest dimension perpendicular to the bedding fabric. The shortest dimension is typically between 30 and 60 μm and the longest dimension is typically 2 to 4 times greater. Thin layers (1 to 3 μm) of translucent orangish yellow exinite surround most of these quartz grains. The similar character of these exinite layers to the flattened Tasmanites that occur throughout the rock, suggest the quartz to be the result of diagenetic silica partially

filling exinitic spheromorphs during early stages of compaction. Another type of quartz that is dispersed throughout the rock is angular silt-size (5-15 μm) monocrystalline quartz. These are considered to be detrital grains of eolian origin and comprise less than 2 vol% of the rock. Cryptocrystalline pyrite occurs evenly dispersed through the groundmass and concentrated in a few discontinuous laminae.

Petrographic examinations showed no significant differences between the original rock and the cores pyrolyzed for 72 hours at 200° and 250°C. Previous hydrous pyrolysis experiments on the Woodford Shale by Lewan [4,5]. showed that kerogen decomposition to bitumen became apparent at 300°C for 72 hours, and the bitumen-generation stage is referred to as incipient-oil generation. Photomicrographs of the core pyrolyzed at 300°C for 72 hours show that the generation of bitumen becomes obvious by the darkening of the groundmass (Photos 3 and 4 of Plate 1). This darkening is the result of generated bitumen forming a continuous network along the planar bedding fabric of the rock. The original amorphous masses of organic matter become indistinct, and the quartz-filled spheromorphs and Tasmanites become darker in color. Impregnation of the groundmass by bitumen continues through the primary-oil generation stage and eventually results in an opaque groundmass. This is shown in the photomicrographs of the core pyrolyzed at 352°C for 72 hours (Photos 5 and 6 of Plate 1), which may be equated to the end of the primary oil generation stage [4,5]. It is during this stage of petroleum generation that significant amounts of oil are produced from thermal decomposition of the bitumen network and expelled from the rock. The quartz-filled spheromorphs and the flattened Tasmanites are completely absent in this stage with only blue epoxy filling the remaining voids.

3.2 Natural Maturation Series

Organic geochemical parameters measured on the samples representing the natural maturation series are given in Table 3. All of the stages of petroleum generation are represented in this natural data set, with the exception of the incipient-oil generation stage. The interpreted stages of petroleum generation are based on the atomic H/C ratio of the kerogens. Lewan [5] has demonstrated this parameter to be a good indicator of petroleum generation because it is not influenced by kinetic variations in the rates of petroleum generation, which may vary considerably for amorphous type-II kerogens. Conversely, reflectance measurements on the minor amounts of vitrinite within a sample may be a good indicator of thermal stress, but may not always be a good indicator of the stages of petroleum generation [5]. In spite of

PLATE 2
NATURAL MATURATION SERIES

PHOTO 1. – WOODFORD SHALE SAMPLE WD–4 IN PRE-OIL GENERATION STAGE: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

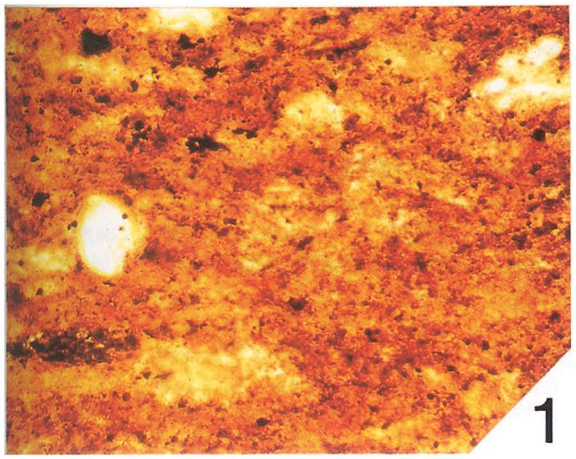
PHOTO 2. – CHATTANOOGA SHALE SAMPLE CH–58 IN PRIMARY-OIL GENERATION STAGE: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

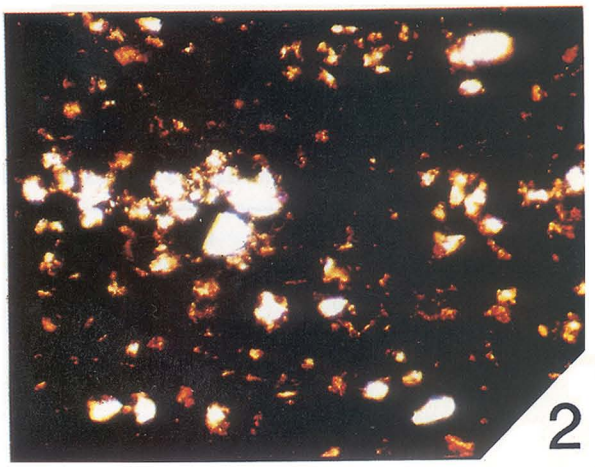
PHOTO 3. – CHATTANOOGA SHALE SAMPLE CH–37 IN PRIMARY – OIL GENERATION STAGE: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

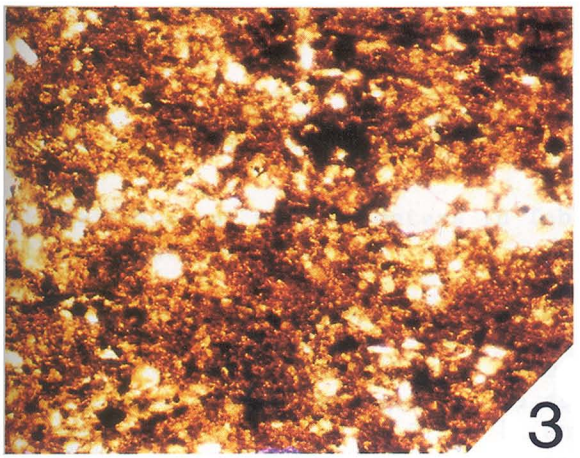
PHOTO 4. – ARKANSAS NOVACULITE SAMPLE NO–14 IN POST-OIL GENERATION STAGE: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

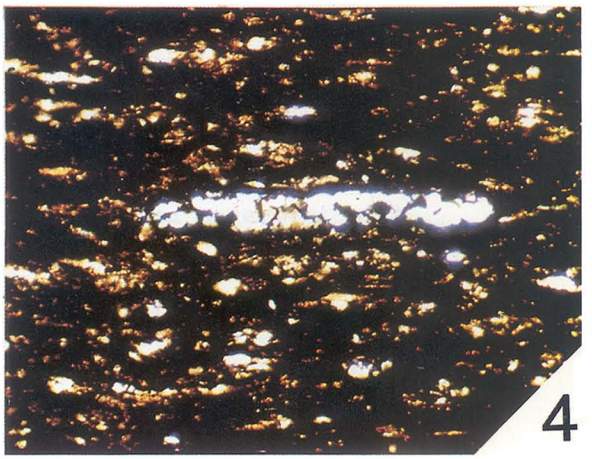
PHOTO 5. – ARKANSAS NOVACULITE SAMPLE NO–15 IN POST-OIL GENERATION STAGE: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

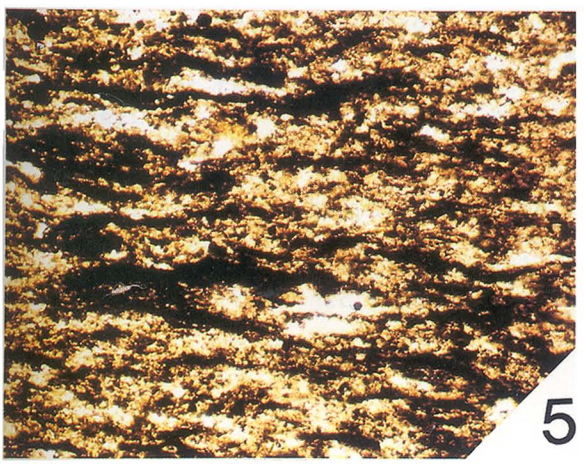
PHOTO 6. – ARKANSAS NOVACULITE SAMPLE NO–10 IN POST-OIL GENERATION STAGE: LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.











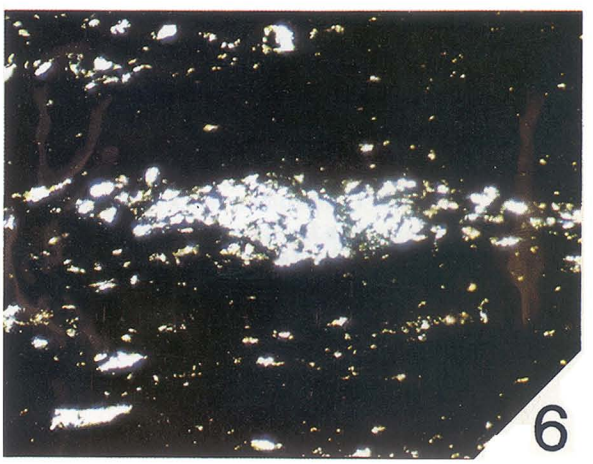


PLATE 2

TABLE 3
ORGANIC GEOCHEMICAL PARAMETERS AND INTERPRETED STAGES OF PETROLEUM GENERATION

SAMPLING SITE NO.	SAMPLE NO.	ORGANIC CARBON (WT.%)	BITUMEN‡ / ORG.CARBON	ATOMIC H/C RATIO	VITRINITE R_o (MEAN %)	PRODUCTION INDEX*	STAGE OF PETROLEUM GENERATION+
1	WD-27	14.0	0.03	1.14	0.44	0.03	PRE-OIL
	WD-4	4.3	0.03	1.17	0.38	0.02	PRE-OIL
	WD-5	12.7	0.03	1.18	0.44	0.03	PRE-OIL
	WD-7	13.0	0.03	1.21	0.35	0.03	PRE-OIL
2	CH-58	5.8	0.19	0.77	1.02	0.26	PRIMARY-OIL
	CH-57	5.4	0.18	0.76	1.05	0.23	PRIMARY-OIL
	CH-55	5.5	0.19	0.78	0.91	0.25	PRIMARY-OIL
	CH-54	5.8	0.16	0.77	0.91	0.25	PRIMARY-OIL
3	CH-36	2.1	0.25	0.72	1.19	0.45	PRIMARY-OIL
	CH-38	2.4	0.29	0.73	1.06	0.34	PRIMARY-OIL
	CH-37	2.4	0.30	0.77	1.09	0.35	PRIMARY-OIL
4	NO-14	4.1	BDL	0.30	3.41	BDL	POST-OIL
	NO-15	1.5	BDL	0.31	3.09	BDL	POST-OIL
5	NO-10	4.4	BDL	0.15	4.82	BDL	POST-OIL
	NO-11	7.0	BDL	0.14	4.57	BDL	POST-OIL

BDL = BELOW DETECTION LIMIT. ‡ BITUMEN EXTRACTED WITH DICHLOROMETHANE IN A SOXHLET APPARATUS.
* ROCK-EVAL RATIO OF S_1 DIVIDED BY THE SUM OF $S_1 + S_2$. + BASED ON DEFINITIONS PROPOSED BY LEWAN (1983 AND 1985).

these concerns, the parameters in Table 3 show good agreement with the interpretations.

Samples from the Springer outcrop (Fig. 1, site 1) are in the pre-oil generation stage. Thin sections of the claystones and chert have a translucent light- to medium-brown groundmass with amorphous masses of kerogen and no obvious signs of bitumen development (Photos 1 and 2 of Plate 1, and Photo 1 of Plate 2). Tasmanites are filled with quartz and are less flattened in the chert than in the claystones. These groundmasses are in sharp contrast to those of the claystones from the Eucha Lake outcrop (Fig. 1, site 2), which are in the primary-oil generation stage. Thin sections show the groundmass of these samples to be completely darkened by the impregnation of bitumen (Photo 2 of Plate 2) and are in agreement with the hydrous pyrolysis results (Photos 5 and 6 of Plate 1). Spheromorphs and Tasmanites were not observed in these samples, but this may be attributed to their original absence in the sediment, as well as their possible thermal decomposition at this maturity level.

Similar to the samples at Eucha Lake outcrop, the samples from the Ginger Blue outcrop (Fig. 1, site 3) are argillaceous claystones in the primary-oil generation stage. In spite of these similarities, thin sections of the Ginger Blue samples show a

mottled darkening of the groundmass (Photo 3 of Plate 2). Bitumen impregnation of the groundmass appears to have occurred within the darkened mottles, but even in these areas bitumen impregnation does not appear to be complete. The lack of a continuous bitumen network at this stage of petroleum generation suggests that the amount of organic matter within these samples is not sufficient and the generation of an expelled oil is unlikely. Organic carbon contents of these samples range from 2.1 to 2.4 wt%, while those of the Eucha Lake samples range from 5.4 to 5.8 wt% (Table 3). This suggests that somewhere between these two ranges of values there is a critical organic carbon content for this lithology to be an effective source rock. Although a critical organic carbon value greater than 2.4 wt% appears high in comparison to typically employed values of 0.5 to 1.0 wt%, it is in general agreement with the value of 2.5 wt% proposed by Jones [7].

The claystones in the post-oil generation stage from Caddo Gap and Malvern Quarry (Fig. 1, sites 4 and 5) have groundmasses that are completely opaque (Photos 4 and 6 of Plate 2). This is attributed to the carbonization of the original bitumen network to pyrobitumen. Petrographically, color is the main difference between the groundmasses in the primary-oil generation stage and the post-oil generation stage, with the former being dark brown and the latter being black. Preservation of the bitumen network in the form of pyrobitumen insures the recognition of effective source rocks well into the post-oil generation stage. The complete bitumen impregnation of these claystones suggests they generated expelled oils and were effective source rocks. Conversely, the pyrobitumen network in the chert from Caddo Gap is not complete (Photo 5 of Plate 2) and suggests that it was not an effective source rock. The critical organic carbon content for this lithology to be an effective source rock appears to be greater than its present organic carbon content of 1.5 wt%.

3.3 Indigenous and Exogenous Petroleum

Migration of oil expelled from a mature source rock into its own immature equivalent or some other immature source rock may lead to the incorrect interpretation that oil generation may occur at abnormally low levels of thermal maturity. Emplacement of exogenous oil is most likely to occur within fractures of a source rock and petrographic examination of the groundmass may help in correctly interpreting the situation. Claystones and cherts in the upper portion of the Woodford Shale at the Springer Outcrop contain some petroleum-filled fractures that run parallel, oblique, and perpendicular to the bedding fabric. Sample WD-27 contains several of these petroleum-filled fractures, and one of

the fracture zones that run parallel to the bedding fabric is shown in Photo 1 of Plate 3. Although these anastomosing petroleum-filled fractures give the impression of a continuous bitumen network, the lack of a bitumen-impregnated groundmass suggests they are exogenous oil rather than indigenous bitumen. This is further demonstrated by the hydrous pyrolysis experiment in which a sawed block of sample WD-27 was pyrolyzed at 340°C for 72 hours. Generated oil was expelled from the rock under these conditions, and the same fracture zone in Photo 1 of Plate 3 is indistinguishable from the bitumen-impregnated groundmass (Photo 2 of Plate 3) that developed during the experiment.

Petroleum-filled fractures also occur in the chert from Caddo Gap. The cherts within this exposure range from 5 to 15 cm in thickness and alternate with claystones that range from 2 to 8 cm in thickness. These rocks are in the post-oil generation stage and as a result the petroleum within the fractures is carbonized (Photo 3 of Plate 3). Although some of this petroleum may have come from the incomplete bitumen network of the chert, a more effective source would be from the complete bitumen network of the adjacent claystones (Photo 4 of Plate 2). These petroleum-filled fractures suggest they are indigenous with respect to the entire exposure, but exogenous with respect to the chert beds.

3.4 Cautionary Notes

Thin sections of rocks containing more than 20 wt% organic carbon are difficult to prepare and interpret. Rocks of this type in the pre-oil generation stage usually require thicknesses of 15 μm or less for transmission of sufficient light to properly evaluate their groundmass. Thicknesses of this magnitude are difficult to maintain uniformly over a section and plucking of the groundmass is common. It is for these reasons that rocks with organic carbon contents less than 20 wt% and preferably less than 15 wt% are the most suitable for petrographic studies.

Recognizing a continuous bitumen network is difficult in rocks that contain an abundance of silt- or sand-size mineral grains. Differential compaction of the groundmass between these larger grains tends to concentrate the organic matter, and the resulting dark character of the groundmass gives the impression of a continuous bitumen network. This is particularly common in carbonate concretions, where diagenetic growth of carbonate minerals concentrate organic matter at the grain boundaries (Photo 4 of Plate 3). Organic matter may also be concentrated in laminae (Photo 5 of Plate 3) as a result of conditions in the environment of deposition. These organic concentrations may be formed by

PLATE 3
EXOGENOUS OILS AND DECEPTIVE GROUNDMASSES

PHOTO 1. – PHOTOMICROGRAPH OF WOODFORD SHALE SAMPLE WD–27 SHOWING EXOGENOUS OIL IN A ZONE OF BEDDING – PLANE FRACTURES (F). LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.88 mm.

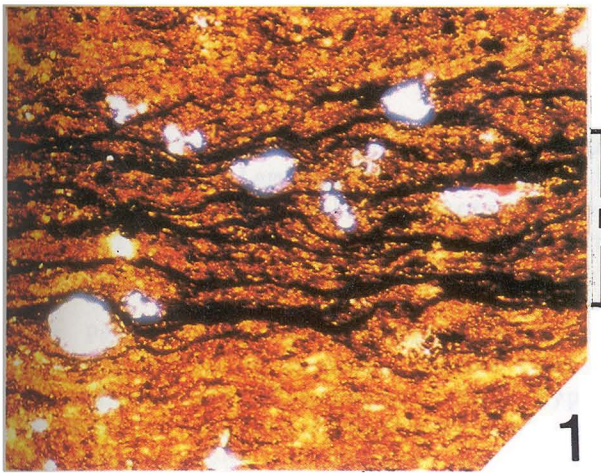
PHOTO 2. – PHOTOMICROGRAPH OF WOODFORD SHALE SAMPLE WD–27 SHOWING THE SAME OIL–FILLED FRACTURE ZONE (F) IN PHOTO 1, AFTER HYDROUS PYROLYSIS AT 340 ° C FOR 72 HOURS. LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.88 mm.

PHOTO 3. – PHOTOMICROGRAPH OF ARKANSAS NOVACULITE SAMPLE NO–10 SHOWING A CARBONIZED OIL-FILLED FRACTURE. LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

PHOTO 4. – PHOTOMICROGRAPH OF NEW ALBANY SHALE SAMPLE NA–18 SHOWING THE CONCENTRATION OF ORGANIC MATTER AT THE GRAIN BOUNDARIES IN A DOLOMITE NODULE. THE SAMPLE IS FROM THE SILVER CREEK OUTCROP, CLARK CO., INDIANA [2] . THE PREDOMINANTLY AMORPHOUS-TYPE II KEROGEN WITHIN THIS ROCK IS IN THE PRE-OIL GENERATION STAGE WITH AN ATOMIC H/C RATIO OF 1.21. LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.30 mm.

PHOTO 5. – PHOTOMICROGRAPH OF MONTEREY SHALE SAMPLE MR–28 SHOWING THE CONCENTRATION OF ORGANIC MATTER IN LAMINATIONS OF A CRISTOBALITIC CHERT. THE SAMPLE IS FROM THE SHELL BEACH EXPOSURE, SAN LUIS OBISPO CO., CALIFORNIA. THE PREDOMINANTLY AMORPHOUS KEROGEN WITHIN THIS ROCK IS IN THE PRE-OIL GENERATION STAGE WITH AN ATOMIC H/C RATIO OF 1.40. LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 0.44 mm.

PHOTO 6. – PHOTOMICROGRAPH OF SAMPLE KC-S1 SHOWING THE OPAQUE CHARACTER OF THE GROUNDMASS RESULTING FROM THE CONCENTRATION OF INHERENTLY BLACK STRUCTURED-TYPE III KEROGEN. LENGTH OF PHOTOMICROGRAPH IS EQUAL TO 1.49 mm.



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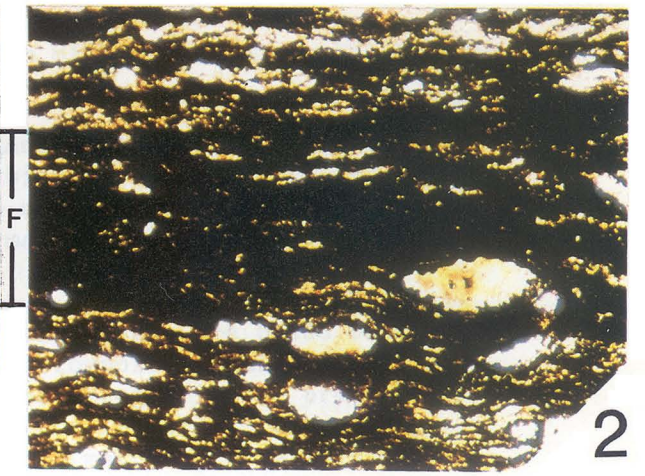

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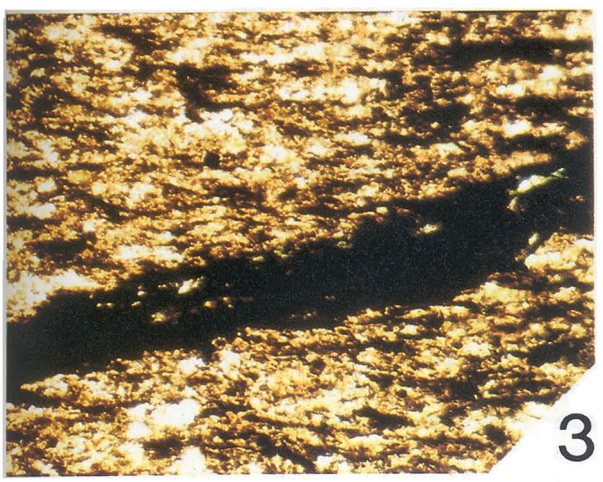

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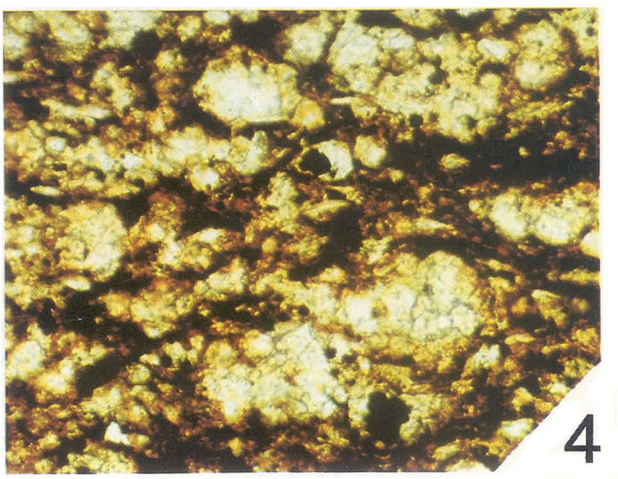

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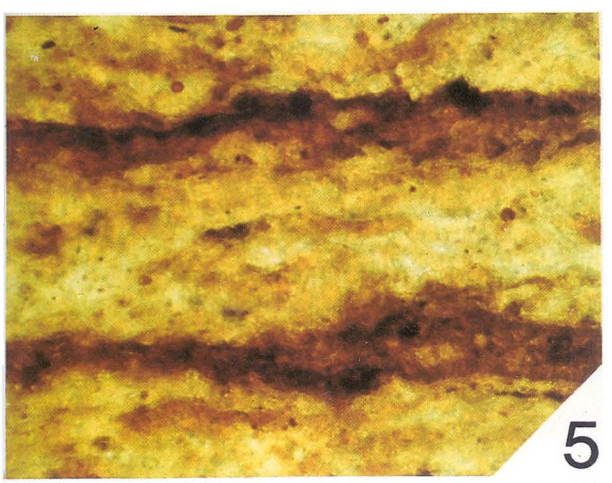

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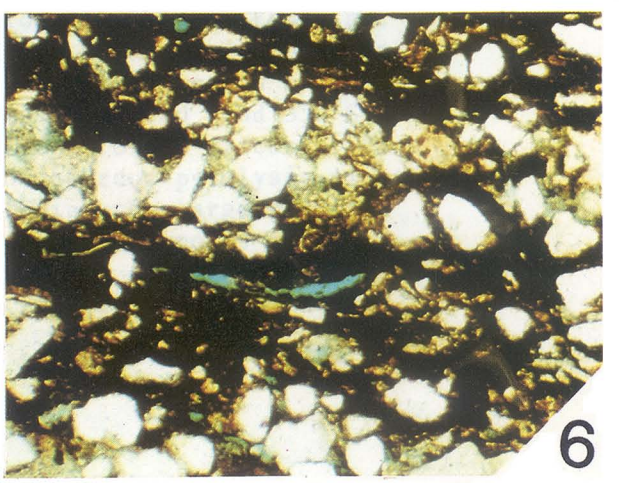

6

PLATE 3

cyclic sedimentation or growth of organic mats. Distinguishing between these laminae and continuous bitumen networks or oil-filled bedding plane fractures is usually possible in the pre-oil generation stage, but as thermal maturity increases this distinction becomes more tenuous.

Petrographic observations made in this study are based on rocks containing organic matter that is composed mainly of amorphous-type II kerogen. This type of kerogen in the pre-oil generation stage is light- to medium-brown in color. Conversely, structured-type III kerogen at comparable maturity levels is dark brown to black in color. As a result, lower concentrations of this kerogen type may give a more opaque character to the groundmass and make recognition of bitumen networks more difficult. This is illustrated in Photo 6 of Plate 3 by the alternating laminae of sandstone and mudstone of Kimmeridgian age from northeastern Scotland. More than 80 vol% of the organic matter in this rock is structured-type III kerogen with a mean vitrinite reflectance of 0.45%Ro and a bitumen/organic-carbon ratio of 0.01. The concentration of this inherently dark organic matter in the groundmass of the mudstone and between the grains in the sandstone gives the false impression of a continuous bitumen network.

3.5 Factors Controlling Primary Migration

Development of a bitumen network and expulsion of generated oil is considered to be the result of a net increase in volume of the organic components within a more confined mineral matrix. This volume increase may be attributed to the thermal cracking reactions involved in petroleum formation and the thermal expansion of the bitumen and oil products. The volume of products generated by thermal cracking of petroleum is usually greater than the initial volume of the reactants [8,p. 215; 9,p. 668]. Thermal expansion of the bitumen and oil may also be significant with the coefficient of cubic expansion for oil being in the range of 10^{-3} volume units/$^{\circ}$C [10]. These net increases in volume of the organic phases may be accommodated within the mineral matrix by generation of submicron parting separations in which bitumen networks develop, and by expulsion of oil into adjacent regional or tectonic fractures. The large parting separations noted in the cores from the hydrous pyrolysis experiments at 300° and 352°C are considered to be exaggerated examples of the former process. Lack of a confining stress on the cores in the hydrous pyrolysis experiments appears to be responsible for allowing the large parting separations to develop. Conversely, overburden imposes a confining stress on naturally maturing rocks, and as a result no large parting separations were observed in the naturally matured samples.

Impregnation of the groundmass with bitumen to form a continuous network appears to be a prerequisite for the expulsion of generated oil. Although the amount of oil-prone organic matter within a rock is critical, the distribution of this organic matter and the character of the groundmass may also be critical. The combined use of petrographic studies and hydrous pyrolysis experiments on rocks provides a means of assessing these factors. Results from this study indicate that the critical amount of organic carbon necessary for a continuous bitumen network to develop is greater than 1.5 wt% for the cherts and between 2.4 and 5.4 wt% for the argillaceous claystones. It is anticipated that the critical organic-carbon values will vary with lithology. Rocks containing organic matter concentrated along laminae are likely to have a lower critical value than those containing organic matter dispersed throughout the groundmass. Character of the groundmass is also likely to have an effect, with the critical value increasing as the porosity of the groundmass increases.

The effectiveness of a source rock may also be influenced by the character of its fracture system into which generated oil is expelled. Regional and tectonic fracture systems with open, slickensided, or vuggy fractures as defined by Nelson [11] appear to be the most favorable. The fracture systems are expected initially to be water filled and unmineralized prior to the primary-oil generation stage. Additional characteristics to consider in evaluating the fracture systems of potential source rocks include fracture width, spacing, and matrix communication. Vertical micro-fractures induced by petroleum generation were not observed in the naturally or artificially matured samples, but such fractures may be obscured by the dark character of the bitumen-impregnated groundmasses.

4. CONCLUSIONS

Petrographic observations used in conjunction with organic geochemical parameters provide information on primary petroleum migration and source rock effectiveness. The main objective in this approach is to establish whether a bitumen network has developed in the groundmass of a rock. Initial darkening of a translucent light- to medium-brown groundmass is attributed to the generation of bitumen from the thermal decomposition of kerogen. Within the confined mineral matrix of a rock, the volume increase accompanying this overall reaction and the thermal expansion of generated bitumen results in the impregnation of the groundmass with bitumen. This occurs through the development of submicron parting separations parallel to the bedding fabric of the rock. As thermal stress increases, an oil is generated from the thermal

decomposition of the bitumen. If a continuous bitumen network is present, generated oil is expelled into adjacent fractures. Petrographic observations suggest that in the primary-oil generation stage the complete darkening of a groundmass constitutes a continuous bitumen network, while the partial or mottled darkening of a groundmass constitutes an incomplete bitumen network. The former observation is considered indicative of an effective source rock, and the latter observation is considered indicative of an ineffective source rock. Rocks subjected to hydrous pyrolysis experiments showed darkening of their groundmass in a manner similar to that of naturally matured rocks. This suggests that the expulsion of oil in hydrous pyrolysis experiments on rocks is mechanistically similar to the natural system and useful in estimating the effectiveness of a source rock.

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