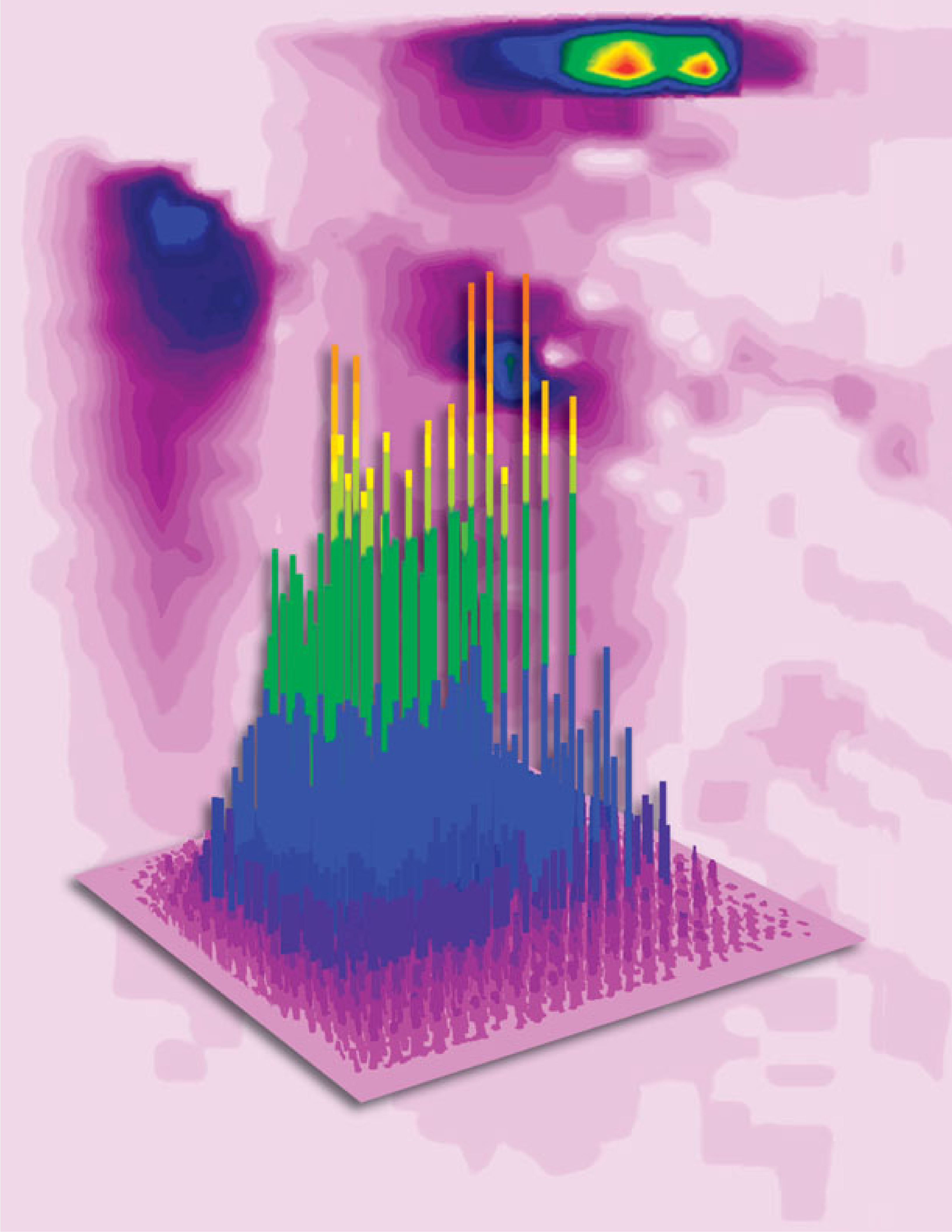

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# PETROLEOMICS: MS Returns to Its Roots

The industry that single-handedly launched MS into the analytical mainstream is once again at the forefront of recent advances.

Since its commercial birth, MS has been intimately tied to the petrochemical industry—petroleum producers sell molecules, and therefore oil's chemical composition determines its economic value. The composition of the oil also determines both its upstream (production) and downstream (processing) behavior. Determining the composition of those species that contain the heteroatoms nitrogen, sulfur, and oxygen is especially important, because these species contribute to solid deposition, flocculation, catalyst deactivation, storage instability, and refinery corrosion problems, and these factors affect the efficiency with which we collectively use our finite world petroleum reserve. The supply of "light" sweet crudes is diminishing, and the world oil market is therefore shifting toward "heavier" crudes rich in heteroatoms. Characterization of these heavier crudes is limited because of their immense complexity. For oil companies, compositional knowledge equals power—the power to develop oil reserves more efficiently, predict production problems, prevent pipe fouling and failures, reduce refining byproducts and waste, make money, and better manage the world's oil reserve.

National security issues are also of concern because of the political instability of many oil-rich nations. North and South America are relatively secure regions and have substantial petroleum reserves, albeit of lower quality, namely heavy crude oil or tar sand. For example, the province of Alberta, Canada, rests on a substantial petroleum reserve. Alberta tar sands alone contain an estimated reserve of ~2 trillion barrels or ~175 billion barrels of recoverable crude oil, compared with Saudi Arabia's ~260 billion barrels of crude oil. The North and South American sources produce heavy, heteroatomic-rich crudes, and they will continue to do so for the immediate future. Compositional knowledge of these crudes could improve production and processing and subsequently reduce our dependence on Middle Eastern oil.

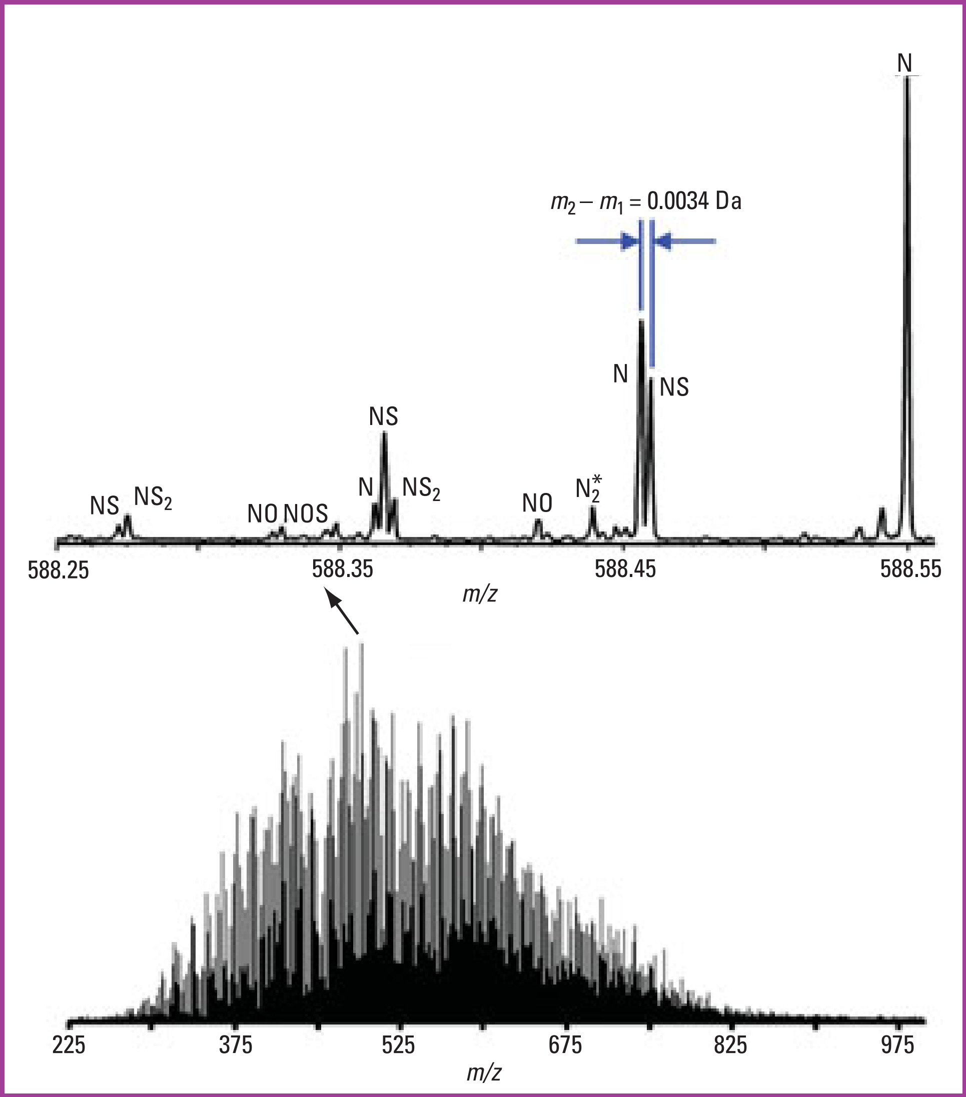


**FIGURE 1.** ESI FTICR mass spectra of South American crude oil taken on a 9.4-T instrument.

(bottom) The 11,127 peaks represent the most complex chemical mixture ever resolved and identified in a single mass spectrum. (top) Zoom mass inset showing the baseline resolution of 25 peaks at *m/z* 588. For brevity, only 12 of the 25 assigned elemental compositions are given. Peaks highlighted with blue demonstrate an isobaric mass split ($C_3$ vs $SH_4$, 0.0034 Da) important to petroleomics applications.

## Infant years

At the birth of commercial MS—and even today, some 50 years later—petrochemists and petroleum engineers had little compositional information. Oil companies began purchasing mass spectrometers that, at that time, were built to determine the composition of light, and therefore much less complex, distillates. Electron ionization, which was the most practical approach at the time, limited analysis to volatile and semivolatile organics. Moreover, early mass spectrometers based on the magnetic sector technology of the 1940s and 1950s could achieve mass resolving power of 10,000 or higher but were inherently limited by slit-dependent resolution (*1*, *2*). Narrowing the slit increased resolving power but at the expense of reduced S/N. Furthermore, scanning the magnetic field magnitude to obtain a broadband high-resolution mass spectrum took hours.

GC/MS emerged in the mid-1950s and offered detailed compositional analysis of the lightest petroleum distillates (*3–5*). However, the applications were—and still are—restricted by the maximum temperature of the GC oven because of the thermal integrity of the separation column. The combined capabilities of GC/MS, LC/MS, tandem MS, and high-resolution MS have done an excellent job of characterizing petroleum distillates such as gasoline, diesel fuel, and gas oil. However, until recently, very little was known about the composition of heavy distillates and heavy crude oils. If ever there was an insatiable, demanding taskmaster in MS, the oil industry was it. MS advances were ultimately judged against arguably the most complex mixture in the world, in terms of the number of chemically distinct species and concentration range over which they exist. With every instrument and every new ion source, the oil industry remained dissatisfied.

In principle, chemical composition ultimately determines the chemical and physical properties and behavior of petroleum and its products. “Petroleomics” is exactly that, namely, the prediction of properties and behavior from composition, to aid in solving oil production and processing problems. Petroleomics is not a new idea. In the early 1990s, Quann and Jaffe pointed out that composition variability must be considered to accurately predict the behavior and reactivity of petroleum fluids (*6*). They introduced the concept of structure-oriented lumping to deal with the sample complexity within the limitations of the then-available analytical techniques (*7*). Another seminal series of reports, by Boduszynski and others, on the composition of heavy petroleum

drew on a variety of analytical techniques to derive a surprisingly inclusive description of complex petrochemicals (*8–11*).

The high mass resolution and high mass accuracy of FT ion cyclotron resonance (FTICR) MS made it an attractive candidate for complex mixture analysis when it made its debut in the mid-1970s, although those capabilities were fully realized only in the last decade or so (*12–14*). These strengths and the rapid development of computer technology now promise to make petroleomics feasible. Recent developments in FTICR MS instrumentation and ion sources have shed new light on the immense complexity of crude oil, making it possible to resolve and identify ~17,000 species from a single crude sample (*15*). Moreover, the observed complexity comprises only the polar species present in the crude oil (~10% by weight), and thus even conservative estimates of the total number of chemically distinct species in a crude oil are sure to exceed 50,000.

## Why FTICR is a good idea

All mass spectrometers, except those based on ion mobility, measure *m/z*. The recent success of FTICR MS in the petroleum field derives in large part from recent advances in ion-source technology. Generation of odd-electron molecular ions from both electron impact and field desorption/field ionization (FD/FI) sustained petroleum mass-spectral analysis for decades (*16–19*), and those techniques have been successfully coupled to FTICR mass spectrometers (*20–24*). However, extensive fragmentation of aliphatic hydrocarbon chains and the need for highly volatile analytes severely limit application of electron ionization to petroleum. Fragmentation is deleterious, because generation of more than one signal per analyte ion can greatly complicate an already crowded mass spectrum.

The generation of quasimolecular ions [e.g., $(M+H)^+$ and $(M–H)^-$] by chemical ionization, ESI, laser desorption (LD), and MALDI has enabled the detailed characterization of previously inaccessible low-volatility species. Fenn and Zhan were the first to point out that ESI could ionize the most polar species in petroleum samples (*25*), even though they constitute <10% of the sample by weight, and thereby inspired the launch of FTICR MS into petroleomics. Major advantages of ESI are that it ionizes only the most polar species in crude oil (namely, those that contain nitrogen, sulfur, and oxygen); fragmentation during ionization is minimal, so that only one ionic species is produced for each neutral analyte originally present; and it provides limited chemical speciation. For example, nitrogen-containing compounds observed with positive-ion ESI typically originate from pyridinic (basic) species (*26*), whereas those observed with negative-ion ESI derive from pyrrolic (acidic) species (*27*). Similar trends may be used to discriminate $O_x$, $SO_x$, $NS_x$, $N_x$, and $NO_x$ chemical functionalities.

For the immediate future, FD/FI, ESI, and LD/MALDI ionization techniques are the most applicable ion sources for petroleomics because, unlike in most types of analytical spectrometry, each analyte produces essentially one feature in the observed mass spectrum. Even so, the natural complexity of petrochemical samples exceeds the peak capacity (i.e., the spectral range divided by the width of a typical peak) of most mass analyzers. Consider the ~11,000 unique elemental compositions assigned from a positive-ion ESI FTICR mass spectrum (Figure 1, bottom). Ultrahigh mass resolving power ($m/\Delta m_{50\%} > 350{,}000$, in which $\Delta m_{50\%}$ denotes mass spectral peak fwhm) is needed to distinguish between the various species, and subparts-per-million mass accuracy over a wide mass range (50–1500 Da) is needed to determine a unique chemical formula, $C_cH_hN_nO_oS_s$, for each species. Only high-field FTICR MS meets these requirements.

## Mass resolution and mass accuracy

For complex mixture analysis, the high mass resolving power of FTICR can separate signals from ions of very similar masses (e.g., the 0.0034 Da split between isobars differing in elemental composition by $SH_4$ vs $C_3$, both with a nominal mass of 36 Da; Figure 1, top). Resolution of such isobars allows speciation of

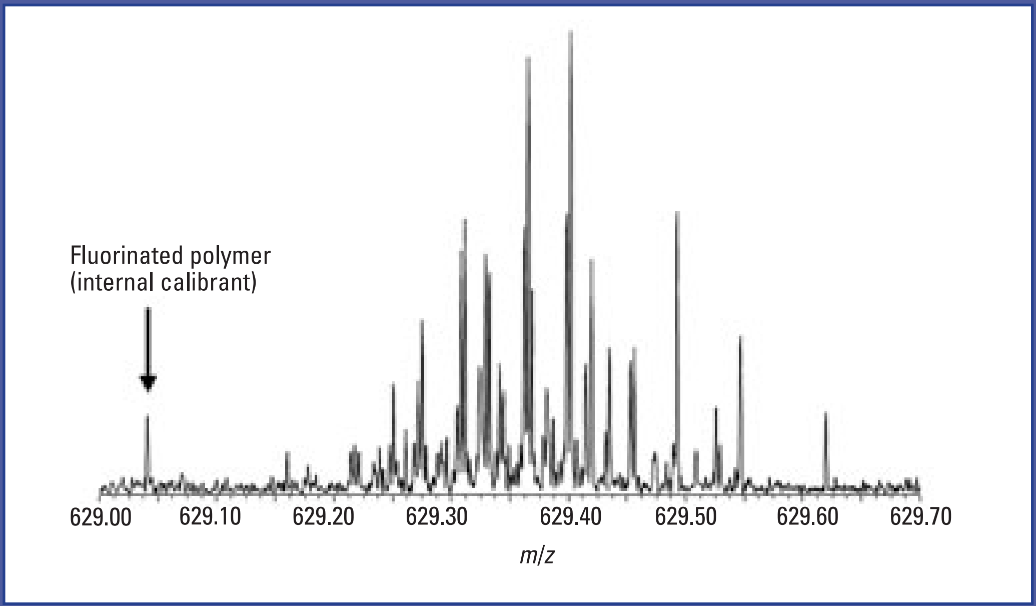


**FIGURE 2.** Negative-ion ESI FTICR in selective-ion-accumulation mode of acidic asphaltenes taken with a 9.4-T instrument resolves 55 peaks at a single nominal mass.

chemical classes that, for the same mixture, are not observed with other MS techniques (*7*). Of the several figures of merit for ICR performance that improve linearly or quadratically as a function of magnetic field strength, two that are especially significant for complex mixture analysis are the maximum number of trapped ions (which limits the dynamic range) and the decreased tendency for coalescence of closely spaced peaks (*28, 29*). Considerable improvement in those respects has been realized with the advent of high-field (>7 T) superconducting solenoid ICR magnets that provide high temporal stability (<50 ppb/h field drift) and spatial homogeneity (<10 ppm peak-to-peak variation within the measurement volume), both of which enable highly accurate mass measurement. Finally, the ability to measure ICR frequencies with parts-per-billion accuracy imparts potentially the same accuracy to the measurement of $m/z$.

After ions are injected into the magnetic field center, they are confined radially (in a plane perpendicular to the magnetic field) by the magnetic field. Ions are confined along the axis of the magnetic field by an additional axial electrostatic field. However, that trapping potential perturbs the relationship of the ICR frequency to $m/z$ (*28*). To obtain the subparts-per-million mass accuracy needed for petrochemical analysis, the frequency-to-$m/z$ conversion must be determined from the measured ICR frequencies and known masses of calibrant ions of at least two different $m/z$ values in the same mass spectrum (*30*). Because both analyte and calibrant ions experience the same electric and magnetic fields during excitation and detection, internal calibration can produce startlingly high mass accuracy over a broad mass range. For petrochemical samples, it is especially convenient to calibrate the mass spectrum from universally present ions of a homologous alkylation series (i.e., species differing in elemental composition by multiples of $-CH_2$) that span most of the observed $m/z$ range (*27*).

FTICR mass accuracy is best at a low trapping potential; thus, few ions are in the trap and the S/N is relatively low. However, the dynamic concentration range (ratio of strongest to weakest signal) and the need for accurate relative abundances for petroleum samples require a high S/N. To reconcile these contradictory requirements, high-resolution, high-mass-accuracy FTICR mass spectra of petrochemicals are usually generated by ensemble-averaging numerous (~50–100) scans, each acquired at a low (~0.5 V) trapping potential.

Figure 2 is the negative-ion ESI FTICR mass spectrum of acidic asphaltenes isolated from South American crude oil and shows >50 chemically distinct species resolved over a 1-Da spectral segment. Comparable complexity is observed at every nominal mass over the range 200–1000 Da. The $m/z$ spacing between $^{12}C_c$ and $^{13}C^{12}C_{c-1}$ versions of otherwise compositionally identical species allows the ionic charge $z$ to be determined (*31, 32*). In this way, we find that all ionic species in Figure 2 have $z = -1$, and therefore the measured $m/z$ is the ionic mass in daltons. A common misconception is that mass accuracy alone provides the elemental composition assignment. However, even if we have subparts-per-million mass accuracy and knowledge of the ionic charge state, elemental compositions may be unambiguously assigned only up to ~400 Da. Elemental compositions for higher-mass ions require data reduction based on the Kendrick mass scale and helpful spacings in the mass spectrum (*33*, *34*).

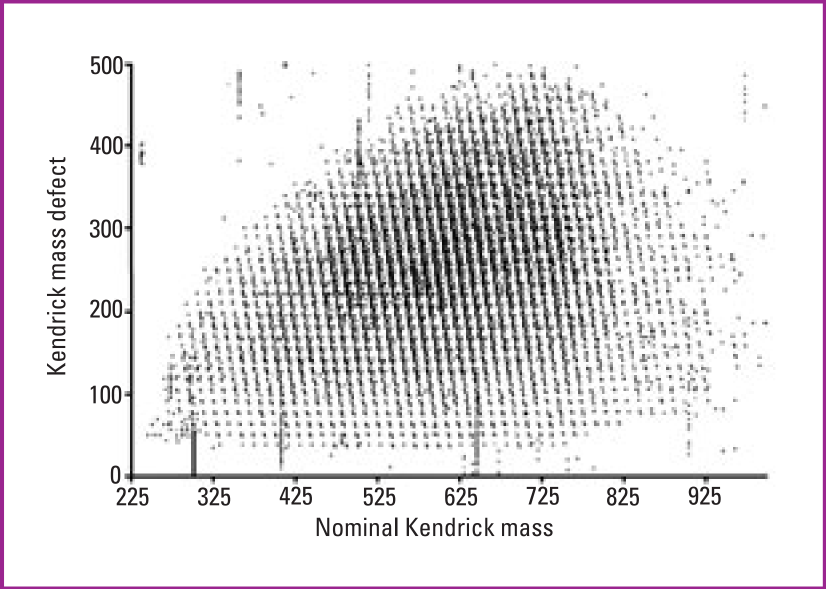


**FIGURE 3.** Kendrick mass defect vs nominal Kendrick mass for all resolved peaks in the bottom spectrum in Figure 1.

This single-page plot displays all of the 11,127 peaks in the original mass spectrum and reveals each ion's class and type (by projection to the vertical axis) and carbon distribution (by projection to the horizontal axis).

## Kendrick and van Krevelen

For ultrahigh-resolution measurements, it is useful to convert the measured mass to the Kendrick mass (*35*), which sorts compounds into homologous series according to alkylation, classes (numbers of heteroatoms), and types (rings plus double bonds). For example, the IUPAC mass of $CH_2$, 14.0157 Da, becomes a Kendrick mass of 14.0000 Da. Compounds with the same nitrogen, oxygen, and sulfur composition and the same number of rings plus double bonds but different numbers of $CH_2$ units will differ in Kendrick mass by integer multiples of 14.0000 Da; these compounds are thus easily identified as members of a homologous series. Stated another way, members of a homologous series will have the same Kendrick mass defect (KMD), defined as [Kendrick nearest-integer (nominal) mass – Kendrick exact mass] × 1000, which is unique to that series.

For example, the alkylation series of simple alcohols (methanol, ethanol, propanol, butanol, etc.) share the same heteroatom composition ($O_1$) and number of rings plus double bonds but differ simply in the number of $CH_2$ units. Therefore, Kendrick normalization yields a series with an identical mass defect that appears as a horizontal row in a plot of KMD versus Kendrick mass; that series is easily distinguished from species of other classes and types. Most notably, unambiguous assignment of a single elemental composition for a low-mass member of a homologous series serves to identify all other members of that series. In this way, Kendrick mass sorting extends elemental composition assignment to masses up to 3× higher than would be possible based on mass-measurement accuracy alone. Figure 3 is a 2-D Kendrick mass plot for South American crude oil, from which 11,127 unique elemental compositions may be identified. Note the number and mass range of homologous series identified as horizontal rows of points in the analysis. It is only with high-resolution and high-mass-accuracy FTICR MS that the complete type and carbon number for each class may be determined for mixtures this complex.

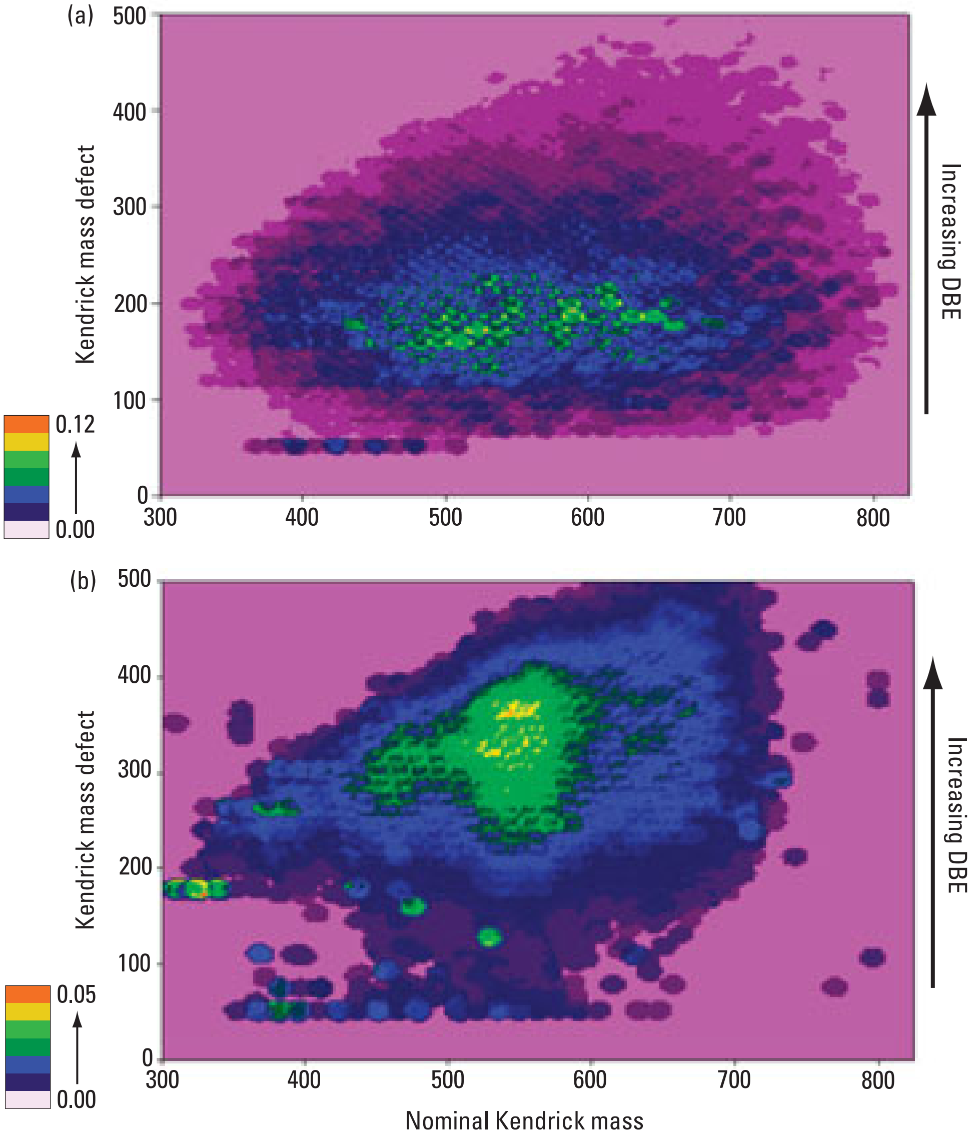
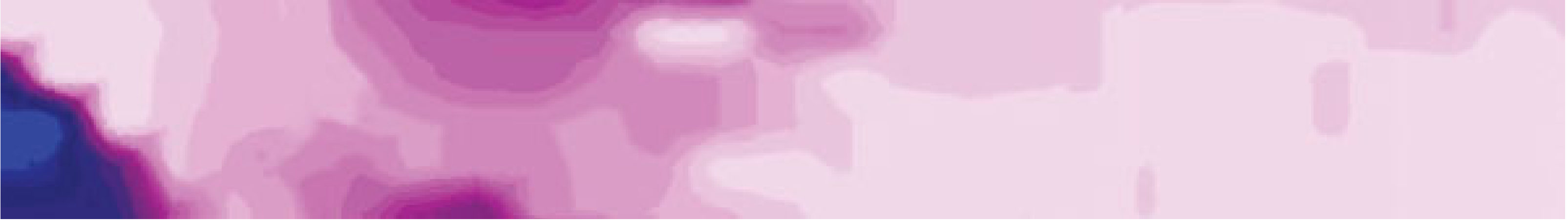


**FIGURE 4.** 3-D Kendrick plots of (a) North American oil and (b) its associated production deposit generated from an entire broadband negative-ion ESI FTICR mass spectrum allow for rapid determination of variation in the carbon number (width in *x* direction) and double-bond equivalents (DBE; width in *y* direction) for all identified species. The deposit shows a clear shift to higher Kendrick mass defect (higher DBE), indicating the preferential deposition of more aromatic species.

2-D Kendrick mass plots aid in the assignment of unique elemental compositions >~400 Da, but they also constitute a chemically sorted display of thousands of mass spectral data points in a single plot. Thus, comparison of Kendrick plots for samples of different geochemical history, maturity, and stages of fractionation and processing can highlight compositional differences (*26*, *36*, *37*). The plots can be rendered more informative by color-coding relative abundances of every identified species, thereby converting the entire mass spectrum to an image. In the 3-D Kendrick plots for a North American crude oil and its associated production deposit obtained from the corresponding negative-ion ESI FTICR mass spectra (Figure 4), it is immediately apparent that there is a shift in the relative abundances and identified species to a higher KMD. Although the 1-D mass distributions are similar, the higher KMD (higher number of rings and double bonds) reflects a selective deposition of more aromatic species in the oil production equipment. The 3-D Kendrick plots allow rapid identification of general trends in the mass spectra of sample groups, but they do not readily expose class-based compositional differences.

Class-specific compositions may be visualized with a van Krevelen diagram, whose axes are ratios of the relative abundances of all species containing oxygen, nitrogen, sulfur, or carbon atoms (*38*, *39*). Because FTICR MS analysis allows for elemental composition assignment of all resolved species, it is uniquely suited to highlight detailed class information obtained from the mass spectrum. The *y* axis of a van Krevelen diagram is hydrogen/carbon, and the *z* axis is color-coded for relative abundance. The type of *x* axis can be chosen (*X*/carbon, where *X* is nitrogen, oxygen, or sulfur), and the plot then becomes graphically class-



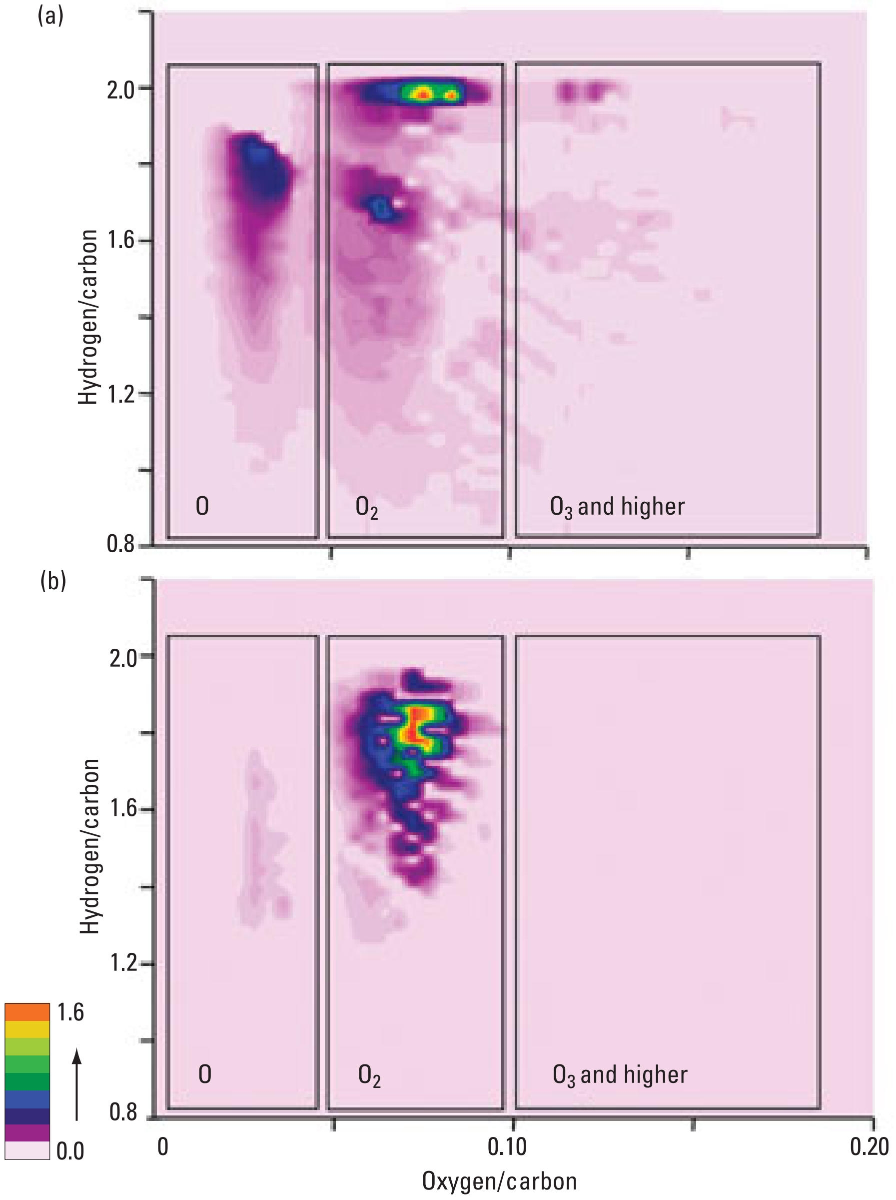


**FIGURE 5.** 3-D van Krevelen diagrams for (a) undegraded and (b) biodegraded crude oils generated from only the oxygen-containing species identified in the negative-ion ESI FTICR mass spectra. Biodegradation trends in the oxygen-containing species are visualized and show preferential formation and thus enrichment of $O_2$-containing species identified as naphthenic acids.

specific for the *X*-containing species of interest. In Figure 5, 3-D van Krevelen plots of undegraded and biodegraded crude oils define the effects of biodegradation according to class (O vs $O_2$ vs $O_3$ and higher). The visual display facilitates the identification of oxygen-dependent biodegradation trends and highlights areas of similarity and difference for more detailed compositional analysis, such as aromaticity and carbon-number distribution.

In summary, 3-D Kendrick plots allow for rapid determination of gross compositional differences among sample sets, whereas 3-D van Krevelen plots highlight class-specific variations of heteroatom-containing species. However, because the Kendrick plot allows for elemental composition assignment for those species >~400 Da, the success of the van Krevelen diagram is ultimately tied to the prior implementation of Kendrick mass sorting.

## Applications and future directions

Petroleomics applications include the identification of thousands of acidic and basic species in crude oils (*7*, *40*, *41*); polar compositional dependence of oil maturity and geochemical history (*27*, *37*); nitrogen, sulfur, and oxygen compositional variations as a result of diesel processing (*22*, *23*, *26*) and oil upgrading; acid composition as it relates to process corrosion (*41*, *42*); biodegradation-induced compositional changes; the end point of polar species in process distillation; monitoring changes in aromatic hydrocarbon content for different refinery process streams (*43*); observation of fate and transport of natural petroleum signatures in terrestrial water systems; and characterization of the nonpolar composition of coal. However, petroleomics is not limited to just oil and its derived products. Additional possibilities being investigated include other fossil fuels (*36*) as well as environmental (*44–49*), geochemical (*27*, *37*), foodstuff, and forensic (*50*, *51*) applications.

ESI FTICR MS is not the only analytical tool for petroleomics. Thousands of nonpolar species (paraffins, cycloparaffins, aromatics, thiophenes, etc.) remain to be identified. We have begun to characterize them with FD (*24*, *43*) and atmospheric pressure photoionization. However, the compositions of saturates and olefins pose a particularly difficult obstacle to direct mass spectral characterization because of their tendency to fragment and undergo gas-phase reactions during ionization. For those species, high-temperature GC seems capable of determining the composition for modeling purposes (*53*, *54*). Moreover, mass measurement alone does not discern structural isomers. Class-specific chromatographic separations will be needed to chemically speciate compound classes.

Finally, because ionization efficiency (for any method) for one species can be greatly affected by the presence of other species (the matrix effect), it is not easy to relate the observed ion relative abundances to the relative abundances of their precursor neutrals in the original sample. For example, positive-ion ESI favors the most basic compounds, whose presence can reduce the relative abundance of species of lower basicity. Ultimately, it will be necessary to calibrate the relative ionization efficiencies by spiking the mixture with species of various chemical functionality of known ionization efficiency. However, even if this technique is successful, quantitative and qualitative compositional information is not enough. The simple question is: What is the best way to exploit detailed compositional information? Ultimately, compositional data from all sources will serve as the basis for predictions of oil behavior. Therefore, advances in informatics and predictive modeling will be paramount.

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We thank the following individuals, who have participated as coauthors and colleagues in the body of work and research underlying this article: Andrew Yen, Samuel Asomaning, K. V. Andersen, Erin N. Blumer, Helen J. Cooper, William T. Cooper, Mark R. Emmett, Anne Fievre, Michael A. Freitas, Shenheng Guan, Mark A. Greaney, Christopher L. Hendrickson, Christine A. Hughey, Sara Jernström, William M. Landing, Daniel G. McIntosh, Kuangnan Qian, John P. Quinn, Winston K. Robbins, Stuart E. Scheppele, Michael V. Senko, Touradj Solouki, Alexandra C. Stenson, Clifford C. Walters, Forest M. White, Sunghwan Kim, Geoffrey C. Klein, and Zhigang Wu. Finally, we thank Carol L. Nilsson for suggesting the term "petroleomics". This work was supported by Amoco, ExxonMobil Research and Engineering, the National Science Foundation (currently CHE-99-09502), Florida State University, the Ohio State University, and the National High Magnetic Field Laboratory.

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## References

(1) Johnson, E. G.; Nier, A. O. *Phys. Rev.* **1953**, *91*, 10–17.
(2) Mattauch, J.; Herzog, R. *Z. Phys.* **1934**, *89*, 786–795.
(3) McLafferty, F. W.; Michnowicz, J. A. *J. Am. Soc. Mass Spectrom.* **1993**, *4*, 367–371.
(4) McLafferty, F. W.; Michnowicz, J. A. *CHEMTECH* **1992**, *22*, 182–189.
(5) Beynon J. H. *Mikrochim. Acta* **1956**, 437–453.
(6) Quann, R. J.; Jaffe, S. B. *Chem. Eng. Sci.* **1996**, *51*, 1615–1635.
(7) Quann, R. J.; Jaffe, S. B. *Ind. Eng. Chem. Res.* **1992**, *31*, 2483–2497.
(8) Boduszynski, M. M. *Energy Fuels* **1987**, *1*, 2–11.
(9) Boduszynski, M. M. *Energy Fuels* **1988**, *2*, 597–613.
(10) Boduszynski, M. M.; Altgelt, K. H. *Energy Fuels* **1992**, *6*, 72–76.
(11) Altgelt, K. H.; Boduszynski, M. M. *Energy Fuels* **1992**, *6*, 68–72.
(12) Comisarow, M. B.; Marshall, A. G. *Chem. Phys. Lett.* **1974**, *25*, 282–283.
(13) Comisarow, M. B.; Marshall, A. G. *Chem. Phys. Lett.* **1974**, *26*, 489–490.
(14) Qian, K.; et al. *Energy Fuels* **2001**, *15*, 492–498.
(15) Marshall, A. G.; Rodgers, R. P. *Acc. Chem. Res.* **2004**, *37*, 53–59.
(16) Aczel, T.; et al. *Anal. Chem.* **1970**, *42*, 341–347.
(17) Brown, R. A. *Anal. Chem.* **1951**, *23*, 430–437.
(18) Lumpkin, H. E.; Johnson, B. H. *Anal. Chem.* **1954**, *26*, 1719–1722.
(19) Lumpkin, H. E. *Anal. Chem.* **1964**, *36*, 2399–2401.
(20) Hsu, C. S.; Liang, Z.; Campana, J. E. *Anal. Chem.* **1994**, *66*, 850–855.
(21) Guan, S.; Marshall, A. G.; Scheppele, S. E. *Anal. Chem.* **1996**, *68*, 46–71.
(22) Rodgers, R. P.; et al. *Anal. Chem.* **1998**, *70*, 4743–4750.
(23) Rodgers, R. P.; et al. *Rev. Sci. Instrum.* **1998**, *69*, 2278–2284.
(24) Schaub, T. M.; et al. *Anal. Chem.* **2003**, *75*, 2172–2176.
(25) Zhan, D. L.; Fenn, J. B. *Int. J. Mass Spectrom.* **2000**, *194*, 197–208.
(26) Hughey, C. A.; et al. *Energy Fuels* **2001**, *15*, 1186–1193.
(27) Hughey, C. A.; et al. *Org. Geochem.* **2002**, *33*, 743–759.
(27) Marshall, A. G.; Hendrickson, C. L.; Jackson, G. S. *Mass Spectrom. Rev.* **1998**, *17*, 1–35.
(29) Marshall, A. G.; Guan, S. *Rapid Commun. Mass Spectrom.* **1996**, *10*, 1819–1823.
(30) Ledford, E. B., Jr.; Rempel, D. L.; Gross, M. L. *Anal. Chem.* **1984**, *56*, 2744–2748.
(31) Senko, M. W.; Beu, S. C.; McLafferty, F. W. *J. Am. Soc. Mass Spectrom.* **1993**, *4*, 828–830.
(32) Senko, M. W.; Beu, S. C.; McLafferty, F. W. *J. Am. Soc. Mass Spectrom.* **1995**, *6*, 52–56.
(33) Hsu, C. S.; Qian, K.; Chen, Y. C. *Anal. Chim. Acta* **1992**, *264*, 79–89.
(34) Kendrick, E. *Anal. Chem.* **1963**, *35*, 2146–2154.
(35) Hughey, C. A.; et al. *Anal. Chem.* **2001**, *73*, 4676–4681.
(36) Wu, Z.; et al. *Energy Fuels* **2002**, *17*, 946–953.
(37) Hughey, C. A.; et al. *Org. Geochem.* **2004**, *35*, 863–880.
(38) Kim, S.; Kramer, R. W.; Hatcher, P. G. *Anal. Chem.* **2003**, *75*, 5336–5344.
(39) van Krevelen, D. W. *Fuel* **1950**, *29*, 269–284.
(40) Hughey, C. A.; Rodgers, R. P.; Marshall, A. G. *Anal. Chem.* **2002**, *74*, 4145–4149.
(41) Qian, K.; et al. *Energy Fuels* **2001**, *15*, 1505–1511.
(42) Barrow, M. P.; et al. *Anal. Chem.* **2003**, *75*, 860–866.
(43) Schaub, T. M. L.; et al. *Rapid Commun. Mass Spectrom.* **2004**, *18*, 1641–1644.
(44) Llewellyn, J. M.; et al. *Anal. Chem.* **2002**, *74*, 600–606.
(45) Kujawinski, E. B.; Freitas, M. A.; Zang, X.; Hatcher, P. G.; Green-Church, K. B.; Jone, R. B. *Org. Geochem.* **2002**, *33*, 171–180.
(46) Kujawinski, E. B.; Hatcher, P. G.; Freitas, M. A. *Anal. Chem.* **2002**, *74*, 413–419.
(47) Rodgers, R. P.; Blumer, E. N.; Freitas, M. A.; Marshall, A. G. *Environ. Sci. Technol.* **2000**, *34*, 535.
(48) Rodgers, R. P.; Blumer, E. N.; Freitas, M. A.; Marshall, A. G. *Anal. Chem.* **1999**, *71*, 5171–5176.
(49) Fievre, A.; Solouki, T.; Marshall, A. G.; Cooper, W. T. *Energy Fuels* **1997**, *11*, 554–560.
(50) Rodgers, R. P.; Blumer, E. N.; Freitas, M. A.; Marshall, A. G. *J. Forensic Sci.* **2001**, *46*, 268–279.
(51) Wu, Z.; et al. *Anal. Chem.* **2002**, *74*, 1879–1883.
(52) Levy, E. M.; Webber, L. R.; Moffatt, J. D. *J. Chromatogr. Sci.* **1973**, *11*, 591–593.
(53) Guehenneux, G.; et al. *Oil Gas Sci. Technol.* **2002**, *57*, 139–147.