

Petroleomics by Ultrahigh-Resolution Time-of-Flight Mass Spectrometry

Clécio F. Klitzke,[†] Yuri E. Corilo,^{†,‡} Kevin Siek,[§] Joe Binkley,[§] Jeffrey Patrick,^{*,§} and Marcos N. Eberlin^{*,†}

[†]ThoMSon Mass Spectrometry Laboratory, Institute of Chemistry, University of Campinas (UNICAMP), Campinas, São Paulo (SP) 13083-970, Brazil

[‡]Ion Cyclotron Resonance Program, National High Magnetic Field Laboratory, Tallahassee, Florida 32310, United States

[§]LECO Separation Sciences, St. Joseph, Michigan 490805, United States

ABSTRACT: The ability of time-of-flight (TOF) mass spectrometry using an ultrahigh resolving power (R_p of 100 000 at m/z 400) analyzer (HRT) to provide a proper platform for comprehensive petroleomic studies has been evaluated. The innovative HRT design for ultrahigh resolution using a “zig-zag” multi-reflecting analyzer with a folded flight path, efficient ion refocusing, and no substantial loss of ion transmission was tested. For comparison, samples were also analyzed by Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS) using variable R_p (from 100 000 at m/z 400 to 400 000 at m/z 400). Both HRT and FT-ICR MS data were processed and compared using software specifically designed to process either TOF or FT-ICR data for petroleomic studies. Owing to the increase in R_p with m/z , the 100 000 at m/z 400 R_p of the HRT is found to be, overall, comparable to that of a 200 000 at m/z 400 FT-ICR. This R_p is sufficient to allow for proper resolution, correctly resolve most isobaric interferences, and accurately measure m/z values, leading to proper characterization of petroleum components via assignments of molecular formulas and classes. Results using electrospray ionization (ESI) focus on polar components, and their molecular formulas were properly translated to heteroatom classes, unsaturation levels measured via double bond equivalents (DBEs), and carbon number, which were displayed via classical geochemical plots. Data have shown that the compositional information provided by HRT is comparable to FT-ICR for most operational routine analyses. HRT operating with a R_p of 100 000 at m/z 400 was therefore found to offer a fast, accurate, sensitive, and cost-effective platform suitable for accurate petroleomic MS fingerprinting of crude oils and distillates.

■ INTRODUCTION

Profiles of polar components have been shown to provide characteristic “molecular signatures” for petroleum crude oils¹ and distillates.² Although diluted in HC compounds and representing just a minor fraction (typically 5%) of the oil,² these most ancient hetero (N, O, S)-cyclic polar molecules have been shown to function as effective crude oil markers, being diagnostic in regard to major geochemical parameters, such as type, origin, biodegradation, and maturation.^{1,3} These polar molecules are also the most problematic with respect to pollution, fouling of catalysts, corrosion, formation of deposits and emulsions during production and processing and are sometimes removed from distillates via treatments, extractions, and catalysis.^{1,3,4}

Crude oils contain, however, many thousands of polar molecules; hence, their comprehensive analysis has posed an enormous analytical challenge. However, when electrospray ionization (ESI) was introduced by Fenn et al.⁵ and its gentleness and efficacy was demonstrated for polar molecules,¹⁴ direct analysis by mass spectrometry (MS) emerged as a possible solution to such complex analysis⁶ and the field of petroleomic MS flourished.¹ ESI is well-suited for the analysis of polar components of crude oils because ionization occurs mainly via a single species, commonly either the protonated molecules $[M + H]^+$ for ESI(+) or deprotonated molecules $[M - H]^-$ for ESI(−). Despite this simplifying “one molecule—one ion” relationship of ESI that leads to relatively sparse spectra, many

thousands of ions are produced because of the numerous polar components, with much isobaric interference. This myriad of gaseous ions poses now a tremendous challenge with regard to mass measurement. MS analyzers with ultrahigh resolution, accuracy, and sensitivity have therefore been indispensable to properly separate the multitude of ESI polar marker ions and to measure their exact masses, to assign their correct molecular formulas needed to determine class, double bond equivalent (DBE), and carbon numbers.

Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometers with resolving power (R_p) of at least 100 000 at m/z 400 have thus far been the only mass analyzers able to provide the ultrahigh resolution⁷ and accuracy demands of polar petroleomic MS.¹ FT-ICR mass spectrometers are, however, also of ultrahigh costs and highly demanding to maintain (high consumption of liquid nitrogen and helium). Recently, the more affordable and less demanding orbitrap mass spectrometers operating at 100 000 at m/z 400 R_p have also been suggested as a reasonably accurate petroleomic platform.⁸ The LTQ orbitrap XL was operated without apodization to improve resolution using “slicing” for spectrum acquisition with nine scan events along m/z 100 wide windows.

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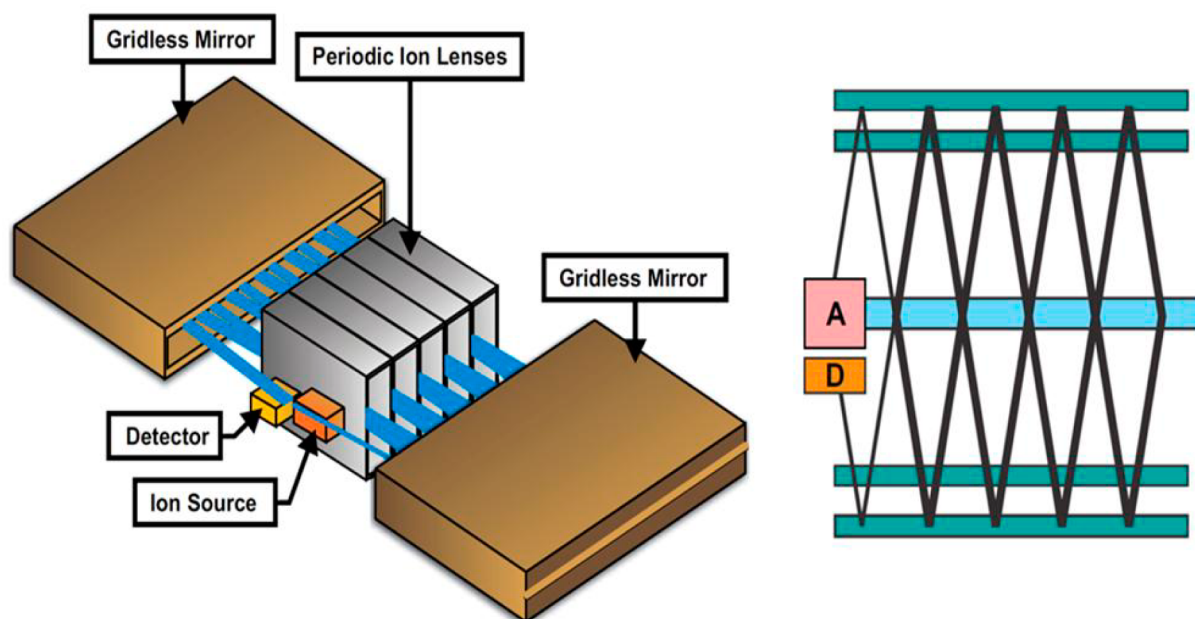


Figure 1. Design of the FFP technology and the ultrahigh R_p (100 000 at m/z 400) mode of operation of the HRT with two long full passes across the TOF analyzer for a total of 40 m flight (A, accelerator; D, detector).

Very recently, however, an ultrahigh-resolution time-of-flight (TOF) mass spectrometer (HRT) with an innovative multi-reflecting “zig-zag” design and refocusing strategy for minimal loss in ion transmission has been introduced.⁹ TOF is regarded as the mass analyzer with the best cost/benefit ratio, because of its high speed, simplicity, non-discriminative mass analysis, and relatively low costs.¹⁰ In addition, contrary to FT-ICR and orbitraps, in which resolution decreases exponentially with m/z , TOF R_p increases with m/z , and this feature adds to the attractiveness of TOF analyzers. For crude oil analysis, this feature is particularly attractive for the analysis of the heavy high ends of the refining process. The HRT analyzer operating in the ultrahigh R_p mode (100 000 at m/z 400) therefore seems to offer an attractive platform for petroleomic MS. Herein, we explore the suitability of HRT for petroleomic studies by comparing the performance of the new HRT system with that of a 7.2 T hybrid linear trap FT-ICR mass spectrometer operating at variable R_p .¹¹

EXPERIMENTAL SECTION

Crude Oil Sample Preparation. Samples of typical crude oils¹² were dissolved in 1:1 toluene/methanol without additives to a concentration of 2.2 and 0.7 mg mL⁻¹ for MS analysis via HRT and FT-ICR, respectively. The solution was directly infused into the ESI source operated in the positive- or negative-ion modes. Solvents were of high-performance liquid chromatography (HPLC) grade, purchased from Sigma-Aldrich, and used as received.

HRT. In brief, the Citius LC–HRT system (LECO Corporation, St. Joseph, MI) uses an innovative multi-reflecting TOF (Figure 1) with a folded flight path (FFP) developed by Verentchikov et al.⁹ The ions pass between ion mirrors and through an Einzel lens array. Transmission in the FFP is maximized by nonlinear electrostatic fields in the gridless mirrors, via which the ions are constantly refocused as they traverse the flight path, creating the extended flight path needed to enhance TOF resolution. Ion loss is minimized by the gridless design. The HRT offers three effective flight “zig-zag” paths of 2 m length for unit resolution, 20 m for high R_p (50 000 at m/z 400), and 40 m for ultrahigh R_p (100 000 at m/z 400). The LC–HRT is also capable of mass accuracies at or below 1 ppm [root mean square (rms)] and acquisition rates of up to 200 spectra/s written to disk. The system offers a mass range of

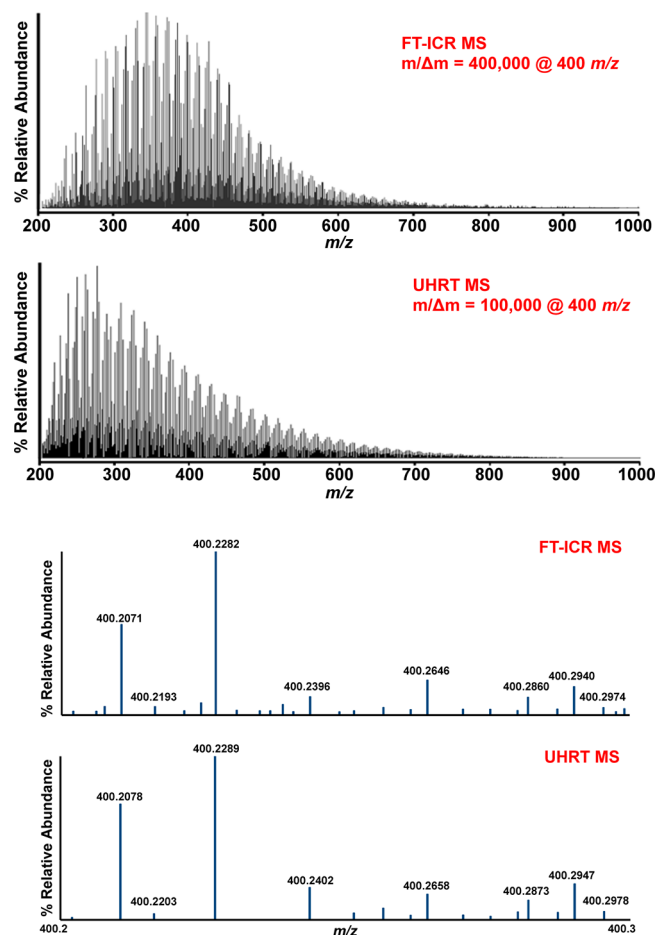


Figure 2. ESI(+) typical broadband spectra of a representative crude oil with typical average levels of biodegradation and maturation obtained by FT-ICR MS and HRT MS analysis as well as expanded m/z 0.1 window views in the m/z 400.2–400.3 range.

m/z 50–2500 in nominal and high-resolution modes and a 1:4 range in ultrahigh resolving power mode (m/z 200–800 or 300–1200 for instance).

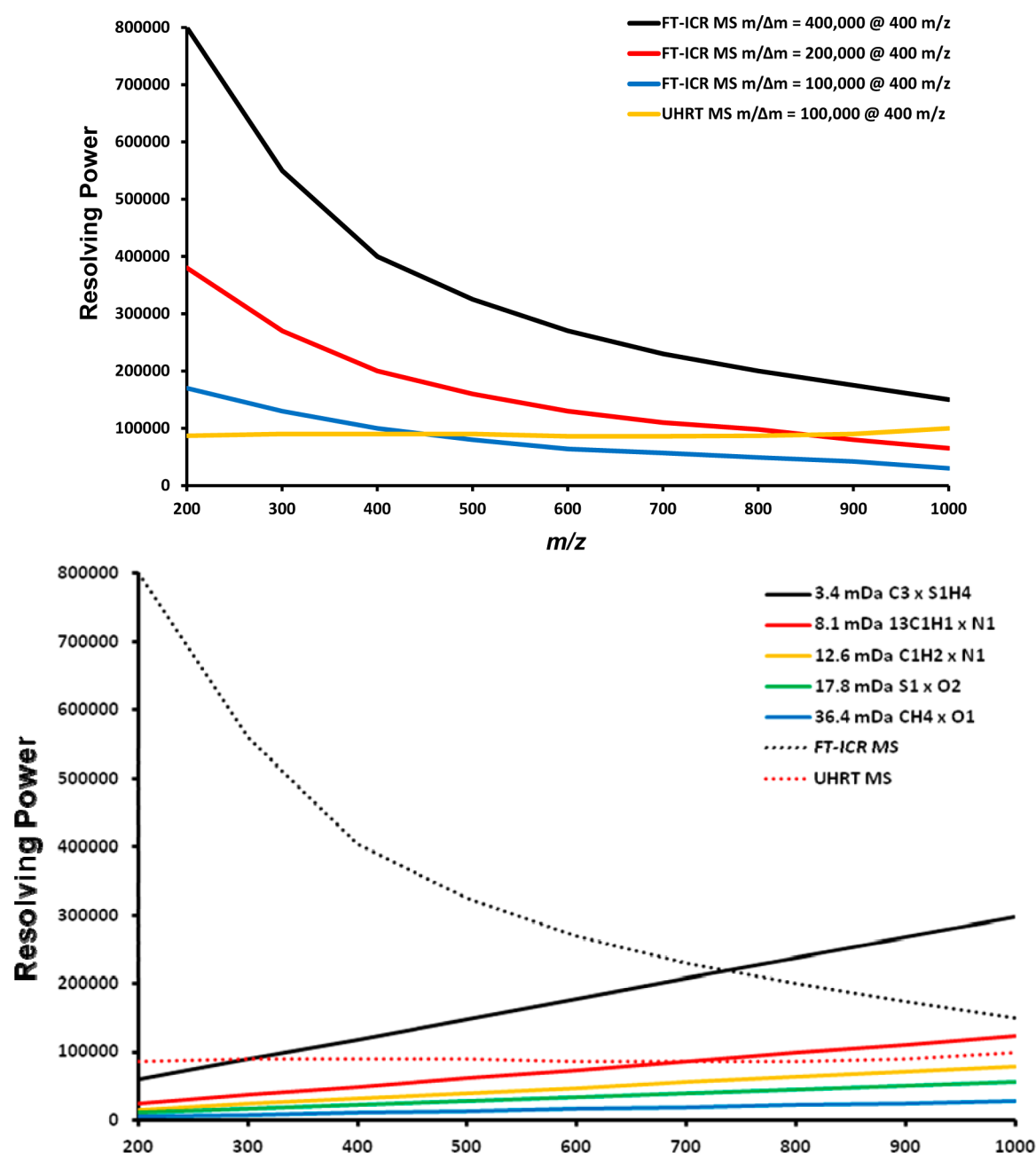


Figure 3. (Top) R_p obtained from the analysis of a typical crude oil sample in FT-ICR MS and HRT MS using ESI(+) data from the N class and (bottom) minimum R_p needed to resolve isobaric doublets and R_p of FT-ICR MS (400 000 at m/z 400) and HRT MS (100 000 at m/z 400) as a function of m/z .

The sample solution was directly infused into the ESI source of the Citius LC–HRT system at a flow rate of $10 \mu\text{L min}^{-1}$. The ESI probe was operated with the following parameters: spray voltage, 2.9 kV; nozzle potential, 130 V; Q1 direct current (DC) potential, 120 V; skimmer potential, 60 V; nebulizer pressure, 30 psi; N_2 desolvation flow, 7.5 L min^{-1} ; desolvation temperature, 900°C ; and nozzle temperature, 125°C . In this exploratory study, to ensure full coverage of the m/z range of interest for petroleomic studies, data were recorded in full MS mode in ESI(+) in two scan events, from m/z 200 to 600 and from m/z 300 to 1000. The combined mass range was m/z 200–1000. A single run from m/z 250 to 1000 would be sufficient, however, for most studies and would provide similar data. For ESI(–), for instance, a single run in the m/z 200–600 range was applied here for maximum speed and single-run acquisition and found to cover most ions of interest. Mass spectra were the result of over 100 scans at 100 000 resolving power ($m/\Delta m$) accumulated via the Chroma-TOF software (LECO Corporation, St. Joseph, MI).

FT-ICR. The sample solution was directly infused into the ESI source of a 7.2 T LTQ FT ultra mass spectrometer (Thermo Scientific, Bremen, Germany) at a flow rate of $5 \mu\text{L min}^{-1}$. ESI was operated with the following parameters: spray voltage, 3.6 kV; capillary potential, 40 V; tube lens potential, 100 V; and capillary temperature, 280°C . Data were recorded in full MS mode in ESI(+) from m/z 200 to 1000. Mass spectra were the result of over 100 microscans at 100 000 at m/z 400, 200 000 at m/z 400, and 400 000 at m/z 400 R_p ($m/\Delta m$ at m/z 400) processed via the Xcalibur 2.0 software (Thermo Scientific, Bremen, Germany).

Data Processing. For petroleomic information, mass spectra from FT-ICR were further processed with the PetroORG software specially designed for formula attribution, automatic recalibration for known homologous series from the measured m/z values of polar crude oil markers, which is able to equally process data from both ICR and TOF analyzers. Approximately 3000 monoisotopic components were assigned at the molecular level for the ESI(+) HRT mass spectra, and

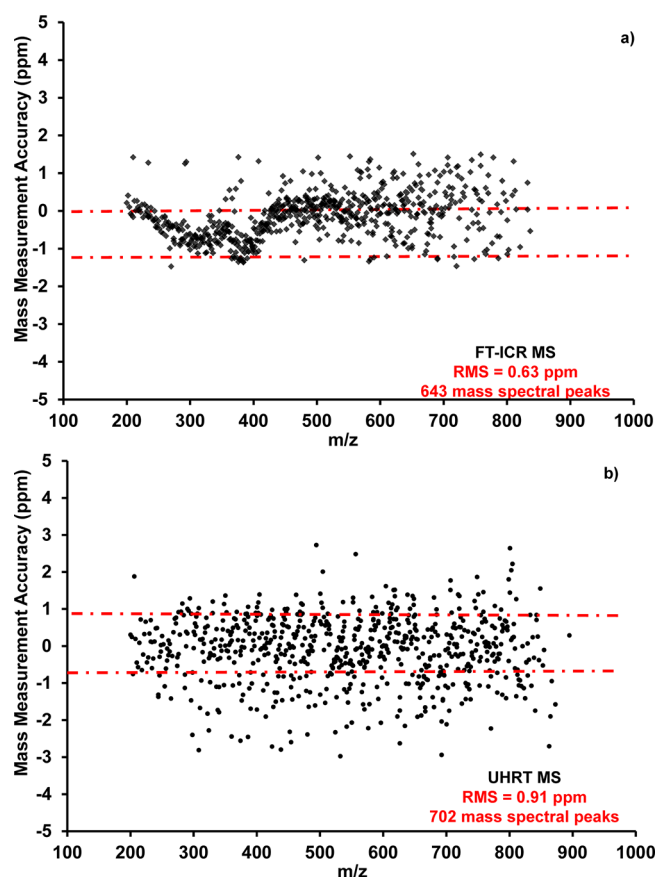


Figure 4. Accuracy for m/z measurements obtained from the analysis of a typical crude oil sample via ESI(+) using (a) FT-ICR MS at 400 000 at m/z 400 R_p and (b) HRT MS at 100 000 at m/z 400 R_p . Data are for the N class after internal standard calibration.

approximately 3900 components were assigned at the molecular level for the ESI(−) HRT mass spectra. For FT-ICR, 3600 and 5400 components were assigned from ESI(+) and ESI(−) spectra, respectively.

RESULTS AND DISCUSSION

Figure 2 shows the ESI(+) spectra for the same sample of crude typical oil⁴ acquired by both FT-ICR with 400 000 at m/z 400 R_p and HRT with 100 000 at m/z 400 R_p . Both spectra display similar Gaussian-like distributions typical for crude oil polar markers.¹ In comparison to FT-ICR, however, the HRT distribution is shifted to lower m/z . The reasons for such a shift may be various, including detection mechanisms, ion optics for transport into the mass analyzers, and tuning parameters. For the FT-ICR used herein, the population of ions created in the ESI source traverses a series of ion guides, is trapped inside a linear quadrupole ion trap, and is then transferred to the ICR cell via an octapole ion guide, whereas TOF effects will change the ion population that arrives at different times at the ICR cell. Therefore, each TOF microscan is modified to try to acquire the best average of ion population, leading to the best possible ion distribution. Hence, for comparative petroleomic studies, ion optics in FT-ICR is optimized for best overall transmission and mass distributions within the whole m/z range of interest. For the HRT, however, no ion-optics strategies for a well-balanced distribution of ions were attempted. Standard tuning and operation conditions commonly used on the HRT were applied, but optimized transmission and detection could be

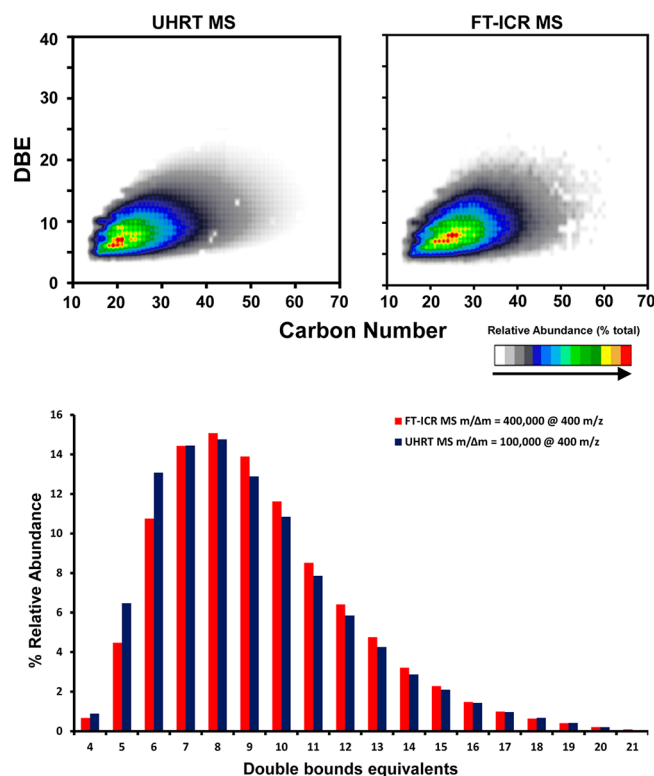


Figure 5. (Top) Plots of carbon number versus DBE for the N class of polar components and (bottom) N class versus DBE distribution from both ESI(+) HRT MS at 100 000 at m/z 400 R_p and FT-ICR MS at 400 000 at m/z 400 R_p in the m/z 200–1000 range.

further improved for best HRT performance in petroleomic studies. However, we also run the same sample in a Synapt Q-TOF mass spectrometer (Waters Micromass, Manchester, U.K.) using standard acquisition parameters and obtained a distribution (not shown) intermediate between the FT-ICR and HRT but interestingly quite more similar to the HRT data.

For the higher m/z range, a contributing factor to the appearance of bias is the observable peak height in each technique as a function of m/z . The resolution is effectively flat in the HRT, and as such, relative peak width is constant. In the FT-ICR MS, resolution drops as a function of m/z , meaning that width increases and height (for the same number of ions) is reduced. This detection bias may contribute to differences in relative responses (inductive current versus electron cascade at an EMT). In the HRT system, however, simpler ion optics is involved and the full pack of ions is accelerated and subjected to the flight with no major m/z discrimination being observed; hence, the HRT seems to provide proper features to detect actual distributions of polar markers created by ESI. Overall, however, because petroleomic studies are mostly based on comparative evaluation of profiles, the use of standard protocols for ESI ionization and m/z analysis is always required. Further manipulation of the tuning parameters could significantly impact the observed or detected HRT distribution but may not serve a purpose if relative differences are what is desired.

Figure 2 also shows extended views of the spectra in an illustrative m/z 0.1 window. To maximize performance, HRT data are normally collected in the centroid mode. The centroid mode in HRT is used as a mechanism to minimize data file size and maximize mass accuracy. All descriptive aspects of the peak

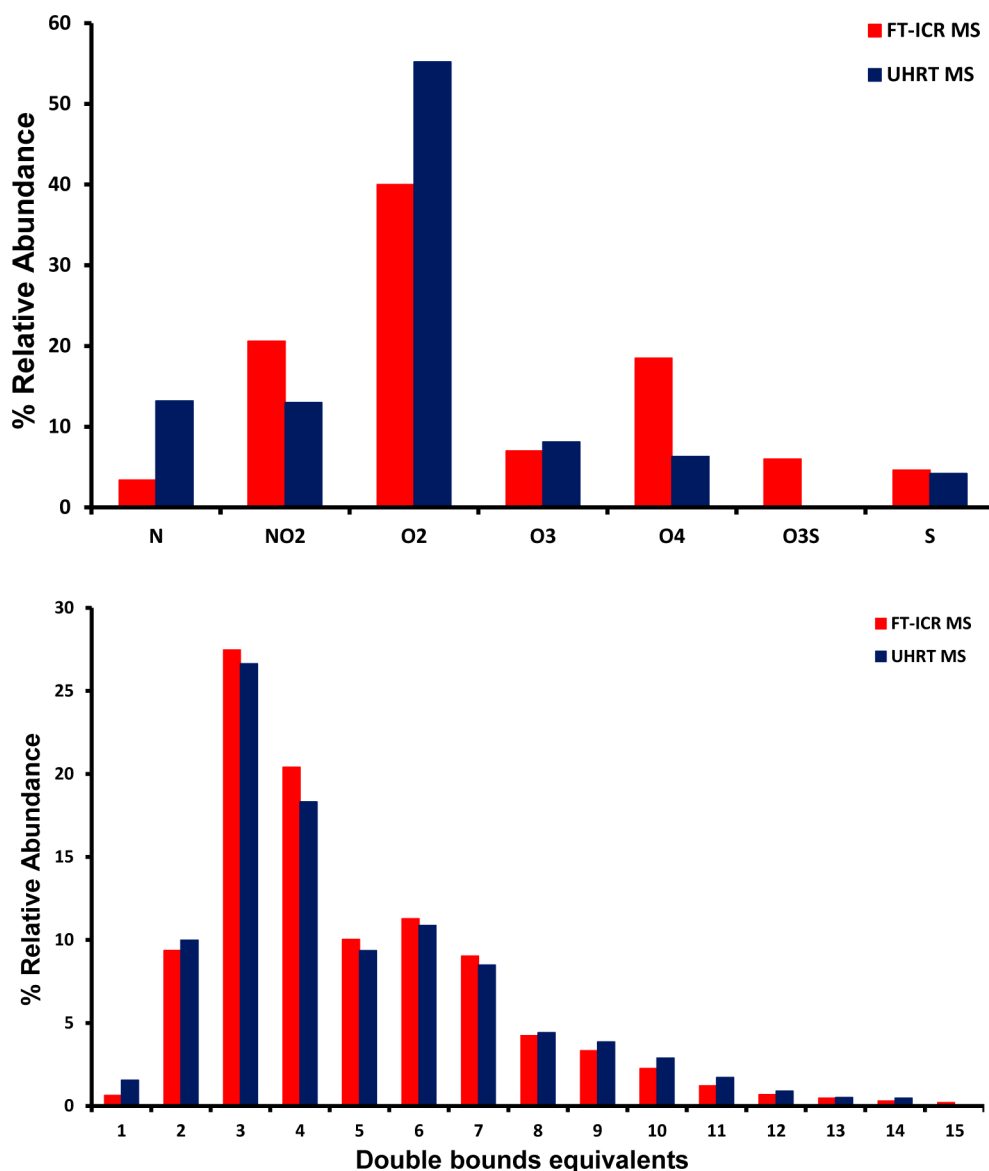


Figure 6. (Top) Heteroatom class distributions and (bottom) O₂ class versus DBE profiles measured by ESI(−) FT-ICR MS at 400 000 at m/z 400 R_p and ESI(−) HRT MS at 100 000 at m/z 400 R_p in the m/z 200–1000 range.

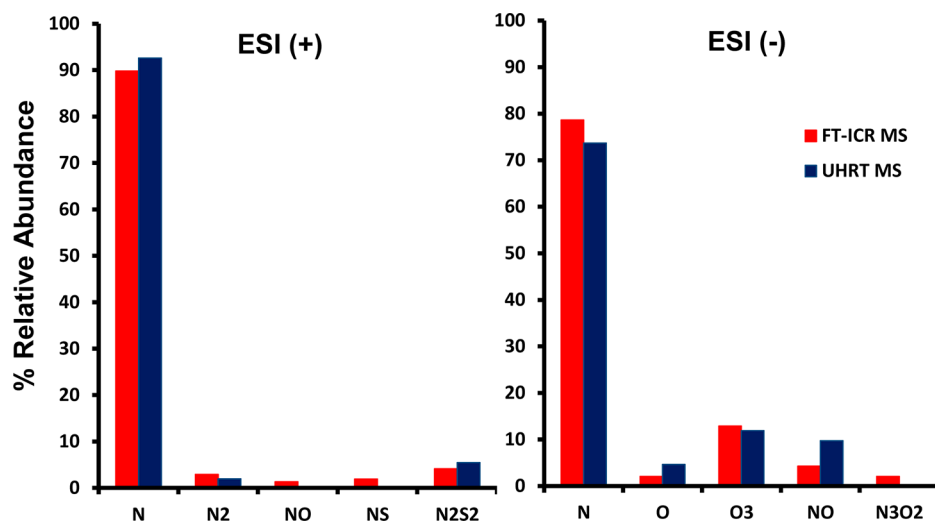


Figure 7. Heteroatom class distributions of a crude oil with reduced maturation and biodegradation levels measured by ESI(+) and ESI(−) FT-ICR MS and HRT MS at the m/z 200–1000 range.

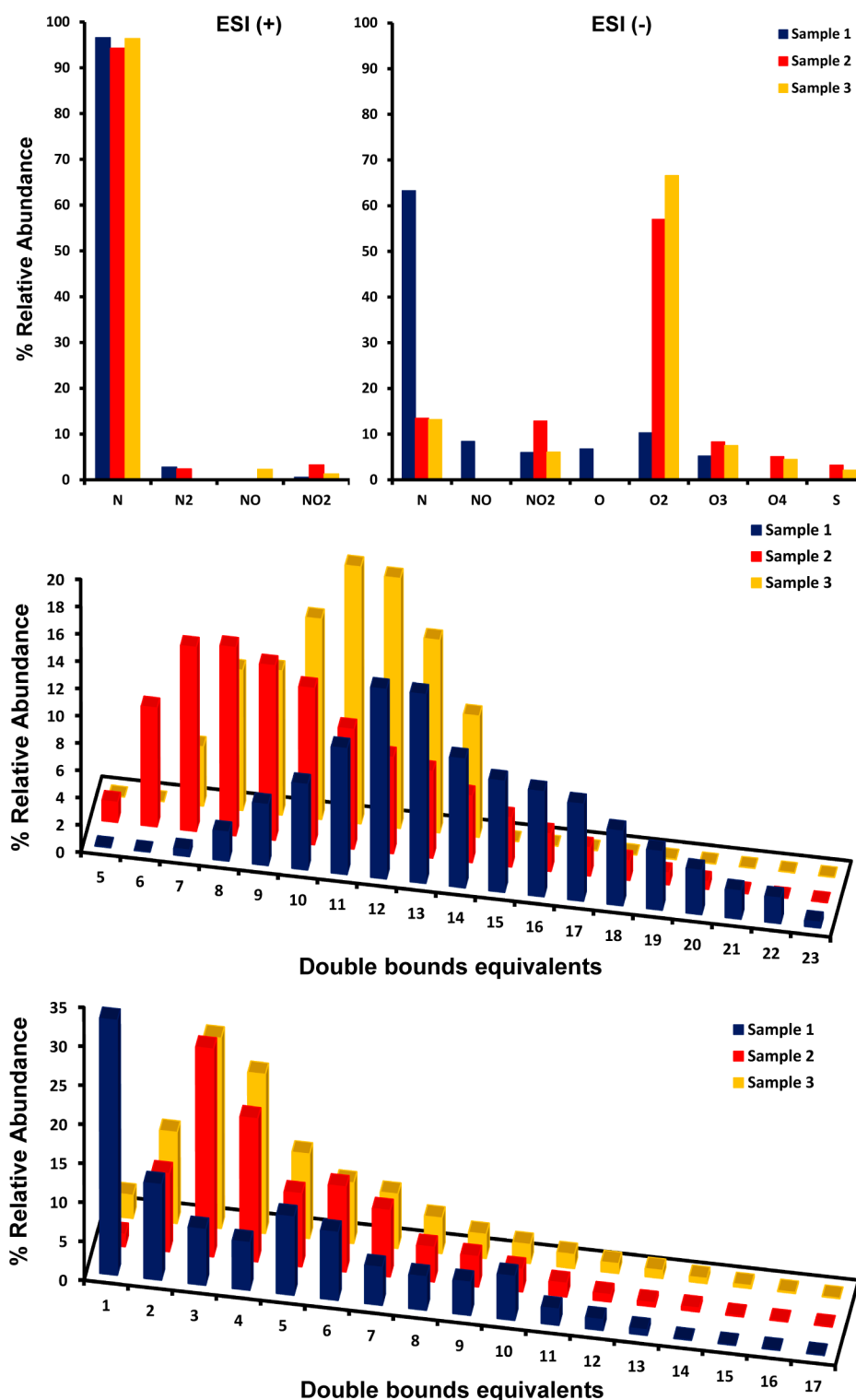


Figure 8. (Top) Heteroatom class distributions and (middle) NO₂ and (bottom) O₂ class versus DBE distributions for three crude oil samples measured by ESI(±) in the top panels and ESI(−) in the middle and bottom panels and HRT MS at 100 000 at m/z 400 R_p for three crude oil samples with different levels of maturation and biodegradation.

shape, defining resolution, are retained with the centroided peak and can be presented in the spectra as peak widths and shape. Although the FT-ICR R_p used in Figure 2 at m/z 400 (400 000) is 4 times higher than the HRT (100 000), note that both mass analyzers were able to resolve similar sets of ions with very close accurate m/z values. This means that, although peaks may overlap to some extent by not being baseline-resolved because of inferior

resolution and some of the least abundant peaks were missed likely because of burying in undetectable shoulders of the most abundant neighbor peaks, still the majority of the ions could be properly recognized and their m/z values could be accurately determined via 100 000 at m/z 400 R_p HRT with the Citius instrument. This is further demonstrated by the plots presented below.

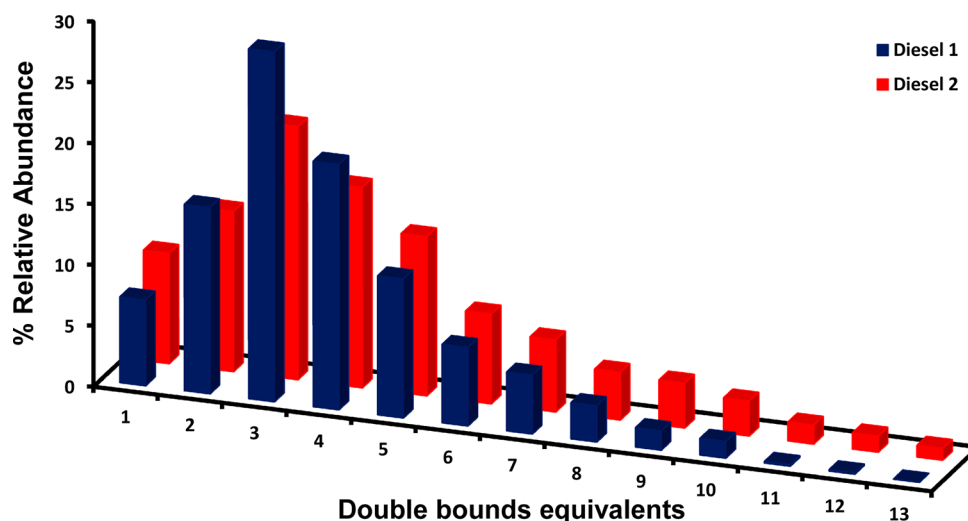


Figure 9. O_2 class versus DBE distribution for two diesel samples measured by ESI(−) HRT MS at 100 000 at m/z 400 R_p .

Peak resolution and accuracy in the m/z measurements are indispensable requirements for petroleomic MS studies for proper separation of ions and correct formula assignments. The top panel of Figure 3 shows the R_p trends obtained along the full FT-ICR mass spectrum operating at three different R_p : 100 000 at m/z 400, 200 000 at m/z 400, and 400 000 at m/z 400, as well as for HRT at 100 000 at m/z 400. Because it is intrinsic to ICR, the R_p of the FT-ICR cell decreases rapidly as a function of m/z .^{1,8} For the HRT, R_p slightly increases with m/z , from 90 000 at m/z 200 to near 110 000 at m/z 1000. The trends of the top panel of Figure 3 therefore show that, overall, in the full m/z 300–1000 range most typical for petroleomic studies, the resolution performance of HRT at 100 000 at m/z 400 R_p is superior to that of a FT-ICR at 100 000 at m/z 400 R_p and comparable to that for a FT-ICR at 200 000 at m/z 400 R_p , whereas it comes close at higher m/z to that of a FT-ICR at 400 000 at m/z 400 R_p . This indeed represents an extraordinary R_p for a TOF analyzer. Note that R_p of 400 000 at m/z 400 has been considered as the “gold standard” for ESI petroleomic studies in FT-ICR mass spectrometers.¹

In petroleomic MS studies, ultrahigh resolution is required particularly to resolve most challenging isobaric doublets, such as C_3/SH_4 , $^{13}CH/N$, CH_2/N , S/O_2 , and CH_4/O . Note in the bottom panel of Figure 3 that a FT-ICR MS operating at 400 000 at m/z 400 R_p properly resolves all of these doublets up to m/z ~750. The present HRT performance is insufficient to resolve C_3/SH_4 in the full m/z 200–1000 range, but the other doublets are fully or adequately resolved up to m/z 1000. The only problematic situation would be encountered therefore for samples in which sulfur components (NS and OS classes for instance) are of high abundance and would be crucial for accessing geochemical parameters. However, because HRT resolution increases with m/z (whereas that of FT-ICR MS decreases drastically with m/z), the performance of the HRT becomes comparable to that of a 400 000 at m/z 400 FT-ICR MS for isobaric doublet resolution at m/z higher than 750 and nearly the same beyond m/z 1000.

Figure 4 compares the m/z accuracy (after internal recalibration) for both FT-ICR at 400 000 at m/z 400 and HRT analysis at 100 000 at m/z 400. The accuracy for HRT after recalibration (~0.91 ppm rms) is just slightly inferior to that of FT-ICR (0.63 ppm rms). This result shows the outstanding accuracy of

the HRT (below 1 ppm), which is high enough for major class attributions in petroleomic studies.¹³

In the ESI(+) mode, data treatment shows that the crude oil sample analyzed displays ca. 88% of N class components. Figure 5 therefore compares typical petroleomic plots used to evaluate common geochemical crude oil properties, viz., the distributions of carbon number versus DBE and the DBE distributions, respectively, for this predominant N class obtained via both HRT and FT-ICR. These plots have been used to access, for instance, the level of biodegradation and thermal evolution in crude oils.^{1c,3} The FT-ICR plot in the top panels of Figure 5 is slightly broader, because of the broader mass distribution observed in the spectrum (Figure 2), but the overall “shapes” of both plots are essentially the same. For the DBE profiles (bottom panel of Figure 5), similar trends are also observed, again with the shift to lower m/z typical of the HRT data. This indicates the reliability of HRT in comparative petroleomic studies for samples of different geochemical properties, with similar conclusions as compared to FT-ICR. Note from the discussion of data from Figure 2 that HRT seems to provide a more realistic distribution of ESI(+) ions, as compared to that of FT-ICR.

As the top panel of Figure 6 illustrates, ESI(−) MS data using both FT-ICR and HRT of the crude oil samples were both able to detect distributions of seven classes of polar compounds, with the O_2 class being the most abundant. Note again the comparable class profiles and their suitability for comparative petroleomic studies. The bottom panel of Figure 6 compares the DBE profiles for the most abundant O_2 class detected by ESI(−). Again, the HRT at 100 000 at m/z 400 R_p provides a profile quite similar to that of the FT-ICR at 400 000 at m/z 400 R_p . This similarity is indeed encouraging for the suitability of HRT for petroleomic studies because the major O_2 class detected by ESI(−) represents mostly naphthenic and aromatic acids, which are a target class for the evaluation of several crude oil properties.^{4,14}

Figure 7 compares the FT-ICR MS and HRT MS performances in both ESI(+) and ESI(−) modes for class attribution of another typical crude oil with a quite diverse distribution of classes of polar components and a much reduced level of maturation and biodegradation, as compared to the sample from Figures 2–4.⁴ Note that, for the major classes, which are most often used as markers in petroleomic studies, the profiles and relative abundances are quite similar, whereas HRT MS fails to discriminate the least abundant classes.

Having established the suitability of HRT MS for petroleomic studies, three additional crude oil samples with contrasting properties in terms of biodegradation and maturation were analyzed by HRT MS at 100 000 at m/z 400 R_p in the m/z 200–600 range (Figure 8). Differences in the relative abundances of the NO and NO₂ classes are indicators of maturation, whereas the O₂ class is also used as a marker for biodegradation. The trends observed in Figure 8 correlate nicely with the trends predicted from FT-ICR MS analysis.^{4,11}

Note in the middle panel of Figure 8 that sample 1 displays a profile for the NO₂ class centered at a much higher DBE, which correlates well with its higher level of maturation. For the O₂ class (bottom panel of Figure 8), samples 2 and 3 display similar profiles, which correlates well with their similar levels of maturation, whereas sample 1 displays a quite contrasting profile, in which DBE = 1 predominates, indicating a high abundance of saturated aliphatic carboxylic acids. This trend correlates well with the high level of maturation and biodegradation of sample 1.

Figure 9 displays, as an additional example of the application of ultrahigh-resolution HRT MS, the profile for the O₂ class versus DBE for two diesel samples obtained from crude oils with contrasting biodegradation levels. Note for sample diesel 2 a broader distribution and greater abundance of naphthenic and aromatic acids with higher insaturation levels, particularly at DBE 8–13.

CONCLUSION

As shown herein by comparison to a FT-ICR, the innovative “zig-zag” multi-reflecting design of the ultrahigh-resolution (100 000 at m/z 400) HRT system displays sufficient resolution and accuracy to provide fast and accurate MS fingerprints of the polar composition of crude oils and distillates. Although petroleomic studies using other less gentle ionization techniques, which provide much denser mass spectra, may still require the exceedingly high resolution and mass accuracy of the ultrahigh-resolution FT-ICR mass analyzer operating at least with 400 000 at m/z 400 resolution and less overall coverage in terms of ion attribution was observed, the HRT system provides comparable capabilities to a FT-ICR, thus offering a fast, single-run, accurate, sensitive, and cost-effective alternative for most routine petroleomic MS studies using the ESI technique. Future improvements in the first generation of the HRT mass analyzer tested herein may also further enhance resolution, sensitivity, and accuracy, therefore expanding its applicability to petroleomic MS studies.

AUTHOR INFORMATION

Corresponding Author

*Jeff Patrick. e-mail: Telephone: 269-985-5876 (J.P.); 55-19-3521-3049 (M.N.E.). Fax: 55-19-3521-3049 (M.N.E.). E-mail: jeff_patrick@leco.com (J.P.); eberlin@iqm.unicamp.br (M.N.E.).

Notes

The authors declare no competing financial interest.

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REFERENCES

- (1) (a) Marshall, A. G.; Rodgers, R. P. *Acc. Chem. Res.* **2004**, *37*, 53–59. (b) Rodgers, R. P.; Schaub, T. M.; Marshall, A. G. *Anal. Chem.* **2005**, *77*, 20A–27A. (c) Marshall, A. G.; Rodgers, R. P. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, *105*, 18090–18095.
- (2) (a) Fu, J. M.; Kim, S.; Rodgers, R. P.; Hendrickson, C. L.; Marshall, A. G.; Qian, K. N. *Energy Fuels* **2006**, *20*, 661–667. (b) Haddad, R.; Regiani, T.; Klitzke, C. F.; Sanvido, G. B.; Corilo, Y. E.; Augusti, D. V.; Pasa, V. M. D.; Pereira, R. C. C.; Romão, W.; Vaz, B. G.; Augusti, R.; Eberlin, M. N. *Energy Fuels* **2012**, *26*, 3542–3547.
- (3) (a) Hughey, C. A.; Rodgers, R. P.; Marshall, A. G.; Qian, K.; Robbins, W. K. *Org. Geochem.* **2002**, *33*, 743–759. (b) Hughey, C. A.; Rodgers, R. P.; Marshall, A. G.; Walters, C. C.; Qian, K.; Mankiewicz, P. *Org. Geochem.* **2004**, *35*, 863–880. (c) Klein, G. C.; Rodgers, R. P.; Marshall, A. G. *Fuel* **2006**, *85*, 2071–2080.
- (4) (a) Mapolelo, M. M.; Stanford, L. A.; Rodgers, R. P.; Yen, A. T.; Debord, J. D.; Asomaning, S.; Marshall, A. G. *Energy Fuels* **2009**, *23*, 349–355. (b) Mapolelo, M. M.; Rodgers, R. P.; Blakney, G. T.; Yen, A. T.; Asomaning, S. A.; Marshall, A. G. *Int. J. Mass Spectrom.* **2011**, *300*, 149–157.
- (5) (a) Fenn, J. B.; Mann, M.; Meng, C. K.; Wong, S. F.; Whitehouse, C. M. *Science* **1989**, *246*, 64–71. (b) Coelho, F.; Eberlin, M. N. *Angew. Chem., Int. Ed.* **2011**, *50*, 5261–5263.
- (6) Zhan, D.; Fenn, J. B. *Int. J. Mass Spectrom.* **2000**, *194*, 197–208.
- (7) The most common definition of R_p is used here: $(m/z)/(\Delta m/z)_{50\%}$.
- (8) Pomerantz, A. E.; Mullins, O. C.; Paul, G.; Ruzicka, J.; Sanders, M. *Energy Fuels* **2011**, *25*, 3077–3082.
- (9) (a) Verentchikov, A. N.; Yavor, M. I.; Hasin, Y. I.; Gavrik, M. A. *Tech. Phys.* **2005**, *50*, 73–81. (b) Verentchikov, A. N.; Yavor, M. I.; Hasin, Y. I.; Gavrik, M. A. *Tech. Phys.* **2005**, *50*, 82–86.
- (10) (a) Guilhaus, M.; Selby, D.; Mlynski, V. *Mass Spectrom. Rev.* **2000**, *19*, 65–107. (b) Weickhardt, C.; Moritz, F.; Grotemeyer, J. *Mass Spectrom. Rev.* **1996**, *15*, 139–162. (c) *Time-of-Flight Mass Spectrometry—Instrumentation and Applications in Biological Research*; Cotter, R. J., Ed.; American Chemical Society: Washington, D.C., 1997.
- (11) Corilo, Y. E.; Vaz, B. G.; Simas, R. C.; Nascimento, H. D. L.; Klitzke, C. F.; Pereira, R. C. L.; Bastos, W. L.; Santos-Neto, E. V.; Rodgers, R. P.; Eberlin, M. N. *Anal. Chem.* **2010**, *82*, 3990–3996.
- (12) For representative samples, we selected crude oils with average and contrasting levels of biodegradation and maturation and broadest distributions of polar markers.
- (13) Guan, S.; Marshall, A. G.; Scheppele, S. E. *Anal. Chem.* **1996**, *68*, 46–71.
- (14) Barrow, M. P.; McDonnell, L. A.; Feng, X.; Walker, J.; SDerrick, P. *J. Anal. Chem.* **2003**, *75*, 860–866.