Oklahoma GEOLOGY Notes

OKLAHOMA GEOLOGICAL SURVEY VOL. 48, NO. 1 FEBRUARY 1988

On the cover—

Collings Ranch Conglomerate in the Arbuckle Mountains

Excellent exposures of the Pennsylvanian Collings Ranch Conglomerate are present in road cuts along Interstate 35 through the Arbuckle Mountains of southern Oklahoma. Shown here is a broad synclinal fold exposed on the east side of the southbound lane; the view is toward the northeast, from the rest stop near the center of sec. 31, T. 1 S., R. 2 E., in Murray County.

The Collings Ranch consists of boulders and cobbles of limestone derived from nearby folded pre-Pennsylvanian strata. It is the first, the thickest, and the coarsest orogenic deposit to accompany folding of the Arbuckle anticline during the Virgilian Arbuckle orogeny. The Collings Ranch was undoubtedly laid down over a wide area, but the mountain system was still rising during conglomerate deposition, and most of the conglomerate was subsequently eroded. It is now best preserved in the synclinal graben exposed here and near Turner Falls on U.S. Highway 77.

Kenneth S. Johnson

OKLAHOMA GEOLOGICAL SURVEY
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Oklahoma Geology Notes, ISSN 0030-1736, is published bimonthly by the Oklahoma Geological Survey. It contains short technical articles, mineral-industry and petroleum news and statistics, abstracts, notices of new publications, and announcements of general pertinence to Oklahoma geology. Single copies, $1.50; yearly subscription, $6. Send subscription orders to the Survey at 830 Van Vleet Oval, Room 163, Norman, Oklahoma 73019. Short articles on aspects of Oklahoma geology are welcome from contributors; general guidelines will be sent on request.

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Oklahoma
GEOLOGY
Notes

Contents

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PRELIMINARY GEOCHEMICAL CHARACTERIZATION OF SOME OKLAHOMA TAR-SAND BITUMENS

Jane L. Weber[1]

Abstract

Detailed analysis of tar-sand bitumens obtained by coring in Carter and Murray Counties, Oklahoma, produced variable and sometimes conflicting evidence concerning the extent of bacterial degradation experienced by the bitumens. Neither chemical composition nor degree of biodegradation appears to be depth-related; nor are values for one particular depth interval predictive for neighboring intervals.

Bulk-composition data generated by adsorption chromatography are characteristic of a degraded oil. Limited gas chromatography–mass spectrometry results show sterane assemblages indicative of moderate to severe biodegradation. Two terpane fragmentograms, though inconclusive, provide potential evidence of severe bacterial activity. Capillary-column gas chromatograms demonstrate moderate to severe degradation, while simultaneously displaying traces of normal alkanes in approximately one-fourth of the samples examined. Equally significant is the finding in three samples of both normal alkanes and bacterially altered hopanes. This combination is attributed to mixing of non-biodegraded and biodegraded oils in the reservoir.

Introduction

Most major tar sands are generally believed to be degraded remnants from the chemical and microbial alteration of pooled liquid petroleum (Bailey and others, 1973; Deroo and others, 1974; Demaison, 1977; Rubinstein and others, 1977; Volkman and others, 1983; Scott and Kosar, 1984). Oxygen-bearing meteoric water filtering through near-surface reservoirs dissolves the more water-soluble petroleum compounds, especially the light aromatics (Bailey and others, 1973; Demaison, 1977; Miiller and others, 1984). It also transports bacteria which consume hydrocarbons in a predictable, geochemically significant sequence starting with normal (straight-chain) alkanes; progressing through branched alkanes, naphthenes (cyclic alkanes), and some aromatics; and, finally, affecting

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steranes and hopanes (Bailey and others, 1973; Demaison, 1977; Wardroper and others, 1984; Philp and Lewis, 1987). Over a period of time, these processes of dissolution and bacterial metabolism, aided by vaporization and oxidation by atmospheric oxygen, deplete petroleum of its simpler, lower-boiling components. The resulting tarry residue eventually qualifies the reservoir as a tar-sand deposit.

Tar-sand bitumens have been defined as naturally occurring, highly viscous (>10,000 centipoises), low gravity (<10° API), mainly heavy-hydrocarbon mixtures not recoverable by conventional oil-well technology (Walters, 1974; Ristau, 1984; Marchant, 1985). Investigating and characterizing these bitumens is one approach to studying the effects of biodegradation on crude-oil composition. Although this topic is fairly well understood and has been reported on in great detail in recent years, some questions still remain unanswered. Perhaps this is because, as Philp and Lewis (1987) suggest, each case of biodegradation is unique to its location in the basin. The current study was undertaken to determine the extent of biodegradation experienced by certain Oklahoma tar sands. Such information, when integrated with geologic considerations, will be useful in proposing avenues of oil migration and accumulation in the area, and in attempting geochemical correlations between regional oils and the tar-sand bitumens.

This report presents preliminary geochemical results for five drill cores obtained during an earlier U.S. Department of Energy–Oklahoma Geological Survey tar-sands project.

Resource Area

Samples were obtained from five core holes representing three localities in Carter and Murray Counties, Oklahoma (Fig. 1). Tar sands in the Sulphur area (Murray County) occur mostly in the Ordovician Oil Creek sandstone (Harrison and Burchfield, 1984). Because Williams (1983) found no local source rocks for these hydrocarbons, he suggested that they were emplaced before the Arbuckle Mountains orogeny thrust the Oil Creek closer to the surface. Cores selected from this area were from the Griffitts #1 (3 samples between 30 and 73 ft) and Kirby #3 (10 samples between 22 and 130 ft).

Bitumen-impregnated sandstones of the South Woodford deposit in Carter County are Mississippian or Pennsylvanian in age (Harrison and others, 1981; Harrison and Burchfield, 1984). They are thought to have resulted from surface alteration of heavy oil that ascended along vertical bedding planes, since heavy oil is produced nearby from shallow depths (Harrison and Burchfield, 1984). Cores chosen from this area were from the Fitzgerald #3 (9 samples between 10 and 90 ft) and Fitzgerald #5 (11 samples between 20 and 240 ft).

The Overbrook deposit (Carter County), found in Pennsylvanian or Permian sandstones (Harrison and others, 1981; Harrison and Burchfield, 1984) is located on the edge of the Overbrook Field. Overbrook's commercial production consists of light crudes (39–50° API gravity) from the Springer and Deese Groups at 2,000–7,000 ft (International Oil Scouts Association, 1980; Harrison and Burchfield, 1984). The only core available from this locality was from the Overbrook #1, which provided 6 samples between 18 and 44 ft.

Experimental

Bitumens previously extracted from core sections during the DOE–OGS program (see Harrison and Burchfield, 1984, for extraction procedure) served as starting materials for this investigation. Asphaltenes were precipitated with an excess of hot heptane, collected on Celite, reclaimed with dichloromethane and methanol, and finally weighed after solvent removal. C_{15}+ non-asphaltenes were separated into compound types by adsorption chromatography on columns of wet-packed silica gel topped with alumina. Successive elutions with heptane, benzene, and chloroform-methanol (1:1) yielded saturate, aromatic, and heterocompound

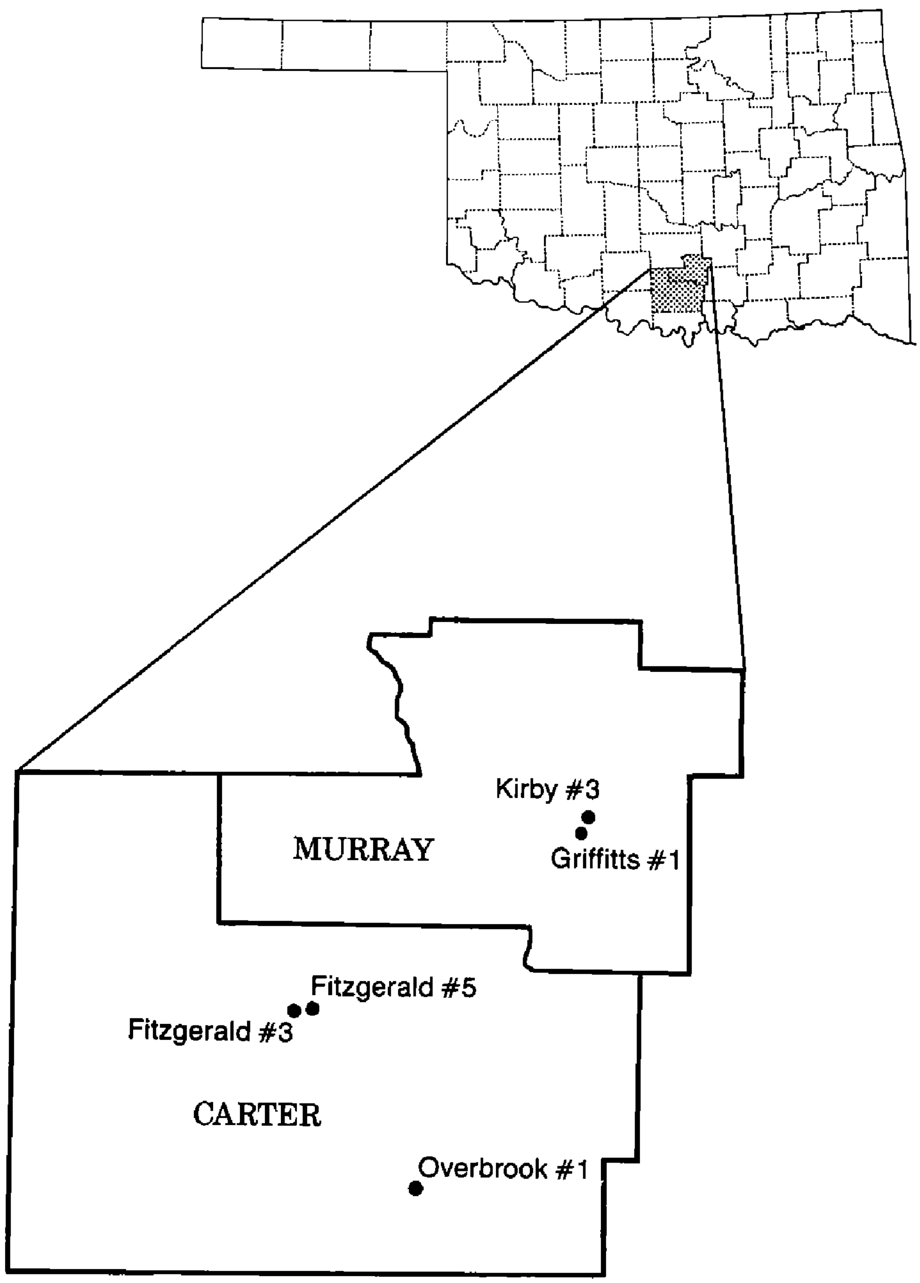

Figure 1. Location of tar-sand boreholes in Carter and Murray Counties, Oklahoma.

(NSO) fractions, respectively. After rotary evaporation of solvents, fractions were air-dried and weighed.

Saturate and aromatic fractions were analyzed by gas chromatography (GC) on a Hewlett-Packard 5840, equipped with a fused-silica OV-101 capillary column and a flame-ionization detector. The oven was programmed from 70° to 290°C (8°C/min), with a final hold time of 12 min. An n-alkane-pristane-phytane solution prepared in-house to contain n-alkanes from C_9 through C_{26} and even-numbered n-alkanes from C_{28} to C_{34} was used as an external standard for identification purposes where applicable.

Additional characterization of two selected saturate fractions was achieved with coupled gas chromatography–mass spectrometry (GC–MS), using a Finnigan 4200 system operated at 70 eV in the electron-impact mode. The SE-54 column was programmed from 40° to 100° at 20°C/min and 100° to 280° at 4°C/min. Tentative identification of steranes and terpanes was made by comparison of retention sequences with published fragmentograms.

All solvents were glass-distilled as purchased. A solvent blank was carried through the procedure. About one in eight samples was analyzed in duplicate as a quality-control measure.

Results and Discussion

Bacteria selectively metabolize different hydrocarbon families of petroleum in a stepwise manner, leaving a chemical signature of the extent of their activity. Although the steps of the process are neither discrete nor totally independent of one another, they are nevertheless definable and generally followed (Bailey and others, 1973; Seifert and Moldowan, 1979; Volkman and others, 1983; Philp and Lewis, 1987). Loss of n-alkanes indicates a mild level of biodegradation (Müller and others, 1984). Moderate attack removes branched alkanes, including the acyclic isoprenoids, followed by some aromatic and naphthenic structures (Mackenzie, 1984). Severe biodegradation can affect the more-resistant hopanes, sometimes causing the loss of a methyl group from the hopane nucleus (Rullkötter and Wendisch, 1982); it can also preferentially remove the regular steranes (Müller and others, 1984; Philp, 1985). In excessively biodegraded samples, not only do tricyclic terpanes survive, but also their relative quantities appear to increase because other compounds are stripped away (Aquino Neto and others, 1983; Leenheer, 1984). This order of microbial attack, as revealed primarily through GC profiles and mass fragmentograms, will be the basis for discussing the results and implications of this study.

Bulk Composition

Table 1 presents fractionation data. Average material accountability for the combined deasphalting and chromatography steps is close to 90%. In most samples the saturate fraction comprises <20% of the bitumen (defined throughout this paper as *extractable organic matter*), reflecting the selective destruction of n-alkanes and isoprenoids by bacteria. The ratio of saturate to aromatic hydrocarbons hovers around 0.5.

Table 1. Fractionation Data for Oklahoma Tar-Sand Bitumens

Borehole	Sample depth (ft)	Weight percent of total bitumen[a]				Weight percent of starting material recovered	Saturate/ Aromatic
		Saturate[b]	Aromatic[c]	NSO[d]	Asphaltene		
Griffitts #1	30	16.9	34.7	35.4	13.0	92.6	0.5
	35.6	17.7	31.0	34.5	16.8	95.3	0.6
	73	11.7	25.5	26.0	36.7	85.4	0.5
Kirby #3	22	16.7	37.0	36.6	9.7	96.1	0.5
	28	18.2	37.5	34.8	9.4	95.3	0.5
	39	16.8	33.5	34.7	15.0	91.8	0.5
	60A	23.7	36.9	27.2	12.2	91.9	0.6
	60B	23.8	35.8	29.0	11.4	92.2	0.7
	80	25.3	36.5	28.1	10.1	91.2	0.7
	89	23.5	35.2	27.1	14.1	90.8	0.7
	98	23.1	36.0	32.6	8.1	94.1	0.6
	105	27.2	36.6	24.9	11.2	90.9	0.7
	120	20.0	32.2	28.9	18.8	90.0	0.6
	130	21.3	33.5	27.5	17.7	87.7	0.6
Fitzgerald #3	10	19.3	36.8	21.8	22.1	85.1	0.5
	21	19.0	38.8	26.2	15.9	85.6	0.5
	30	19.0	38.7	28.3	13.8	75.4	0.5
	42	18.8	39.1	33.7	8.4	86.6	0.5
	50	19.0	36.3	22.8	22.0	86.3	0.5
	58A	18.9	37.3	20.1	23.6	86.4	0.5
	58B	18.6	36.1	22.4	22.9	86.4	0.5
	70	17.7	36.3	24.7	21.4	84.3	0.5
	82	17.9	36.4	27.2	18.4	89.0	0.5
	90	17.6	34.9	33.5	14.0	90.5	0.5
Fitzgerald #5	20	16.8	25.7	17.6	39.9	87.4	0.6
	40	18.0	34.2	27.1	20.7	87.0	0.5
	60	18.5	33.0	26.2	22.3	87.6	0.6
	80	18.1	34.0	23.2	24.7	87.4	0.5
	100A	17.9	35.4	22.3	24.4	88.0	0.5
	100B	17.9	34.1	20.8	27.2	87.0	0.5
	120	16.9	33.8	20.9	28.4	88.5	0.5
	140	16.8	33.0	24.3	25.9	87.9	0.5
	160	18.1	34.0	26.9	21.0	86.0	0.5
	180	17.6	33.4	25.3	23.7	85.2	0.5
	220	18.5	35.8	23.2	22.6	81.2	0.5
	240A	16.8	33.2	24.5	25.5	87.1	0.5
	240B	16.5	31.9	23.8	27.8	86.2	0.5
Overbrook #1	18	13.7	5.6	11.0	69.7	85.9	2.4
	26	15.5	18.5	23.8	42.7	87.5	0.8
	30	14.4	16.5	17.1	52.0	88.4	0.9
	34A	17.7	32.5	29.6	20.2	88.1	0.5
	34B	17.4	33.0	29.9	19.7	87.1	0.5
	38	18.1	33.7	29.0	19.3	88.9	0.5
	44	18.0	30.8	30.3	20.8	86.9	0.6

[a] Normalized.
[b] Heptane.
[c] Benzene.
[d] Chloroform–methanol (1:1).

The shallowest Overbrook #1 samples are distinguished by their high asphaltene content and low aromatic values. Bitumen from 18 ft dried to "shiny flakes," and that from 26 ft and 30 ft became a "hard, dry solid," whereas all other bitumens retained at least some fluidity. Apparently, at the depths represented by these samples there was a degree or type of degradation different from that experienced by most of the investigated samples. The shallow depths involved and the low aromatic values suggest a greater exposure to water-washing. Samples from 60 to 105 ft in the Kirby #3 borehole differ from all others in their slightly higher saturate content (23–27%) and saturate-to-aromatic ratio (0.7). Asphaltene values for Griffitts #1 increase with depth, while aromatic and NSO values decrease. However, due to the limited number of samples involved, further study is needed before significance can be ascribed to this trend.

Apart from these minor exceptions, the samples in this study show no major differences in bulk composition. The saturate component varies the least, ranging from 12 to 27% of the bitumen. Combined saturate and aromatic hydrocarbons account for roughly half of the bitumen. There appears to be no consistent compositional trend that correlates with depth. The similarity among samples becomes more evident when relative amounts of saturates, aromatics, and asphaltic-plus-NSO compounds are plotted on a ternary diagram (Fig. 2). All

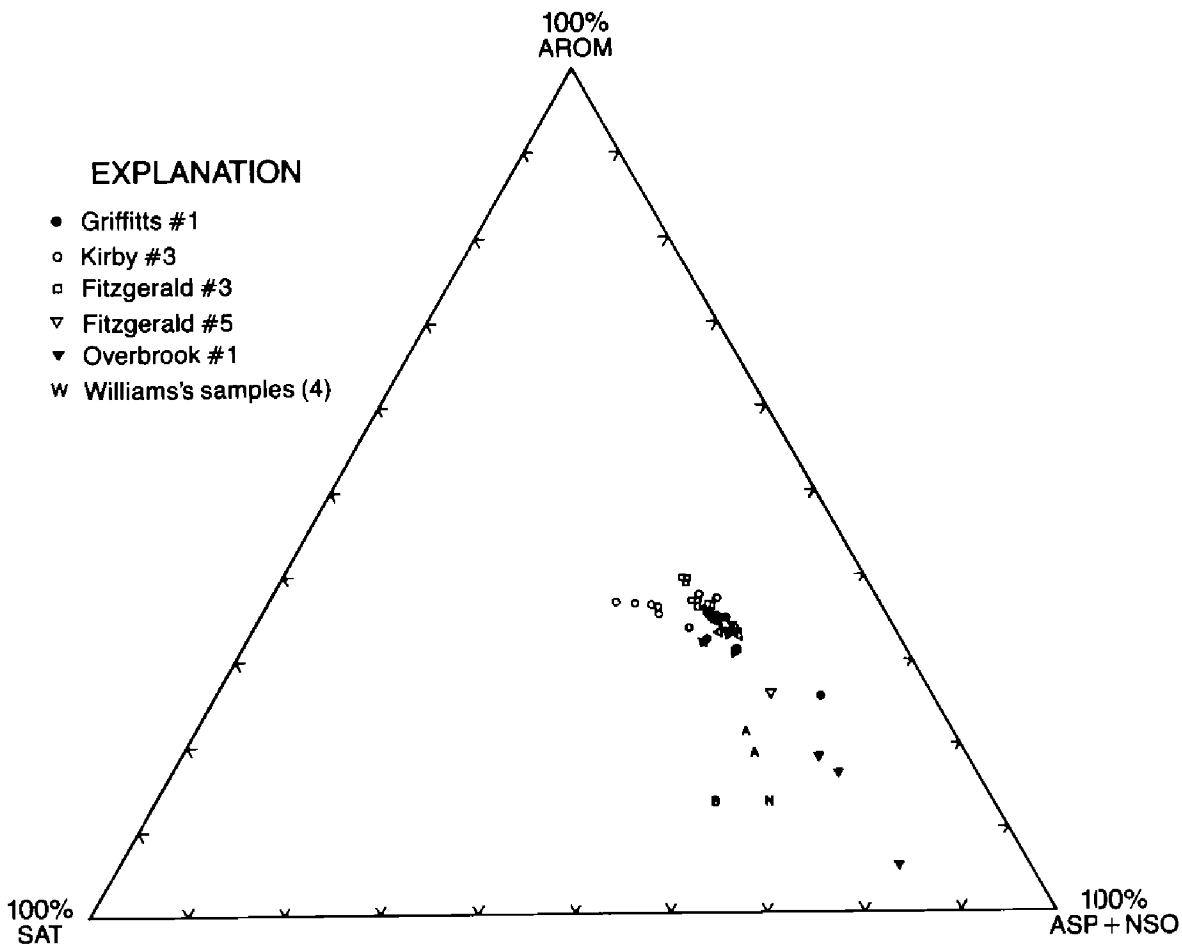

Figure 2. Bulk composition of Oklahoma tar sands. Literature values for Athabasca (A), Bemolanga (B), and Nigeria (N) tar sands are shown for comparison.

samples plot in the same portion of the graph. Furthermore, if one excludes the three shallow Overbrook samples discussed above, the shallowest Fitzgerald #5 sample and the Griffitts 73-ft sample, the plotted points form a tight cluster. Included for comparison are average values for Sulphur tar sands (Williams, 1983), as well as values representative of tar sands from around the world (Andrianasolo and others, 1985; Oluwole and others, 1985). However, direct comparison of these data should be made with caution, since details of separation techniques may vary among laboratories.

For all samples in this study, the bulk-composition values shown in Table 1 are consistent with a biodegraded oil and similar to those of other tar sands.

Capillary-Column Gas Chromatography

Capillary-column GC confirms that the samples are degraded and have much in common, but it also reveals striking differences not detectable by bulk characterization.

Representative saturate profiles from all five boreholes (Fig. 3) illustrate two features shared by all samples: an unresolved complex mixture (UCM) bimodal hump and a group of major peaks in the C_{27}+ region. All but the Griffitts profile contain the same distinguishable peaks in the tricyclic terpane region of the scan. Furthermore, the predominant peak on all but six (including the three Griffitts) generated saturate scans appears to be a C_{29} hopane. Aromatic profiles (Fig. 4) consist of one or two UCM humps and a few peaks at the heavy-molecular-weight end of the scan. The general absence of prominent n-alkanes, isoprenoids, and definable aromatics; the presence of UCM humps on both saturate and aromatic scans; and the seemingly enhanced abundance of steranes, hopanes, and tricyclic terpanes together support the conclusion these bitumens have endured moderate to heavy biodegradation.

The effect of biodegradation on the hopanes as illustrated by gas chromatography is puzzling. In the Fitzgerald #3 hole, the amount of $\geq C_{30}$ hopanes decreases with depth (Fig. 5)—the opposite of what would be expected from a near-surface alteration event. In the other boreholes, the pattern of hopane removal appears to be random (see, for example, the three Fitzgerald #5 scans in Fig. 6). Li-Hua (1987), studying more closely spaced samples from the latter borehole, encountered the same fluctuating pattern of hopane removal.

Excluding the Fitzgerald #3 series, in which there are no recognizable n-alkanes, nearly one-third of the remaining samples show traces of an n-alkane/isoprenoid fingerprint superimposed on the backbone distribution described previously as being associated with severe biodegradation. Examples of these chromatograms are shown in Figure 6. The presence of n-alkanes, ranging in these examples from C_{14} to C_{23}, is incompatible with moderate to severe levels of bacterial activity. As with the altered hopanes, these n-alkanes appear in samples at random intervals down the borehole. Could the complex geology of the region be distorting whatever bacterial degradation pattern developed?

In at least three samples—Kirby #3-28, Fitzgerald #5-180 and 240—it would seem that hopanes have been altered before n-alkanes have been completely removed (see Fig. 6). This particular order of biodegradation events has not been reported previously. Other researchers (Philp, 1983; Volkman and others, 1983; Leenheer, 1984; Philp and Gilbert, 1986; Sofer and others, 1986), faced with similar evidence, proposed that they were dealing with a mixture of biodegraded and non-biodegraded oil. Circumstances which could result in mixing (or apparent mixing) of oil(s) in a reservoir include: (1) multiple phases of oil generation or accumulation, including continuous migration (Volkman and others, 1983; Sofer and others, 1986); (2) cases in which a reservoir, once close to the surface and

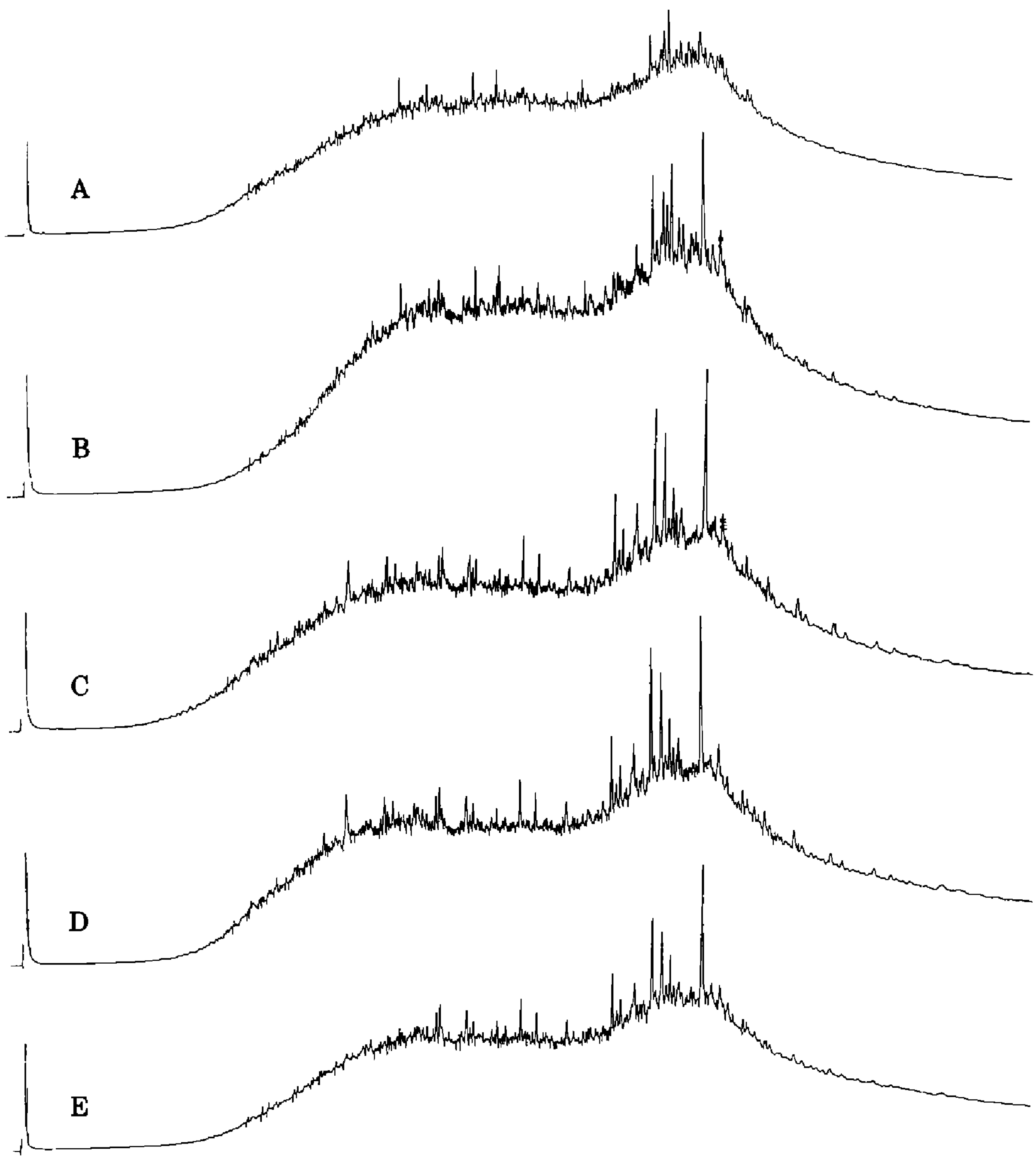

Figure 3. Representative gas chromatograms of saturate fraction. A, Griffitts #1. B, Kirby #3. C, Fitzgerald #3. D, Fitzgerald #5. E, Overbrook #1.

vulnerable to bacterial attack, is later buried to sufficient depth to escape further biodegradation (Howell and others, 1984; Sofer and others, 1986); (3) secondary generation of n-alkanes during in-reservoir maturation of asphaltenes (Amit and Bein, 1979; see also Sofer and others, 1986); (4) seep material working its way back into reservoir rocks (Demaison, 1977) (this would more likely involve lesser amounts of degraded material in larger quantities of non-degraded oil than the reverse); and (5) location in a basin midway between edge (where biodegradation is most advanced) and center (where producing field lies) (Demaison, 1977). Establishing the exact mechanism and/or sequence of events responsible for the contradictory characteristics exhibited by these samples requires not only further examination of their biomarkers but also, more important, consideration of the region's tectonic history.

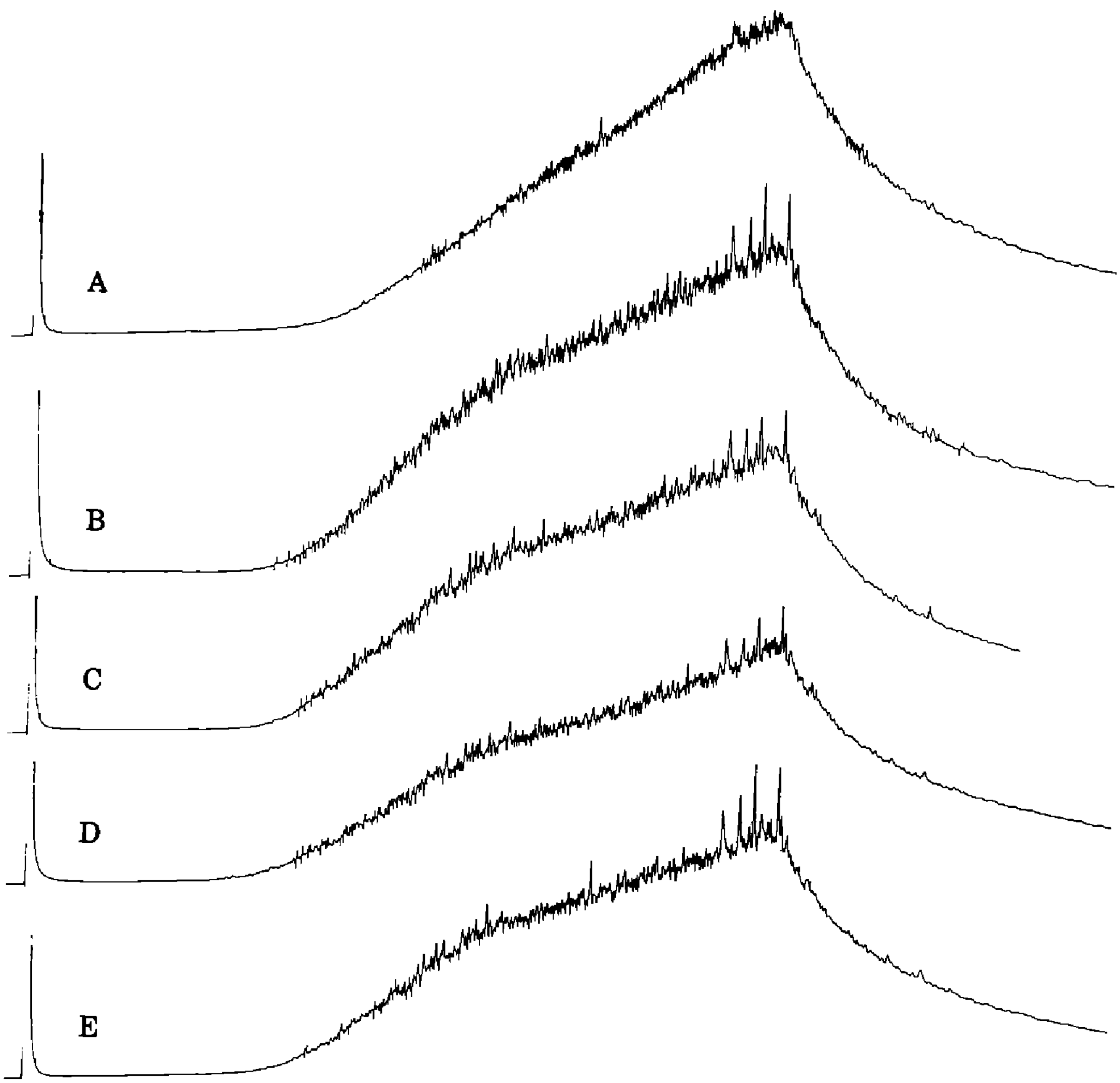

Figure 4. Representative gas chromatograms of aromatic fraction. A, Griffitts #1. B, Kirby #3. C, Fitzgerald #3. D, Fitzgerald #5. E, Overbrook #1.

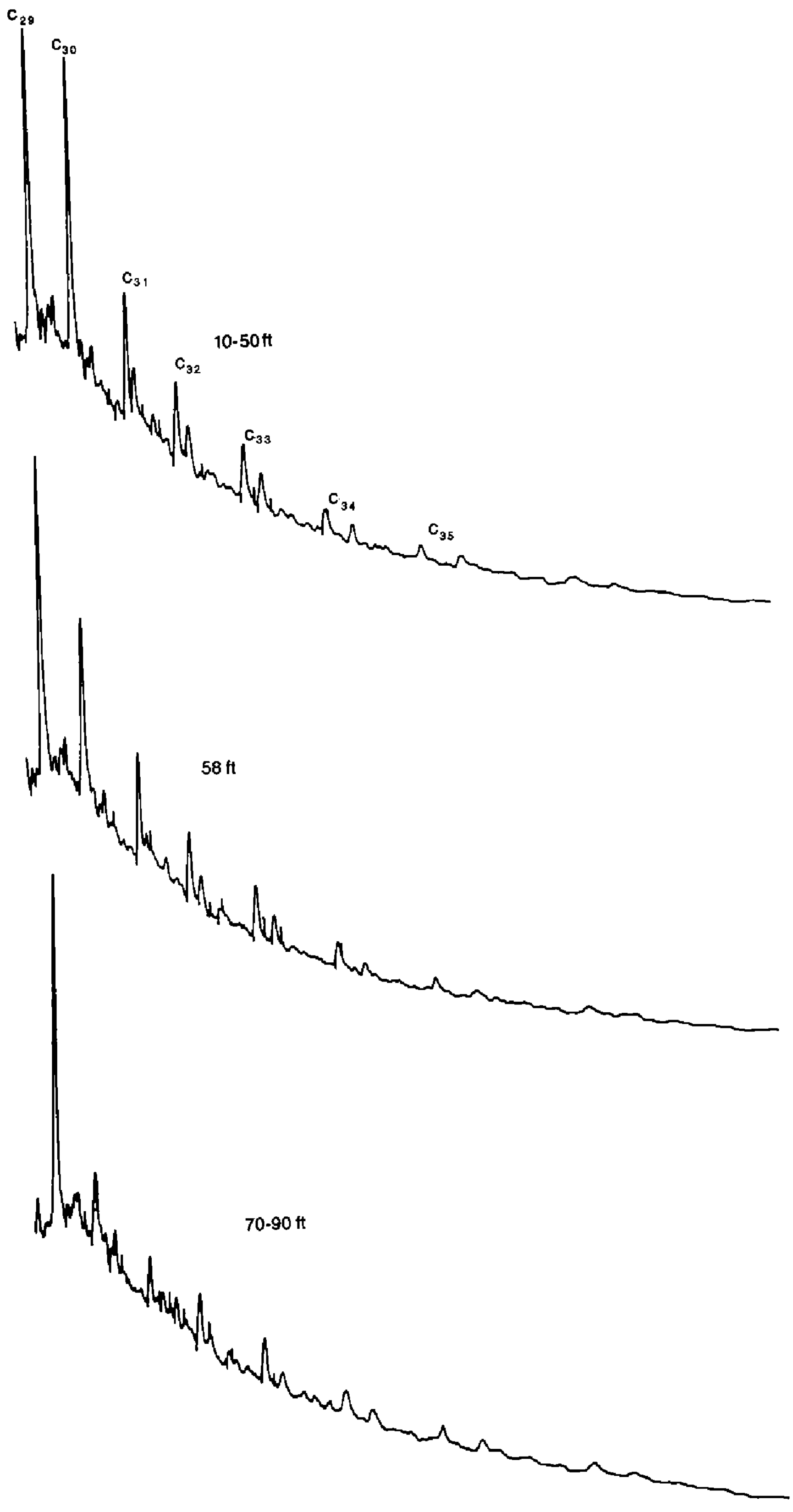

Figure 5. Decrease of hopanes with depth in Fitzgerald #3 borehole.

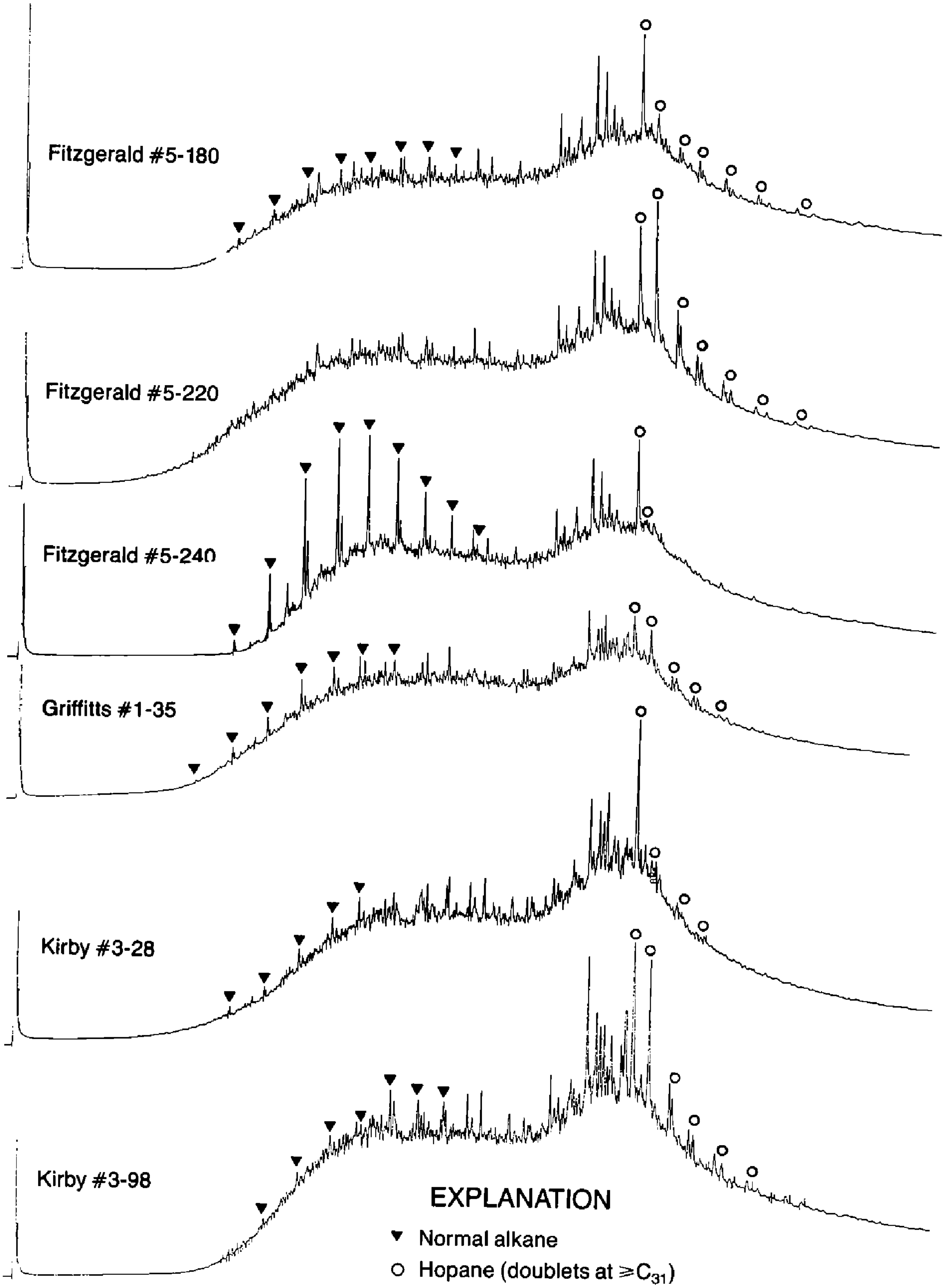

Figure 6. Gas chromatograms of saturate fractions showing presence of normal alkanes and extent of hopane removal.

Gas Chromatography–Mass Spectrometry

Two saturate fractions, Kirby #3-98 and Fitzgerald #3-42, were analyzed by GC–MS to obtain additional information about their levels of biodegradation. Steranes and terpanes were monitored through their characteristic intense fragment ions at m/e 217 and m/e 191, respectively. Tentative peak assignments are based on relative elution order and comparison with published data.

The sterane ion plots (Fig. 7) are not sufficiently resolved to apply ratios of individual isomers as biodegradation indicators. However, overall distributions are significant. The Fitzgerald sample, consisting primarily of rearranged (dia-) steranes, demonstrates almost total destruction of the regular steranes. The Kirby sample appears to have both regular and rearranged steranes, but mainly C_{29} regular steranes. This observation is consistent with previous reports that in a relatively well-degraded oil C_{27} regular steranes are removed prior to their C_{28} and C_{29} counterparts (see, for example, Rullkötter and Wendisch, 1982). Miiller and others (1984) referred to essentially identical sterane patterns obtained from Sulphur area tar sands as "severely biodegraded" and "biodegraded," respectively.

Co-elution on the terpane fragmentograms (Fig. 8) is less of a problem. Both fingerprints contain the same series of distinguishing peaks—tricyclic terpanes, a tetracyclic terpane, and pentacyclic hopanes—although in differing amounts. Since bacteria are not known to attack hopanes when simpler, more easily metabolized hydrocarbons are available, alteration of hopanes equates with a severe level of biodegradation. Clues which might signal hopane alteration include: (1) Depletion of $\geq C_{30}$ hopanes relative to the C_{27} and C_{29} hopanes (Rullkötter and Wendisch, 1982; Miiller and others, 1984). These 191 ion plots show that neither sample is lacking in C_{30} or C_{31} hopanes. Furthermore, gas chromatograms (only one of which is presented here in Fig. 6) of the same samples show hopanes through C_{35}. (2) Selective removal of the R epimer from R and S epimer pairs in extended hopanes (Goodwin and others, 1983; Leenheer, 1984). The 22S/22R ratio for the Kirby sample is 1.4, which is within the 1.4–1.6 range expected of a mature oil at equilibrium (Seifert and Moldowan, 1980; Philp, 1985). However, for the Fitzgerald sample, the ratio is 2.5. The 22R peak is visibly diminished, suggesting the possibility of bacterial activity. (3) Presence of demethylated hopanes (Rullkötter and Wendisch, 1982). Two peaks appear on each fragmentogram where one would expect to find the demethylated hopanes corresponding to C_{29} and C_{30} regular hopanes. For that reason, these peaks have been tentatively identified as demethylated hopanes.

Profiles of the tricyclic terpanes shown here are typical for oils, although the concentrations represented are relatively high (Aquino Neto and others, 1983). This apparent increased abundance is thought to reflect their ability to survive heavy biodegradation while more-susceptible compounds are destroyed (Leenheer, 1984; Mackenzie, 1984). The different relative peak heights of the tricyclic terpanes exhibited by these two samples may result from differences in their original organic material or depositional environment (see Philp and Lewis, 1987). However, migrational (Seifert and Moldowan, 1979) and biodegradational (Howell and others, 1984; Sandstrom and Philp, 1984) factors cannot be ruled out. Distributional variations somewhat similar to those encountered here were found by Sandstrom and Philp (1984) in their study of oil seeps in Tonga. But because the Tonga samples

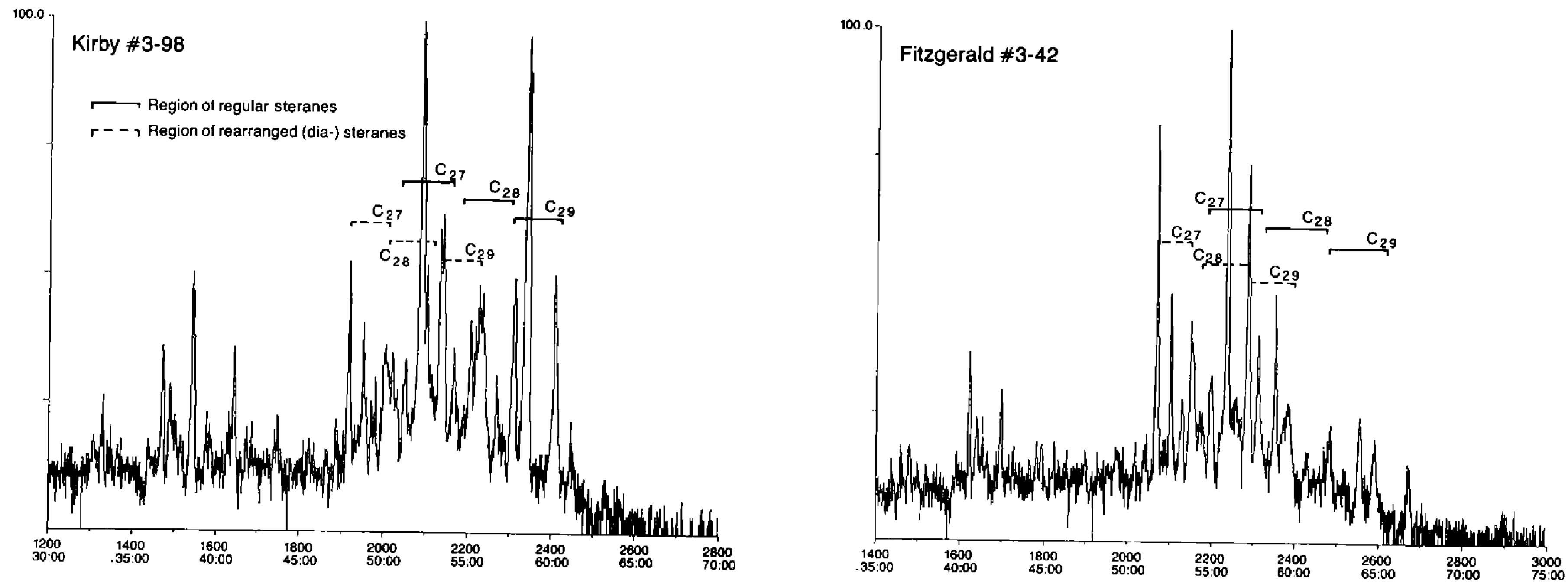

Figure 7. Steranes: m/e 217 mass fragmentograms.

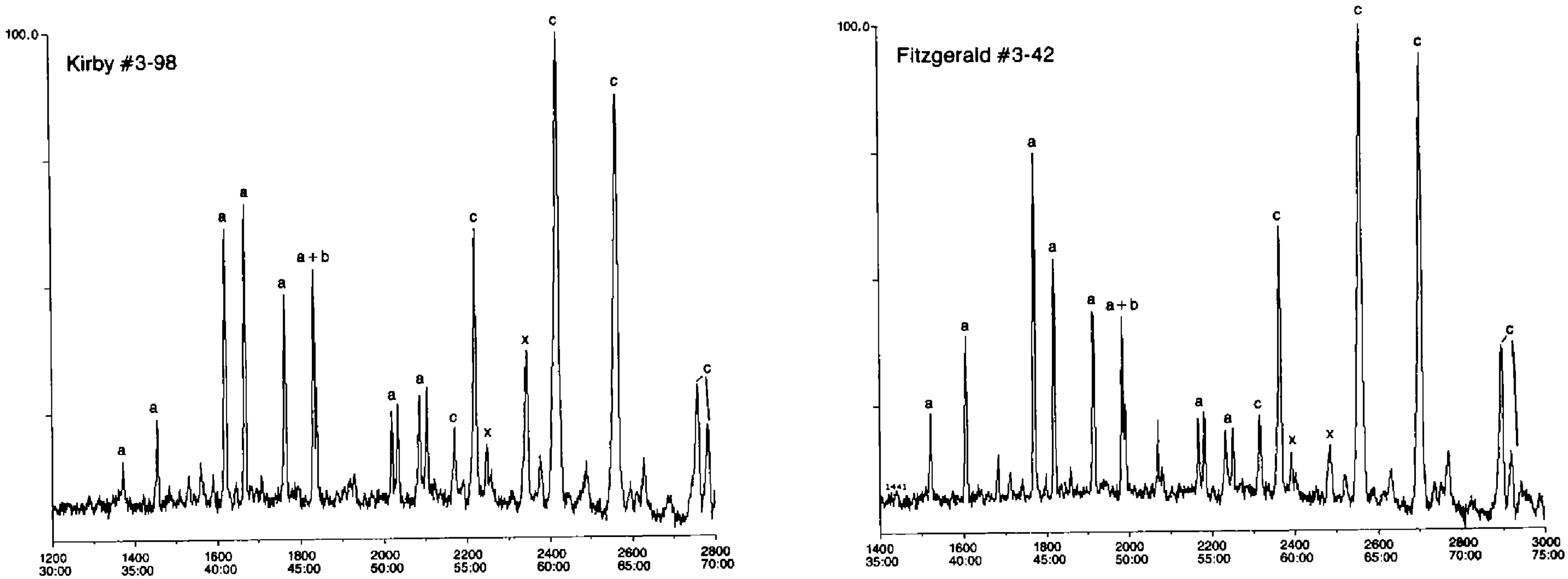

Figure 8. Terpanes: m/e 191 mass fragmentograms. a, tricyclic terpane. b, tetracyclic terpane. c, pentacyclic hopane. x, demethylated hopane(?).

were thought to derive from a common source, those workers suggested different levels of biodegradation as a possible cause for the variation.

In brief, m/e 191 fragmentograms of these two samples offer potential evidence of severe bacterial activity: the likely presence of demethylated hopanes, the prominence of tricyclic terpanes, and the elevated 22S/22R ratio of the C_{31} hopane in the Fitzgerald sample. Corresponding m/e 217 fragmentograms indicate that both samples are degraded, the Fitzgerald sample being severely affected. However, each sample can be presumed to represent only its particular depth interval, as GC analysis has already shown in four boreholes that detailed variations due to biodegradation are neither consistent nor predictable from one interval to the next.

Summary and Recommendation

Tar-sand bitumens from five boreholes in Carter and Murray Counties, Oklahoma, have been characterized by fractionation, capillary-column GC and GC–MS. The bitumens have similar bulk compositions, characteristic of degraded oil and comparable to those of other tar sands. GC analysis yields conflicting results for the degree of bacterial degradation experienced by the bitumens. Traces of n-alkanes are detectable in approximately one-fourth of the samples and appear at random depth intervals in four of the five boreholes. In three samples, n-alkanes co-exist with bacterially altered hopanes. This combination is attributed to the mixing of biodegraded and non-biodegraded oil in the reservoir. Limited GC–MS evidence from two sterane and hopane fragmentograms indicates a high level of biodegradation for the bitumens. Further work—directed toward smaller sample intervals and centered on more-specific information obtainable by GC–MS—is needed to help reconcile inconsistent findings and produce a more coherent picture of the chemical nature of Oklahoma tar sands.

Acknowledgments

I am very much indebted to R. Paul Philp of the University of Oklahoma, whose critical comments and valuable advice contributed greatly to this paper. I gratefully acknowledge Trevor Gilbert (CSIRO, Australia) and R. Paul Philp for providing the GC–MS data. Finally, I want to thank William E. Harrison (ARCO) for encouraging me in this research area and reading the manuscript.

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ANADARKO BASIN SYMPOSIUM SET FOR APRIL 5–6, 1988

The Oklahoma Geological Survey and the U.S. Geological Survey are co-sponsoring a symposium on the Anadarko basin. The meeting will be held April 5–6, 1988, at the Oklahoma Center for Continuing Education (OCCE) of the University of Oklahoma in Norman.

The focus of the symposium will be presentation of 24 papers dealing with current and ongoing research activities. Research topics include basin history, sedimentology, structure, petroleum exploration, source rocks, thermal history, oil characterization and migration, and basinal brines.

Provisional titles and speakers are listed below:

April 5

Geologic Evolution of the Anadarko Basin, by Kenneth S. Johnson

The Greater Anadarko Basin—An Overview of Petroleum Exploration and Development, by Herbert E. Davis and Robert A. Northcutt

Thermal Maturity of the Anadarko Basin, by James W. Schmoker

Thermal Maturation of the Woodford Shale in the Anadarko Basin, by Brian J. Cardott

Characterization and Origins of Natural Gases of the Anadarko Basin, by Dudley D. Rice, Charles N. Threlkeld, and April K. Vuletich

Geochemistry of Oils and Hydrocarbon Source Rocks in the Anadarko Basin, by Robert C. Burruss and Joseph R. Hatch

An Organic Geochemical Study of Oils, Source Rocks, and Tar Sands in the Anadarko Basin, by R. P. Philp, P. J. Jones, C. A. Lewis, L. H. Lin, and G. E. Michael

Structural Evolution of the Southeastern Portion of the Anadarko Basin Region, by William J. Perry, Jr.

Structural Evolution of the Slick Hills on the Southern Margin of the Anadarko Basin, by R. Nowell Donovan

Structural Styles in the Frontal Fault Zone, Wichita Uplift, Southwestern Oklahoma—Interrelationship of Basement Rock/Sedimentary Rock Deformation, by David A. McConnell

April 6

Stress Implications and Stratigraphic Relationships from Well-Bore Breakouts, Oklahoma and Texas Panhandle, by Richard L. Dart

Neotectonics and Seismicity of the Anadarko Basin, by Kenneth V. Luza

Anadarko Basin—Conodont Studies, by John E. Repetski

Diagenesis of Hydrocarbon-Bearing Rocks in the Ordovician Simpson Group, Southeast Anadarko Basin, by Janet K. Pitman and Robert C. Burress

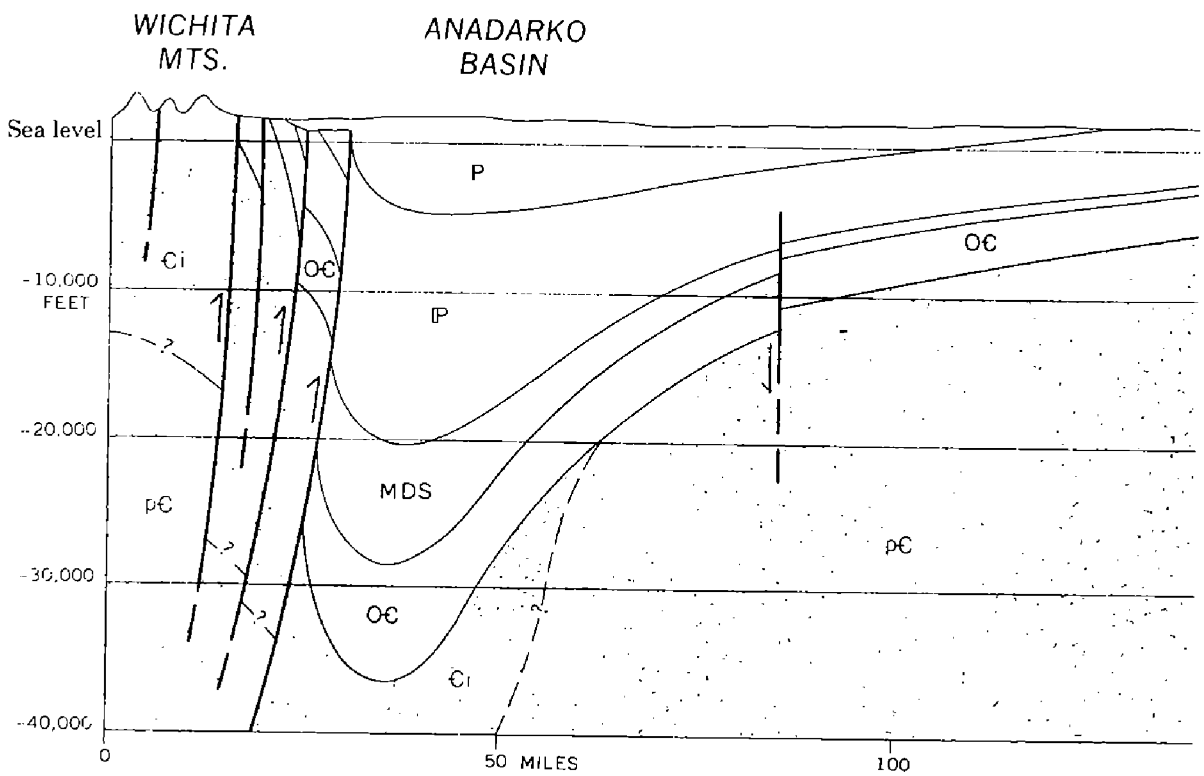
Depositional and Post-Depositional History of Middle Paleozoic (Late Ordovician through Early Devonian) Strata in the Anadarko Basin, by Thomas W. Amsden

Litho/Petro Facies of Siliciclastics of Morrow and Springer Rocks, Anadarko Basin, by C. William Keighin and Romeo M. Flores

Quantitative Petrographic Analysis of Desmoinesian Sandstones from Oklahoma, by Thaddeus S. Dyman
Paleohydrology of the Anadarko Basin, by Donald G. Jorgensen
Mineralogic Relations in Deeply Buried Rocks of the Simpson Group (Middle Ordovician)—Implications in Diagenesis and Applied Petroleum Geology, by Richard M. Pollastro
Magnetization and Sulfide Mineralization, Cement Oil Field, Oklahoma, by Richard L. Reynolds and Neil S. Fishman
Natural Resources Information System (NRIS)—Anadarko Basin Data, by Mary K. Grasmick

Registration costs will be $45 ($55 on-site), including two lunches and a copy of the proceedings. Lodging also will be available at OCCE at rates of about $27 (single) and $32 (double).

Contact Dr. Kenneth S. Johnson, Oklahoma Geological Survey, University of Oklahoma, Norman, OK 73019, phone (405) 325-3031, for registration forms and/or more information.



Presentation of Ian Campbell Award to Charles J. Mankin (right) by Kenneth S. Johnson.

MANKIN PRESENTED IAN CAMPBELL AWARD

The American Geological Institute Award in Memory of Ian Campbell was presented to Dr. Charles J. Mankin, director of the Oklahoma Geological Survey, the University of Oklahoma, on October 26, 1987. The prestigious medal was granted during the Awards Ceremony at the annual meeting of the Geological Society of America in Phoenix, Arizona. Highlights of the Awards Ceremony included the GSA Presidential Address, by Jack E. Oliver, presentations of the Penrose Medal to Marland P. Billings, the Day Medal to Don L. Anderson, and the Ian Campbell Award to Mankin. Presentation of the Ian Campbell Award, on behalf of AGI, was made by Dr. Kenneth S. Johnson, associate director of the OGS.

The award honors the memory of Dr. Ian Campbell, a renowned geologist who gave a lifetime of distinguished service to the geoscience profession and to society. Campbell was an educator, an administrator, and a public servant, and his service was given unselfishly to a great number of individuals and organizations. He had devoted 28 years to teaching and research at the California Institute of Technology, and then served for 10 years as state geologist and chief of the California Division of Mines and Geology. Campbell reached the statutory retirement age of 70 in 1969, but he continued serving many organizations until his death in 1978.

Campbell's recognition as a respected scientist and outstanding leader led him to the presidency of the following: Pacific Division of the American Association for the Advancement of Sciences (1958), American Geological Institute (1961), Mineralogical Society of America (1962), Association of American State Geologists (1965), and the Geological Society of America (1968). He held high offices in numerous other professional organizations, and received many awards from the various societies and groups that he assisted or served. Campbell's life and accomplishments are warmly and fully described by Richard H. Jahns in his *Memorial to Ian Campbell, 1899–1978*, which was published by the Geological Society of America.

As described by AGI, the "AGI medal in memory of Ian Campbell is given in recognition of singular performance in and contribution to the profession of geology. Candidates should be measured against the distinguished career of Ian Campbell, whose service to the profession touched virtually every facet of the geosciences." Since initiation of the award in 1981, a series of distinguished geoscientists have been recipients: Richard H. Jahns (1981), Hollis D. Hedberg (1983), Konrad B. Krauskopf (1984), Robert L. Heller (1985), William B. Heroy, Jr. (1986), and Charles J. Mankin (1987). The last two awards were presented during the Awards Ceremonies at the annual meeting of the GSA, and this has provided a well-deserved recognition to the award and to the recipient.

The following is the text of Johnson's presentation, as made to Mankin at the Awards Ceremony:

"This is a double honor and a privilege for me to be here: first, it is an honor to be able to present the American Geological Institute Award in memory of Ian Campbell, a man who was a respected scientist and an outstanding leader; and second, it is an honor to present the award to Charlie Mankin, who in all ways embodies the qualities of Ian's life and contributions.

"Ian Campbell, who died in 1978, was an exceptional professor and researcher at Cal Tech, and later was the state geologist of California. He served as president, and held many other offices, for most of the major geological societies and associations. Ian was a geologist, an educator, an administrator, and a public servant, and his impact on the geosciences community was great.

"I have known Charlie Mankin for nearly 30 years, and have worked closely with him for the past 20 years. So I am well aware of his many contributions to the geosciences.

"Charlie received his undergraduate and graduate degrees at the University of Texas in Austin, and then spent one year as a postdoctoral fellow at the California Institute of Technology. He arrived at the University of Oklahoma as an assistant professor in 1959, and subsequently became director of the School of Geology and Geophysics (1963–77), director of the Oklahoma Geological Survey (1967–present), and director of the Energy Resources Institute (1978–87). While at the University of Oklahoma, Charlie has supervised more than 50 students in the completion of their master's or doctoral degrees, and has published extensively in the scientific and technical literature.

"In the past 10 years, Charlie's efforts have been mainly in State and national service to the geosciences profession and to the public. He has served as an officer in many technical and scientific organizations, and has served as president of the Association of American State Geologists, the American Geological Institute, the American Institute of Professional Geologists, and the Midcontinent Section of the Society of Economic Paleontologists and Mineralogists. He has also served for the past 20 years as national secretary-treasurer of Sigma Gamma Epsilon, the National Student Earth Science Honorary Society. Charlie is a past member of the Council and of the Executive Committee of the Geological Society of America, and currently serves on the Board of Trustees of the GSA Foundation.

"Charlie has also served on numerous national commissions, councils, and committees. He served as a member of the Commission on Fiscal Accountability of the Nation's Energy Resources, and is now chairing the Advisory Committee on Royalty Management for the U.S. Department of the Interior. He has served on more than a dozen boards and committees of the National Academy of Sciences; at present he chairs the Board on Mineral and Energy Resources, and also chairs the Panel on Earth Sciences and Applications of the Commission on Physical Sciences, Mathematics, and Resources. In 1983 Charlie received the U.S. Department of the Interior Conservation Service Award.

"Charlie is a person who is constantly on the move. He is a uniquely unselfish and giving person whose goal is to contribute to his profession, to his students, to his co-workers, and to society: in this way he embodies the spirit and the memory of Ian Campbell."

Kenneth S. Johnson

Barbara L. Lowry-Chaplin

GEOLOGIC RESEARCH ASSISTANT JOINS OGS

Research assistant Barbara L. Lowry-Chaplin is the newest member of the Oklahoma Geological Survey's coal section.

Working with coal geologists Samuel A. Friedman and LeRoy A. Hemish and organic petrologist Brian J. Cardott, Barbara assists in compiling the coal data base, which is part of a cooperative agreement between the OGS and the U.S. Geological Survey's National Coal Resources Data System (NCRDS) program. Her responsibilities include coding coal data for computer entry and preparing quadrangle maps for digitizing data-point locations by the USGS. She also works with OGS geological data coordinator Michelle Summers, who helps with data computerization.

Barbara recently earned an M.S. in geology from the University of Texas at Arlington; she received a B.S. in geology from Morehead State University in Kentucky. Her master's thesis is a proposed depositional model of a Lower Mississippian deltaic sequence (Cowbell Member, Borden Formation) in northeastern Kentucky. She has co-authored several publications on planetary geology and Mississippian geology in northeastern Kentucky.

While a student, Barbara worked for two years as a graduate teaching assistant in the geology department at the University of Texas at Arlington; for three years as a research assistant in geology at Morehead State University, where she studied Devonian–Mississippian biostratigraphy; and two summers as a research assistant at NASA-Goddard Space Flight Center in Greenbelt, Maryland, where she participated in planetary geologic studies of Mercury and Mars.

Barbara is a member of the Geological Society of America.

AAPG ANNUAL CONVENTION
Houston, Texas, March 20–23, 1988

As members of the Houston Geological Society, we take great pride in hosting the 73rd AAPG annual convention and invite you to join us for a very special three-day event. From the beginning, our goal has been to meet the various technical, social and business interests of all AAPG, SEPM, DPA and EMD members. These efforts have produced a timely program which is broad in scope, yet practical and pertinent to today's environment. The technical program not only spans the operating spectrum from production to exploration, but also the geological spectrum from diagenesis to global event.

The several pre- and post-convention field trips provide special opportunities for viewing first-hand the geology of the three major adjacent hydrocarbon provinces. Your selection spans the local to international, and the subterranean to extraterrestrial. The variety continues with your opportunity to select from nine short courses which span subjects from core workshop to exploration concepts on the grand scale. Similarly, the Exhibits will once again present a broad sample of state-of-the-art technologies available from the service sector of our industry.

In keeping with the changing times, the Employment Information Center will offer not only traditional placement services, but also two seminars directed toward the special problems of operating in today's business environment.

Naturally, the social program will provide a wide range of entertainment, ranging from a favorite sporting event to cultural opportunities. The spouse activities are almost non-stop and highlight Houston's many natural and cultural assets via field trips, tours, and shopping trips.

So join us March 20–23, 1988 and we will ply you with new ideas and fresh experiences amid Houston's beautiful new convention center and the famous bluebonnets and azaleas of the delightful Texas spring.

—Dick Bishop
General Chairman

AAPG Annual Convention Agenda

Technical Program

March 21

AAPG Development Geology I—Case Histories
AAPG Structural/Stratigraphic Evolution of Convergent Basins
Foreland Basin System
SEPM Carbonate Sedimentation
Forum of Business Strategies
SEPM Siliciclastic Depositional Systems I
AAPG Geochemical Formation Damage
AAPG Geology of Arctic National Wildlife Refuge and Other Alaska Provinces
AAPG Applications of Organic Geochemistry

March 22

AAPG Hydrocarbon Distribution and Structural Styles
AAPG Future Petroleum Provinces of North America I—Canada
SEPM Sandstone Diagenesis and Reservoir Quality
SEPM Research Symposium: A Global Comparison of Miocene Reefs I
AAPG Research Symposium: Analysis of Naturally Fractured Reservoirs
EMD Remote Sensing/Energy Minerals Outlook and Applications
AAPG New Exploration Concepts and Methods
AAPG Seismic Expression of Sedimentary Bodies
AAPG Development Geology II—3-D Seismic in Field Development
AAPG Future Petroleum Provinces of North America II—USA
AAPG New Exploration Concepts in Mature Basins
SEPM Research Symposium: A Global Comparison of Miocene Reefs II
AAPG New Concepts on Growth Faults
AAPG Seals for Hydrocarbon Traps
AAPG Subsidence and the Petroleum Industry
SEPM Geology of the Permian, West Texas and New Mexico
SEPM Geochemistry of Fine-Grained Strata

March 23

AAPG Development Geology III—Integrated Field Studies
AAPG Geology of Current Plays—Lower 48
AAPG/SEPM New Looks at Stratigraphic Cyclicity
SEPM Carbonate Diagenesis I
AAPG Structural/Stratigraphic Evolution of Divergent Basins
AAPG Development Geology IV—Facies Control of Reservoir Properties and Fluid Flow
AAPG Major Foreign Exploration Successes, 1983–88
AAPG Salt Tectonics and Patterns of Basin Fill

SEPM Carbonate Diagenesis II—Dolomites
AAPG Basin Evaluation and Assessment
SEPM Surprising New Applications of Paleomagnetism
AAPG New Play Concepts
SEPM Siliciclastic Depositional Systems II

Short Courses

HGS Deltaic Sedimentation on the Northern Gulf of Mexico Continental Shelf, Slope, and Basin, *March 19*
HGS Sequence Stratigraphic Interpretation of Seismic, Well, and Outcrop Data, *March 19*
HGS Exploration in Mature Basins, *March 19*
SEPM Core Workshop for Students (students only), *March 19*
AAPG Development Geology, *March 19–20*
SEPM Clay Minerals for Petroleum Geologists and Engineers, *March 19–20*
HGS Structural and Depositional Styles of Gulf Coast Cenozoic Continental Margins, *March 20*
EMD Remote Sensing for the Petroleum and Energy Minerals Industry: Exploration Applications, *March 20*
SEPM Giant Oil and Gas Fields—A Core Workshop, *March 20*
SEG Seismic and Geological Analysis of Fractured Reservoirs, *March 20*
AAPG Sequence Stratigraphic Interpretation of Seismic, Well, and Outcrop Data (students only), *March 20*

Field Trips

SEPM Lower Cretaceous Carbonates of the Edwards Plateau, Texas, *March 18*
SEPM Coastal and Shallow Marine Sedimentation on the Mississippi River Delta Plain and Chenier Plain, *March 18*
HGS Recent Sediments of Southeast Texas, *March 19*
HGS Environmental Geology of East Harris County, Texas, *March 19*
HGS Houston Downhole Sensors Facility, Schlumberger Well Services, *March 19*
HGS Experience the Third Dimension—3-D Seismic Data Acquisition, *March 19*
HGS Chevron Drilling Technology Center, *March 20*
AAPG Recent Sediments of Southeast Texas (students only), *March 20*
HGS Geology of the Big Bend–Trans-Pecos Region: The Geologic History of the Last 50 Million Years, *March 23*
HGS Inside the Avery Island Salt Dome, *March 23*
HGS Upper Jurassic–Lower Cretaceous Platform Basin System (Northeastern Mexico), *March 23*
HGS Modern Carbonates Sedimentation, San Salvador Island, Bahamas, *March 24*
HGS Johnson Space Center (JSC) and Lunar and Planetary Institute (LPI), *March 24*
HGS Southern Oklahoma Aulacogen, *March 24*
EMD Texas Lignite Belt—A Tour of Outcrops and Producing Mines, *March 24*

SEPM Early Paleozoic Submarine Sedimentation and Facies in the Ouachita Trough, Arkansas and Oklahoma, *March 24*

SEPM Depositional Sequences, Shelf Sandstone Facies, and Hydrocarbon Accumulation in Upper Cretaceous Strata of the San Juan Basin, New Mexico, *March 24*

For further information about the annual meeting, contact AAPG, Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 584-2555. The preregistration deadline is February 20.

ARBUCKLE MOUNTAINS GUIDEBOOK AVAILABLE FROM BAYLOR UNIVERSITY

Tectonism and Sedimentation in the Arbuckle Mountain Region, Southern Oklahoma Aulacogen is a field-trip guidebook prepared in 1985 by members of the Baylor student chapter of AAPG and the Baylor Geological Society. The report is edited by William G. Brown and Robert C. Grayson, Jr., faculty advisors; and William H. Jamieson, Jr., and Jay Timothy Altum, student editors.

The 43-page guidebook contains a discussion of the southern Oklahoma aulacogen and a structural interpretation of the region, along with descriptions of 16 field-trip stops. The first nine stops of the trip emphasize the pre-orogenic paleozoic sediments and structural style of the Arbuckles, whereas the last seven stops emphasize the synorogenic and post-orogenic deposits resulting from the Arbuckle orogeny. The guide includes many of the classic stops that are a "must" on any field trip to the Arbuckles, along with several other interesting stops that are not frequently visited.

The guidebook is well organized and reads well. It was written by a number of Baylor students, under general direction of faculty members, and thus was written at a level that is understandable both by geology students with a background in stratigraphy and structure, and by the professional geologist.

Copies of the guidebook are available at $10 each from Baylor University, Dept. of Geology, Waco, TX 76798; (817) 755-2361.

Kenneth S. Johnson

UPCOMING MEETINGS

Fourth Annual V. E. McKelvey Forum on Mineral and Energy Resources, "Roles of Geological Research in Assessment of Energy Resources," March 1–2, 1988, Denver, Colorado. Information: Buhler and Abraham, Inc., 8700 First Ave., Silver Springs, MD 20910; (301) 588-4177.

American Society for Photogrammetry and Remote Sensing, Annual Convention, March 13–18, 1988, St. Louis, Missouri. Information: American Society for Photogrammetry and Remote Sensing, 210 Little Falls St., Falls Church, VA 22046; (703) 241-2446.

SEPM, North American Micropaleontology Section, Quantitative Biostratigraphy Short Course, March 19–20, 1988, Houston, Texas. Information: Society of Economic Paleontologists and Mineralogists, P.O. Box 4756, Tulsa, OK 74159-0756; (918) 743-9765.

NOTES ON NEW PUBLICATIONS

Planning Report for the Edwards-Trinity Regional Aquifer-System Analysis in Central Texas, Southeast Oklahoma, and Southwest Arkansas

This 15-page USGS water-resources investigations report was written by P. W. Bush.

Order WRI 86-4343 from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Bldg. 41, Box 25425, Denver, CO 80225. The price is $3 for a paper copy and $4 for microfiche; add 25% to the price for foreign shipment.

Petrographic Compositional Data for Atokan through Virgilian Sandstones in Oklahoma

Written by T. S. Dyman, this USGS open-file report contains 15 pages.

Order OF 87-0137 from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Box 25425, Denver, CO 80225. The price is $4 for microfiche and $2.75 for a paper copy; add 25% to the price for foreign shipment.

Annual Yield and Selected Hydrologic Data for the Arkansas River Basin Compact, Arkansas–Oklahoma, 1986 Water Year

M. A. Moore, T. E. Lamb, and S. P. Blumer are the authors of this 38-page USGS open-file report.

Order OF 87-0203 from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Box 25425, Denver, CO 80225. The price is $4 for microfiche and $6.50 for a paper copy; add 25% to the price for shipment outside North America.

OKLAHOMA ABSTRACTS

The Oklahoma Geological Survey thanks the American Association of Petroleum Geologists and the authors for permission to reprint the following abstracts of interest to Oklahoma geologists.

Distribution of Petroleum Reservoirs Relative to Allocycles and Autocycles, Upper Portion of the Cherokee Group (Middle Pennsylvanian, Desmoinesian), Mid-Continent Region, U.S.A.

ROBERT L. BRENNER, University of Iowa, Iowa City, IA, and Kansas Geological Survey, Lawrence, KS

Sequences of mud rocks, lenticular sandstones, coals, and thin carbonates form autocycles and allocycles in the upper portion of the Cherokee Group. Autocycles delineated in eastern Kansas and northern Oklahoma are relatively local in extent, while allocycles are traceable over the entire region. All autocycles delineated in this study are embedded within the regressive portions of allocycles.

Petroleum-bearing sandstones consist of shoestring-shaped and thin sheetlike units in thicker sedimentary lobes. These lobes were deposited as deltaic complexes, which included fluvial and distributary channel sands, interdistributary muds, crevasse splay sands and muds, flood-basin muds, delta-front sands, and predeltaic muds. Delta lobes prograded across the margins of the Middle Pennsylvanian epeiric sea during times of eustatic stillstand or regression. When lobes were abandoned, waves and currents winnowed their upper portions, leaving thin sheetlike lenses of sand. These reworked sands along with marine muds above regressive deltaic sequences form the transgressive parts of autocyclothems. The transgressive parts of allocyclothems, generally consisting of marine shale, resulted from sea level rises that rapidly shifted shorelines far northeastward, moving siliciclastic sources away from the study area.

The positions of reservoir-containing deltaic complexes were determined by strandline positions at various sea levels. Extent of eustatic sea level changes appears to have been the major mechanism that controlled the distribution of petroleum reservoir and source units. In addition, sea level changes probably were a significant factor in the nature of diagenetic alterations that affected reservoir properties.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 534.

Preliminary Statistical Analysis and Provenance Trends in Desmoinesian Sandstones from Central and Eastern Oklahoma

T. S. DYMAN, U.S. Geological Survey, Denver, CO

Desmoinesian sandstones from the northern Oklahoma platform and from the Anadarko, McAlester, and Ardmore basins record a complex interaction between

mid-Pennsylvanian source-area tectonism and cyclic sedimentation patterns associated with transgressions and regressions. Framework grain summaries for 51 thin sections from sandstones of the Krebs, Cabaniss, and Marmaton Groups and their surface and subsurface equivalents were subjected to multivariate statistical analyses to establish regional compositional trends for provenance analysis.

R-mode cluster and correspondence analyses were used to determine the contributing effect (total variance) of key framework grains. Fragments of monocrystalline and polycrystalline quartz, potassium feldspar, chert, metamorphic and volcanic rock, and limestone contribute most to the variation in the grain population. Q-mode cluster and correspondence analysis were used to identify four petrofacies. Petrofacies I is rich in monocrystalline quartz (78 to 98%) and contains rare mica and rock fragments. Petrofacies II is also rich in monocrystalline quartz (60 to 84%) and contains as much as 12% total rock fragments. Petrofacies III and IV are compositionally heterogeneous and contain variable percentages of monocrystalline and polycrystalline quartz, potassium feldspar, mica, chert, and metamorphic and sedimentary rocks.

Quantitative analyses indicate that Desmoinesian sandstones were derived from sedimentary, igneous, and metamorphic source areas. Petrofacies I sandstones are restricted to the eastern and extreme western part of Oklahoma, whereas petrofacies II through IV sandstones are distributed throughout the state. The distribution of petrofacies is related to paleotectonics and basin development, sediment recycling, and varying depositional environments.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 551. [Subsequent author modifications have been added.]

Regional Variations in Crude Oil Geochemistry, Anadarko Basin, Oklahoma, Texas, and Kansas—Evidence for Multiple Sources, Mixing, and Migration Distances

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Geochemical analyses of 96 crude oil and condensate samples from the deep Anadarko basin and adjacent shelf areas show three major oil types, which generally correlate with reservoir age. Analyses include C_3–C_{30} whole oil gas chromatography, $C_{10}+$ saturated hydrocarbon fraction gas chromatography, carbon stable isotopes (ppt relative to PDB) of saturated (sat) and aromatic (arom) hydrocarbon fractions, and computerized GC/MS of selected samples. Three samples from Ordovician Simpson Group reservoirs are "typical" Ordovician oils (type 1), having strong odd-carbon predominance in the C_{13} to Cr_{19} n-alkanes, containing little or no acyclic isoprenoids, and $\delta^{13}C$ of −33.9 ppt (sat) and −33.7 ppt (arom). Oils from Devonian and Mississippian reservoirs (type 2) show little or no odd-carbon predominance in the n-alkanes, an exponential decrease in abundance with increasing carbon number, pristane/phytane ratios (pr/ph) of 1.1 to 1.5, and $\delta^{13}C$ of −30.6 ppt (sat) and −30.1 ppt (arom). Oils in Pennsylvanian reservoirs (type 3) have the greatest amounts of $C_{15}+$ hydrocarbons of all the oils, are isotopically heavy [−27.5 ppt (sat) and −26.4 ppt (arom)], have methyl-cyclohexane as the most abundant hydrocarbon, and have pr/ph values from 1.8 to 0.9. Type 3 oils with pr/ph <1 form a subgroup in the Texas and Oklahoma Panhandles. Condensates correlate with the three oil types based on carbon isotopic and gasoline-range compositions.

Oils of type 2 composition occur in rocks of Ordovician to Pennsylvanian age in complex structural traps near the Arbuckle Mountains and in subcrop plays where Pennsylvanian reservoirs directly overlie Devonian and older rocks. Such traps also contain oils that could be mixtures of types 2 and 3 and types 1 and 2. Oils from the Kansas shelf are similar to the Anadarko oil types except that they have only traces of toluene and no detectable benzene. These compounds are removed by water washing and, hence, could have been lost by contact with formation water during long-distance migration. The lack of mature source rocks in southern and central Kansas and the loss of benzene and toluene is consistent with oil migration from the central Anadarko basin.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 535.

Ouachita–Appalachian Juncture: A Paleozoic Transpressional Zone

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The late Paleozoic collision of the Gondwana supercontinent with the trailing southern margin of North America created the Ouachita and Appalachian orogenic belts. Transecting these belts are several transpressional or wrench fault zones, including the Val Verde basin–Texas lineament system, the Ardmore–Anadarko basin trend, and the Reelfoot rift complex. Vertical movement within these wrench zones resulted in the emplacement of pop-block or flower structures. In Texas and Oklahoma these features are major structural traps for oil and gas. In this work, we propose that the (buried) juncture between the Ouachita and Appalachian foldbelts in Mississippi is a similar transpressional fault zone.

Recent reconstructions of the collision between Gondwana and North America indicate a relative closure direction of southeast to northwest. Normal decollement thrusting occurred in the Appalachian and Ouachita foldbelts, where the structural grain of the North American margin was nearly perpendicular to the closure direction. Where the structural grain was oblique to closure direction, wrench faulting and high-angle thrust faulting occurred, due to the combined effect of both translational and compressional stress fields.

In southwestern Alabama and Mississippi the trailing North American plate margin consisted of Mississippian and Pennsylvanian clastics draped over a thick Cambro–Ordovician carbonate shelf. This shelf trends northeast–southwest in Alabama but turns sharply to trend north–northwest in Mississippi, possibly reflecting changes in Precambrian basement relief. Transpressional stresses would have been generated near this sharp bend during the collision. This study identifies one such transpressional fault zone, on the basis of seismic data and well control, in east-central Mississippi.

The shear zone trends north–south just west of the Alabama–Mississippi state line and lies between the normal northwest-verging overthrusts of the buried Alabama Appalachians and the less-organized structures in the Paleozoic section of central Mississippi. A number of pop-block structures have been identified within this system, and two have been drilled. The results of these wells support the interpretation presented here.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 563.

Facies Analysis, Paleoenvironmental Interpretation, and Diagenetic History of Britt Sandstone (Upper Mississippian), Southeastern Anadarko Basin, Oklahoma

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The Britt sandstones record a regressive-transgressive couplet in response to deltaic progradation, abandonment, and subsidence in the southeastern Anadarko basin during the Late Mississippian. Four principal facies compose the sequence: (1) deltaic bar-finger sands, (2) shelf sand ridges, (3) delta-destructional sand bars, and (4) storm deposits.

Platform sands were reworked into shelf sand ridges in the mid-shelf with elongated delta-destructional bars forming along the subsiding delta front. Storm surges mixed coarse-grained coquinoid sands with muds and silts typical of lower energy environments. Scouring of storm deposits into underlying sediments was common.

Petrologically mature, with the exception of storm deposits, each facies is quartzitic with trace amounts of potassic and plagioclase feldspar, rock fragments, and heavy minerals. Glauconite is restricted to delta-destructional sand bars. Storm deposits are dominated by fragmented fossils and quartzitic sands.

Numerous episodes of diagenetic activity have altered extensively the reservoir quality of these sands. Volumetrically, carbonate and silica cementation were the most important processes. Chlorite is the dominant authigenic clay mineral. Porosity is predominantly secondary; dissolution of quartz and quartz overgrowths provided much of the reservoir in these highly productive strata.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 563.

Aspects of Thermal Evolution of Anadarko Basin, Oklahoma

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Individual microcline-bearing clasts in cores from depths of 2.17, 3.27, 3.34, 3.57, and 4.40 km provided to us by the Oklahoma Geological Survey yield $^{40}Ar/^{39}Ar$ age spectra showing a clear correlation for the Pennsylvanian–Permian granite wash between depth and radiogenic ^{40}Ar ($^{40}Ar^*$) loss, consistent with the expectation that the deeper parts of the Anadarko basin have experienced the higher temperatures. A less-expected result is that the initial ages in the five age spectra converge at ~100 Ma, indicating these samples were hot enough to cause diffusive loss of $^{40}Ar^*$ from the microcline lattice until as late as Albian times. Activation energies for this process are very similar to some of those involved in producing fluid hydrocarbons from organic matter. We therefore suggest that although there is good evidence of petroleum generation in the Anadarko basin by the end of the Permian, progressively larger volumes of source rock may have resided within the oil window in the Triassic to Early Cretaceous as the thick sediments of the basin warmed by conduction. Plateau ages indicate that temperatures as high as 180°C were obtained during the Mesozoic in rocks now lying at a depth of about 4 km. The coherence of the age spectra strongly suggests abrupt uplift of the basin beginning 100 Ma, removing perhaps 2 km of sediment by erosion.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 565.

Relationships Among Thermal Maturity, Sandstone Diagenesis, and Reservoir Quality in Pennsylvanian Strata of the Arkoma Basin

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Relationships among elevated thermal maturity, sandstone diagenesis, and reservoir quality have been examined in Atokan and Desmoinesian strata of the Arkoma basin that are characterized by vitrinite reflectance values ranging from less than 1 to more than 5%. Good reservoir quality and significant gas reserves exist in patterns that do not appear to be influenced by either lateral or vertical thermal maturity trends.

In most sandstones, diagenetic processes that occurred during shallow burial exerted a significant influence on reservoir quality. For example, the presence of early chlorite grain coatings, the occurrence of which is largely facies dependent, helped preserve reservoir quality by inhibiting precipitation of quartz cement. In sandstones lacking chlorite grain coatings, quartz cementation destroyed most porosity prior to the generation of hydrocarbons.

During deeper burial, accumulation of hydrocarbons in porous sandstones located in favorable structural positions effectively terminated inorganic diagenesis and prevented further deterioration of reservoir quality. However, intergranular pressure solution and quartz cementation proceeded below hydrocarbon-water contacts. This postaccumulation diagenesis occurred during or following metagenesis as evidenced by cement filling bubbles and cracks in pyrobitumen. Thus, good reservoir quality was maintained because of the presence of hydrocarbons, even though they were being thermally degraded during continued maturation. These results indicate that sandstone reservoir quality and significant gas reserves can be preserved to extreme levels of thermal maturity ($R_0 > 5\%$) if accumulation predates overmaturation. However, sandstones in positions unfavorable for accumulation experience total destruction of reservoir quality as a result of high-temperature diagenesis.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 568–569.

Effects of Biodegradation upon Porphyrin Biomarkers in Upper Mississippian Tar Sands and Related Oils, Southern Oklahoma

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Organic molecules present in oils which show a structural relationship to their biological precursors are referred to as biomarkers. These compounds are becoming widely used in oil exploration for making oil-oil, oil-source rock correlations and undertaking maturation and migration studies in basin analysis. Treibs first discovered the presence of porphyrins in oils, shales, and coals over 50 years ago. Porphyrins are predominantly derived from chlorophyll precursors present in plants and bacteria. Studies of changes in porphyrin distributions with increasing maturation due to the effects of increased time of burial and temperature have been performed. However, little is known as to how their distributions change with migration, biodegradation, or water washing of oils.

In the present study, 16 tar sand samples were extracted from drill core at depths ranging from 16 to 256 ft obtained from a tar sand quarry in the Ardmore basin, Carter County, Oklahoma. Surrounding oil samples and possible source rocks have also been analyzed to determine the source of the oil in the tar sands. The effects of biodegradation on the porphyrin distributions can be discerned from the effects of migration and maturation by comparing other biomarker distributions within the sands, related oils, and suspected source rocks. Biodegradation of the tar sand samples can be observed within the alkane and other biomarker distributions. The relative effects of biodegradation on biomarkers such as alkanes, steranes, and terpanes have been well documented. By using this information, it is possible to determine the extent of biodegradation or water washing necessary to alter the porphyrin distributions. Once this information has been determined, porphyrin distributions may be used to determine the degree of biodegradation in oils where other biomarkers have been already removed or where other effects, such as maturation or migration, have altered the distribution of the biomarkers beyond the extent to which they are useful for correlation purposes.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 593.

Use of Magnetic Surveys for Delineation of Paleostructural Morrow Sand Reservoirs in Southwestern Kansas

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Oil- and gas-producing Morrow sandstones (Pennsylvanian) are found throughout southeastern Colorado, western Kansas, and western Oklahoma. Valley fill, deltaic, and marine sand bodies of the Morrow Formation make up some of the most productive reservoirs in the southwestern Kansas region. Initial recovery rates are generally in the 300 b/d and 6 MMCFGD ranges. The location and geometry of these sand bodies are controlled largely by the paleostructure of the top of the Mississippian unconformity.

High-resolution ground and air magnetic data were obtained for southwest Kansas. These data were processed using an expert system which incorporated principles of artificial intelligence. The results of this processing were equipotential surfaces reflecting maximum resolution contained in the magnetic data. Using these equipotential maps in conjunction with paleostructure maps of the dominant rock units, the writers observed an excellent visual correlation between the magnetic data and the paleostructure of the Mississippian erosional surface. The implication of this observation is either that the erosion surface of the Mississippian was controlled by movements in the basement rocks or that the basement faults were active when the overlying Morrow Sandstone was deposited.

Evidence supporting the strong correlation between magnetics and paleostructure included the definition of subsurface faults which were suggested by detailed subsurface studies. Additionally, isopach maps of the Morrow sandstones were highly correlatable with the inferred Mississippian paleostructure. The local Morrow depositional environments and rough percentage of clay, hence permeability, were also predicted. Evidence for this interpretation will be presented.

In conclusion, the combination of magnetics, artificial intelligence, and traditional structural data can be used to economically explore large areas which might or might not contain good well control.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 623.

Depositional Model, Dolomitization, and Porosity of Henryhouse Formation (Silurian), Anadarko Basin, Oklahoma

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The Upper Silurian Henryhouse Formation, which is part of the Hunton Group, is a major hydrocarbon reservoir in the Anadarko basin. Three basic lithofacies are present in the Henryhouse, based on sedimentary structures, lithology, fossil content, and fabric relationships. These facies, represented in general by massive lime mudstone with diverse fauna, burrowed dolowackestone/packstone with mainly crinoids, and massive to laminated dolomudstone with fenestral fabrics and sparse fauna, are inferred to represent subtidal, intertidal, and supratidal environments, respectively. These facies comprise a vertical sequence that represents regressive deposition. The Henryhouse consists of several of these sequences.

The Henryhouse commonly is partly or completely dolomitized in western Oklahoma. Three stages of dolomitization were documented: (1) penecontemporaneous hypersaline dolomite occurring as brownish, hypidiotopic rhombs concentrated in the supratidal and intertidal facies; (2) mixed marine and freshwater dolomite occurring as white rims around preexisting hypersaline dolomite, and as subhedral, white rhombs in vugs and molds; and (3) deep-burial vug, mold, and fracture-filling saddle dolomite.

Production in the Henryhouse is generally from porous zones in dolomite. However, lithofacies reflecting depositional environments in which they were formed are equally important in porosity development.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 990.

Assessing the Relative Importance of Compaction Processes and Cementation to Reduction of Porosity in Sandstones

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At the depositional surface, well-sorted sand has approximately 40% porosity. During burial diagenesis, that porosity is reduced by mechanical compaction, intergranular pressure solution, and cementation. Mechanical compaction and intergranular pressure solution can both be considered compactional processes because they irreversibly reduce the intergranular volume of sand. In contrast, cementation occludes, but does not reduce, intergranular volume.

The relative importance of compactional processes and cementation to porosity reduction can be quantified using a graph of intergranular volume vs. cement. This diagram can be used to evaluate which diagenetic processes have been most influential to intergranular porosity reduction and to determine why some sandstones retain better reservoir quality than others. The diagram can also be used to reconstruct pathways taken by sandstones during burial diagenesis.

Results of applying this technique to data from the Nugget Sandstone and Bromide sandstone (Simpson Group) indicate that mechanical compaction and intergranular pressure solution were much more important than cementation in determining ultimate porosity. Moreover, the best porosity is preserved in samples that have undergone the least intergranular pressure solution. These conclusions emphasize the importance of integrating an evaluation of these compactional processes into analyses of reservoir sandstones and into models of burial diagenesis.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 633.

Recognizing and Quantifying Expulsion of Oil from the Woodford Formation and Age-Equivalent Rocks in Oklahoma and Arkansas

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Accumulations of oil in fractures, stylolites, burrows, sandstone lenses, and chert nodules, deeply embedded within organic-rich, mature oil source beds of Late Devonian–Early Mississippian age are considered prima facie evidence of internal migration and expulsion. Most oil migrated internally and was expelled as a separate phase.

Within a given section in which chert and black shale are interbedded, contain the same type of organic matter, and have reached the same level of thermal maturity, black shales typically contain less hydrocarbons per weight percent TOC than cherts. The observed differences represent the amount of oil expelled from the black shales and range from 10 to 15 mg/g TOC for total bitumen, 7 to 8 mg/g TOC for saturated hydrocarbons, and 11 mg/g TOC for volatile hydrocarbons. Approximately 27–33% of the oil generated in these source rocks was calculated to have been expelled. In the main oil-producing region of central and southern

Oklahoma, 22 billion bbl of bitumen and 16 billion bbl of saturated hydrocarbons were estimated to have been expelled from the Woodford formation.

Relatively efficient, separate-phase oil expulsion may be characteristic of very rich oil source rocks like those reported here. Such rocks would reach effective oil saturation and begin to expel oil as a separate phase at a relatively early stage of generation. Timing and efficiency of oil expulsion must then be influenced by the concentration and type of organic matter in the source rock, because these factors determine the volume of oil generated and, hence, the time when a source rock becomes oil saturated.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 844.

Thermal Maturation by Vitrinite Reflectance of Woodford Shale, Anadarko Basin, Oklahoma

[See discussion and reply in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 897–899.]

Starved Euxinic Basin Concept for Oil and Gas Genesis in Oklahoma

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Some black, organic, carbon-rich, Pennsylvanian shales of the Mid-Continent region accumulated in broad, shallow, paleobathymetric troughs at moderate water depth under anoxic conditions during maximum sea level stillstands and sediment starvation. These starved troughs later were filled by northward-prograding wedges and lenses of clastics advancing episodically from southern and eastern highlands. Moreover, biogenic carbonate banks prograded southward along the edges of the trough, resulting in intercalations with the clastics. After several oscillations of sea level, the trough would be nearly filled by the terminal, rapidly deposited sediments of deltas and other shore constructional features. These areas were commonly sites of renewed depression, beginning a new series of sedimentation. The thick, organic-rich shales deposited in these troughs may have served as a petroleum source rock if burial was sufficient. Considerable hydrocarbon migration into the adjoining northern shelf carbonate banks was enhanced by their fracture systems, bedding planes, connected vugs, and intergranular porosity modified by diagenetic alteration.

The early episodes of development exhibit stratigraphic thinning of a carbonate and shale sequence into black, sheety, phosphatic shales and thin fossil hash. These black shales are generally on the order of 1–3 m thick, with several episodes having locally coalesced to form an aggregate more than 8 m thick. These black shales probably represent compaction of original anoxic organic muds that were probably 3–10 times thicker.

Loci of several such starved basins have been delineated by detailed stratigraphic mapping in both Oklahoma and Kansas. These basins may contain many cubic kilometers of hydrocarbon source beds, provided levels of thermal maturation were reached. Migration routes were probably provided by clinoform sands interfingering with black shales, by joint and open faults, and by sand-filled channels incised into these source beds by deltaic episodes.

This scenario provides for much more stratigraphically entrapped oil and gas than has been found to date in Oklahoma.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 990.

Practical Method for Exploration for Misener Sand Bodies on Sylvan Subcrop in Grant and Garfield Counties, Oklahoma

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The Misener sandstone is a highly productive alluvial sand. The rewards for discovering a Misener field are very good; however, the risks involved, including dry holes, have generally negated all or a major portion of any profits. Areas of major Misener sand accumulations become evident through the use of detailed mapping and from knowledge of regional and local stratigraphy as it affects paleotopography.

The major maps needed for a thorough evaluation of a region are (1) Woodford isopach, to determine paleotopography; (2) pre-Woodford subcrop, to locate trend of Sylvan subcrop; (3) Sylvan isopach, to locate "thins" that suggest the presence of paleotopographic valleys; (4) unconformity structure map, to discern lows and channels from nosing and structural thinning; and (5) detailed Sylvan subcrop map, to locate zones that are easily eroded and, consequently, may be areas of channel development.

The Misener sandstone in the northern counties of Oklahoma is a low- to moderate-energy alluvial sand. It occupies depressions cut into the unconformity surface and also lies updip of a resistant zone in the Sylvan Shale. Misener sands also show some reworking and dolomitization in the upper few feet caused by the transgressive Woodford seas.

The maps give the explorationist a detailed look at the pre-Woodford surface and the stratigraphy involved. The Sylvan section generally contains at least one topographically resistant zone that preferentially prohibits deposition of Misener sands. An understanding of the paleotopographic surface and the energies involved in the deposition process are extremely crucial to the location of Misener sand bodies.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 990.

Reservoir Geology of Upper Mississippian St. Louis Limestone, South Mouser Field, Texas County, Oklahoma

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Five porosity zones in the upper 80 ft (24.4 m) of the St. Louis Limestone have a cumulative production of over 1 million bbl of oil since St. Louis production was discovered at South Mouser field, Texas County, Oklahoma, in April 1983. A core from the upper 106 ft (32.3 m) of the St. Louis Limestone at South Mouser field is composed predominantly of bioclast, ooid, and mixed bioclast-ooid packstones, "washed" packstones, and grainstones. These lithologies reflect shifting of near-shoal and shoal environments on the shallow St. Louis shelf in the overall regressive sequence that includes both the upper part of the St. Louis Limestone and lower part of the overlying Ste. Genevieve Limestone. The lower 9 ft (2.7 m) of Ste. Genevieve Limestone in the core is a cross-stratified, fine-grained, sandy limestone.

Porosity in the cored St. Louis Limestone includes primary intergranular, leached grain, and minor vuggy, intragranular, and fracture. Within the five porosity zones, core porosity generally ranges from 6 to 14% and permeability from 1 to 100 md. Porosity development and cementation reflect, for the most part, meteoric diagenesis. Deposition and diagenesis of the upper 100+ ft (30.5+ m) of the St. Louis Limestone were markedly influenced by a local St. Louis paleohigh in approximately the same location as the present structural high at South Mouser field.

Cementation, compaction, and a significant amount of ineffective moldic porosity in the cored interval of the St. Louis Limestone result in increased pore system tortuosity. This indicates that an m value greater than 2.0 may be appropriate in S_w calculations. Additionally, in one porosity zone, ooids contain microporosity visible in SEM study. This porosity may hold irreducible water affecting S_w calculations made from wireline logs and resulting in an inaccurate assessment of the zone's ability to produce hydrocarbons.

Two distinct oil-water contacts occur in the upper St. Louis Limestone at South Mouser. The corresponding reservoirs are separated by a low porosity and permeability layer seen in core and correlated across the field using neutron-density logs.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 991.

Source Rock Potential of Upper Devonian–Lower Mississippian Formations in Oklahoma and Western Arkansas

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In most parts of Oklahoma and Arkansas, Upper Devonian–Lower Mississippian formations are excellent petroleum source rocks with prolific hydrocarbon-generating capability. Exceptions occur in the core area of the Ouachita system where less organic-rich lithologies (chert, siltstone, light-colored shale) are commonly found, and in the deep northwestern part of the Anadarko basin where silty shale predominates.

Regional variations in organic richness reflect Late Devonian–Early Mississippian paleogeography, with the Ouachita core area representing a deep trough in which open ocean circulation prevailed. The Anadarko basin was more restricted, and terrestrial sediments were transported from northwestern source areas to the southeast along the basin axis.

In central and southern Oklahoma, Upper Devonian–Lower Mississippian strata are rich oil source beds (mean =7% TOC) at an early stage of generation. The major accumulations of oil in this region have been documented as coming from the Woodford formation. Equivalent-age source rocks in the deep part of the Anadarko basin have matured to or beyond the gas generation stage and significant gas generation is still occurring within parts of the basin.

Around the Ozark uplift, age-equivalent rocks contain less organic matter (mean = 3.5% TOC) and more terrigenous clastic sediment than in central and southern Oklahoma. Both oil- and gas-generating types of kerogen are present and the organic matter has reached the early to main stages of oil generation.

Upper Devonian–Lower Mississippian source rocks in the Ouachita core area are metamorphosed and no longer have significant hydrocarbon-generating capability. Age-equivalent rocks in the frontal zone are rich oil source beds at an early stage of generation. Significant hydrocarbon accumulations are possible at depth within the frontal zone and from frontal zone rocks that have been overthrust by metamorphosed Ouachita core-area rocks, particularly in the northwestern part of the Ouachita province.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 991.

Red Fork and Lower Skinner Sandstones in Northwest Tecumseh Field, Pottawatomie County, Oklahoma

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The Northwest Tecumseh field, discovered in 1978, produces from the Pennsylvanian Skinner and Red Fork sandstones at 4,800 ft. The 50 wells had produced 6.4 million bbl of oil and 20.8 bcf of gas through 1986. The field is 4.5 mi long, ¾ mi wide, and the vertical section contains up to 132 ft of sandstone with greater than 10% porosity.

These stacked, interconnected north–northeast-trending, channel-fill sandstones are part of a much larger fluvial/distributary system. These channels flowed to the north and cut down into underlying, fossiliferous, carbonate-bearing marine shale. A pre-Pennsylvanian structural low, trending north–northeast, existed in the southern half of the field and created a predisposition for the channel trend which continued through Red Fork and Skinner deposition.

The north–northeast-trending sandstone complex, parallel with present-day regional structural strike, provides the excellent configuration for this efficient stratigraphic trap. The northern end of the field is marked by bifurcation of the channel complex and by the crosscutting of a younger clay-filled channel.

Despite the lenticularity of the sandstone sequence, there appears to be a uniform gas-oil contact and minor southwestward tilt of the oil-water contact in the south part of the pool. The primary reservoir energy is provided by a dissolved gas drive, with some assistance from the 60-ft gas cap. The vertical oil column is 80 ft.

These reservoir sandstones are fine-grained quartzarenites, and the dissolution of ferrodolomite has increased porosities up to 21%. Kaolinite is the predominant clay mineral and has a tendency to migrate and reduce permeability during production.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 991.

A Geochemical Correlation Study of Oklahoma Crude Oils Using a Multivariate Statistical Method

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Despite significant production in the southern Mid-Continent, organic geochemical characterization of oils and potential source rocks has been limited and, with respect to correlation studies, somewhat inconclusive. In the present study, 46 Oklahoma oils of varying reservoir ages (Cambro–Ordovician to Pennsylvanian–Morrowan) from an extensive geographic area were analyzed for saturate and aromatic hydrocarbon distributions, percent S, and stable carbon isotopic compositions. Eighteen of the oils were analyzed by GC/MS for biological marker compound distributions. Similarities and differences between oils were assessed using multivariate statistical methods.

In general, the majority of oils were mature, of marine origin, and very similar with respect to chemical and stable carbon isotopic compositions. Some differences were, however, observed. In particular, oils from the Oklahoma Panhandle (Pennsylvanian–Morrowan) were enriched in ^{13}C and had high Pr/Ph values. Oils from the Marietta basin and the southeast portion of the Anadarko basin (Ordovician) had high $n\text{-}C_{19}/n\text{-}C_{18}$ values. With few exceptions, the remaining oils from throughout the state appeared to be identical. Simultaneous R-mode, Q-mode factor analyses confirm these distinctions, and it is tentatively proposed that the Oklahoma oils that have been analyzed to date represent three distinct families. The geographic distributions of these families may be useful for establishing their respective sources and migration pathways. While the Woodford formation is commonly recognized as the principal source for Oklahoma oils, with organic facies changes accounting for some of the slight differences in oil compositions, other possible local sources as well as the possibility of multiple sources, i.e., mixing, are currently being investigated.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 71, p. 570.