Light hydrocarbon geochemistry: insight into oils/condensates families and inferred source rocks of the Woodford–Mississippian tight oil play in North-Central Oklahoma, USA

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Abstract
The Woodford–Mississippian “Commingled Production” is a prolific unconventional hydrocarbon play in Oklahoma, USA. The tight reservoirs feature variations in produced fluid chemistry usually explained by different possible source rocks. Such chemical variations are regularly obtained from bulk, molecular, and isotopic characteristics. In this study, we present a new geochemical investigation of gasoline range hydrocarbons, biomarkers, and diamondoids in oils from Mississippian carbonate and Woodford Shale. A set of oil/condensate samples were examined using high-performance gas chromatography and mass spectrometry. The result of the condensates from the Anadarko Basin shows a distinct geochemical fingerprint reflected in light hydrocarbon characterized by heptane star diagrams, convinced by biomarker characteristics and diamond tane isomeric distributions. Two possible source rocks were identified, the Woodford Shale and Mississippian mudrocks, with a variable degree of mixing. Thermal maturity based on light hydrocarbon parameters indicates that condensates from the Anadarko Basin are of the highest maturity, followed by “Old” Woodford-sourced oils and central Oklahoma tight oils. These geochemical parameters shed light on petroleum migration within Devonian–Mississippian petroleum systems and mitigate geological risk in exploring and developing petroleum reservoirs.

Keywords Tight oil · Tight condensate · Woodford Shale · Mississippian limestone · Light hydrocarbon geochemistry · Anadarko Basin

1 Introduction
Woodford Shale has not only been proven to be an excellent source rock charging conventional reservoirs in Kansas and Oklahoma (Comer et al. 1987; Burruss and Hatch 1989; Philp et al. 1989; Jones and Philp 1990; Comer 1992; Wang and Philp 1997), but also a frontier for unconventional resource play exploration and production. In areas straddling between the basin and shelf, like the Cana-Woodford Play, the Woodford produces wet gas and condensates. The oil has been commingled produced from the Woodford/Mississippian strata since 2010 on the Anadarko Shelf and Cherokee Platform. Many studies suggest that the Woodford Shale accounts for more than 85% of commercial oil produced from conventional reservoirs in Oklahoma and Kansas (Welte et al. 1975; Lewan et al. 1979; Reber 1988; Burruss and Hatch 1989), but few publications have shown strong evidence to prove the oils were actually sourced from the Woodford Shale. Comer and Hinch (1987) recognized expulsion, or primary migration, of oil from the Woodford Shale in Oklahoma by identifying numerous small-scale accumulations of bitumen within mature parts of the Woodford Shale, including fractures, stylolites, burrows, nodules, and sandstone lenses, all of which are completely enclosed in the source rock. Additional evidence to prove the Woodford Shale has generated oil in situ has been described in Cardott (2014a, b), where extracts found in the surface fractures of the Woodford outcrop in the McAlister cemetery quarry and in the Criner Hills were shown to be low-maturity “oil”
(rock extract filled in the fractures) originating from the local Woodford Shale. Oil samples produced from multiple conventional reservoirs of different ages and extracts of possible source rocks indicated that most of the oils were primarily derived from the Woodford Shale in the Anadarko Basin (Jones and Philip 1990). Burruss and Hatch (1989) undertook a detailed geochemical investigation of 104 crude oils and 190 core samples of dark-colored shales from the Anadarko Basin. They identified three oil end members, which generally correlated with the reservoir and source rock age. One oil shared the stable carbon isotope signature and biomarker fingerprints of the Woodford extracts, indicating that it was possibly derived from the Woodford Shale in the deep Anadarko Basin (Burruss and Hatch 1989).

An important factor affecting hydrocarbon richness in Woodford–Mississippian tight play is associated with source rock heterogeneity. The Woodford Shale is an organic-rich source of hydrocarbon that charged Woodford–Mississippian tight reservoirs, together with Mississippian mudrocks such as Caney Shale (Al Atwah et al. 2015, 2017). Typically, identifying petroleum source rock could be achieved by using a collection of geochemical tools such as molecular and isotopic fingerprints, which include biomarkers together with stable carbon isotopes of saturate and aromatic hydrocarbon fractions (Al Atwah et al. 2017; Wang and Philip 1997). Currently, light hydrocarbon markers remain underutilized in crude oil recovered from Woodford–Mississippian tight reservoirs. Oil–oil correlations, together with hydrocarbon migration and maturity assessment, can be further refined by utilizing the light hydrocarbon markers. Light hydrocarbon geochemistry is an effective tool for defining petroleum systems especially with processes related to petroleum migration and accumulation (Hao et al. 1991; Zhang and Lin 1994; Dai and Wilk 1995). Here, we present new geochemical data of light hydrocarbons produced from Woodford–Mississippian tight reservoirs across the Anadarko Basin in Oklahoma. Data suggest different sources of hydrocarbons, with various thermal maturity stages. Moreover, these data shed light into factors affecting petroleum accumulation in Woodford–Mississippian tight reservoirs such as water-washing and petroleum mixing.

2 Geological settings

In the early Paleozoic time, three major tectonic/depositional provinces existed in Oklahoma: the Oklahoma Basin, the southern Oklahoma Aulacogen, and the Ouachita Trough. The Oklahoma Basin was a shelf-like area that received widespread and thick shallow marine carbonates interbedded with thin marine shales and sandstones (Johnson 1989; Northcutt et al. 2001). The southern Oklahoma Aulacogen was the depocenter for the Oklahoma Basin and the precursor of the Anadarko Basin (Johnson 1989; Northcutt et al. 2001). From Silurian to Middle Devonian clean-washed skeletal limestones, argillaceous, and silty carbonates, referred to as the Hunton Group in Oklahoma, were deposited in a shallow marine setting (Northcutt et al. 2001). Epeirogenic Uplifts interrupted deposition resulting in two regional unconformities. In southern Oklahoma, the pre-Woodford–Chattanooga unconformity eroded out Upper Ordovician and in northern Oklahoma the erosion sculpted out Upper Cambrian–Lower Ordovician rocks (Kirkland et al. 1992; Fig. 1b). The Nemaha Uplift is a buried range of the Ancestral Rocky Mountains associated with a granite high in the pre-Cambrian basement that extends approximately from Nebraska to Central Oklahoma (Gerhard 2004). The major deformation of the Nemaha Uplift took place in pre-Desmoinesian and post-Mississippian time (Lee 1943; Merriam 1946; Gerhard 2004). The Cherokee platform could be considered as part of the stable shelf area of the Arkoma Basin throughout most of the Woodford deposition (Campbell and Northcutt 2001). In the Late Devonian, the Cherokee Platform was a broad shelf separated from the proto-Anadarko Basin by the paleo-Nemaha Ridge (Northcutt and Campbell 1996; Campbell and Northcutt 2001).

The Late Devonian to Early Mississippian age Woodford Shale is an organic-rich black shale widely distributed over most of Oklahoma including the Anadarko Basin, the Anadarko Shelf, Cherokee Platform, and the Arkoma Basin (Comer and Hinch 1987; Comer 1992). On the Cherokee Platform, the Woodford Shale was deposited on a major regional unconformity developed during the Late Devonian (Amsden 1975). It is conformably overlain by limestone and shale of Early Mississippian Age (Fig. 2). The predominant lithology of the Woodford Shale is black shale along with other common lithologies including chert, siltstone, sandstone, dolostone, and light-colored shale (Amsden 1967; Amsden 1975; Comer 1992). The Woodford Shale in Oklahoma is a typical marine clay-rich siliciclastic shale based on three key characteristics found from previous studies: (1) marine non-calcareous siliceous mudstone (Amsden 1975; Kirkland et al. 1992; Comer 2008; Kvale and Bynum 2014); (2) low-to-moderate sulfur content (Jarvie et al. 2007); and (3) high clay mineral content (Kirkland et al. 1992; Comer 2008; Kvale and Bynum 2014).

3 Samples and methods

3.1 Study area and sampling

The study area extends across two major Woodford resource plays, namely Anadarko-Woodford and Nemaha-Woodford (Fig. 1a). Areal coverage includes Dewey, Blaine, Canadian,
Fig. 1  a Map showing the location of examined crude oil samples relative to major geological features and hydrocarbon plays in Oklahoma; the dotted line marks the borders of the Anadarko Basin. b NE-SW structural cross section across the Anadarko Basin (Johnson 1989) (modified from Johnson 1989)
Garfield, Logan, and Payne counties. From a geological perspective, all counties are located within the Anadarko Basin except for Garfield, Logan, and Payne counties which are part of the shallow Cherokee Platform. The Nemaha Uplift is a major structural feature dividing the Cherokee Platform from the Anadarko Basin province.

Crude oil/condensate samples were collected from Mississippian reservoirs, as well as the Woodford Shale strata. A generalized stratigraphic column of the Anadarko Basin is shown in Fig. 2, and major source rocks and all examined crude oils are produced from Devonian–Mississippian petroleum systems. Well-head fluid samples were collected at the separator in 240 ml borosilicate glass bottles and tightly sealed with a PTFE-lined cap. Table 1 lists the 24 crude oil and 5 condensate samples with key bulk characteristics in this study. An aliquot of the crude oil/condensate sample was dissolved in hexane to precipitate asphaltenes; dissolved hydrocarbons in hexane were further fractionated using silica gel column chromatography into saturate, aromatic, and resin fractions. All samples are produced from horizontal wells that have been stimulated with hydraulic fracturing except for the 8 “Old” Woodford-sourced oils (Group-3); therefore, the horizontal targets listed in Table 1 represent the landing zone of the horizontal well and not necessarily the source of the produced oils. Eight “Old” Woodford-sourced oil samples (Group-3), previously produced from vertical wells into conventional reservoirs in Southern Oklahoma and stored in Dr. Philp’s laboratory (University of Oklahoma), were also included in the study for comparative purposes.

### 3.2 Whole oil gas chromatography

For whole oil GC analysis, the crude oil sample was diluted into a 1 mg/ml n-hexane solution and analyzed on an Agilent 6890 series gas chromatograph with a split/splitless capillary injection system and a 100 m × 0.25 mm (i.d.) J&W Scientific DB-Petro 122-10A6 fused silica capillary column coated with a 0.5 µm liquid film. The temperature program started with an initial temperature of 40 °C and 1.5 min hold time and increased to 130 °C at a rate of 2 °C per minute and subsequently increased to 300 °C at a rate of 4 °C per minute followed by an isothermal period of 26 min for a total run of 115 min. C7 light hydrocarbon analysis was performed using the GC data obtained from whole oil/condensates GC analysis stated above. The isolated fractions, saturates, and aromatics, respectively, were analyzed using an Agilent 6890 series gas chromatograph with a splitless capillary injector and a 30 m × 0.25 mm (i.d.) J&W Scientific DB-5 122-5032 fused silica capillary column coated with a 0.25 µm liquid film. The injector was set up in the splitless injection mode, and the temperature was held at 300 °C. The carrier gas was helium (He) with a flow rate of 1.4 ml/min. The temperature program started with an initial temperature of 40 °C held for 1.5 min and increased to 300 °C at a rate of 4 °C per minute followed by an isothermal period of 34 min for a total run time of 100.5 min. The flame ionization detector (FID) temperature was set at 310 °C. n-Alkanes and isoprenoids were identified in each chromatogram by comparing their relative retention times with standards.

### 3.3 Gas chromatography–mass spectrometry

The GC–MS analyses of the branched and cyclic alkanes (B&C) and aromatic fractions were performed on an
Agilent 7890A gas chromatography system coupled with an Agilent Technologies 5975C mass selective detector (MSD) using single ion monitoring. The GC used a 60 m × 0.25 mm Agilent/J&W Scientific DB-5 122-5562 fused silica capillary column coated with a 0.25 µm liquid film. The injected volume of branched and cyclic and aromatic fractions was 1 µl per run. The injector temperature was set at 300 °C. The GC temperature program started at 40 °C with 1.5 min hold time and was later increased to 300 °C at a rate of 4 °C per minute and then held constant for 34 min for a total run time of 100.5 min. Samples were run in splitless mode, and helium was used as the carrier gas at a flow rate of 1.4 ml/min. Biomarker compounds were determined from fragmentograms corresponding to each ion using relative retention times and by comparison with published data.

For diamondoids analysis in crude oils/condensates, the sample was diluted with pentane in the concentration of 16 mg oil/ml pentane. The pentane was reported to be a good solvent for adamantanes and diamantanes in terms of high solubility and low boiling point (Reiser et al. 1996). The oil solution was well homogenized in ultrasonic bath for at least 1 min. 1 µl of the resulting oil solution was injected to Agilent GC–MS to detect adamantanes and diamantanes using SIM mode and key ion fragments: 135, 136, 149, etc., and 188, 187, 201, etc., respectively. DB-5

| Sample          | Reservoir          | API  | %SAT+ | %ARO+ | %NSO+ | %ASP+ | Type       |
|-----------------|--------------------|------|-------|-------|-------|-------|------------|
| Lingo 1-13 H    | Woodford Shale     | 48.92| 7.1   | 1.2   | 0.5   | 91.2  | Condensate |
| Crystal 1-28H   | Woodford Shale     | 47.98| 65.0  | 26.6  | 7.8   | 0.6   | Condensate |
| York 1-2H       | Woodford Shale     | 48.56| 91.9  | 6.2   | 1.1   | 0.8   | Condensate |
| Wion 1-29H      | Woodford Shale     | 49.23| 85.2  | 3.5   | 10.5  | 0.8   | Condensate |
| Bros 1-18H      | Woodford Shale     | 49.39| 96.5  | 1.1   | 1.7   | 0.7   | Condensate |
| Group-2         | Horizontal targets*|   |       |       |       |       |            |
| Johnson 1-33H   | Woodford Shale     | 36.21| 90.9  | 3.5   | 0.1   |       | Medium Oil |
| Matthews 1-33H  | Mississippian “Lime”| 37.93| 81.3  | 10.6  | 3.1   | 5.0   | Medium Oil |
| Wilma 1-16H     | Woodford Shale     | 38.55| 85.1  | 9.4   | 2.1   | 3.3   | Medium Oil |
| Elinore 1-18H   | Mississippian “Lime”| 33.53| 76.0  | 13.7  | 0.9   | 5.5   | Medium Oil |
| Elinore 1-17H   | Woodford Shale     | 38.21| 68.5  | 16.7  | 3.3   | 11.2  | Medium Oil |
| Winney 1-8H     | Mississippian “Lime”| 28.11| 54.4  | 9.3   | 2.0   | 34.3  | Black Oil  |
| Adkisson 1-33H  | Mississippian “Lime”| 38.45| 84.1  | 13.1  | 0.2   | 2.6   | Medium Oil |
| Winney 1-5H     | Woodford Shale     | 38.25| 79.7  | 15.2  | 0.2   | 1.1   | Medium Oil |
| Smith 1-14WH    | Woodford Shale     | 34.22| 88.3  | 1.0   | 0.2   | 4.5   | Medium Oil |
| Smith 1-23MH    | Mississippian “Lime”| 32.55| 78.0  | 9.5   | 1.9   | 12.9  | Medium Oil |
| Hopfer 1-20WH   | Woodford Shale     | 33.45| 83.0  | 9.5   | 1.9   | 1.9   | Medium Oil |
| Peach 1-20WH    | Woodford Shale     | 35.58| 86.6  | 3.5   | 1.3   | 1.3   | Medium Oil |
| Joyce 1-32H     | Woodford Shale     | 33.71| 72.9  | 17.5  | 6.5   | 3.2   | Medium Oil |
| Williams 1-24WH | Woodford Shale     | 36.63| 85.3  | 7.6   | 5.6   | 1.5   | Medium Oil |
| Peach 1-19H     | Mississippian “Lime”| 35.88| 87.5  | 14.0  | 2.9   | 2.9   | Medium Oil |
| C. Matthews 1-8WH | Woodford Shale    | 37.74| 83.2  | 8.3   | 5.2   | 2.8   | Medium Oil |
| Group-3         | Conventional reservoir** |     |       |       |       |       |            |
| Ford-1          | N.A.               | 83.6 | 15.1  | 1.3   | 0.0   |       | Black Oil  |
| Thomas James 1-22 | Pennsylvanian sandstone | 27.13| 75.9  | 9.5   | 2.6   | 12.1  | Black Oil  |
| Anadarko Taylor 2118 | N.A.             | 48.98| 92.2  | 7.8   | 0.0   | 0.0   | Light Oil  |
| “A”            | N.A.               | 36.55| 83.5  | 10.9  | 2.9   | 2.7   | Medium Oil |
| Ellis Lewis Jet | Viola limestone   | 37.93| 87.5  | 7.2   | 2.4   | 2.9   | Medium Oil |
| ST Mary         | N.A.               | 49.49| 99.0  | 1.0   | N.D.  | N.D.  | Light Oil  |
| “F”            | N.A.               | 27.9 | 66.1  | 8.7   | 3.7   | 21.5  | Black Oil  |
| 7-5 N-5E        | N.A.               | 22.1 | 73.7  | 9.9   | 3.7   | 12.7  | Black Oil  |

*Horizontal targets indicate the landing zone of the horizontal well, and not necessarily the actual source of the oil. +SAT: weight percentage of saturate hydrocarbons; ARO: weight percentage of aromatic hydrocarbons; POL: weight percentage of polar resin compounds (NSO); ASP: weight percentage of asphaltene. N.A. denotes not available
MS 60 m × 0.25 mm × 0.25 micron in film thickness was used. Temperature program started at 40 °C and held it for 1.5 min before ramping 4 °C/min to 300 °C, and then held this temperature for 34 min. Compound ratios were calculated directly from peak areas or peak heights of targeted markers and compared with internal standards.

4 Results and discussion

4.1 Bulk geochemical parameters

Crude oils exhibit slight differences in bulk parameters that are consistent with the type of fluid, in which the majority of the samples are classified as medium oil. Key bulk parameters of the crude oils are listed in Table 1, including fluid type, API gravity, and SARA (short for saturates, aromatics, resin and asphaltene) component classes. API gravity values ranged from 22.1 to 49.49, as reflected in the fluid type, in which lower API values are associated with heavier black oils and higher API values from light oils. All of the oil samples are dominated by saturate hydrocarbons compared to aromatic, resin, and asphaltene. Heavier crude oils, such as Winney 1-8H, were higher in asphaltene content relative to the rest of the oil samples. The crude oil bulk characteristic is a useful descriptive source of data with some inherent limits. The dominance of the saturated hydrocarbon is reasonable to be found in thermogenic hydrocarbons expelled from petroleum source rocks. Such enrichment in saturated hydrocarbons is usually observed in naturally produced crude oil (Lewan et al. 2006). However, the source rock of petroleum cannot be determined solely from bulk parameters; therefore, characteristics of molecular fingerprints discussed below can aid to identify hydrocarbon sources.

4.2 Light hydrocarbon analysis

4.2.1 Source parameters

Heptane (C$_7$) variability reflected the geographic location among the three distinct oil groups. Table 2 lists the ratios used for constructing the oil correlation star diagram (OCSD) and oil transformation star diagram (OTSD) (Halpern 1995). Group-1 samples located within the Anadarko Basin exhibited a unique fingerprint of the C$_7$ OCSD (Figs. 3, 4). Specifically, these oils are enriched in the 3,3-dimethylpentane isomer relative to the rest of heptane isomers. Similarly, enrichment in 2,2-dimethylpentane and 2,4-dimethylpentane is observed within tight oils located on the Cherokee Platform (Group-2). Additionally, Group-1 condensates varied the most for 2,2-dimethylpentane, followed by 3,3-dimethylpentane isomers (Figs. 3, 4). However, even with those variations, the overall star diagram fingerprint is unique to the condensates (Group-1) from the Anadarko Basin compared to other oil groups (Figs. 3, 4). Group-2 oils located in Cherokee Platform, Central Oklahoma, showed a narrow OCSD pattern, with significant enrichment in 3-ethylpentane (Table 2). Group-3 oils displayed more subtle variability where some oils are enriched in 3,3-dimethylpentane and relatively lower in 2,4-dimethylpentane isomer, while other oils display the opposite trend.

The observed variation of star diagram fingerprints across crude oil groups is a function of source rock inherent variation and evaporative fractionation. Mango (1987) reported that light hydrocarbons in crude oil are formed via metal-catalyzed steady-state kinetic reaction of the kerogen. Moreover, it was observed that while the absolute concentration of light hydrocarbons from the same source varied by orders of magnitude, certain ratios of light hydrocarbons kept constant, such as the sum of 2-methylhexane and 2,3-dimethylpentane relative to the sum of 3-methylhexane and 2,4-dimethylpentane (K1) (Mango 1987). To explain the invariance of the C$_6$-C$_7$ hydrocarbons, Mango (1987) postulated that light hydrocarbons originate from a higher saturated hydrocarbon and the presence of metal catalysts will result in a similar reaction rate for homologous series. OCSD parameters are based on branched C$_7$ alkanes; therefore, those ratios would keep constant observed by Mango (1987). In examined crude oils, the variations in OCSD fingerprints between Group-1 and Group-2 are clearly indicating two different sources of hydrocarbons (Fig. 4), whereas Group-3 presumably is a mix of the two end members or from a third source. Within the Anadarko Basin, a number of source rocks have been studied ranging in age from Cambrian to Pennsylvanian (Al Atwah et al. 2017; Wang and Philp 1997). Observations from light hydrocarbon source parameters are discussed in the biomarker section below.

4.2.2 Alteration assessment

The oil transformation star diagrams (OTSD), a multivariate plot in polar coordinates developed by Halpern based on different ratios of C$_4$-C$_7$ hydrocarbons to characterize secondary alterations of crude oils (Halpern 1995), are illustrated in Fig. 4 with ratios used to construct the diagrams listed in Table 2. Although light hydrocarbons are controlled by the organic matter source, secondary alterations can affect light hydrocarbon distribution (i.e., biodegradation, water-washing, thermal maturity, and evaporation). In all the oil samples, lowest ratio values are observed at TR-6 ranging from 0.01 to 1.09 (Table 2), with Group-1 samples exhibiting the highest TR-1 values compared to the other two groups. Overall, Group-1 and Group-3 showed a relatively similar OTSD pattern maximizing at TR-4 followed by TR-3, whereas Group-2 highest ratio coexists at TR-7 and TR-8 followed by TR-6. The
Table 2  Key light hydrocarbon ratios of crude oil samples sensitive to source, transformation, and maturity

| Sample       | Oil correlation parameters | Oil transformation ratio | Maturity |
|--------------|---------------------------|--------------------------|----------|
|              | 2,3-DMP | 2,2-DMP | EtCP/P | 3,3-DMP | 2,4-DMP | TR-1 | TR-2 | TR-3 | TR-4 | TR-5 | TR-6 | TR-7 | TR-8 | C7 ratio | iso-C7 ratio |
| Group-1      |         |         |        |         |         |      |      |      |      |      |      |      |      |         |             |
| Lingo 1-13 H | 1.1     | 0.2     | 0.8    | 0.2     | 0.6     | 7.7  | 38.6 | 16.7 | 15.3 | 32.0 | 0.1  | 1.3  | 5.3  | 37.3     | 8.4         |
| Crystal 1-28H| 0.9     | 0.2     | 0.3    | 0.3     | 0.5     | 18.1 | 23.6 | 8.9  | 8.3  | 17.2 | 0.1  | 1.1  | 4.5  | 31.7     | 6.1         |
| York 1-2H    | 1.1     | 0.2     | 0.9    | 0.3     | 0.6     | 5.5  | 18.6 | 7.0  | 6.1  | 13.1 | 0.1  | 1.3  | 4.7  | 33.0     | 4.5         |
| Wion 1-29H   | 0.7     | 0.3     | 0.6    | 0.3     | 0.4     | 25.5 | 27.5 | 11.2 | 11.2 | 22.4 | 0.1  | 1.1  | 4.1  | 32.4     | 8.0         |
| Bros 1-18H   | 1.3     | 0.2     | 1.0    | 0.2     | 0.6     | 4.8  | 23.1 | 8.7  | 7.3  | 16.0 | 0.1  | 1.4  | 5.2  | 36.0     | 4.7         |
| Group-2      |         |         |        |         |         |      |      |      |      |      |      |      |      |      |         |             |
| Johnson 1-33H| 3.5     | 0.1     | 3.1    | 0.0     | 0.9     | 3.2  | 13.1 | 5.0  | 3.1  | 8.1  | 0.5  | 2.9  | 4.1  | 26.9     | 0.8         |
| Matthews 1-33H| 2.8    | 0.1     | 2.3    | 0.1     | 0.1     | 3.0  | 12.7 | 4.9  | 3.1  | 8.0  | 0.5  | 2.8  | 3.9  | 26.7     | 0.8         |
| Wilma 1-16H  | 2.5     | 0.1     | 2.3    | 0.2     | 0.8     | 4.2  | 15.8 | 5.2  | 3.5  | 8.7  | 0.5  | 2.8  | 3.9  | 30.1     | 0.9         |
| Elinore 1-18H| 3.0     | 0.1     | 4.1    | 0.2     | 0.8     | 2.3  | 16.7 | 6.7  | 3.9  | 10.7 | 1.0  | 4.4  | 4.0  | 26.7     | 0.6         |
| Elinore 1-17H| 3.5     | 0.1     | 5.0    | 0.0     | 0.9     | 2.2  | 6.4  | 6.6  | 3.8  | 10.5 | 1.1  | 4.6  | 4.1  | 29.6     | 0.6         |
| Winney 1-8H  | 3.5     | 0.1     | 3.7    | 0.0     | 0.9     | 3.0  | 14.9 | 5.5  | 3.3  | 8.9  | 0.7  | 3.3  | 4.1  | 27.4     | 0.7         |
| Adkisson 1-33H| 3.4    | 0.2     | 3.3    | 0.0     | 0.8     | 3.0  | 10.8 | 4.4  | 2.7  | 7.1  | 0.6  | 2.9  | 3.9  | 25.9     | 0.7         |
| Winney 1-5H  | 3.0     | 0.1     | 3.0    | 0.2     | 0.7     | 3.1  | 13.0 | 5.1  | 3.1  | 8.3  | 0.7  | 3.2  | 3.8  | 26.2     | 0.7         |
| Smith 1-14WH | 2.3     | 0.1     | 1.7    | 0.2     | 0.7     | 3.8  | 14.8 | 5.4  | 3.7  | 9.1  | 0.4  | 2.4  | 3.8  | 29.2     | 1.1         |
| Smith 1-23MH | 2.8     | 0.1     | 2.7    | 0.2     | 0.7     | 4.5  | 15.1 | 5.5  | 3.2  | 8.2  | 0.5  | 2.6  | 3.8  | 29.8     | 0.9         |
| Group-3      |         |         |        |         |         |      |      |      |      |      |      |      |      |      |         |             |
| Ford-1       | 2.4     | 0.1     | 3.6    | 0.2     | 0.7     | 7.6  | 32.7 | 11.8 | 7.6  | 19.3 | 1.1  | 4.8  | 4.5  | 33.3     | 1.1         |
| Thomas James 1–22 | 3.6 | 0.0     | 3.9    | 0.0     | 1.0     | 4.4  | 26.0 | 9.3  | 15.7 | 0.5  | 3.3  | 5.2  | 34.7     | 1.4         |
| Anadarko Taylor 2118 | 2.2 | 0.1     | 2.1    | 0.2     | 0.7     | 6.8  | 42.7 | 15.5 | 11.1 | 8.2  | 0.5  | 3.5  | 5.0  | 39.3     | 2.5         |
| “A”          | 3.4     | 0.1     | 3.9    | 0.1     | 0.8     | 2.4  | 13.0 | 4.8  | 2.9  | 7.7  | 0.6  | 3.0  | 3.7  | 27.1     | 0.7         |
| Ellis Lewis Jet| 2.4    | 0.1     | 2.8    | 0.2     | 0.7     | 5.3  | 31.1 | 10.6 | 7.2  | 17.8 | 0.6  | 3.5  | 4.8  | 37.2     | 1.5         |
| ST Mary      | 2.0     | 0.2     | 2.2    | 0.3     | 0.5     | 16.3 | 53.8 | 17.6 | 14.2 | 31.8 | 0.0  | 2.8  | 5.5  | 40.9     | 4.7         |
| “F”          | 4.9     | 0.0     | 6.1    | 0.0     | 1.0     | 4.7  | 14.3 | 5.1  | 3.0  | 8.2  | 0.6  | 3.1  | 4.1  | 27.9     | 0.7         |

P1: 2,2-dimethylpentane + 2,3-dimethylpentane + 2,4-dimethylpentane + 3,3-dimethylpentane + 3-ethylpentane; 2,2-DMP: 2,2-dimethylpentane/P1; 2,3-DMP: 2,3-dimethylpentane/P1; 2,4-DMP: 2,4-dimethylpentane/P1; 3,3-DMP: 3,3-dimethylpentane/P1; EtP: 3-ethylpentane/P1; X: 1,1-dimethylcyclopentane; P2: 2-methylhexane + 3-methylhexane; TR1: toluene/X; TR2: n C7/X; TR3: 3-methylhexane/X; TR4: 2-methylhexane/X; TR5: P2/X; TR6: 1-cis-2-dimethylcyclopentane/X; TR7: 1-trans-3-dimethylcyclopentane/X; TR8: P1/P2; C7 ratio: 100*n-heptane/cyclohexane + 2-methylhexane + 1,1-dimethylcyclopentane (DMCP) + 3-methylhexane + 1-cis-3-DMCP + 1-trans-3DMCP + 1-trans-2-DMCP + n-heptane + methylcyclohexane; iso-C7 ratio: 2-methylhexane + 3-methylhexane/1-cis-3-DMCP + 1-trans-3DMCP + 1-trans-2-DMCP.
apparent depletion in TR-1 in the oil samples is related to the effect of water-washing, which is characterized by using the ratio of toluene relative to 1,1-dimethylcyclopentane. (Toluene is more water-soluble; therefore, a decreasing trend in TR-1 indicated water-washing (Mango 1997.) From OTSD, it is clear that water-washing effects occurred, but at different magnitudes, Group-2 was severely water-washed, while Group-1 and Group-3 were relatively slightly washed. No crude oil exhibited any evidence of microbial biodegradation as observed from the high values of the transformation values ranging from TR-2 to TR-8 (Table 2). In the Anadarko Basin, variation in toluene abundance has been observed with a uniquely decreasing trend moving away from the basin depocenter toward the shallower shelf area. The low molecular weight aromatic hydrocarbons, benzene and toluene, are the most water-soluble components in crude oils (Price 1976). As oils migrate farther, they contact progressively larger amounts of formation water into which the water-soluble components will partition. There

| Peak # | Compound                  | Abbreviation |
|--------|---------------------------|--------------|
| 1      | n-Hexane                  | n-C6         |
| 2      | 2,2-Dimethylpentane       | 2,2-DMP      |
| 3      | Methylcyclopentane        | MCP          |
| 4      | 2,4-Dimethylpentane       | 2,4-DMP      |
| 5      | Benzene                   | 3,3-DMP      |
| 6      | 3,3-Dimethylpentane       | B            |
| 7      | Cyclohexane               | CH           |
| 8      | 2,3-Dimethylpentane       | 2,3-DMP      |
| 9      | 2-Methylhexane            | 2-MH         |
| 10     | 1,1-Dimethylcyclopentane | 1,1-DMCP     |
| 11     | 3-Methylhexane            | 3-MH         |
| 12     | Cis-1,3-Dimethylcyclopentane | C1,3-DMCP  |
| 13     | Trans-1,3-Dimethylcyclopentane | T1,3-DMCP |
| 14     | Trans-2-Dimethylcyclopentane | T1,2-DMCP |
| 15     | 3-Methylpentane           | 3-EP         |
| 16     | 2,4-Dimethylpentane       | 2,2,4-TMP    |
| 17     | n-Hexane                  | n-C6         |
| 18     | 2,2-Dimethylhexane        | 2,2-DMH      |
| 19     | Cis-1,2-Dimethylcyclopentane | C1,2-DMCP  |
| 20     | Methylcyclohexane         | MCH          |
| 21     | Ethylcyclopentane         | ECP          |
| 22     | 2,5-Dimethylhexane        | 2,5-DMH      |
| 23     | 2,4-Dimethylhexane        | 2,4-DMH      |
| 24     | 1,2,4-Trimethylcyclopentane | 1,2,4-TMCP |
| 25     | 1,2,3-Trimethylcyclopentane | 1,2,3-TMCP |
| 26     | 2,3,4-Trimethylpentane    | 2,3-4-TMP    |
| 27     | 2,3,3-Trimethylpentane    | 2,3,3-TMP    |
| 28     | Toluene                   | Tol          |
| 29     | Isooctane                 | i-C8         |
| 30     | n-Pentane                 | n-C5         |
| 31     | 2,2-Dimethylbutane        | 2,2-DBM      |
| 32     | 2,3-Dimethylbutane        | 2,3-DBM      |
| 33     | 2-methylpentane           | 2-MP         |
| 34     | 3-methylpentane           | 3-3MP        |

Fig. 3 Gas chromatogram (C7 light hydrocarbon range) of typical sample of different groups (compounds identified in the table above)
is also the possibility that toluene concentration is related
to thermal maturation; however, the trend of toluene con-
centration versus depth is not strong, a fact shown by the
relatively low concentrations of toluene in the central,
deep-basin oils from Silurian and Devonian reservoirs
and from Pennsylvanian reservoirs. Therefore, such a
trend was reported to indicate long-distance migration of
hydrocarbons (Burruss and Hatch 1989).

4.2.3 Thermal maturity

Light hydrocarbons are a useful geochemical tool to evaluate
thermal maturity. A number of light hydrocarbon-(C₆–C₇)
based maturity parameters have been published in the literature, pioneered by Hunt et al. (1980). These authors observed that certain ratios of light hydrocarbons such as 2,2-dimethylbutane/2,3-dimethylbutane tend to increase with increase in depth. A similar work was done by Thompson who introduced the heptane ratio as a maturity parameter, which is calculated by the ratio of n-heptane relative to the sum of different heptane isomers (Thompson 1983). Thompson defined stages for maturity estimation of oils based on heptane ratio as follows: the heptane ratio from 18 to 22 is normal uncracked oil, 22 to 30 is classified as mature oil, and heptane ratio >30 is classified as supermature (Thompson 1983). Not only heptane ratio, isohexane ratio was also introduced by Walters et al. (2003) to better characterize maturity stage, who proposed an empirical heptane ratio (H) versus isohexane ratio (I) diagram based on the C7 ratios measured for oils/condensates from the North Sea to investigate the thermal maturity of oils/condensates. In this study, thermal maturity is accessed using a cross-plot (Fig. 5) comparing the heptane versus isohexane ratio (listed in Table 2) with maturity levels according to Walters et al. (2003). The heptane ratio ranged from 25.8 to 45.8, and isohexane ranged from 0.6 to 8.3. Group-1 exhibited the highest thermal maturity level followed by Group-3, whereas Group-2 was the least mature (Fig. 5). The variability of heptane ratios in the different oil groups can be explained based on the trend of Woodford Shale thermal maturity across the Anadarko Basin. Particularly, Group-1 condensates are located at the eastern edge of the Anadarko Basin, where the Woodford Shale has been reported within the late oil thermal maturity stage (Cardott 1989, 2012). “Old” Woodford-sourced oils (Group-3) showed the highest heptane ratios; however, they are located at a shallower depth where thermal maturity is not sufficient for oil generation (lower than 0.6 VRo %), and hence, these fluids may have resulted from long-distance migration from the Anadarko depocenter where source rocks are buried at higher maturity levels (Al Atwah et al. 2017). Oil exception within Group-3 oils is sample ST Mary, which exhibits the feature of a light oil from its bulk characteristics (Table 1) while plotting within normal oils in Fig. 5. This in part could be due to evaporative fractionation effect caused by light hydrocarbons partitioning from initially normal oil as a function of migration distance and associated rock–fluid interactions within the carrier beds (Dzou and Hughes 1993; Kim and Philp 2001). Low heptane ratios of Group-2 oils can be classified as normal paraffinic oil, which coincide with the overall maturity of the Woodford Shale (0.7 to 0.8 VRo %) in areas east of the Nemaha Uplift. The base map of Fig. 8 shows the Woodford Shale maturity based on the measured vitrinite reflectance (Cardott 1989, 2012, 2017). The overall Woodford Shale maturity trend coincides with the three groups’ oil maturity stages. However, Group-1 exhibits a higher maturity level than the rocks’ maturity where they are produced. This is due to the hydrocarbon charge history which is discussed in the following section.

### 4.3 Biomarkers and Diamondoids Analysis

Biomarker and diamondoid distributions in crude oils were investigated to support gasoline-ranged hydrocarbons presented earlier. Selected biomarker and diamondoid ratios are listed in Table 3. Certain specific ratios of sterane and terpane in the examined sample exhibit a wide variation. For example, Group-3 oils are enriched in C29 regular sterane relative to C27, whereas Group-1 condensates are enriched in C27 regular sterane relative to C29, with a Reg C27/C29 ratio ranging from 0.6 to 1.4 in Group-3, whereas Group-1 condensates range from 1.9 to 5.6. Most notably, the extended tricyclic terpanes (ETT) relative to the hopane (Hop) ratio exhibit the highest variance among the biomarker ratios. The ETT/Hop ratio stays around 0.6 in Group-1 condensates and ranges from 0.6 to 1.3 in Group-2 oils and 0.3 to 0.7 in Group-3. The relative abundance of selected alkyl diamantane isomers (diamondoids) is listed in Table 3. Group-1 condensates showed a higher relative abundance of 3,4-dimethyldiamantane, and Group-2 oils are slightly higher in 8,4-dimethyldiamantane, whereas Group-3
oils exhibit similar abundance between these two isomers (Fig. 6a).

Biomarker ratio variation is controlled by the source rock inherent composition. For example, enrichment in C29 sterane of Group-3 oils has been observed in Woodford-sourced crude oil and rock extracts (Miceli Romero and Philp 2012; Wang et al. 2017; 2018; Wang and Philp 2019). C29 steranes (stigmastane) are derived from terrigenous organic matter sources and marine algae (Volkman 1986). Therefore, C29 sterane enrichment was previously reported in terrigenously derived oils; Paleozoic marine shales were reported to have a similar fingerprint, too (Moldowan et al. 1985). Group-1 condensates show enrichment in hopane with a clear homohopane mass-chromatogram trace (Fig. 7). Hopanes are pentacyclic terpanes (Van Dorsselaer et al. 1977) that originate from hopanoids present in prokaryotes (bacteria and cyanobacteria) and higher plants but appear to be absent in eukaryotic algae (Ourisson et al. 1979). Such an abundance of hopanes in the examined oils is consistent with previous studies, in which the abundance of hopanes is diagnostic for the Woodford Shale extracts. From the oil correlation star diagram in Fig. 4, Group-1 condensates reflect hydrocarbons originated from the Woodford Shale. Additionally, the most notable biomarker characteristic of Group-2 is the abundance of extended tricyclic terpanes up to C39 (Fig. 7).

### Table 3  Key biomarker and diamondoid ratios sensitive to organic matter type and source rock lithology

| Sample          | Biomarker parameter | Diamondoids parameter |
|-----------------|---------------------|-----------------------|
|                 | RegC27/RegC29 | DiaC27/RegC29 | Hop/RegC29 | ETT/HH | C23TT/Hop | Rc | 4,8-DMD | 4,9-DMD | 3,4-DMD |
| Group-1         |                    |                      |            |        |           |    |         |         |         |
| Lingo 1-13 H    | N.D.         | N.D.             | N.D.       | N.D.   | N.D.     | 1.31| 0.33    | 0.22    | 0.45    |
| Crystal 1-28H   | 3.0          | 0.5              | 0.7        | 0.6    | 0.7      | 1.52| 0.35    | 0.26    | 0.25    |
| York 1-2H       | 5.6          | 0.7              | 0.0        | N.D.   | N.D.     | 1.23| 0.38    | 0.25    | 0.14    |
| Wion 1-29H      | 1.9          | 0.5              | 0.9        | 0.0    | 0.2      | 1.75| 0.35    | 0.27    | 0.38    |
| Bros 1-18H      | N.D.         | N.D.             | N.D.       | N.D.   | N.D.     | 1.33| 0.44    | 0.23    | 0.33    |
| Group-2         |                    |                      |            |        |           |    |         |         |         |
| Johnson 1-33H   | 1.3          | 0.6              | 0.6        | 1.5    | 0.6      | 0.90| 0.41    | 0.28    | 0.31    |
| Matthews 1-33H  | 2.2          | 0.5              | 0.7        | 1.5    | 0.7      | 1.12| 0.49    | 0.24    | 0.27    |
| Wilma 1-16H     | 2.2          | 0.5              | 0.6        | 1.0    | 0.6      | 0.76| 0.51    | 0.26    | 0.23    |
| Elinore 1-18H   | 1.0          | 0.4              | 0.6        | 0.5    | 0.4      | 0.83| 0.52    | 0.23    | 0.25    |
| Elinore 1-17H   | 1.0          | 0.4              | 0.7        | 0.6    | 0.5      | 0.85| 0.41    | 0.28    | 0.31    |
| Winney 1-8H     | 2.3          | 0.5              | 0.7        | 0.8    | 0.5      | 0.75| 0.56    | 0.22    | 0.22    |
| Adkisson 1-33H  | 1.1          | 0.5              | 0.7        | 0.8    | 0.6      | 0.75| 0.51    | 0.26    | 0.23    |
| Winney 1-5H     | 2.2          | 0.5              | 0.7        | 1.2    | 0.6      | 0.75| 0.40    | 0.22    | 0.37    |
| Smith 1-14WH    | 0.9          | 0.6              | 0.7        | 0.8    | 0.5      | 0.75| 0.40    | 0.28    | 0.32    |
| Smith 1-23MH    | 3.3          | 0.4              | 0.7        | 1.1    | 0.7      | 0.77| 0.49    | 0.25    | 0.26    |
| Group-3         |                    |                      |            |        |           |    |         |         |         |
| Ford-1          | 0.8          | 0.4              | 0.6        | 0.4    | 0.4      | 0.74| N.D.    | N.D.    | N.D.    |
| Thomas James 1–22 | 1.0        | 0.5              | 0.7        | 0.5    | 0.5      | 0.81| N.D.    | N.D.    | N.D.    |
| Anadarko Taylor 2118 | 1.4    | 0.5              | 0.5        | 0.8    | 0.90     | 0.90| 0.33    | 0.25    | 0.42    |
| “A”             | 1.0          | 0.5              | 0.5        | 0.7    | 0.6      | 0.71| N.D.    | N.D.    | N.D.    |
| Ellis Lewis Jet  | 1.0          | 0.5              | 0.7        | 0.7    | 0.5      | 0.82| N.D.    | N.D.    | N.D.    |
| ST Mary         | N.D.         | N.D.             | N.D.       | N.D.   | N.D.     | 0.39| 0.39    | 0.19    | 0.42    |
| “F”             | 1.0          | 0.5              | 0.5        | 0.7    | 0.5      | 0.88| N.D.    | N.D.    | N.D.    |
| 7-5N-5E         | 0.6          | 0.5              | 0.6        | 0.3    | 0.3      | 0.79| N.D.    | N.D.    | N.D.    |
and homohopane relative to tricyclic terpanes, together with dominance of C_{27} regular sterane relative to the C_{29} counterpart (Table 3). These biomarkers signature are diagnostic of a Mississippian-sourced oil and a Mississippian-extracted bitumen (Kim and Philp 2001). Group-2 oils should have had at least Mississippian source contribution, evidenced in the narrow star diagram fingerprint in Fig. 4. Within Group-2 samples, two oils are recovered from the horizontal wells landed in the Woodford Formation including Johnson 1-33H and Matthews 1-33H (Table 1). However, since these oils show a strong Mississippian biomarker characteristic and a Mississippian OCSD imprint, it is likely that the stimulated rock volume has exceeded the Woodford into the Mississippian Formation resulting in a mixing fluid with relatively comparable contributions from the Mississippian and Woodford sources.

Diamondoids are rigid fused-ring cycloalkanes with a diamond-like structure that shows high thermal stability.
Comparing methyldiamantane versus stigmastane (C29 mixtures) and extent of cracking are usually accessed by maturity indicators already thermally destroyed. Hydrocarbon samples (over 1.1% Ro) when biomarker thermal maturity are good thermal maturity indicators for high-maturity probable precursors in living organisms. Diamondoids in marine shale of the Woodford Shale Formation, and grams, with Group-1 and Group-3 likely sourced from such observations support biomarker and C7 star dialations on acidic clay minerals in petroleum source rocks (Schleyer 1990). Hence, the isomeric distribution of certain diamondoids could be sensitive to the source rock lithology. In particular, the alkylated diamantine infers source rock facies by comparing the relative abundance of three isomers of dimethyldiamantanes to distinguish different kerogen contributions (e.g., II-carbonate, type II marl, and type III) (Schulz et al. 2001). According to ternary plots developed for identifying source rock facies, most of the Group-1 and Group-3 samples plot within marine shale polygon, while Group-2 oils are plotted in between marine shale and carbonates polygon (Fig. 6a). Such observations support biomarker and C7 star diagrams, with Group-1 and Group-3 likely sourced from marine shale of the Woodford Shale Formation, and Group-2 a mixture of the two end members. Unlike biomarkers, diamondoids in crude oils and source rocks are structurally very different from their probable precursors in living organisms. Diamondoids are good thermal maturity indicators for high-maturity samples (over 1.1% Ro) when biomarker thermal maturity indicators already thermally destroyed. Hydrocarbon mixing and extent of cracking are usually accessed by comparing methyldiamantane versus stigmastane (C29 sterane) biomarker (Dahl et al. 1999). Figure 6b shows the different oil groups and their control of methyladamantoid versus stigmastane. Group-1 samples are clearly enriched in diamondoids and depleted in stigmastane indicating strong extent of oil cracking, whereas Group-2 oils are depleted in diamondoids which suggest low-maturity stage without oil cracking yet. Group-3 oils are depleted in diamondoids and rich in stigmastane. Moreover, Group-3 oils plot on the diamondoid baseline, which has been defined from immature rock extracts. This suggests that Group-2 oils were migrated likely from source rock in deep Anadarko Basin as the source rock was at the mature. From a petroleum systems perspective, such hydrocarbon charge trend coincides with previous studies that postulated that oils in the southern part of Oklahoma are a result of long-distance migration from the depocenter of the Anadarko Basin, whereas oils east of the Nemaha Uplift are a result of localized hydrocarbon charge with no contribution from deep Anadarko (Al Atwah et al. 2017; Wang and Philp 2019). Moreover, this explains the inconsistent signature between the isoheptane ratio and buck crude oil parameters of Group-1 and Group-3 oils, whereas the former suggests highly mature fluids, whereas the latter indicates black oils.

4.4 Proposed petroleum system

Based on the results of the oil/condensates family grouping, integration of the Woodford thermal maturity map, and burial and thermal history (Schmoker 1988), it is proposed that there are three petroleum systems in the study area (Fig. 8). The first is in the shallow part of the Anadarko Basin (Group-1), where the averaged measured Ro value of the Woodford Shale is 1.2% (Cardott 2014a, b), which is within the Rc range determined for the condensates based on methyl adamantine index (MAI) values. The Rc from the MAI values is provided in Table 3. Therefore, the Group-1 condensates were generated in situ. The second is in the Nemaha area (Group-2, Logan County and western Payne County), where the average measured Ro value of the Woodford Shale is 0.65%, which is within the Rc range determined for this oils based on methylphenanthrene index (MPI) values. The Rc from the MPI values is provided in Table 3. The oil samples in this system share significant Mississippian and Woodford source signatures and appear to be mixtures of Woodford- and Mississippian-derived oils that have probably been generated in situ. The third petroleum system is in the southern Oklahoma (Group-3; Garvin County); the Rc of oils is 0.81% in average (Table 3). This observation suggests these oils probably migrated short distances through the central Oklahoma faults zone from deeper Woodford Shale in the basin to the reservoirs. Schmoker (1988) proposed the Woodford Shale in Caddo County, Canadian County, and Grady County, Oklahoma (“area 3” in Schmoker’s paper) went into the oil window circa 260 Ma (late Permian). This area might be the kitchen for those old Woodford-type oils, which migrated via some faults or other pathways formed during the Ouachita–Marathon orogeny (starting from Middle to Late Pennsylvanian until early Permian). Such type of migration has been previously proposed by Buruss and Hatch (1989) and Jones and Philp (1990) to suggest these oils may have migrated from the more mature parts of the Anadarko Basin in southern Oklahoma.

5 Conclusions

Light hydrocarbon geochemistry provides an effective tool to elucidate hydrocarbon source, maturity, and secondary alterations within Woodford–Mississippian tight reservoirs across the Anadarko Basin, Anadarko Shelf, and Cherokee Platform of North-Central Oklahoma by the following:
Petroleum system and proposed migration pathway of central Oklahoma (with the Woodford rock maturity in measured Ro %).

Devon = Devon Energy. OGS = Oklahoma Geological Survey

1. Two diagnostic molecular fingerprints for two petroleum source rocks, Mississippian mudrocks and Woodford Shale, based on light hydrocarbons have been captured and further convinced by biomarker and diamondoid evidence;
2. Condensates produced from the Woodford–Mississippian tight reservoir within the Anadarko Basin (Group-1) exhibit a distinct fingerprint and sourced from the Woodford Shale;
3. Tight oil from the Woodford–Mississippian tight reservoir on the Cherokee Platform (east of Nemaha Uplift) (Group-2) exhibits a “mixed source” fingerprint and in situ sourced by Mississippian mudrocks and Woodford Shale with variable contribution;
4. Crude oil sampled from conventional reservoirs in southern Oklahoma (Group-3) was derived from the Woodford Shale of the deep Anadarko Basin via long-distance migration;
5. Thermal maturity based on light hydrocarbon parameters indicates that condensates from the Anadarko Basin (Group-1) are of the highest maturity, followed by “Old” Woodford-sourced oils (Group-3) and central Oklahoma oils (Group-2).

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