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The Oil Creek–Arbuckle (!) Petroleum System, Major County, Oklahoma

David K. Curtiss and David A. Wavrek
Energy and Geoscience Institute
University of Utah
Salt Lake City, Utah

ABSTRACT.—A petroleum system includes a mature hydrocarbon source rock, genetically related oil and gas accumulations, and the geologic elements and processes responsible for the hydrocarbon deposits to exist. This study defines the Oil Creek–Arbuckle (!) petroleum system. Geochemical analysis correlates the effective source rock of the lower shale member of the Oil Creek Formation to its related hydrocarbons in the underlying Arbuckle Group reservoir. Optical and chemical methods indicate that the section has achieved a maturity level equivalent to 1.2%–1.3% vitrinite reflectance equivalence. A burial-history model defines the critical moment of peak hydrocarbon generation and expulsion to have occurred at 225 Ma. An events chart documents the petroleum system's development through time.

The generation accumulation efficiency (GAE) compares the amount of hydrocarbons generated in the petroleum source rock to the amount trapped in reservoirs. This petroleum system generated 145 MMBO (million barrels of oil), which, combined with current ultimate reserve estimates, establishes a GAE of 37%. The remaining 63% of the hydrocarbons generated were either lost (i.e., not trapped) or represent the potential for future discovery. Thus, the economic implications for future oil exploration in the structure appear to be positive, contingent on a clearer understanding of the Arbuckle reservoir.

INTRODUCTION

This paper describes the elements and processes (defined below) that led to generation and accumulation of hydrocarbons within the Ames feature; a semicircular structural depression of Cambrian–Ordovician Arbuckle sedimentary rocks in the southeast corner of Major County, Oklahoma (Tps. 20–21 N., Rs. 9–10 W.). Much debate surrounds the origin of the Ames feature. The most popular theory is that the feature is an astrobleme or impact crater (Carpenter and Carlson, 1992,1997; Koeberl, 1997; Koeberl and others, 1997), a convenient working hypothesis for the oil and gas industry (Hamm and Olsen, 1992). Other researchers dispute these findings, claiming the Ames feature has a volcanic origin (Roemer and others, 1992; Coughlon and Denney, 1993, 1997). Still others attribute the subsidence to solution collapse on the midcontinental carbonate platform (Bridges, 1997) that dominated the Ordovician Period, analogous to such events displayed in the European Alps (Fruth and Scherreiks, 1984; Köster and others, 1988). For this study (largely taken from Curtiss, 1995), the mode of origin is irrelevant since the subsidence predates the elements (i.e., source rock and hydrocarbons) and processes considered.

Petroleum-System Framework

This study is set within a petroleum-system framework, according to the standard promoted by Magoon and Dow (1994). The essential elements are a mature hydrocarbon source rock and genetically related oil and gas accumulations. The processes are the generation, expulsion, migration, and entrapment of the petroleum, which includes hydrocarbons in solid, liquid, and gas forms.

Generation refers to the transformation of buried organic matter to kerogen and then petroleum, first through microbial activity and then by ther-

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David K. Curtiss, EGI, University of Utah, 423 Wakara Way, Suite 300, Salt Lake City, UT 84108; David A. Wavrek, EGI–Geochemistry Unit, University of Utah, 421 Wakara Way, Suite 125, Salt Lake City, UT 84108.

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mal stress (Horsfield and Rullkötter, 1994). Thermal stress is usually associated with deeper burial and can be locally influenced by orogenic and/or igneous activity (Lopatin, 1971; Waples, 1980; Tissot and Welte, 1984).

Expulsion describes the movement of hydrocarbons from the petroleum source rock into the carrier bed or migration conduit. A combination of factors drives the expulsion event, including compaction, chemical reactions, source richness, kerogen type, and thermal expansion (Barker, 1972; Momper, 1978; Ungerer, 1990; Burnham and Sweeney, 1991). Source rocks with greater permeability generate small pressure differentials within pore spaces, whereas less permeable source rocks build up pressures sufficient to fracture the rock. Such pressures within a source rock create vertical fractures that provide conduits for hydrocarbon movement across bedding. Where the pressure gradient generated within the homogeneous source rock exceeds hydrostatic pressure, expulsion will be downward and out of the bottom of the source rock, as well as upward through the top. In cases where organic-rich facies are concentrated at the base of the formation, expulsion from the base can be more significant than from the top. Similarly, expulsion from a thick shale section requires more thermal stress (thermal expansion, hydrocarbon generation) than required for expulsion from a section of shales interbedded with sandstones (Wavrek, unpublished data).

Migration describes the movement of oil through a carrier bed or migration conduit until it is physically trapped. Buoyancy and hydrodynamic forces are the primary factors driving migration; they are most effective in highly permeable strata (England and others, 1991; England, 1994). The migration and drainage style within an individual petroleum system (Demaison and Huizinga, 1991,1994) can be characterized by its vertical and/or lateral components. Vertical migration occurs mainly along faults and fractures that breach a seal, whereas lateral migration dominates in systems with stratigraphically continuous seal-conduit pairs.

Entrapment of petroleum depends on the structural and stratigraphic framework of the system as well as the presence of a seal. A trap occurs where the movement of petroleum toward the surface ceases, usually where a structure has an effective seal prohibiting further migration (Demaison and Huizinga, 1994).

Once identified and described, these elements and processes are placed within a stratigraphic, geographic, and temporal framework. To accomplish the framework definition, Magoon and Dow (1994) suggested the use of four figures and a table: a burial-history chart, map and cross section drawn at the critical moment, an events chart chronicling the kinematic development of the system through time, and a table of related accumulations. The standardized petroleum-system nomenclature is source rock–major reservoir rock followed by punctuation within parentheses indicating a level of certainty for the oil–source-rock correlation: known (!), hypothetical (.), and speculative (?).

In addition to defining the essential elements and processes of the petroleum system, we calculate the petroleum system's generation accumulation efficiency (GAE). The GAE describes what percentage of the hydrocarbons generated accumulated in viable traps. This knowledge is directly applicable to the management of exploration programs (Lewan, 1994).

None of these elements and processes is novel to the petroleum-system concept. The purpose and advantage of this tool is that it reduces exploration risk by insisting on a multidisciplinary, cross-functional approach to exploration. By integrating geology, petroleum, and time into a unified package, the focus shifts from a basinwide emphasis on geology and geophysics to specific oil and gas accumulations within the basin. The objectives are more precise and the decision points more definitive, which in turn lowers the exploration risk (Magoon and Sánchez, 1995).

MATERIALS AND METHODS

Materials

The geochemical database consists of source-rock samples and crude oils. Forty rock samples selected for this study are from the lower shale member of the Oil Creek Formation, a specific facies that is areally confined within the Ames feature. (Repetski [1997] has suggested, on the basis of biostratigraphy, that the "crater shale" may actually correlate to a younger unit. This study, however, retains the "traditional" stratigraphic interpretation.) Thickness ranges from zero at the perimeter to 225 ft in the southern half. Potential source-rock samples came from three wells: the Nicor no. 18-4 Chestnut (n = 21; sec. 18, T. 21 N., R. 9 W.) and the D & J no. 1-20 James (n = 9; sec. 20, T. 21 N., R. 9 W.) in the north-central part of the structure and the DLB no. 5-13 Darin (n = 10; sec. 5, T. 20 N., R. 9 W.) in the south-central half (Table 1). The 30 crude-oil samples analyzed in this study are from wells distributed throughout the feature and represent production from five stratigraphic intervals (Table 2; Fig. 1).

The petrophysical database (Table 3) consists of 30 well logs from wells within the structure. This suite allowed evaluation of several log-based geochemical techniques within the source-rock interval. An isopach map of the source-rock interval (Fig. 1) supplied by DLB was used in conjunction with the well-log techniques to determine the total volume of organic carbon in the lower shale member of the Oil Creek Formation.

TABLE 1.—SOURCE-ROCK SAMPLE INFORMATION

Sample no.	Company	Well name	Depth interval (ft)
MC008R	D & J	no. 1-20 James	8840.3
MC009R	D & J	no. 1-20 James	8858.5
MC010R	D & J	no. 1-20 James	8876.5
MC011R	D & J	no. 1-20 James	8887.5
MC012R	D & J	no. 1-20 James	8891.5
MC013R	D & J	no. 1-20 James	8892.5
MC014R	D & J	no. 1-20 James	8897.1
MC015R	D & J	no. 1-20 James	8902.3
MC016R	D & J	no. 1-20 James	8907.5
MC017R	D & J	no. 1-20 James	8915.9
MC018R	D & J	no. 1-20 James	8919.7
MC019R	D & J	no. 1-20 James	8927.5
MC020R	Nicor	no. 18-4 Chestnut	8969
MC021R	Nicor	no. 18-4 Chestnut	8979
MC022R	Nicor	no. 18-4 Chestnut	8994
MC023R	Nicor	no. 18-4 Chestnut	8970.1
MC024R	Nicor	no. 18-4 Chestnut	8972.1
MC025R	Nicor	no. 18-4 Chestnut	8973.9
MC026R	Nicor	no. 18-4 Chestnut	8975.9
MC027R	Nicor	no. 18-4 Chestnut	8978.1
MC028R	Nicor	no. 18-4 Chestnut	8979.9
MC029R	Nicor	no. 18-4 Chestnut	8982
MC030R	Nicor	no. 18-4 Chestnut	8984.1
MC031R	Nicor	no. 18-4 Chestnut	8985.9
MC032R	Nicor	no. 18-4 Chestnut	8988.1
MC033R	Nicor	no. 18-4 Chestnut	8990.1
MC034R	Nicor	no. 18-4 Chestnut	8991.9
MC035R	Nicor	no. 18-4 Chestnut	8993.9
MC036R	Nicor	no. 18-4 Chestnut	8996
MC037R	Nicor	no. 18-4 Chestnut	8998
MC038R	Nicor	no. 18-4 Chestnut	8999.9
MC039R	Nicor	no. 18-4 Chestnut	9002.1
MC040R	Nicor	no. 18-4 Chestnut	9002.8
MC041R	Nicor	no. 18-4 Chestnut	9003.6
MC042R	Nicor	no. 18-4 Chestnut	9006.7
MC043R	Nicor	no. 18-4 Chestnut	9010.8
MC044R	Nicor	no. 18-4 Chestnut	9013.6
MC045R	DLB	no. 5-13 Darin	9410–9420
MC046R	DLB	no. 5-13 Darin	9440–9450
MC047R	DLB	no. 5-13 Darin	9460–9470
MC048R	DLB	no. 5-13 Darin	9480–9490
MC049R	DLB	no. 5-13 Darin	9500–9510
MC050R	DLB	no. 5-13 Darin	9510–9520
MC051R	DLB	no. 5-13 Darin	9520–9530
MC052R	DLB	no. 5-13 Darin	9530–9540
MC053R	DLB	no. 5-13 Darin	9540–9550
MC054R	DLB	no. 5-13 Darin	9560–9570

Methods

Geochemical Investigation

The analytical methods used in this study were bulk analysis and chromatographic characterization. Bulk analysis included total organic carbon (TOC) and Rock Eval pyrolysis for source-rock samples, as well as API gravity and weight percent sulfur for the crude oils. Both rocks and oils were subjected to carbon isotope analysis.

Chromatographic analysis required the extraction of selected source-rock samples using a Soxhlet apparatus. These rock extracts and the crude oils were then analyzed with gas chromatography–flame ionization detection (GC-FID). Subsequently, rock extracts and selected crude oils ($n = 12$) were split into saturate and aromatic fractions by column chromatography followed by gas chromatography–mass spectrometry (GC-MS) analysis. Two samples were selected and prepared for reflected- and/or transmitted-light microscopy for maturity and depositional-environment analysis.

Burial-History Modeling

The Continental Resources no. 1-19 Chet well was selected for burial-history reconstruction because it penetrates the Arbuckle Group, providing a complete stratigraphic column for calculations, and because it is close to producing oil wells. The model was generated by using BasinMod (Platte River Associates) software, incorporating chronostratigraphic ages for formation tops estimated from Haq and van Eysinga (1987), compaction from Baldwin and Butler (1985), a nominal heat flow of 63 mW/m^2 based on data presented by Gallardo (1989), and no geothermal events or unusually high or low paleo–heat flows (Schmoker, 1986).

Petrophysical Investigation

The sonic and resistivity overlay ($\Delta \log R$) technique (Passey and others, 1990) selected for this study is based on the predictable response of the sonic and resistivity tools within an organic-rich interval. Sonic and resistivity traces generally track together in fine-grained rocks lacking appreciable organic matter. In organic-rich intervals, however, the sonic and resistivity curves separate (see Fig. 13 for an example) because of the response of the porosity curve to the low-density, low-velocity kerogen and the resistivity response to the formation fluid. The magnitude of this separation in source rocks can be calibrated to the total organic carbon and maturity, which allows the estimation of organic richness in absence of actual data.

Notations and Calculations

The generation accumulation efficiency (GAE) is defined as the ratio of in-place hydrocarbon re-

TABLE 2.—CRUDE-OIL SAMPLE INFORMATION

Sample	Company	Well name	Producing intervals
A-049C	D & J	no. 1-17 Shelby	Arbuckle
A-050C	D & J	no. 1-18 Peggy	Arbuckle
A-051C	D & J	no. 1-17 Lloyd	Arbuckle
A-052C	D & J	no. 1-20 Gregory	Arbuckle
A-053C	Continental	no. 1-19 Dorothy	Arbuckle
A-054C	Continental	no. 1-19 Heinrich	Arbuckle
A-055C	Continental	no. 1-19 Chet	Arbuckle
A-056C	Continental	no. 1-31 Fred	Arbuckle
A-057C	Continental	no. 1-21 Stansberry	Arbuckle
A-058C	Continental	no. 1-22 Mary Ellen	Arbuckle
A-059C	Continental	no. 1-21 Pacific	Arbuckle
A-060C	Continental	no. 1-34 Terry	Arbuckle
A-061C	White Shield Oil & Gas	no. 1-36 Oliver	Manning, Mississippi, Hunton
A-062C	Petro-Lewis	no. 1-6 Monsees	Mississippi
A-063C	Petro-Lewis	no. 1-27 Oscar	Misener, Mississippi, Manning
A-064C	Hamm Production	no. 1-2 Scott	Mississippi, Manning
A-065C	Staats	no. 1-3 Suit	Mississippi, Manning
A-066C	Petro-Lewis	no. 1-6 Wheeler	Hunton, Mississippi
A-067C	Rodman	no. 1-14 White	Mississippi
A-068C	Petro-Lewis	no. 2-14 White	Mississippi
A-069C	Basin Petroleum	no. 1-5 Bode	Mississippi
A-070C	Getty Oil Co.	no. 1 H. G. Dittmeyer	Hunton
A-071C	Staats	no. 1-21 Detrick	Manning
A-072C	Hamm Production	no. 2-22 Ethel	Hunton, Mississippi, Manning
A-073C	Petro-Lewis	no. 1-16 Fyffe	Mississippi
A-074C	Rodman	no. 1-7 Harvey	Hunton, Mississippi
A-075C	Hamm Production	no. 2-7 Harvey	Hunton, Mississippi, Inola
A-076C	Petro-Lewis	no. 2-7 Hammer	Mississippi
A-077C	Rodman	no. 1-14 Kellogg	Mississippi, Hunton
A-078C	White Shield	no. 1-25 Osborne	Hunton, Mississippi

serves (IHC in kilograms of HC) to hydrocarbons generated (HCG in kilograms of HC) (Magoon and Dow, 1994).

$$\mathrm{GAE} = [\mathrm{IHC}/\mathrm{HCG}] \times 100\% \qquad (1)$$

In this study, HCG were calculated whereas IHC were extracted from the literature.

Hydrocarbons Generated (HCG)

Schmoker (1994) presented a calculation method involving four steps. The first step consists of identifying and defining the source-rock interval and then dividing it into sections of approximately equal organic carbon content. Step two involves determining the mass (M, in grams) of organic carbon (TOC, in wt%) in each source-rock section according to the following equation:

$$M = [\mathrm{TOC}/100] \times \rho \times V \qquad (2)$$

where TOC and density (ρ, in g/cm^3) are averaged over the source-rock section and V (in cm^3), is calculated for the same section (discussed in detail below). The objective of the third step is to determine the mass of hydrocarbons generated per unit mass of organic carbon R (in milligrams of HC per 1 g of TOC), described in equation 3:

$$R = \mathrm{HI}_o - \mathrm{HI}_p \qquad (3)$$

The hydrogen index (HI, in milligrams of HC per 1 g of TOC) indicates the potential of a source rock to produce additional hydrocarbons. Thus, the difference between original HI (HI_o) and present-day HI (HI_p) is the amount of hydrocarbons actually generated. Rock-Eval pyrolysis analysis determines HI_p. Estimating HI_o is possible because of an empirical relationship between hydrogen index and maturity levels (Fig. 2). The

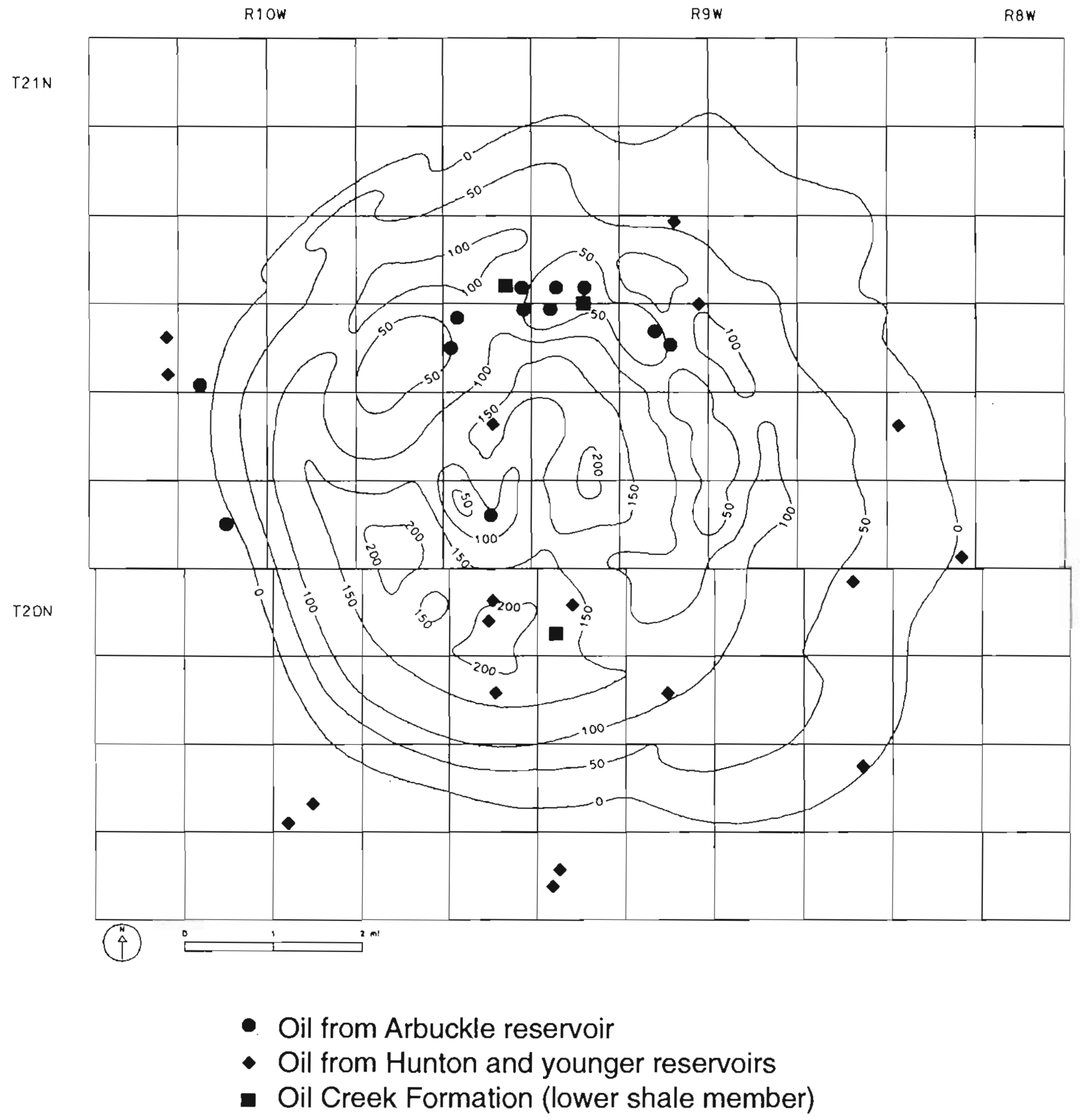

Figure 1. Distribution of crude-oil and source-rock samples throughout the Ames structure. Isopach map of the lower shale member of the Oil Creek Formation (in feet) prepared by M. Kuykendall; used with permission of R. Carlson (DLB).

final step computes the total mass of hydrocarbons generated:

$$\mathrm{HCG} = R \times M \times 10^{-6} \qquad (4)$$

In this study, calculations 2 through 4 are performed for each distinct source-rock section. The results are then summed to calculate total mass of hydrocarbons generated for the entire structure.

RESULTS AND DISCUSSION

Geochemical Investigation

The crude oils in this study fall into two groups: oils produced from Arbuckle reservoirs and those produced from shallower horizons (Table 2). GC-FID data clearly demonstrate chemical differences between these groups on the basis of relative iso-

TABLE 3.—AVAILABILITY OF PETROPHYSICAL INFORMATION

		Logs available					
Operator	Well name	Gamma ray	Neutron	Micro-log	Latero-log	Sonic	Comments
DLB	no. 28-9 Bierig	X	X	X	X		*
Universal Resources	no. 1-33 Bland	X	X	X	X		
R. E. Blaik	no. 1-14 Bohn	X	X	X	X		*
DLB	no. 20-2 Bullis	X	X	X	X		*
Bogo Energy	no. 3-35 Campbell	X	X	X	X		
Hazelwood	no. 10-1 Carolyn Sue	X	X	X			
DLB	no. 27-4 Cecil	X	X		X		*
Nicor	no. 18-4 Chestnut	X	X	X	X		
Ward	no. 1-1 Cleora	X	X	X		X	
DLB	no. 5-13 Darin	X	X	X			
Continental	no. 1-19 Dorothy	X	X		X	X	
Hazelwood	no. 2-2 Edwards	X	X				
DLB	no. 23-3 Elsie	X	X	X			
Continental	no. 6 Fisher	X	X	X	X	X	*
Continental	no. 1-31 Fred	X	X	X			
Miracle	no. 2-16 Fyffe	X	X	X	X	X	
BRG	no. 2-23 Gregory	X	X		X		*
Continental	no. 1-19 Heinrich	X	X	X			
D & J	no. 1-20 Herman	X	X	X	X		
D & J	no. 1-20 James	X	X	X	X		
DLB	no. 27-12 Jesse	X	X	X	X		*
Bromar Oil	no. 26-7 Jim	X	X	X			*
Cross Timbers	no. 1-10 Kennedy	X	X	X		X	
DLB	no. 14-1 Lillie	X	X	X			
D & J	no. 1-17 Mary Helen	X	X				
Continental	no. 2-26 Mason	X	X			X	*
Unknown	no. 36-4 Monsees	X	X	X			
J. L. Thomas	no. 1-9 Munkres	X	X	X	X	X	
Continental	no. 1-21 Stansberry	X	X	X	X	X	
Continental	no. 1-34 Terry	X	X	X	X		*

*Well logs do not penetrate lower member of the Oil Creek shale.

prenoid abundance and carbon-number preference (Figs. 3 and 4). These differences imply that the oils in the Hunton (Devonian) and younger reservoirs are not genetically related to the Oil Creek source facies and consequently not part of the Oil Creek–Arbuckle (!) petroleum system. Therefore, they were excluded from further analysis.

Within the oils in Arbuckle reservoirs, GC-FID analysis differentiates two subtypes (Fig. 5). Genetically, these oils are clearly related although the type A-2 oils have an enhanced abundance of low-molecular-weight (LMW or lower than nC_{15}) compounds and slightly depleted acyclic isoprenoid abundances. Geographically, the A-1 oils accumulated in the interior of the feature, whereas the A-2 oils occur on the rim. The enhanced concentration of the LMW fraction in the A-2 oils likely results from additional thermal stress required for hydrocarbon generation and expulsion. However, the oils appear strikingly similar if the profiles are normalized to the nC_{15} alkane (note internal standard). Noteworthy is the empirical relationship that type A-1 oils are associated with paraffin-related production problems. The reason for these problems is that the LMW compounds act as a natural solvent for these paraffins. When LMW compounds are present in lower abundance, the paraffin is prone to precipitation. In the Ames feature, chemical injectors with carbon disulfide combat these paraffin-

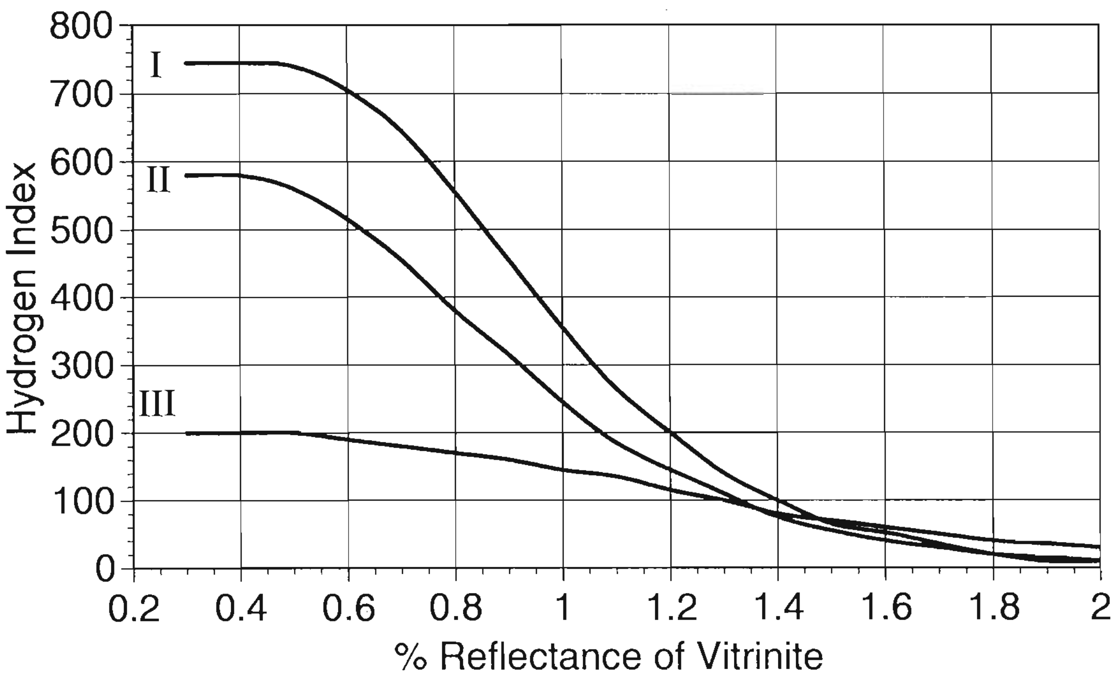

Figure 2. Change of hydrogen index with increasing maturity for types I, II, and III kerogen. (Courtesy of J. Quick; modified after Lo, 1995.)

related production problems (Mike Barnes, personal communication).

Significant features noted in the GC-MS analysis include the distribution of *n*-alkylcyclohexanes that exhibit a mixture of odd- and even-carbon preferences at different carbon numbers. Biomarker analyses indicate a terpane fraction dominated by tricyclic members (C_{23} and C_{24}). The trisnorhopane known as Tm appears to be preferred over Ts, but this apppearance is actually an artifact of a coeluting compound. Pentacyclic terpanes occur in low quantitative abundance, but show enhanced C_{29}Ts and C_{30} diahopanes. The methyl hopanes and demethylated hopanes can be considered absent. Steranes are in low quantitative abundance (sterane concentration average of 35 ppm), although the C_{28} members are relatively enhanced. C_{27} $\beta\alpha$ rearranged steranes are fairly abundant, and methyl steranes are only present in trace concentrations.

Correlation

The principle of oil–source-rock correlation hinges on the ability to formulate a converging argument by using bulk and specific parameters. Table 4 displays the results of the crude-oil bulk analysis; Table 5 the results of the rock bulk analysis. Chromatographically, the rock extract traces mimic those of the crude oils in the Arbuckle reservoirs. Collectively, the carbon isotopes (Fig. 6), GC-FID (Figs. 3 and 7), and GC-MS (Fig. 8) data support a genetic relationship between the lower shale member of the Oil Creek Formation and the crude oils in the Arbuckle reservoirs.

Maturity Analysis

Accurate assessment of a petroleum system's maturity state is critical to defining the generation and expulsion events and the migration and trapping events. The tools used to quantify maturity include a combination of chemical methods (biomarker-based isomerization reactions, thermal destruction of compound classes, Rock Eval pyrolysis) and optical methods (vitrinite reflectance, fluorescence character, thermal alteration indices). These techniques are integrated in this study to provide a collective maturity value of 1.2–1.3% Ro_{eq} at the base of the Oil Creek Formation. However, true vitrinite is not present in these samples since they predate the evolution of vascular plants. The reflecting particles that could be measured ($Ro_{eq} = 1.09$, $n = 15$) were small and sparse. Additional observations that support this maturity are the lack of fluorescence emission from the amorphous kerogen (Stach and others, 1982) and the presence of condensed gray amorphous matter (Castaño, 1995). Native bitumen was also reported to be sparse (J. Quick, personal communication).

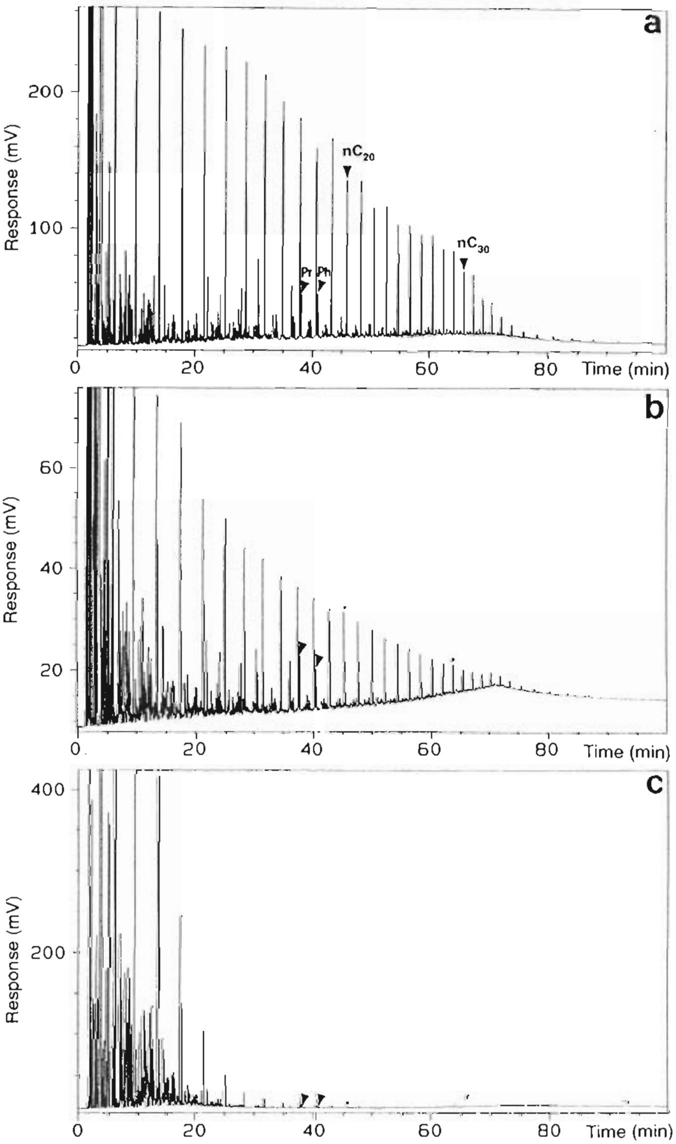

Figure 3. Typical GC-FID traces. *a*—Type A-1 crude oil. *b*—Crude oil in Hunton reservoirs. *c*—Crude oil in younger reservoirs.

Depositional Environment

Debate continues over whether the shale in the Oil Creek Formation is a lacustrine or marine shale. Traditionally, the observed features such as the odd-carbon preference (OCP) in the $n\mathrm{C}_{23}$ to $n\mathrm{C}_{31}$ range, the enhanced C_{28} steranes, and the enhanced paraffin content (Huang and Meinschein, 1979; Peters and Moldowan, 1993) have signified a lacustrine environment. However, these responses are also observed in marine depositional systems (Wavrek, unpublished), which is consistent with optical observations including abundant amorphous material, marine acritarchs, and skelecodonts (D. Englehardt, personal communication), along with abundant framboidal pyrite (J. Quick, personal communication).

Burial-History Modeling

Effective modeling for the generation and migration of hydrocarbons in the Ames feature requires knowledge of the sedimentation and tectonic and thermal history, as well as the distribution and quality of the organic matter within the feature. Synthesizing these variables generates an integrated basin model. This model establishes the timing of oil generation and expulsion from the major source rocks, documents the orientation of major migration pathways responsible for the hydrocarbon charge, and aids in the recognition of undiscovered oil reserves (Waples, 1980).

Figure 9 shows the burial-history chart for the no. 1-19 Chet well, with oil windows superimposed. The lower shale member of the Oil Creek Formation is located at the bottom of the Simpson Group. This unit entered the early-mature oil window at 280 Ma and remained in it until 254 Ma. From 254 to 206.8 Ma, the source facies remained in the peak oil-generation window, and the critical moment (i.e., when the bulk of the petroleum was generated and expelled from the source rock) was at 225 Ma. Subsequent late oil generation lasted until the present, with a calculated maturity of 1.34% $\mathrm{Ro}_{\mathrm{eq}}$ at the base of the Oil Creek shale. Although this calculated maturity is consistent with the value observed from actual analyses, it does conflict with other data in the region (Cardott, 1989). The rationale for the discrepancy can be resolved with additional analyses of vertical maturity profiles within the Ames region.

Figure 10 shows a cross section of the Ames feature at the critical moment. Figure 11 shows the geographic extent of the petroleum system at the critical moment. No hydrocarbon accumulations and migration pathways are shown in Figure 11 since expulsion was downward and into the underlying Arbuckle reservoir. The events chart (Fig. 12) chronicles the development of the Oil Creek–Arbuckle (!) petroleum system through time. The table of related accumulations is covered by the summary offered by Evans (1997) of the petroleum

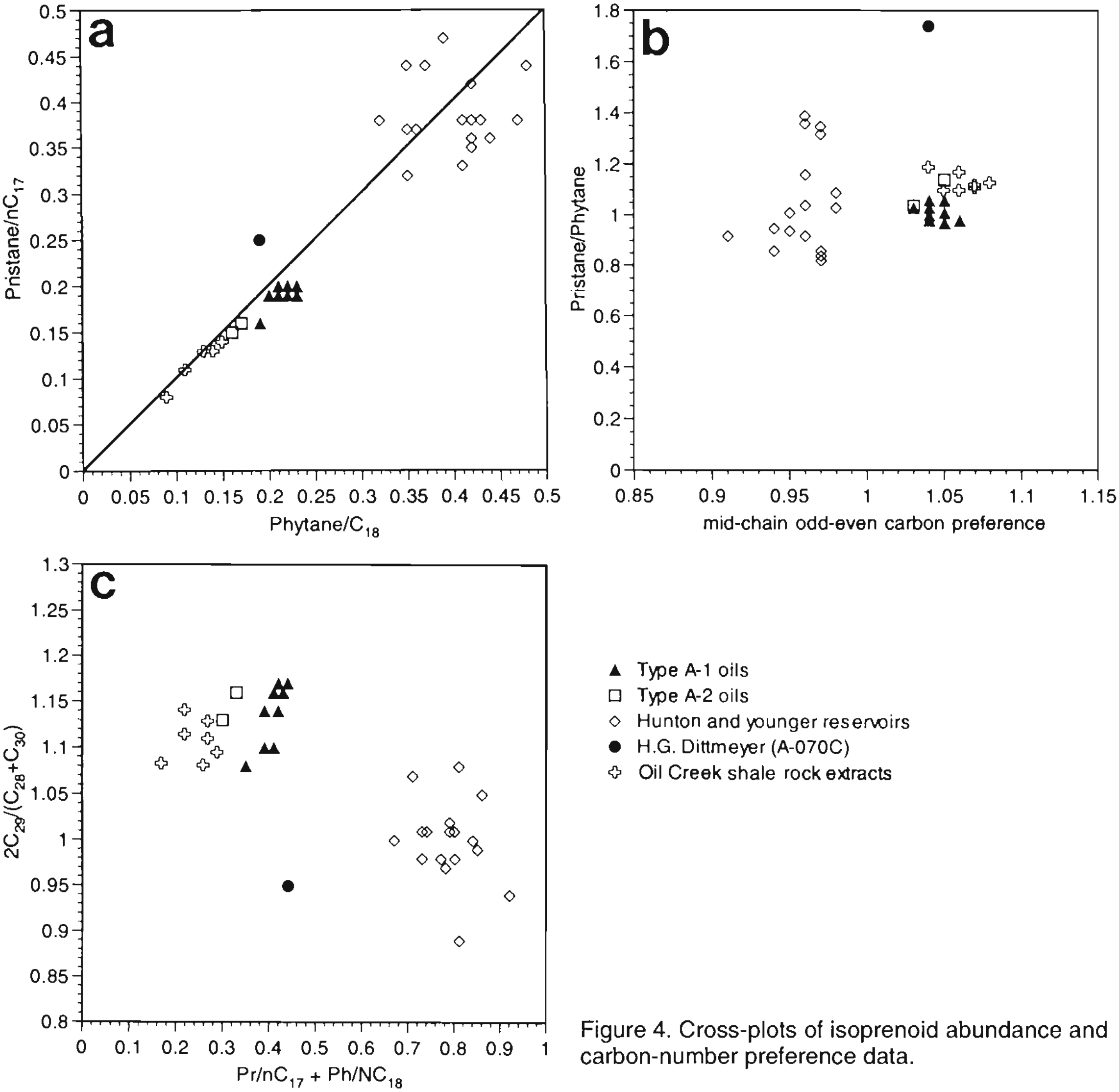

Figure 4. Cross-plots of isoprenoid abundance and carbon-number preference data.

accumulations associated with this petroleum system.

Petrophysical Investigation

Petroleum geologists have long sought a method to identify potential source rocks through well-log analysis. Initial attempts dating back to the mid-1940s concentrated on single logging tool methods (e.g., Schmoker, 1981; Herron and Le Tendre, 1990; Herron and others, 1988; Hester and others, 1990; Schmoker and Hester, 1989,1990; and references therein). Difficulties arose, however, because inherent source-rock characteristics (i.e., sulfur content) adversely affected log response, which limited application. Therefore, several methods using combined logging tools were developed, including the sonic and resistivity overlay method of Passey and others (1990) employed in this study.

The purpose of this investigation is to estimate source-rock volume and organic carbon richness throughout the structure. Units containing significant organic matter display a distinct Δ log R separation (Fig. 13). Unfortunately, this separation could not be calibrated owing to a lack of sonic logs in wells for which TOC data were available for this study. Consequently, the Δ log R response was compared to nearby wells (approximately 2,000 ft away) for which TOC data were available.

Volume Estimates and Organic Richness

The rock samples and well-log response data indicate a systematic variation in organic richness within the Ames feature. Therefore, to proceed

TABLE 4.—SUMMARY OF CRUDE-OIL BULK ANALYSIS DATA

Sample	Relative density	API gravity	wt% sulfur	Carbon isotopes	
				Saturate	Aromatic
A-049C	0.830	38.2	0.05	–31.4	–30.8
A-050C	0.834	37.4	0.00		
A-051C	0.827	38.8	0.05		
A-052C	0.829	38.4	0.05		
A-053C	0.825	39.2	0.04		
A-054C	0.829	38.4	0.04		
A-055C	0.828	38.6	0.03		
A-056C	0.824	39.4	0.00		
A-057C	0.827	38.8	0.02		
A-058C	0.817	40.9	0.02		
A-059C	0.829	38.4	0.06		
A-060C	0.8793	46.1	0.02	–31.0	–30.3

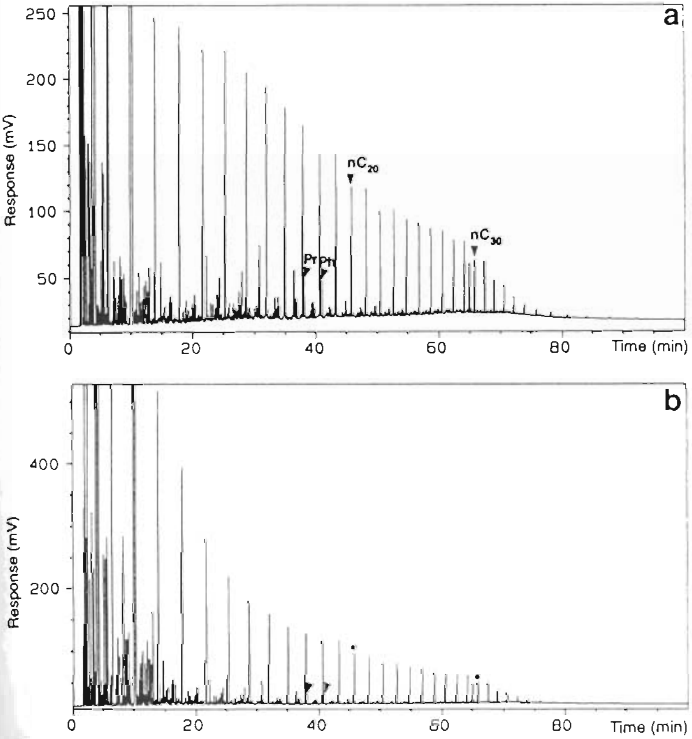

Figure 5. GC-FID traces showing crude oil types. *a*—Type A-1 crude oil. *b*—Type A-2 crude oil, found in the Arbuckle Group reservoirs. The internal standard is the peak eluting prior to nC_{30}.

with the analysis, the source rock was divided into three sections; within each, the TOC was approximately constant (see Fig. 14). In section A (where the source rock has a thickness of 75 to 225 ft), the source rock appears uniformly very lean with an average TOC of 0.3 wt%. In the southern half of the feature, the source rock making up section B (thickness of 0 to 75 ft) has an average TOC of 0.25 wt%. In the northern flank of the feature, section C source rock (also with a thickness of 0 to 75 ft) displays an increased TOC that averages 1.2 wt%.

Generation Accumulation Efficiency

The parameters used to calculate these efficiencies are most easily understood in an organic carbon mass-balance framework. At any given time during hydrocarbon migration from source rock to trap, all of the organic carbon originally deposited in the source rock can be accounted for by totaling (1) the residual hydrocarbons in the source rock after generation and expulsion (Price and others, 1984; Price and Lefever, 1992), (2) the hydrocarbon losses along the migration pathway (England, 1994; England and others, 1987; Mackenzie and Quigley, 1988), and (3) the known and undiscovered hydrocarbon reserves (England, 1994).

Table 6 identifies the lithologically distinct sections and summarizes the calculated HCG values. IHC are the hydrocarbons trapped and approximately equal the reserve estimates. Kuykendall and others (1997) estimated the reserves to be 50 MMBO + 3.1 MMBOeq of gas. From these values, the following efficiency parameters can be calculated:

$$\begin{aligned}\text{GAE} &= [\text{IHC}/\text{HCG}] \times 100\% \\ &= [53.1\ \text{MMBO}/145\ \text{MMBO}] \\ &\quad \times 100\% \\ &= 36.6 \approx 37\%\end{aligned}$$

The generation accumulation efficiency (GAE) is a particularly useful parameter in economic assessments. By quantifying the efficiency with which a petroleum system accumulates hydrocarbons, the explorationist can better assess a basin's

Table 5.—Summary of Source-Rock Bulk Analysis Data

Sample no.	TOC	S1	S2	S3	Tmax	HI	OI	S1/ TOC	S2/S3	PI*	TGP*	RCI*	Carbon isotopes	
													Saturate	Aromatic
MC008R	0.50	0.11	0.24	0.37	424 L	48	74	0.22	0.65	0.31	0.35	7.00		
MC009R	0.50	0.11	0.28	0.33	421 L	56	66	0.22	0.85	0.28	0.39	7.80		
MC010R	0.47													
MC011R	0.80	0.31	0.63	0.31	434	79	39	0.39	2.03	0.33	0.94	11.75		
MC012R	1.36	0.79	1.73	0.31	443	127	23	0.58	5.58	0.31	2.52	18.53		
MC013R	1.25	0.81	1.69	0.29	443	135	23	0.65	5.83	0.32	2.50	20.00		
MC014R	1.13	0.88	1.68	0.32	438	149	28	0.78	5.25	0.34	2.56	22.65		
MC015R	1.05	0.75	1.45	0.35	440	138	33	0.71	4.14	0.34	2.20	20.95		
MC016R	1.04	0.70	1.37	0.34	437	132	33	0.67	4.03	0.34	2.07	19.90		
MC017R	1.62	1.14	2.63	0.38	444	162	23	0.70	6.92	0.30	3.77	23.27		
MC018R	1.94	1.59	3.2	0.32	442	165	16	0.82	10.00	0.33	4.79	24.69	–30.7	–30.1
MC019R	1.03	0.40	0.98	0.31	436	95	30	0.39	3.16	0.29	1.38	13.40		
MC020R	1.70	1.56	3.67	0.35	447	216	21	0.92	10.49	0.30	5.23	30.76		
MC021R	1.74	1.35	3.76	0.36	447	216	21	0.78	10.44	0.26	5.11	29.37		
MC022R	1.58	0.57	2.52	0.26	445	159	16	0.36	9.69	0.18	3.09	19.56		
MC023R	1.60	1.60	4.47	0.34	444	279	21	1.00	13.15	0.26	6.07	37.94		
MC024R	1.61	1.58	4.16	0.25	446	258	16	0.98	16.64	0.28	5.74	35.65		
MC025R	1.76	1.78	4.43	0.32	445	252	18	1.01	13.84	0.29	6.21	35.28		
MC026R	1.18	1.24	3.21	0.24	443	272	20	1.05	13.38	0.28	4.45	37.71		
MC027R	1.26	1.08	3.27	0.37	444	260	29	0.86	8.84	0.25	4.35	34.52		
MC028R	1.46	1.06	3.91	0.28	446	268	19	0.73	13.96	0.21	4.97	34.04		
MC029R	1.90	1.15	4.7	0.22	449	247	12	0.61	21.36	0.20	5.85	30.79		
MC030R	0.83	0.72	2.57	0.2	442	247	32	0.89	7.83	0.27	2.45	33.56		
MC031R	0.79	0.71	2.01	0.32	438	254	41	0.90	6.28	0.26	2.72	34.43		
MC032R	0.73	0.65	1.8	0.23	442	247	32	0.89	7.83	0.27	2.45	33.56		
MC033R	0.68	0.69	2.04	0.22	433	300	32	1.01	9.27	0.25	2.73	40.15		
MC034R	0.67	0.57	1.64	0.37	435	245	55	0.85	4.43	0.26	2.21	32.99		
MC035R	0.56	0.42	1.5	0.26	438	268	46	0.75	5.77	0.22	1.92	34.29		
MC036R	2.42	0.81	3.82	0.21	450	158	9	0.33	18.19	0.17	4.63	19.13		
MC037R	0.45													
MC038R	0.36													
MC039R	0.29													
MC040R	0.27													
MC041R	0.12													
MC042R	0.11													
MC043R	0.13													
MC044R	0.07													
MC045R	0.24													
MC046R	0.25													
MC047R	0.23													
MC048R	0.27													
MC049R	0.31													
MC050R	0.29													
MC051R	0.30													
MC052R	0.32													
MC053R	0.31													
MC054R	0.35													

* PI = S1/(S1 + S2)
TGP = S1 + S2
RCI = 10 × (S1 + S2)/TOC

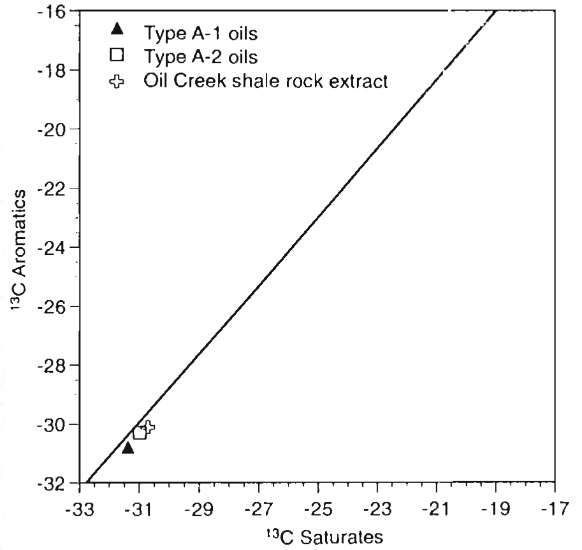

Figure 6. Sofer plot showing $\delta^{13}C$ values (in ‰ relative to PDB [Peedee belemnite] standard) of saturate and aromatic fractions of rock extract and crude oils. Line shows best separation between marine environments (below) and nonmarine environments (above), as established by Sofer (1984). Graph axes represent global variation for crude oils.

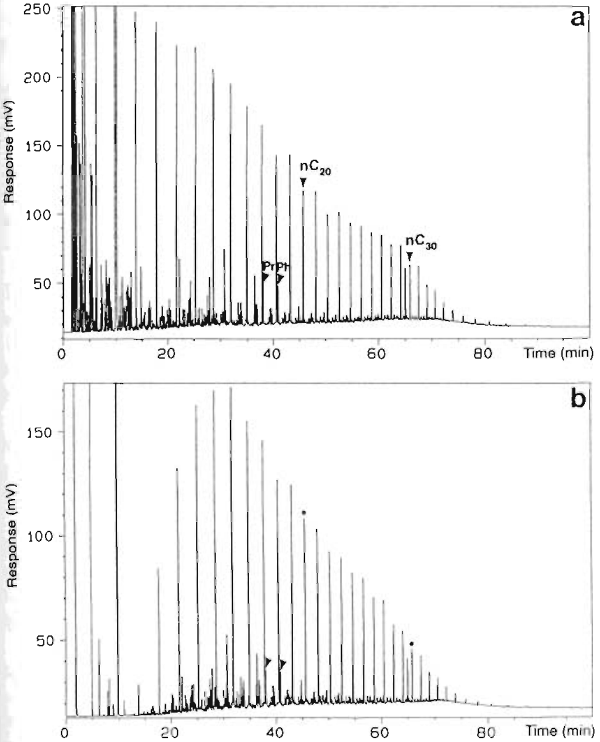

Figure 7. GC-FID traces. *a*—Crude oil in Arbuckle reservoir. *b*—Genetically related source rock from lower shale member of the Oil Creek Formation.

hydrocarbon potential. Large petroleum systems or multiple petroleum systems within a basin increase the likelihood of finding commercial hydrocarbon deposits (Magoon and Dow, 1994). The generation accumulation efficiency calculated shows that 37% (53 MMBO) of the 145 MMBO generated by the lower shale member of the Oil Creek Formation were trapped. The 92 MMBO remnant comprises hydrocarbons that were either not trapped or remain undiscovered (Fig. 15). The calculated GAE appears comparable to similar mass-balance calculations within petroleum systems on a global basis (Hunt, 1996).

The current thought within the petroleum industry is that little new oil will be discovered in the Ames feature (Evans, 1997). In contrast, we view the Ames petroleum system more optimistically, and we anticipate that a clearer understanding of the Arbuckle reservoir will yield additional reserves. This optimism is based upon the limited geographic extent and an advanced knowledge of the elements and processes of this petroleum system. Although this study shows that there was no vertical migration of oils from the Oil Creek source-rock facies, lateral migration was not investigated. Further research on oils updip from the Ames feature may provide insight into the fate of the missing 92 MMBO.

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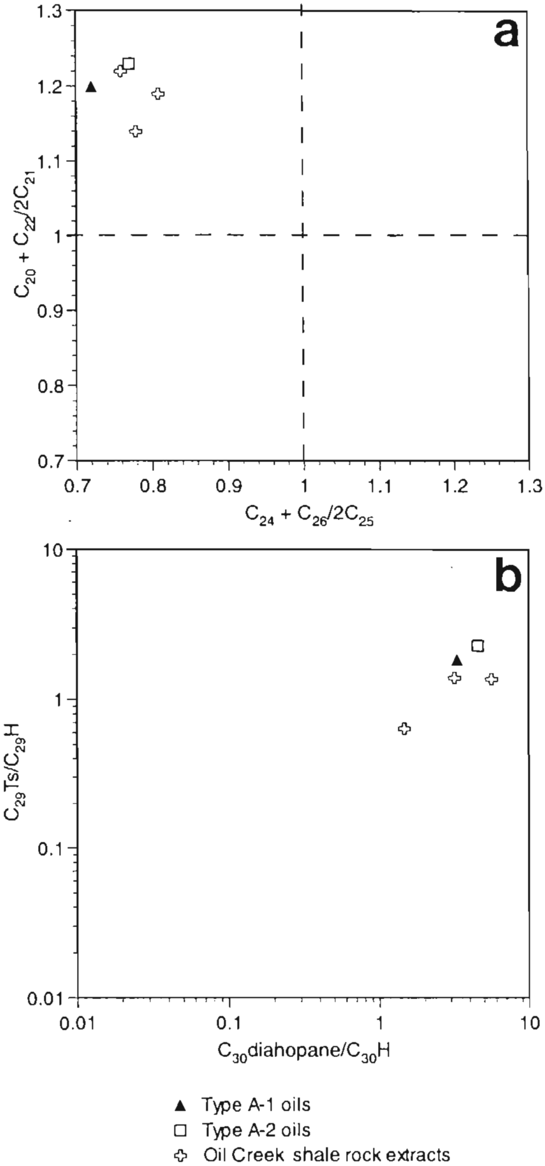

Figure 8. *a*—Cross-plot of the even- vs. odd-carbon preferences for the *n*-alkylcyclohexanes (*m/z* 82) in rock extracts and crude oils. *b*—Cross-plot of the C_{30} diahopane/C_{30} hopane ratio vs. the $C_{29}Ts/C_{29}$ hopane ratio for rock extracts and crude oils. Axes represent range of variation on global basis.

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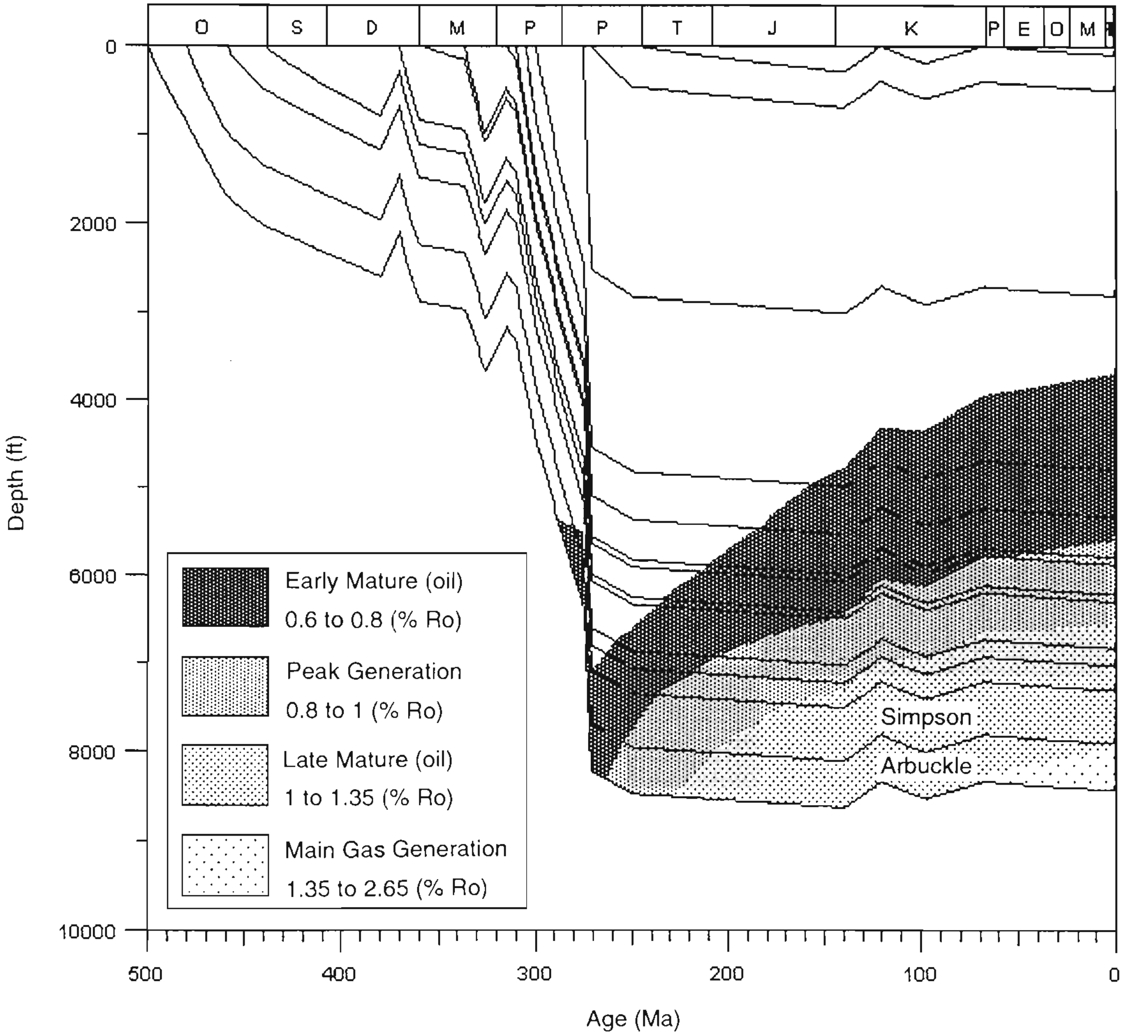

Figure 9. Burial-history reconstruction showing the maturation status for source-rock intervals in the no. 1-19 Chet well. Maturity levels are based on TTI maturity calculations.

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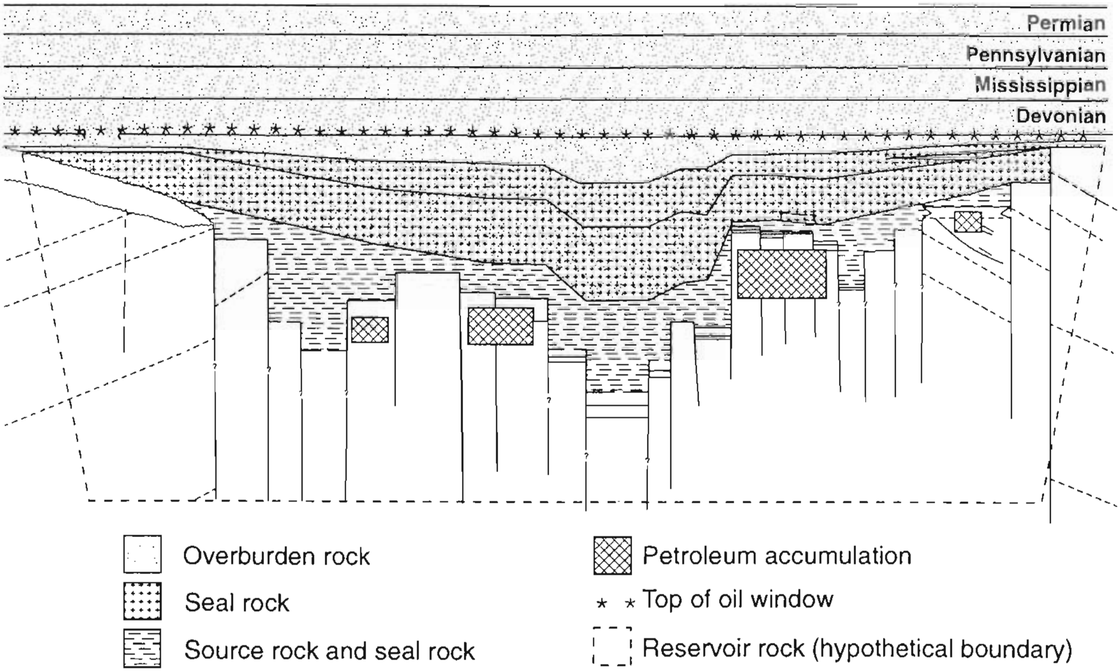


Figure 10. Two-dimensional “time-slice” of the Ames feature at the critical moment (225 Ma). The Devonian and younger section (≈7,000 ft thick) is not to scale. The petroleum accumulations are adjacent to downdropped structures.

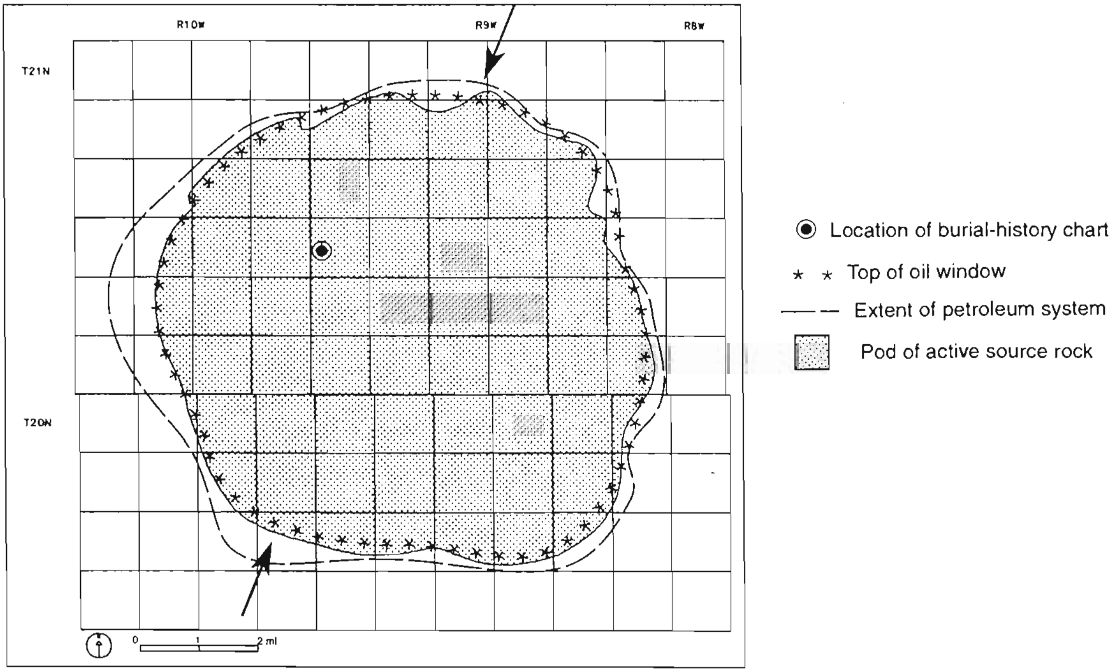
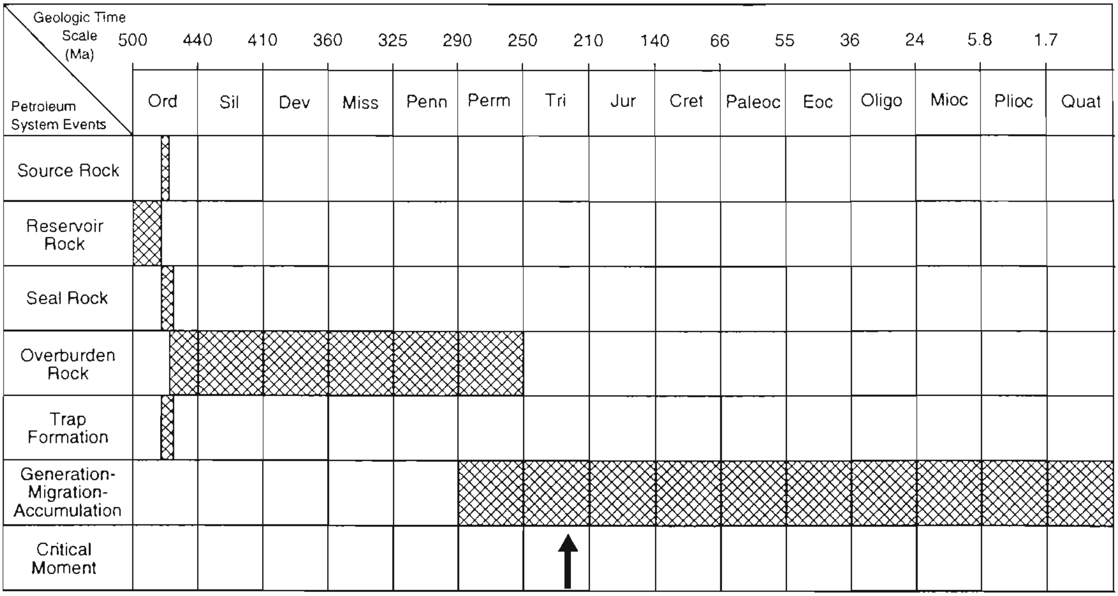


Figure 11. Map showing the geographic extent of the petroleum system at the critical moment.



Geologic Time Scale (Ma)	500	440	410	360	325	290	250	210	140	66	55	36	24	5.8	1.7
Petroleum System Events	Ord	Sil	Dev	Miss	Penn	Perm	Tri	Jur	Cret	Paleoc	Eoc	Oligo	Mioc	Plioc	Quat
Source Rock	▨														
Reservoir Rock	▨														
Seal Rock	▨														
Overburden Rock	▨	▨	▨	▨	▨	▨									
Trap Formation	▨														
Generation-Migration-Accumulation						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Critical Moment							↑								

Figure 12. Events chart summarizing the history of the petroleum system.

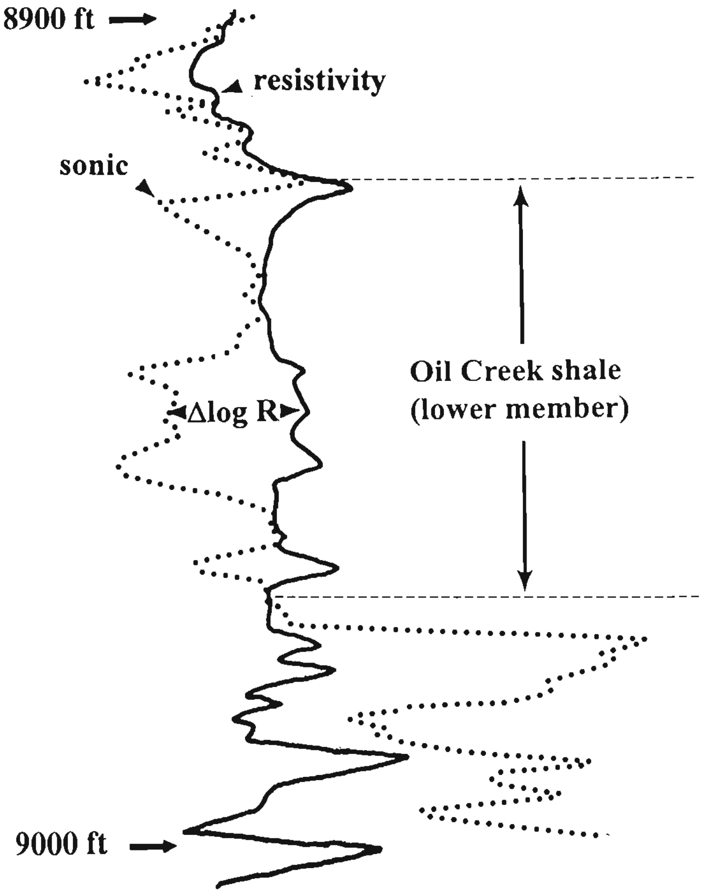


Figure 13. Sonic and resistivity overlay for a section in the Continental Resources Inc. no. 1-19 Dorothy well, showing organic-rich intervals throughout the lower shale member of the Oil Creek Formation.

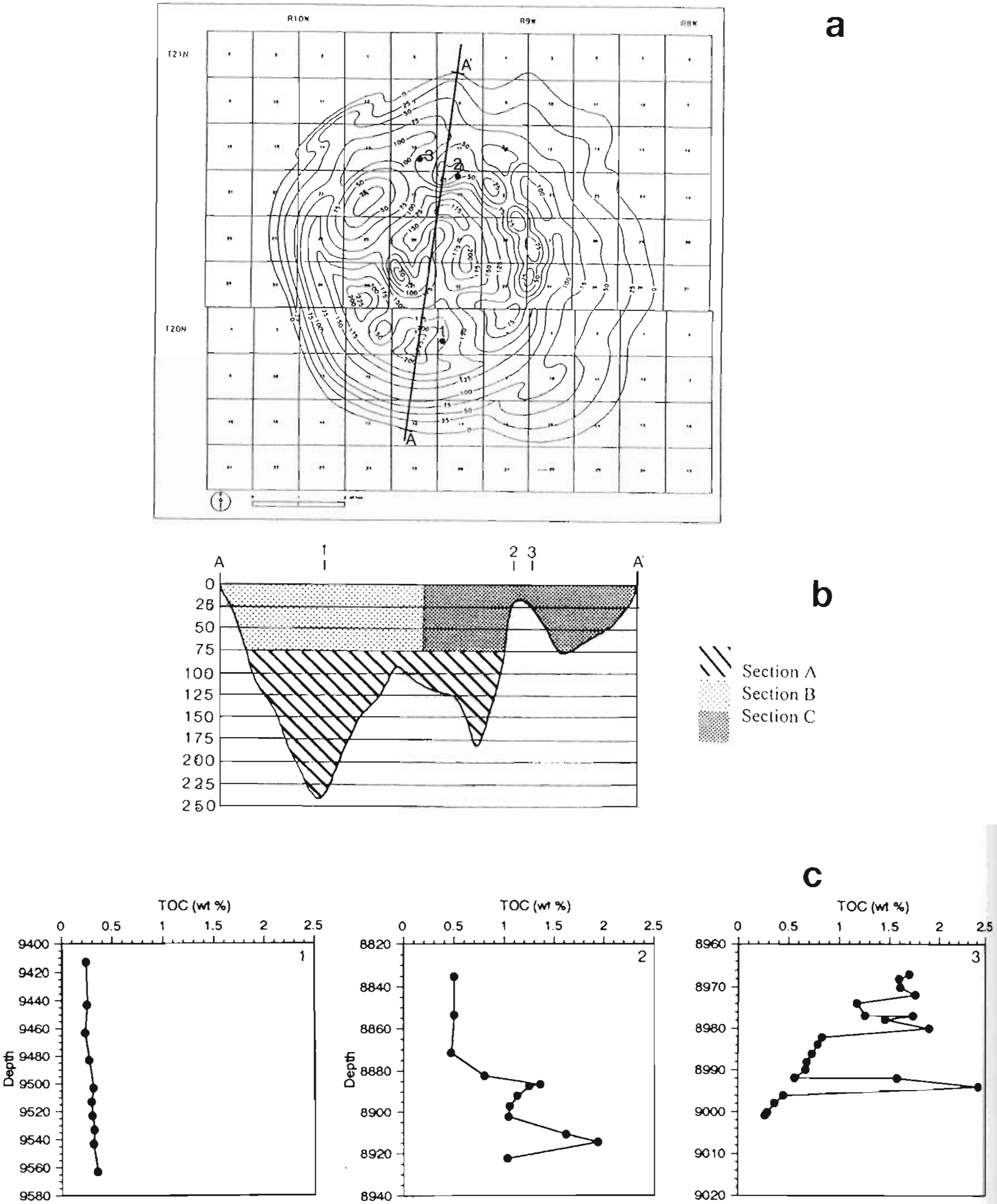


Figure 14. Organic richness distribution in the Ames feature based on a cross section (b) of the Oil Creek Formation (lower shale member) isopach map (a) combined with TOC profiles (c) for the three wells (DLB Darin 5-13 [1], D & J James 1-20 [2], and Nicor Chestnut 18-4 [3]) from which sample suite was obtained.

TABLE 6.—SUMMARY OF PARAMETERS NEEDED FOR CALCULATIONS OF GENERATION ACCUMULATION EFFICIENCY (GAE)

GAE parameters	Lithologic sections A	B	C	Total
Average TOC (wt%)	0.31	0.25	1.18	
Average density (g/cm^3)	2.63	2.62	2.62	
Volume (cm^3)	1.10×10^{10}	1.51×10^{10}	1.09×10^{10}	3.70×10^{10}
M (g TOC)	8.97×10^{12}	9.89×10^{12}	3.37×10^{13}	5.26×10^{13}
HI_o (mg HC/g TOC)	420	400	580	
HI_p (mg HC/g TOC)	107	93.5	171.3	
R (mg HC/g TOC)	313	306.5	408.7	
HCG (kg HC)	2.81×10^9	3.03×10^9	1.38×10^{10}	1.96×10^{10}

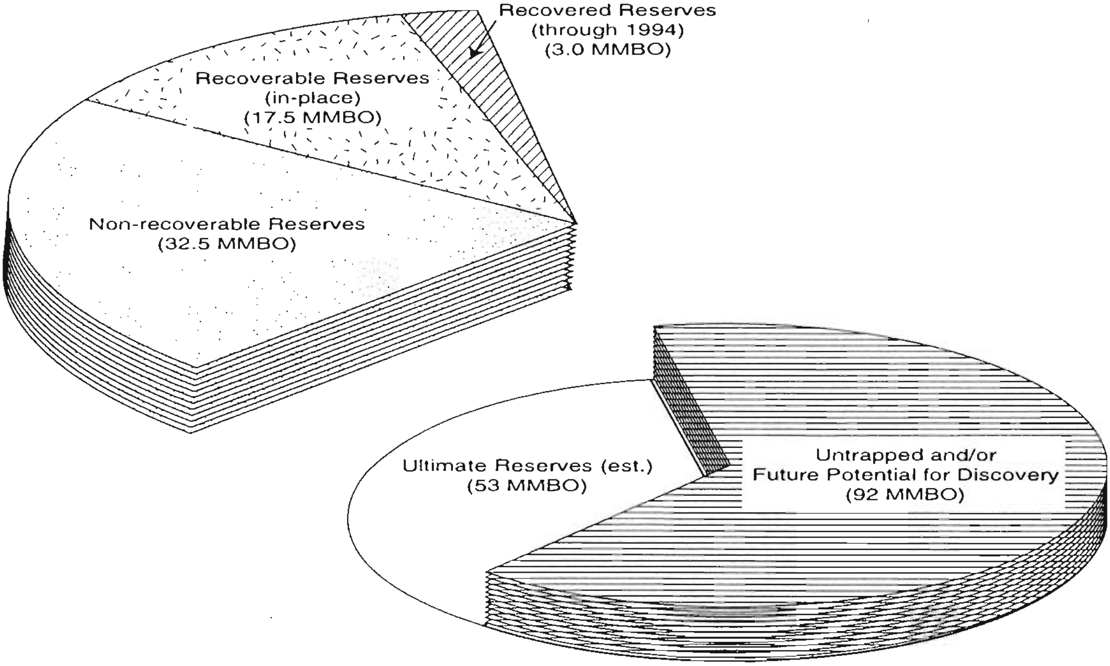


Figure 15. Pie chart showing present distribution of total hydrocarbons generated in the Ames feature.

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