



Biomarker characteristics of the heterocyclic and polycyclic aromatic hydrocarbons in the crude oils from West Siberian Basin, Russia: an implication for correlation with organic matter input, depositional environment and maturity

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Abstract

The distribution of aromatic hydrocarbon in sediments and oils is known to be affected by thermal maturity, source input and depositional conditions. Hence, the aromatic hydrocarbon fraction of four oil samples from different wells of the West Siberian Basin (central Russia) was investigated to determine the source of organic matter (OM), depositional environment and maturity of their source rocks. Biomarker ratios and parameters of aromatic compounds indicate that the studied oils were generated from clay-rich source rocks containing a mixed organic matter of marine and terrestrial origin, which were deposited in freshwater/deltaic to marine environmental settings under suboxic to relatively oxic conditions. Furthermore, the maturity-sensitive aromatic hydrocarbon parameters indicate that the source rocks are thermally mature, and in the peak to late maturity stage of the oil generation window. Oil–oil correlation results of various established aromatic biomarker proxies for organic matter origin, depositional environment and lithology suggests that the analyzed west Siberian Basin's oils were generated from a variety of geological sources and can be grouped into two distinct oil families. The first oil family (group I) was generated from clay-rich source rock containing mixed organic matter with relatively high amounts of terrestrial plant input and deposited in a non-marine (freshwater/deltaic) environment under relatively oxic conditions, while the second oil family (group II) was derived from mixed organic matter with high marine OM input that was deposited in marine environment under suboxic conditions. The findings of the heterocyclic and polycyclic aromatics highlighted in this study can help for better understanding of the genetic ties between oils and their sources and have an impact on traditional hydrocarbon development in the Basin.

Keywords Oil family · Oil–oil correlation · Aromatic compounds · West Siberian Basin · Russia

Abbreviations

BP	Biphenyl	DMBP	Dimethylbiphenyls
DBF	Dibenzofuran	DMF	Dimethyl fluorenes
DBT	Dibenzothiophene	DMN	Dimethylnaphthalenes
DMP	Dimethylphenanthrenes	DMP	Dimethylphenanthrenes
		DMR	Dimethylnaphthalene

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DNR	Dimethylnaphthalene
DPR	Dimethylphenanthrene
F	Fluorene
MBP	Methyl biphenyls
MDBF	Methyldibenzofuran
MDBT	Methyldibenzothiophenes
MDR	Methyldibenzothiophene
MF	Methyl fluorenes
MN	Methyl naphthalenes
MNR	Methylnaphthalene
MP	Methyl phenanthrenes
MPDF	Methyldibenzofurans
MPI	Methylphenanthrene index
MPR	Methylphenanthrene
N	Naphthalene
OM	Organic matter
P	Phenanthrene
Ph	Phytane
Pr	Pristane
%R _c	Calculated Vitrinite Reflectance
SARA	Satuarte-Aromatic-Resion-Asphalten
TeMN	Tetramethylnaphthalene
TIC	Total Ion Chromatogram
TMN	Trimethylnaphthalenes
TMNr	Trimethylnaphthalene
TMP	Trimethylphenanthrenes
TMR	Trimethylnaphthalene
TNR	Trimethylnaphthalene

Introduction

The distribution of heterocyclic and polycyclic aromatic hydrocarbons in crude oils have been proposed as indicators of the source organic matter (OM), depositional environment, and thermal maturity of the parent source rocks (Radke et al. 1982, 1986, 2000; Alexander et al. 1992; Jinggaui et al. 2005; Armstroff et al. 2006). Heterocyclic aromatic hydrocarbons, i.e., dibenzothiophene (DBT), dibenzofuran (DBF) phenanthrene (P) and fluorene (F) have similar structure skeletons and have been suggested to originate from a similar precursor (Asif et al. 2010), and the abundance of these compounds has been related to the nature of the OM and its depositional environment and also used for source and oil correlations (Fan et al. 1990; Radke and Willsch 1994; Radke et al. 2000; Jinggaui et al. 2005; Xiangchun et al. 2011).

The West Siberian Basin in Russia (Fig. 1) is one of the most prolific oil and gas sedimentary basins in the world, with huge potential for future exploration. In addition, the West Siberian Basin has gained the attention of the academic community and upstream operators owing to its excellent source rock characteristics and commercial hydrocarbon

accumulations (e.g., Pyatkov et al. 1988; Kontorovich et al. 1991; Belkin and Bachurin 1991; Peters et al. 1993; Afanasyev et al. 1993; Petrov 1994; Lopatin et al. 1997; Kontorovich et al. 1997). Most of the previous studies have focused on the organic geochemical characteristics of the shale facies within the Mesozoic sedimentary rocks and concluded favorable source rock intervals in the Jurassic succession with oil generation potential (Lopatin et al. 1997, 1998; Kontorovich et al. 1997). Nevertheless, due to the slow drilling campaign in the super Basin, untapped petroleum potential remains in underexplored huge structures. Hence, additional data and research are required to unlock potential in mature areas. In this work, the distribution of heterocyclic and polycyclic aromatic hydrocarbons in West Siberian oils was studied to better understand the source of the organic matter, lithology and depositional environment. The aromatic maturity indicators and their equivalent vitrinite reflectance (%R_c) were also applied to evaluate the maturity of the parent source rocks. Additionally, organic matter origin and depositional environment-related aromatic biomarkers were also used to infer the oil families and their potential source rocks.

First, the studied oil samples have been fractionated into oil composition (SARA). Then, the gas chromatography–mass spectrometry (GC–MS) analysis has been performed on the aromatic hydrocarbon fraction. Afterward, the heterocyclic and polycyclic aromatic compounds in the aromatic hydrocarbon fraction and their ratios were quantified using several ions like 166, 168, 175, 178, 182, 184, 192, and 198 and were used to evaluate the thermal maturity, source input and depositional conditions.

Geological background

The West Siberian Basin is an early Triassic rift Basin filled by Mesozoic sedimentary succession, ranging from the Triassic to the Cretaceous (Surkov et al. 1997). The lithostratigraphic column of the studied Basin is presented in Fig. 2. The Triassic to Cretaceous sediments were deposited unconformably above the Triassic volcanic rocks, which are mainly composed of clastic sediments that are punctuated by unconformities of different magnitudes and ages (Fig. 2).

Clastic sediments of the Tampey Formation represent the Triassic sedimentation while the marine sediments of the Tyumen, Abalak and Bazhenov formations form the Jurassic package. The Lower–middle Jurassic Tyumen Formation is overlain conformably by the Tampey Formation in the Northern Basin and with unconformable contact in the central and south of the Basin (Fig. 2). This formation comprises dominantly shale, along with subordinate sandstone. The stratigraphic equivalents of the Tampey Formation also consist largely of continental coal-bearing clastic rocks in

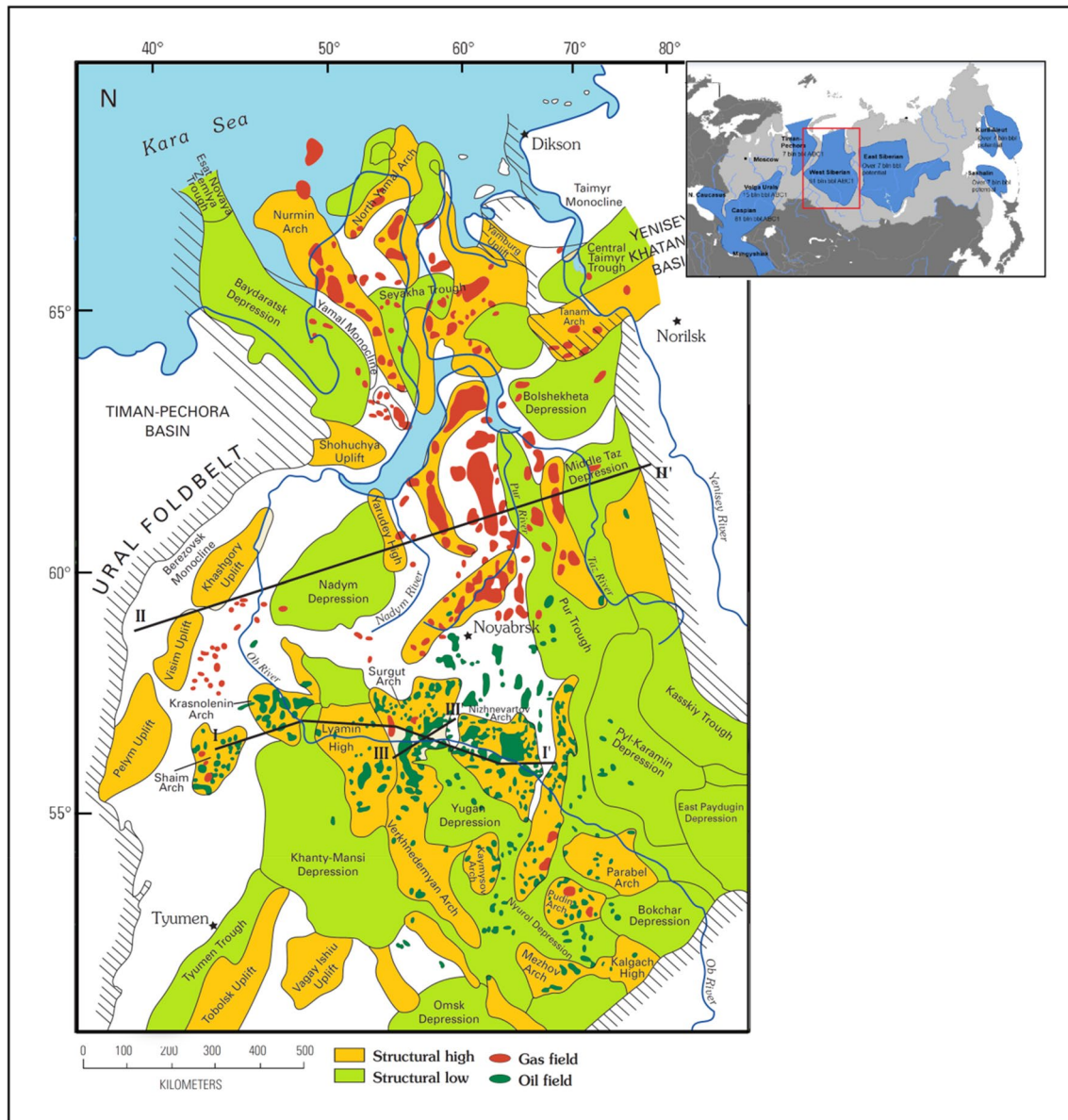


Fig. 1 Structural map of West Siberian Basin, including oil and gas fields in the Basin (modified from Rovenskaya and Nemchenko (1992))

the southern Basin areas (Fig. 2). During Callovian to Kimmeridgian, the sediments of the Abalak Formation were deposited unconformably above the Tampey Formation in the central and south areas of the Basin. The Abalak Formation comprises mainly shale in the Northern Basin and its stratigraphic equivalents consist largely of sandstones of the Vnsyugan Formation in the central and southern areas (Fig. 2).

The Abalak Formation is conformably overlain by the deep marine shale sequence of the latest Jurassic–earliest

Cretaceous (Volgian–early Berriasian) Bazhenov Formation. The organic-rich Bazhenov Formation was deposited in a deep-water anoxic depression formed in the entire central part of the West Siberian Basin (Vyshemirsky 1986; Rudkevich et al. 1988). The shale units of the Jurassic Tampey Bazhenov formations are potential source rocks with high oil generation potential (Lopatin et al. 1997, 1998; Kontorovich et al. 1997). It also is conformably overlain by the mixed sandstone and shale sequence of the Early to Late Cretaceous formations (Fig. 2).

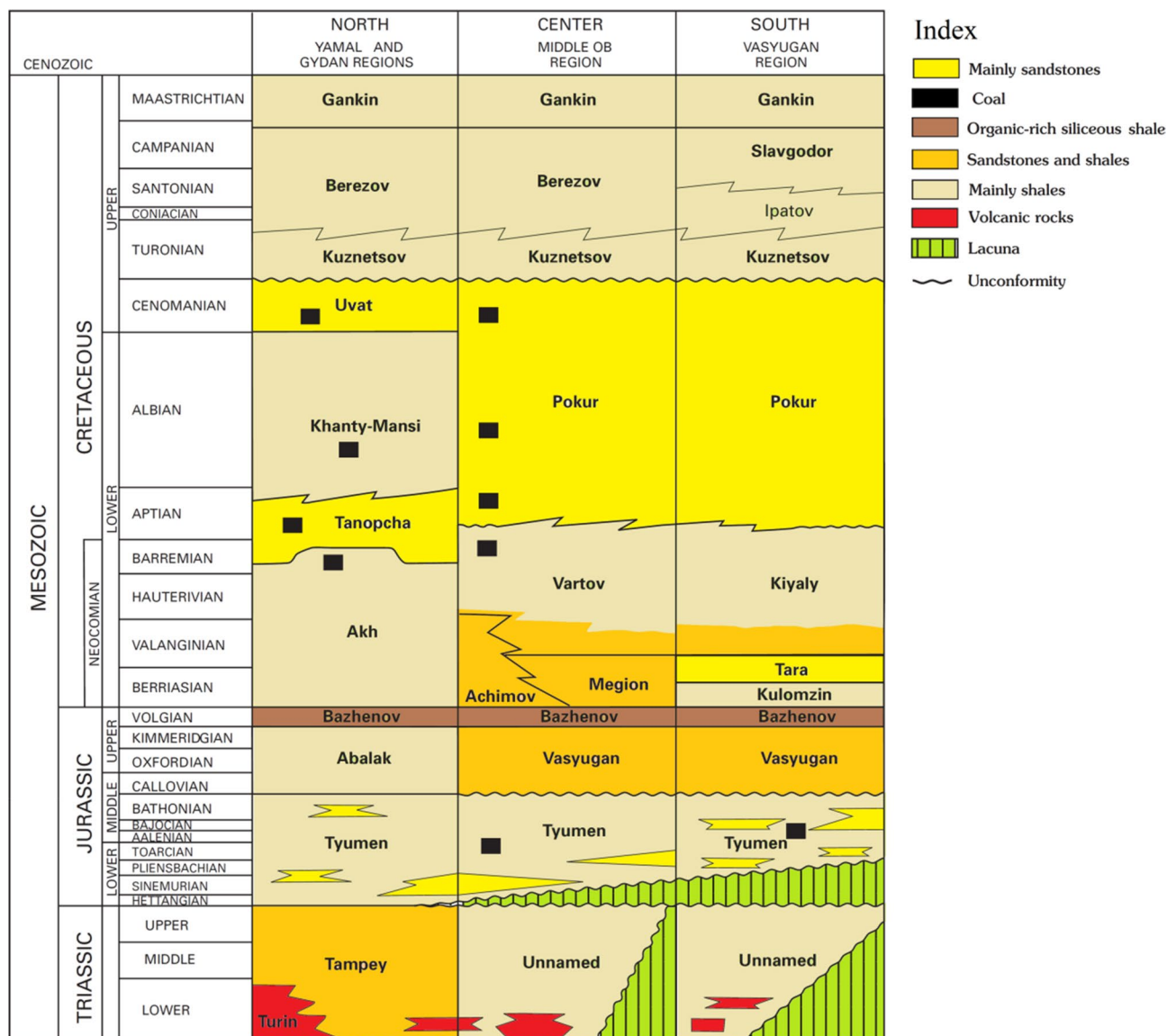


Fig. 2 Generalized stratigraphic column of the Mesozoic succession in the West Siberian Basin

Materials and methods

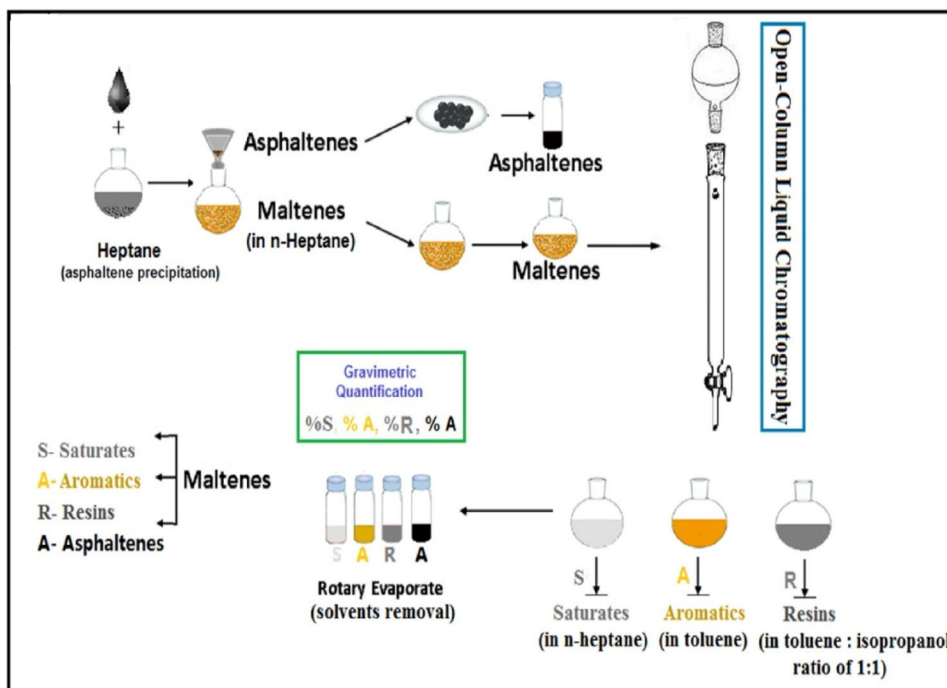
In the current study, four oil samples were collected from the reservoir rocks exposed along oilfields in the West Siberian Basin as shown in Fig. 1. These oil samples were subjected to bulk fractionation process of oil composition (SARA) and gas chromatography–mass spectrometry (GC–MS) analysis of the aromatic hydrocarbon fraction at the Departments of Petroleum Engineering and Physical Chemistry, Kazan Federal University, Russia.

For SARA analysis, the asphaltene fraction was precipitated from the studied oils by dissolution in hexane (1:40). Others fractions, i.e., saturate, aromatic and resin were

thereafter fractionated using liquid column chromatography and solvents of different polarity (Fig. 3).

GC–MS was utilized to separate the compounds in the aromatic hydrocarbon fraction of the analyzed oil samples. The test was performed on the Agilent 7890B with a flame ionization detector. Within the GC–MS furnace, the capillary column had a length of 30 m and a diameter of 0.32 mm. The samples were warmed from 40 to 300 °C (at 4 °C/min rate), after which temperature was held at 300 °C for 30 min. Finally, the heterocyclic and polycyclic aromatic compounds in the aromatic hydrocarbon fraction were detected and quantified based on their peak heights.

Fig. 3 The illustration scheme of the SARA separation process



Results and discussion

The analyzed West Siberian Basin oils are medium (23.55–32.57° API) and paraffinic in nature, with saturate/aromatic ratios between 3.48 and 8.64. The physical and geochemical characteristics together with the hydrocarbon distribution of normal alkanes and isoprenoids show the absence of biodegradation (Hakimi et al. 2022). In addition, the normal alkane and isoprenoid distributions of the analyzed samples implied oil generation from source rocks containing mixed organic matter and deposited under sub-oxic to relatively oxic conditions (Hakimi et al. 2022).

Total ion chromatogram (TIC)

The total ion chromatograms (TICs) of aromatic fractions of the analyzed oil samples are shown in Fig. 4. The TICs of the aromatic are dominated by diaromatic and triaromatic hydrocarbons (Fig. 4).

In the current study, the heterocyclic and aromatic compounds such as alkylnaphthalenes, alkylphenanthrenes, alkylidibenzothiophenes, alkylidibenzofurans, alkylbiphenyls, and alkylfluorenes were identified in the aromatic fractions of the investigated oil samples (Fig. 4). It can be seen that each compound of heterocyclic and aromatic hydrocarbon shows distinctive distributions in the analyzed samples. The

dimethylnaphthalenes (DMN) and methyl biphenyls (MBP) are equally abundant in samples A, B and C while trimethylnaphthalenes (TMN) and dimethylbiphenyls (DMBP) are higher in sample D oil. It was also noted that, MBP > DMN and TMN > DMBP. Samples A and C oils also show a higher abundance of MN and DMN than other oil samples (see Fig. 4). In addition, tetramethylnaphthalenes (TeMN), MF, phenanthrene (P), dimethyl fluorenes (DMF), methyl phenanthrenes (MP) and dimethylphenanthrenes (DMP) are most abundant in sample D oil (Fig. 4). These observations of the relative distributions of heterocyclic and polycyclic aromatic hydrocarbons indicate in the West Siberian Basin are attributed to the source of organic matter input and depositional settings of the source rocks (Odier and Artaud 1992; Radke et al. 2000; Fenton et al. 2007). For example, the BP and MBP are significantly higher in their relative abundance in samples B and C oil in the other two oil samples (Fig. 4), suggesting abundant in terrestrially-derived OM (Odier and Artaud 1992; Fenton et al. 2007).

Thermal maturity evolution

In this study, multiple biomarker maturity ratios and parameters of the methylated phenanthrene and naphthalene distributions in the aromatic hydrocarbon fraction of the analyzed oil samples can be employed to assess the thermal

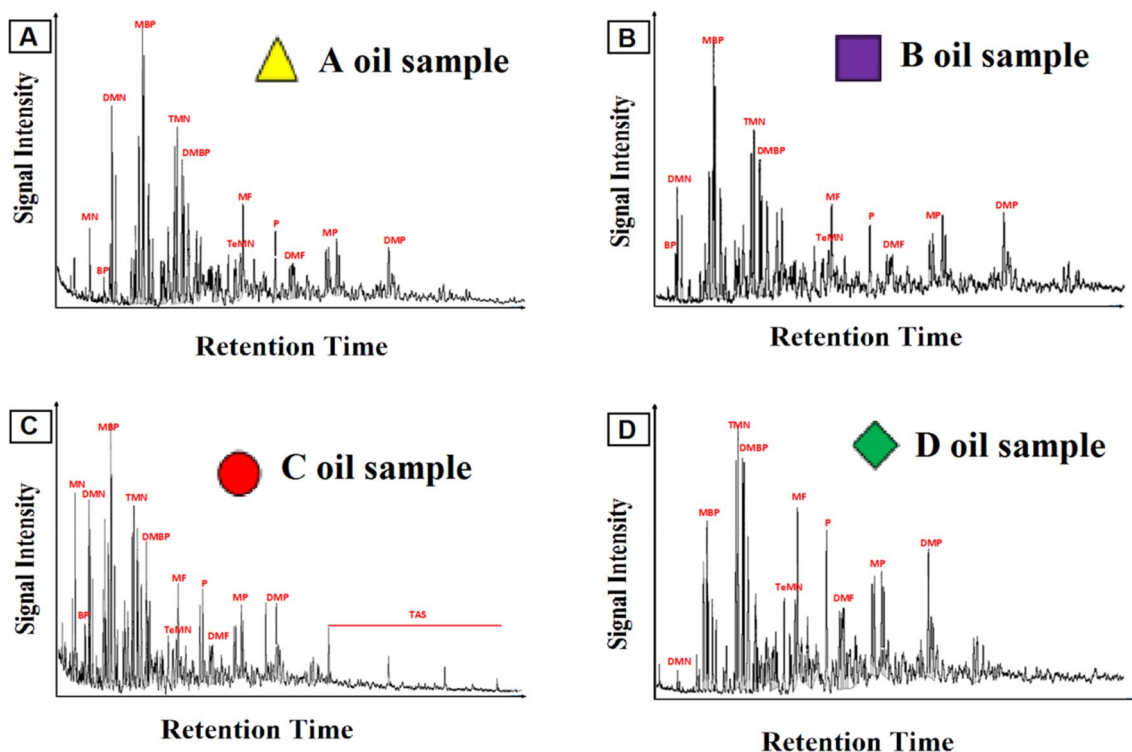


Fig. 4 TICs distributions of heterocyclic and aromatic HCs in the aromatic fraction of the oil samples (A–D samples) from the western Siberian Basin, Russia; MN, DMN, TMN, TeMN, BP, MBP, DMBP, P, MP, MF, DMP, DMF, and TMP (Please see "Abbreviations" section)

maturity of organic matter (Radke and Welte 1983; Radke et al. 1984, 1986; Alexander et al. 1985; Budzinski et al. 1995; van Aarssen et al. 1999). The application of aromatic hydrocarbons in maturity assessment is based on the thermodynamic stability of isomers with increasing thermal stress. The aromatic maturity parameters presented in Table 1 includes methylphenanthrene ratio (MPR) methylphenanthrene index (MPI-1), alkyldibenzothiophene parameter (MDR), methylnaphthalene ratio (MNR), dimethylnaphthalene ratio (DNR-1) and trimethylnaphthalene ratio (TNR-2). The methylphenanthenes and alkyldibenzothiophene show the dominant abundance of 3-MP and 2-MP in m/z 192 mass fragmentograms, while 4-MDBT is more abundance in the m/z 198 mass fragmentograms (Fig. 5).

However, the MPI-1 and MDR values were estimated and range from 0.74 to 1.01 and 5.73 to 7.54, respectively (Table 1). These high values of methylphenanthrene index (MPI-1) and alkyldibenzothiophene (MDR) of the analyzed oil samples show equivalent vitrinite reflectance ($\%R_c$ MPI and $\%R_c$ MDR) in the range of 0.85–1.01% and 0.93–1.06%, respectively (Table 1), implying oil generation from mature source rocks in the peak to late mature of oil generation

window (Radke and Welte 1983; Jiang and George 2019). This finding is demonstrated by the correlation diagram of calculated reflectance values from MPI-1 and MDR (Fig. 6a).

Furthermore, the high thermal maturity of the analyzed oil samples is also consistent with the equivalent vitrinite reflectance ($\%R_c$ MPR, $\%R_c$ MNR and $\%R_c$ TNR-2) calculated from MPR, MNR, and TNR-2 parameters (Table 1). The calculated reflectance values of the TNR-2 and MPR range from 0.92 to 0.96% and 0.94 to 1.05%, respectively (Table 1), while calculated reflectance from MNR is higher and ranges between 1.04% and 1.14% (Table 1). Additionally, the correlation diagrams of $\%R_c$ MPI-1 versus $\%R_c$ TNR-2 (Fig. 6b) and $\%R_c$ MNR versus $\%R_c$ MDR (Fig. 6c) indicate the oils are in the late maturity generation window.

Characteristics of aromatic biomarker and their interpretation in relation to OM input and environmental conditions

Numerous heterocyclic and polycyclic aromatic compounds are more abundant in terrestrial plants in general and are

Table 1 Partial aromatic hydrocarbon ratios of oil samples from West Siberian Basin, Russia (Please see "Abbreviations" section)

Parameters/ oil samples	A	B	C	D
MPI-1	1.01	0.74	0.87	0.92
%R _c (MPI-1)	1.01	0.85	0.92	0.95
MPR	1.29	1.00	1.00	1.15
%R _c (MPR)	1.05	0.94	0.94	1.00
MPDF	0.52	0.44	0.47	0.49
DPR	0.13	0.10	0.11	0.11
Log (1-MP/9-MP)	-0.15	-0.16	-0.11	-0.10
Log (1,7-DMP/ 1,3- + 3,9- + 2,10- + 3,10-DMP)	-0.33	-0.40	-0.37	-0.42
MNR	1.63	1.38	1.30	1.90
%R _c (MNR)	1.10	1.05	1.04	1.14
DNR-1	5.42	4.05	5.36	3.61
DNR-x	1.30	1.27	1.49	2.37
DMR	1.13	1.02	1.05	1.16
TNR-1	0.95	0.91	0.87	1.00
TNR-2	0.91	0.86	0.88	0.94
%R _c (TNR-2)	0.94	0.92	0.93	0.96
TMR	0.37	0.30	0.32	0.33
TBR	12.43	14.33	10.75	12.57
TMNr	0.78	0.80	0.78	0.75
TeMNR	0.80	0.83	0.83	0.81
TMNs/MNs	2.58	2.41	2.61	5.04
Log (1,2,5-TMN/1,3,6-TMN)	-0.60	-0.68	-0.59	-0.53
Log (1,2,7-TMN/1,3,7-TMN)	-0.73	-0.65	-0.63	-0.57
MDR	7.33	7.17	5.73	7.54
%R _c (MDR)	1.05	1.03	0.93	1.06
DBT/P	0.25	0.19	0.22	0.25
MDBT/MP	0.49	0.53	0.49	0.48
DBF/P	0.59	0.26	0.37	0.71
MDBF/MP	0.66	0.28	0.39	0.67
%F	54.2	68.6	63.2	50.9
%DBF	32.0	18.3	23.3	36.3
%DBT	13.8	13.1	13.5	12.9
%MF	31.7	45.8	39.3	30.9
%MDBF	39.2	18.8	26.6	40.4
%MDBT	29.0	35.5	34.1	28.7

MNR ratio = 2-MN/1MN; %R_c-MNR = (0.17 * MNR) + 0.82; DNR ratio; DNRx = (2,6-DMN + 2,7-DMN)/1,6-DMN; DNR-1 = (2,6-DMN + 2,7-DMN)/1,5-DMN; DMR ratio = (1,5-DMN + 1,6-DMN)/(1,3-DMN + 1,7-DMN); TNR ratio; TNR-1 = 2,3,6-TMN/(1,4,6-TMN + 1,3,5-TMN); TNR-2 = (1,3,7-TMN + 2,3,6-TMN)/(1,3,5-TMN + 1,3,6-TMN + 1,4,6-TMN); %R_c-TNR-2 = 0.4 + (0.6 * TNR-2); TMR ratio = 1,2,5-TMN/2,3,6-TMN; TMNr ratio = 1,3,7-TMN/(1,3,7- + 1,2,5-TMN); TeMNR ratio = 1,3,6,7-TMN/(1,3,6,7- + 1,2,5,6- + 1,2,3,5-TMN); MPR ratio = 2-MP/1-MP; MPDF = (3-MP + 2-MP)/(3-MP + 2-MP + 1-MP + 9-MP); %R_c-MPDF = (2.242 * MPDF) - 0.166; MPI-1 = 1.5 * (2-MP + 3MP)/(P + 1-MP + 9-MP); %R_c-MPI-1 = (0.6 * MPI-1) + 0.4; MPI-2 = 3 * 2-MP/(P + 1-MP + 9-MP); DPR ratio = 2,6- + 2,7- + 3,5- DMP/(1,3 + 2,10 + 3,9 + 3,10-DMP + 1,6 + 2,5 + 2,9-DMP); MDR ratio = 4-MDBT/1-MDBT; %R_c-MDR = (0.073 * MDR) + 0.51; %DBT = DBT/(DBT + DBF + F) * 100; %DBF = DBF/(DBT + DBF + F) * 100; %F = F/(DBT + DBF + F) * 100

useful indicators of source organic facies type, depositional environment and lithologies (Fan Pu et al. 1990; Budzinski et al. 1995; Hughes et al. 1995; Radke et al. 2000; Li et al. 2013; Asahina and Suzuki 2018; Asif and Wenger 2019).

The distributions of alkylated phenanthrenes and naphthalenes have been widely employed as indicators of OM origin. Elevated abundances of 9-MP, 2,10-DMP, 3,9-DMP and 3,10-DMP have been observed in sediments of marine origin while high amounts of 1-MP and 1,7-DMP are found in sediments with higher plant origin (Budzinski et al. 1995). The 9-MP is generally abundant, with significant amounts of 1-MP in all analyzed oil samples (Fig. 5), indicating a marine organic matter with notable amounts of land plant inputs. The cross-plot of Log (1-MP/9-MP) and Log (1,7-DMP/1,3 + 2,10 + 3,9 + 3,10-DMP) in Fig. 7a delineates the organic matter source inputs. The analyzed oils plot in the bottom left quadrant of Fig. 7a, indicating a predominant input of 9-MP and 1,3 + 2,10 + 3,9 + 3,10-DMP that signifies a marine algal OM source. Similarly, the oils plot in the bottom left quadrant of the cross-plot of log (1,2,5-TMN/1,3,6-TMN) and log (1,2,7-TMN/1,3,7-TMN) in Fig. 7b, signifying the predominant abundances of 1,3,6-TMN and 1,3,7-TMN, which are associated with a marine organic matter and higher thermal maturity, respectively (van Aarssen et al. 1999; Kang et al. 2020).

This finding is also demonstrated by the alkylated naphthalene ratios such as trimethylnaphthalene (TMR) and dimethylnaphthalene (DMR) (Asahina and Suzuki 2018). Asahina and Suzuki (2018) proposed that the alkylated naphthalene ratios (TMR and DMR) as indicators of organic matter source input and concluded that TMR values > 0.8 and DMR values > 1.0 signify terrestrial OM origin. The DMR values (1.0–2.4) of all studied oils are > 1.0 while TMR values range from 0.5 to 1.4 (Table 1). The cross-plot of TMR and DMR shows that the analyzed oils are sourced mainly from mixed organic matter, but with the considerable contribution of marine OM for oil samples B and C (Fig. 8a).

Furthermore, this interpretation is supported by dibenzofuran/phenanthrene (DBF/P) and methyl dibenzofurans/methylphenanthrenes (MDBFs/MPs) ratios. Baydjanova and George (2019) proposed the cross-plot of dibenzofuran/phenanthrene (DBF/P) against methyl dibenzofurans/methylphenanthrenes (MDBFs/MPs) ratios to distinguish between marine- and terrestrial-sourced organic matter. Accordingly, the studied oil samples are sourced from both terrigenous and marine organic matter (Fig. 8b). However, the elevated abundance of dibenzofuran (DBF) has been noted in the oil samples A and D is indicative of considerable terrigenous OM input (Radke et al. 2000; Asif and Wegner 2019; Fig. 8b). The relative abundances of heterocyclic aromatic compounds and their alkylated isomers have been applied to reconstruct the environment of deposition (Hughes 1984;

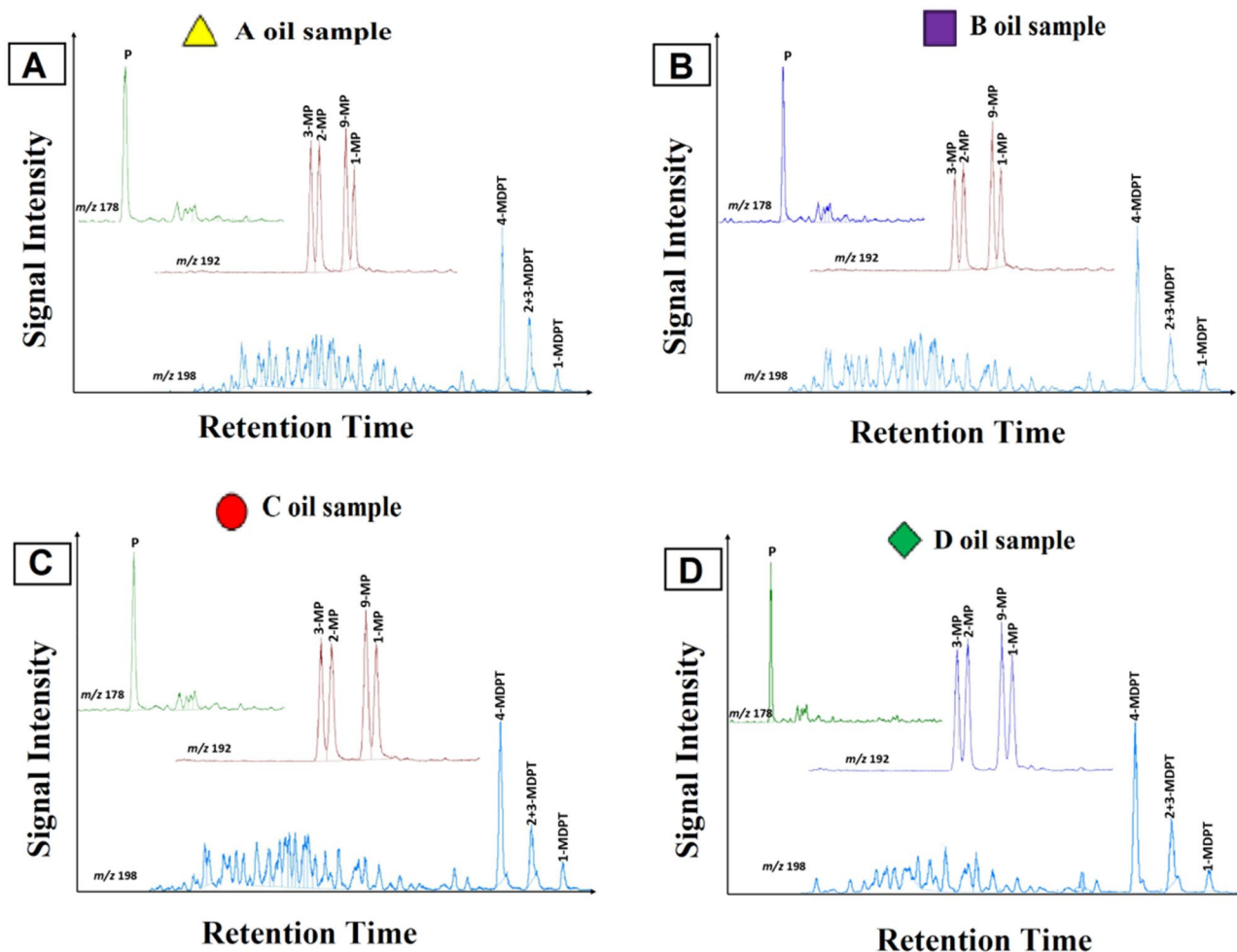


Fig. 5 Partial m/z 178 + 192 + 198 mass chromatograms showing distribution of P, MP and MDPT isomers in the aromatic fraction of the western Siberian Basin's oils (A–D samples) (Please see "Abbreviations" section)

Schou and Myhr 1988; Jinggui et al. 2005; Radke et al. 2000; Asif and Wegner 2019; Baydjanova and George 2019). Higher abundances of dibenzothiophene (DBT) and naphthalene are relatively higher in source rocks from marine environments while phenanthrene (P), dibenzofuran (DBF), and fluorene (F) are higher in source rocks from freshwater sedimentary environments (Fan et al. 1990; Radke et al. 2000; Jinggui et al. 2005; Xiangchun et al. 2011).

In the analyzed oils, the relative abundances of DBF, MDBF, DBT, MDBT, MP, and F are determined from the sums of the peak heights of their diagnostic ions (i.e., m/z 168, 182, 184, 198, and 166, respectively) and are shown in Figs. 5 and 9 as well as Table 1.

Ternary diagrams of the relative abundances of the above aromatic compounds show that the variations in the relative abundances of these aromatic compounds are effective markers of facies and depositional environments (Pu et al. 1990; Radke et al. 2000; Asif and Wegner 2019). Asif and Wegner (2019) differentiated source facies using a ternary diagram of %F, %DBF and %DBT and observed that freshwater lacustrine-, coaly-, and marine carbonate-sourced oils have the highest abundance of F, DBF and DBT, respectively. In this study, the relative abundances of F, DBF and DBT in the studied oils were observed in the 50.9–68.6%, 18.3–36.3%, and 12.9–13.8% range, respectively (Table 1). The Li et al. (2013) ternary diagram of

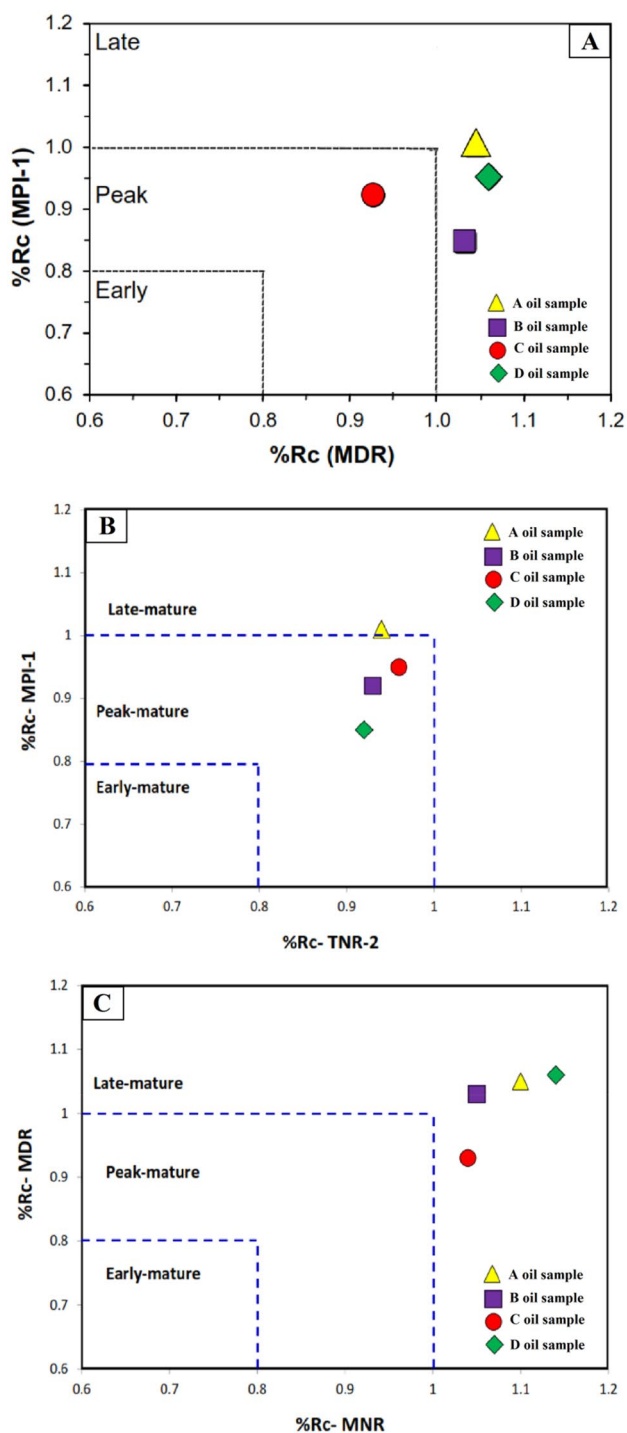


Fig. 6 Thermal maturity cross-plots of the %Rc from: **A** MDR ratio and MPI-1, **B** TNR ratio and MPI-1, and **C** MDR and MNR ratios; showing that the western Siberian Basin’s oils were generated from mature source rocks in the range of peak-mature to late-mature of oil generation window (Please see "Abbreviations" section)

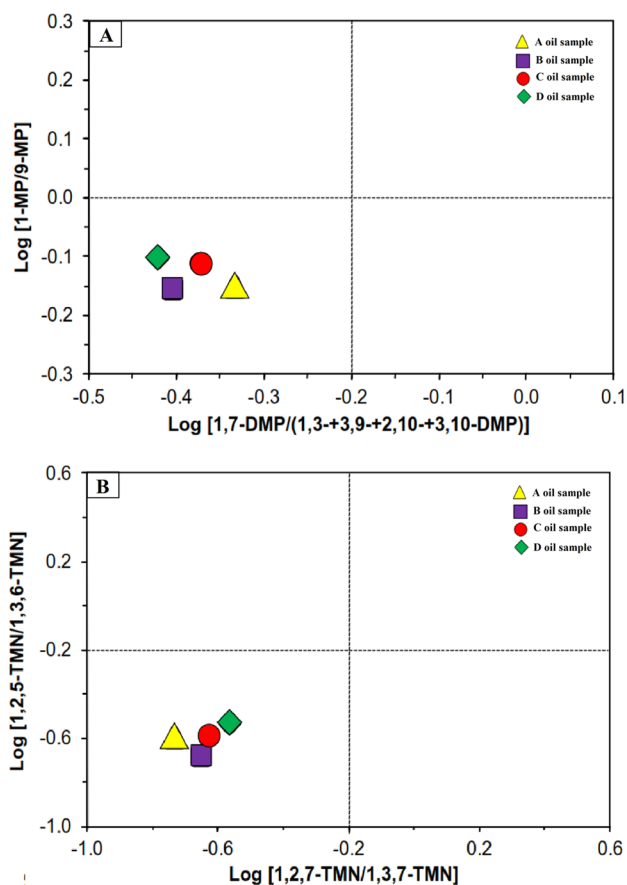


Fig. 7 Cross plots of **A** Log [1,7-DMP/(1,3-+3,9-+2,10-+3,10-DMP)] versus Log [1-MP/9-MP], and **B** Log [1,2,7-TMN/1,3,7-TMN] versus Log [1,2,5-TMN/1,3,6-TMN] for the oils (Please see "Abbreviations" section)

F–DBF–DBT shows that the relative abundances of F decrease from freshwater/deltaic terrestrial to marine environments while the abundance of DBF increases (Fig. 10a). The dominance of F over DBF and DBT in the samples A and D is indicative of a non-marine (freshwater/deltaic) depositional environment (Fig. 10a). In contrast, the relatively marine depositional environment of the probable source rock for the oil samples B and C are located away from the DBT and F maxima and is found near to the DBF (Fig. 10a). In addition, the relative abundances of P compared to DBF and DBT in these oil samples supports the interpretation of freshwater/deltaic to marine depositional environments (Fig. 10b; Pu et al. 1990).

The varying abundance of dibenzothiophene (DBT) is also used to provide information about the different source

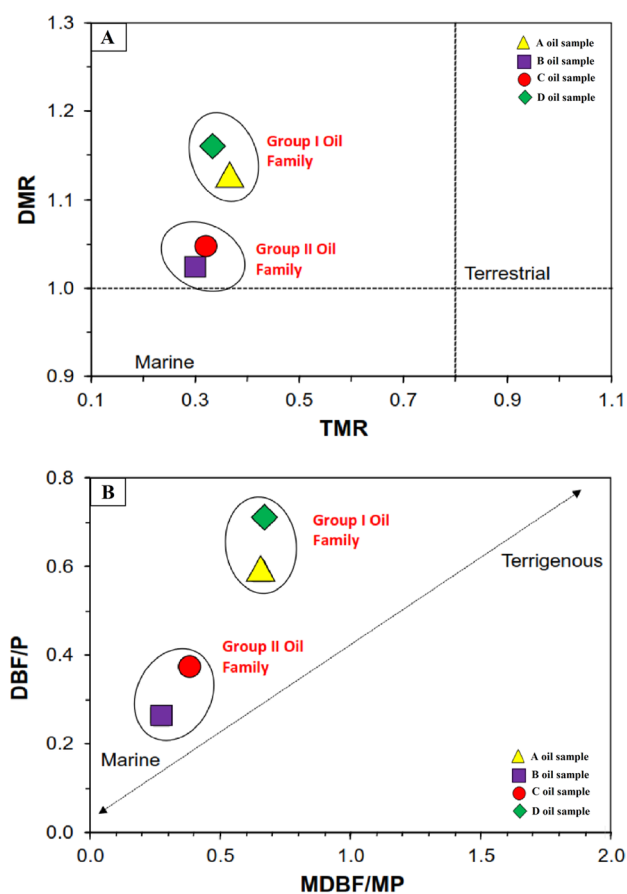


Fig. 8 Cross plots of **A** DMR and TMR ratios (after Asahina and Suzuki 2018), and **B** MDBF/MP versus DBF/P (after Baydjanova and George 2019); showing the organic matter into the source rocks for the analyzed oils (Please see "Abbreviations" section)

facies and depositional environments (Hughes et al. (1995). Hughes et al. (1995) employed the cross-plot of Pr/Ph and dibenzothiophene/phenanthrene (DBT/P) to differentiate five distinct environments and lithologies.

The Pr/Ph ratios for the studied oils range from 1.61 to 2.17, indicating deposition under sub-oxic to relatively oxic conditions (Didyk et al. 1978). The oil samples plot in zone 3 of the Hughes et al. (1995) diagram, which corresponds to marine clay-rich source rock (Fig. 11a). Similarly, the oil samples plot in the site and close to zone 3 of the modified

diagram of Radke et al. (2000), corroborating the interpretation of oil from marine shale source facies (Fig. 11b). In addition, the MDBT/MDBF ratio also supports the interpretation of two oil groups sourced from a variety of sources of organic matter (Fig. 11b). The clay-rich source facies of the oil samples is further demonstrated from the cross-plot of $\sum\text{TMN}/\sum\text{MN}$ ratios versus MNR values (Asahina and Suzuki 2018; Fig. 11c).

Oil–oil correlation

In this work, the oil–oil correlation and its implication for oil families and their potential source rocks were investigated using the organic matter (OM) origin, depositional environment and lithology-related biomarkers in the heterocyclic and polycyclic aromatic hydrocarbons distributions. The evaluation of these oils as a result of oil–oil correlation show that the four oil samples studied in the present paper could be grouped into two oil families (Fig. 12). These concept two unique categories are supported by the source organic matter, and environmental-related aromatic biomarker ratios that outlined in the previous subsection (Sect. "Characteristics of aromatic biomarker and their interpretation in relation to OM input and environmental conditions") and cross-plots between these oils (Figs. 8, 10). Indeed, oil samples A and D can be incorporated into a single oil family, while samples B and C can be recognized as a different oil family (Fig. 12).

Group (I) of the oil family consists of two oil samples (A and D), which are characterized by a relatively high Ph/Ph ratio between 2.11 and 2.17 (Table 1) and high abundant of 9-MP with significant amounts of 1-MP (Fig. 5), indicating a mixed organic matter with high amounts from the land plants to the source rock that deposited under suboxic to relatively oxic environmental conditions. This finding of the high terrestrial organic matter contributions is also supported by the distribution higher relative abundance of DBF and higher DMR (Fig. 8a, b). In addition, the oils from group A are mainly generated from source rocks deposited in non-marine (freshwater/deltaic) environments as demonstrated by the high abundances of F and DBF over DBT (Fig. 10).

The group II oil family includes two oil samples B and C with relatively lower Ph/Ph ratios (1.61 and 2.09) when compared to group I oils (Table 1), which indicates source rock deposited under suboxic environmental conditions. These

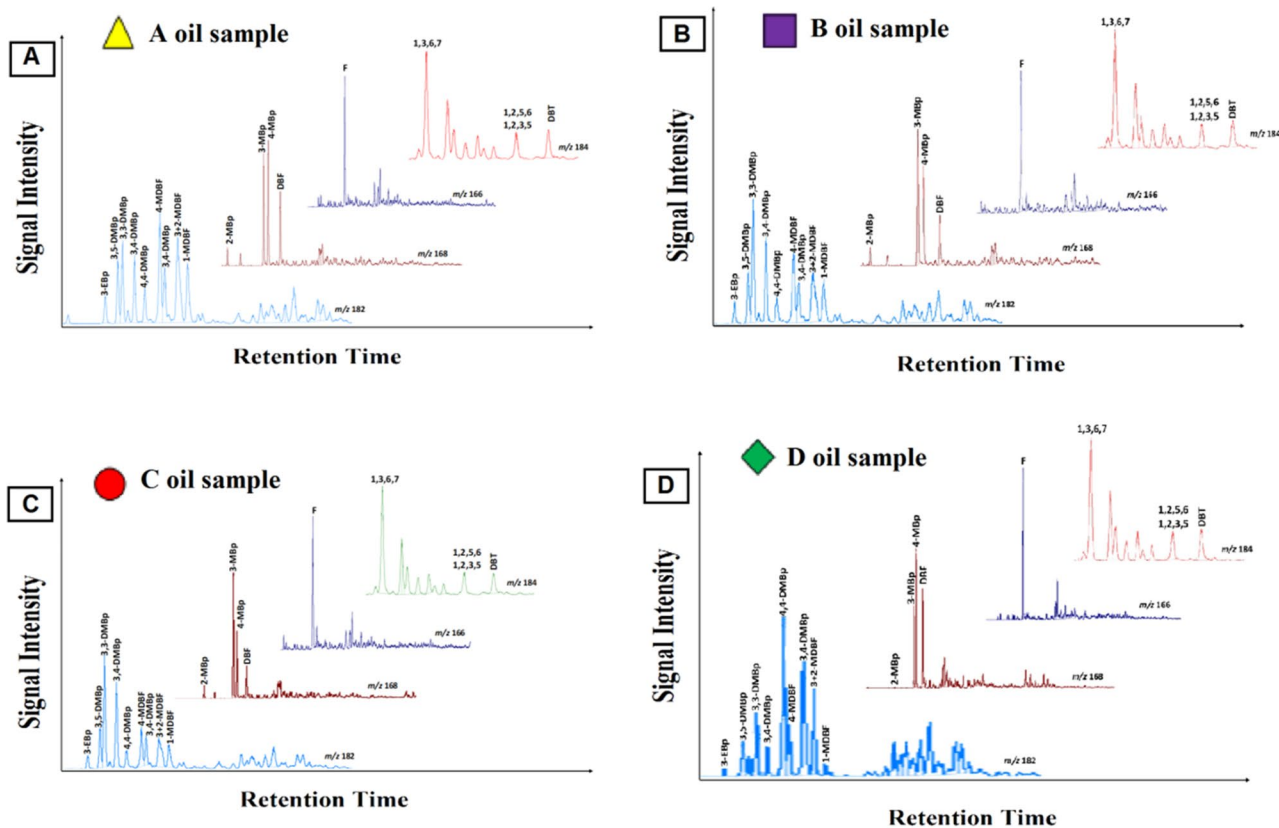


Fig. 9 Partial m/z 166 + 168 + 182 + 184 mass chromatograms showing distribution of DBT, F, MBP, DMBP, and MDBF isomers in the aromatic fractions of the western Siberian Basin’s oils (A–D samples) (Please see "Abbreviations" section)

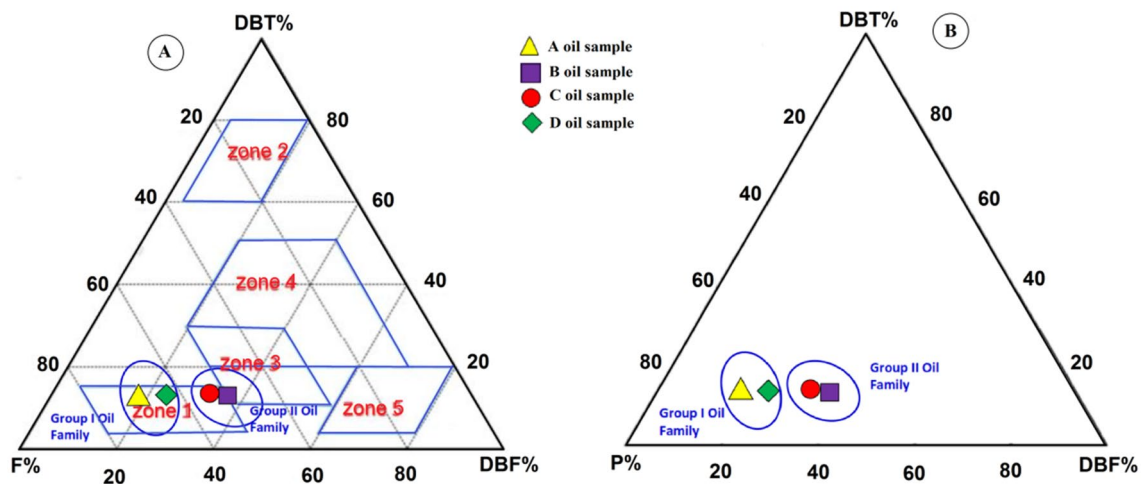


Fig. 10 Ternary plots of **A** P, F, DBT, and **B** P, DBF, and DBT, showing depositional environment and lithology (after Li et al. 2013; Fan Pu et al. 1990) (Please see "Abbreviations" section)

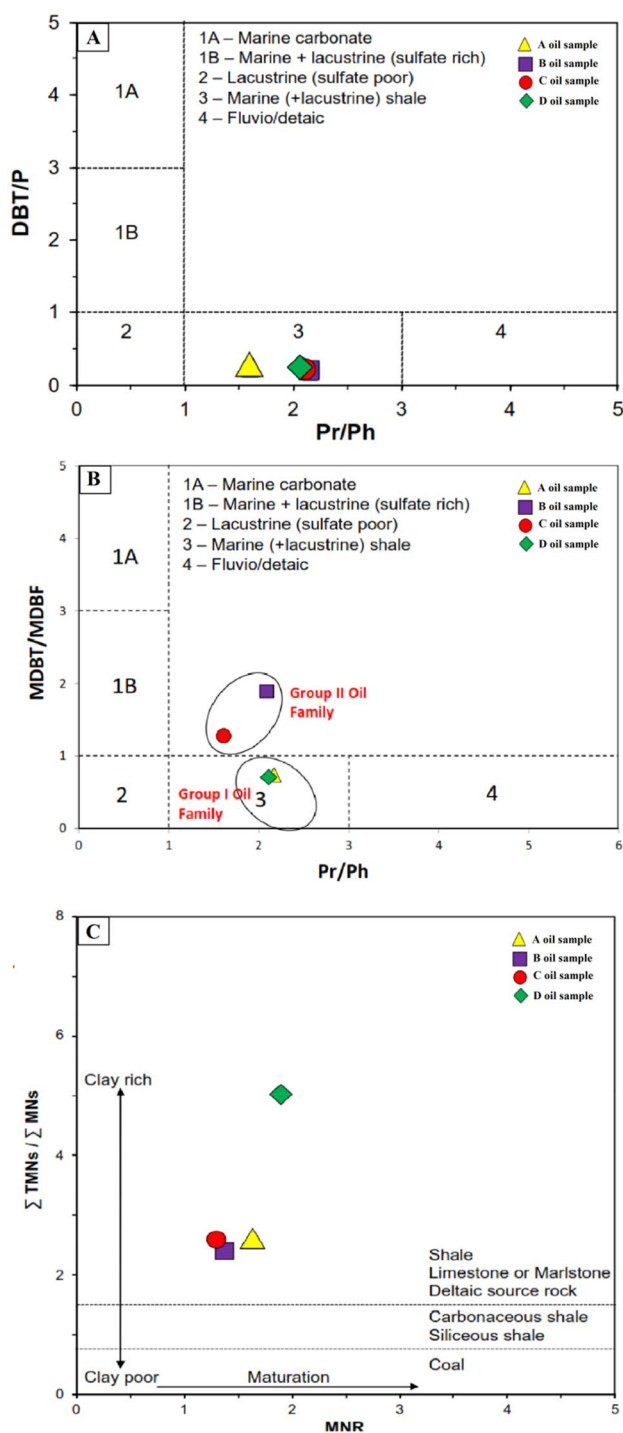


Fig. 11 Cross-plots of **A** Pr/Ph versus DBT/P ratios (after Hughes et al. 1995), **B** MDBT/MDBF versus Pr/Ph ratios (after Radke et al. 2000) and **C** Σ TMNs/ Σ MNs ratios and MNR values (after Asahina and Suzuki 2018); showing depositional environment and lithology of the source rocks for the analyzed oils (Please see "Abbreviations" section)

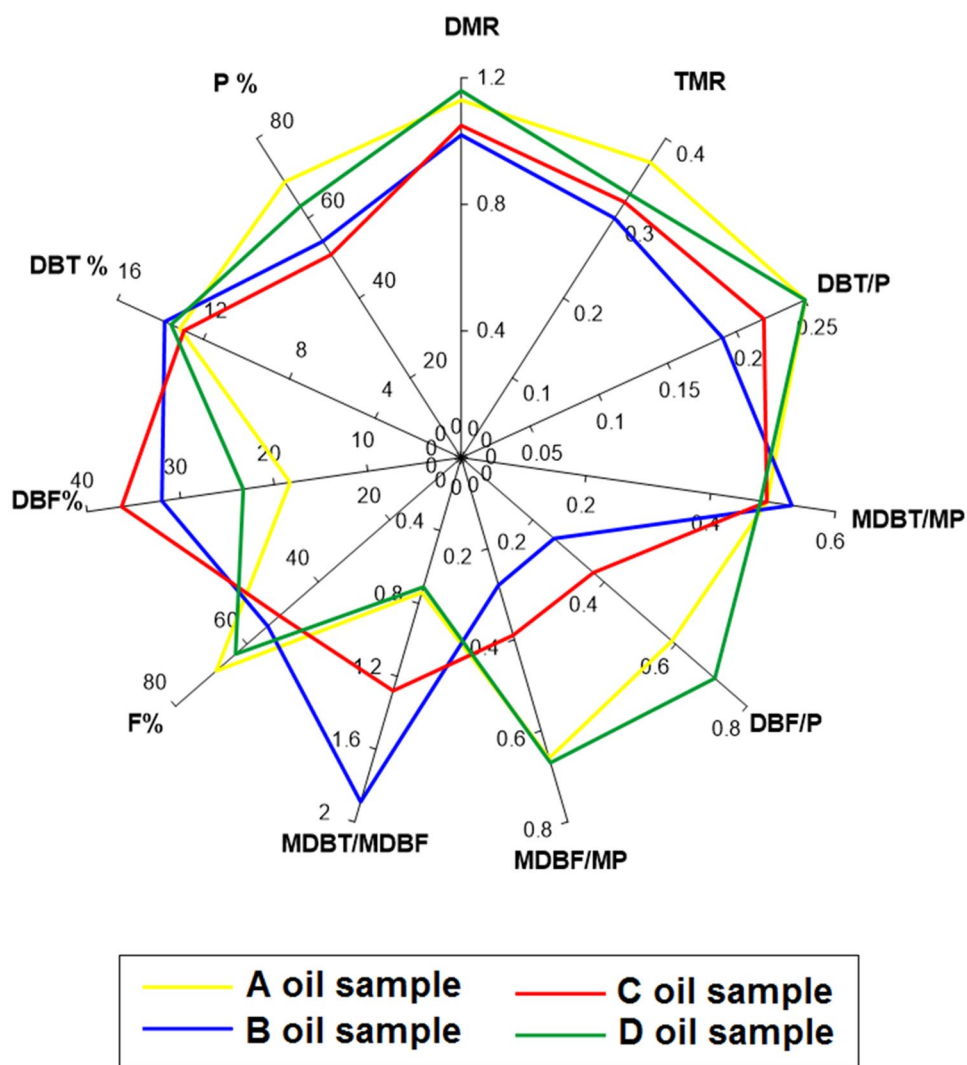
oils also have a relatively low abundance of DBF and lower DMR that is suggestive of higher contributions of marine OM (Fig. 8a, b). The higher abundance of F in the group II oils is suggestive of a lacustrine depositional environment (Li et. al. 2013; Asif and Wegner 2019).

Summary and conclusions

Four oil samples taken from wells in the West Siberian Basin, central Russia, were geochemically analyzed and characterized to determine the organic matter (OM) origin, thermal maturity, lithology, and depositional conditions of the probable source rocks. Additionally, oil–oil correlation was utilized to determine the oil families in the samples and their genetic relationship to oil's source rock.

- (1) Heterocyclic and polycyclic aromatic hydrocarbons reveal that the oils generally sourced from clay-rich source rock, containing mixed organic matter and deposited in fluvial-deltaic to lacustrine environments under suboxic to relatively oxic conditions.
- (2) Maturity-sensitive aromatic hydrocarbon parameters indicate that the oils were generated from source rocks in the peak-mature to late mature range of the oil generation window.
- (3) Result of oil–oil correlation analysis show two distinct oil families. The oils of group (I) oil family were generated from source rocks with relatively higher input of land plants that were deposited in freshwater/deltaic environment.
- (4) Oils of the group II oil family were sourced from rocks with relatively higher marine algal OM input and deposited in a lacustrine environment under suboxic conditions.
- (5) The heterocyclic and polycyclic aromatic results can be used as a foundation for further genetic correlation of the oils, particularly in the organic matter input and thermal maturity degree of their source rocks.

Fig. 12 Star diagram of the selected organic matter origin and depositional environment-related aromatic biomarkers for oil–oil correlation, showing two source rocks for the studied west Siberian Basin’s oils (A–D samples)



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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

- Afanasyev SA, Bukreeva GF, Vakulenko AS, Mosina OA (1993) Typification of the JK10 horizon sections of the Talinskoye deposit according to macro-heterogeneity character: Russian. *Geol Geophys* 34:36–40
- Alexander R, Kagi RI, Rowland SJ, Sheppard PN, Chirila TV (1985) The effects of thermal maturity on distributions of dimethylnaphthalenes and trimethylnaphthalenes in some ancient sediments and petroleum. *Geochim Cosmochim Acta* 49:385–395
- Alexander R, Bastow TB, Kagi RI, Singh RK (1992) Identification of 1, 2, 2, 5 tetramethyltetralin and 1, 2, 2, 5, 6-pentamethyltetralin as racemates in petroleum. *J Chem Soc Chem Commun* 23:1712–1714
- Armstroff A, Wilkes H, Schwarzbauer J, Littke R, Horsfield B (2006) Aromatic hydrocarbon biomarkers in terrestrial organic matter

- of Devonian to Permian age. *Palaeogeogr Palaeoclimatol Palaeoecol* 240:253–274
- Asahina K, Suzuki N (2018) Methylated naphthalenes as indicators for evaluating the source and source rock lithology of degraded oils. *Org Geochem* 124:46–62
- Asif M, Wenger LM (2019) Heterocyclic aromatic hydrocarbon distributions in petroleum: a source facies assessment tool. *Org Geochem* 137:103896
- Asif M, Alexander R, Fazeelat T, Grice K (2010) Sedimentary processes for the geosynthesis of heterocyclic aromatic hydrocarbons and fluorenes by surface reactions. *Org Geochem* 41:522–530
- Baydjanova S, George SC (2019) Depositional environment, organic matter sources, and variable $17\alpha(\text{H})$ -diahopane distribution in Early Permian samples, southern Sydney Basin. *Aust Org Geochim* 131:60–75
- Belkin VI, Bachurin AK (1991) The structure and origin of highly permeable reservoir rocks in the basal beds of the Jurassic in the Tallinskoye field: transactions of the USSR Academy of Sciences. *Earth Sci Sect* 310:102–104
- Budzinski H, Garrigues P, Connan J, Devillers J, Domine D, Radke M, Oudins JL (1995) Alkylated phenanthrene distributions as maturity and origin indicators in crude oils and rock extracts. *Geochim Cosmochim Acta* 59:2043–2056
- Didyk BM, Simoneit BRT, Brassell SC, Eglinton G (1978) Organic geochemical indicators of palaeoenvironmental conditions of sedimentation. *Nature* 272:216–222
- Fan P, Philp RP, Zhenxi L, Guangguo Y (1990) Geochemical characteristics of aromatic hydrocarbons of crude oils and source rocks from different sedimentary environments. *Org Geochem* 16:427–435
- Fenton S, Grice K, Twitchett RJ, Bottcher ME, Looy CV, Nabbefeld B (2007) Changes in biomarker abundances and sulfur isotopes of pyrite across the Permian–Triassic (P/Tr) Schuchert Dal section (East Greenland). *Earth Planet Sci Lett* 262:230–239
- Hakimi MH, Saeed AA, Al-Muntaser AA, Varfolomeev MA, Djimasbe R, Lashin A, Yelwa NA, Suwaid MA (2022) The origins of paraffinic oils from oilfields in the west Siberian Basin, Russia: implications from geochemical and physical characteristics. *J Petrol Explor Prod Technol* 12:35–49
- Hughes WB (1984) Use of thiophenic organosulfur compounds in characterizing crude oil derived from carbonate versus siliclastic sources. In: Palacas JB (ed) *Petroleum geochemistry and source rock potential of carbonate rocks*, 181–196
- Hughes WB, Holba AG, Dzou LIP (1995) The ratios of dibenzothiophene to phenanthrene and pristane to phytane as indicators of depositional environment and lithology of petroleum source rocks. *Geochim Cosmochim Acta* 59:3581–3598
- Jiang L, George SC (2019) Biomarker signatures of Upper Cretaceous Latrobe Group petroleum source rocks, Gippsland Basin, Australia: distribution and geological significance of aromatic hydrocarbons. *Org Geochem* 138:103905
- Jingguo L, Philp P, Zifang M, Wenhui L, Jianjing Z, Guojun C, Mei L, Zhaoyun W (2005) Aromatic compounds in crude oils and source rocks and their application to oil-source rock correlations in the Tarim Basin, NW China. *J Asian Earth Sci* 25:251–268
- Kang S, Shao L, Qin L, Li S, Liu J, Shen W, Chen X, Eriksson KA, Zhou O (2020) Hydrocarbon generation potential and depositional setting of Eocene oil-prone coaly source rocks in the Xihu Sag, East China Sea Shelf Basin. *ACS Omega* 50:32267–32285
- Kontorovich AE, Ivanov IA, Koveshnikov AE, Krasnov VI, Perozio GN (1991) Geologic conditions of oil and gas productivity in the upper part of the Paleozoic sequence of West Siberia. In: Surkov VS, Kontorovich AE (eds) *Theoretical and regional problems of oil and gas geology (Teoreticheskie i regionalnye problem geologii nefti i gaza)*: Novosibirsk. Nauka, Russia, pp 152–171
- Kontorovich AE, Moskvina VI, Bostikov OI, Danilova VP, Fomin AN, Fomichev AS, Kostyreva EA, Melenevsky VN (1997) Main oil source formations of the West Siberian Basin. *Pet Geosci* 3:343–358
- Li M, Wang T, Zhong N, Zhang W, Sadik A, Li H (2013) Ternary diagram of fluorenes, dibenzothiophenes and dibenzofurans: Indicating depositional environment of crude oil source rocks. *Energy Explor Exploit* 31:569–588
- Lopatin NV, Emets TP, Simonenkova OI, Galushkin YuI (1997) Source rocks for oils in the weathering crust and top of the Paleozoic basement in fields of the Middle Ob region: *Geologiya. Geofizikai Razrabotka Neftnykh Mestorozhdeniy* 7:7–22
- Lopatin NV, Emets TP, Simonenkova OI, Erben JP (1998) Bazhenov petroleum-generation and accumulation system in the west Khantey antecline: *Geologiya. Geofizika i Razrabotka Neftnykh Mestorozhdeniy* 5:2–27
- Odiar K, Artaud I (1992) Degradation of lignin. In: Winkelmann G (ed) *Microbial degradation of natural products*. VCH Inc., New York
- Peters KE, Kontorovich AE, Moldowan JM, Andrushevich VE, Huizinga BJ, Demaison GJ, Stasova OF (1993) Geochemistry of selected oils and rocks from the central portion of the West Siberian Basin, Russia. *Am Assoc Petrol Geol Bull* 77:863–887
- Petrov AI (1994) Biomarkers and geochemical conditions of oil generation in Russia. *Geologiya Nefti i Gaza* 6:13–18
- Pu F, Philip RP, Zhenxi L, Guangguo Y (1990) Geochemical characteristics of 1052 aromatic hydrocarbons of crude oils and source rocks from different sedimentary 1053 environments. *Org Geochem* 16:427–435
- Pyatkov MI, Pitkevich VP, Kiseleva TYu (1988) Composition of vuggy and porous rocks of the Talin field and their relation to reservoir properties. In: Medvedsky RI (ed) *Physico-lithological characteristics and reservoir properties of productive, deeply buried rocks of West Siberia (Fiziko-litologicheskiye osobennosti i kollektorskiye svoystva produktivnykh porod glubokikh gorizontov Zapadnoy Sibiri)*: Tyumen. Russia, ZapSibNIGNI, pp 128–135
- Radke M, Welte DH (1983) The methylphenanthrene index (MPI): a maturity parameter based on aromatic hydrocarbons. In: Bjory M (ed) *Advances in Organic Geochemistry 1981*, pp 504–512
- Radke M, Willsch H (1994) Extractable alkyldibenzothiophenes in Posidonia Shale (Toarcian) source rocks: relationship of yields to petroleum formation and expulsion. *Geochim Cosmochim Acta* 58:5223–5244
- Radke M, Willsch H, Leythaeuser D, Teichmüller M (1982) Aromatic components of coal: relation of distribution pattern to rank. *Geochim Cosmochim Acta* 46:1831–1848
- Radke M, Leythaeuser D, Teichmüller M (1984) Relationship between rank and composition of aromatic hydrocarbons for coals of different origins. *Org Geochem* 6:423–430
- Radke M, Welte DH, Willsch H (1986) Maturity parameters based on aromatic hydrocarbons: influence of the organic matter type. *Org Geochem* 10:51–63
- Radke M, Vriend SP, Ramanampisoa LR (2000) Alkyldibenzofurans in terrestrial rocks: influence of organic facies and maturation. *Geochim Cosmochim Acta* 64:275–286
- Rovenskaya AS, Nemchenko NN (1992) Prediction of hydrocarbons in the West Siberian basin: bulletin centre de recherche exploration-production Elf Aquitaine. vol 16, pp 285–318
- Rudkevich MY, Ozeranskaya LS, Chistyakova NF, Kornev VA, Maksimov EM (1988) Petroleum-productive complexes of the West Siberian Basin (Neftegazonosnye kompleksy Zapadno-Sibirskogo basseyna): Moscow, Nedra, 304 p
- Schou L, Myhr MB (1988) Sulfur aromatic compounds as maturity parameters. In: Mattavelli L, Novelli L (eds) *Advances in organic geochemistry*. Pergamon Press, Oxford, pp 61–66

- Surkov VS, Kazakov AM, Devyatov VP, Smirnov LV (1997) Lower middle Triassic rift-ogenetic complex of the West Siberian Basin. *Otechestvennaya Geol* 3:31–37
- Van Aarssen BGK, Bastow TP, Alexander R, Kagi RI (1999) Distributions of methylated naphthalenes in crude oils: indicators of maturity, biodegradation and mixing. *Organ Geochem* 30:1213–1227
- Vyshemirsky VS (1986) Bazhenov Horizon of West Siberia (Bazhenovskiy gorizont Zapadnoy Sibiri): Novosibirsk. Nauka, Russia, p 217
- Xiangchun C, Zuozen H, Xiaofei S, Chengpeng Y (2011) Geochemical characteristics of aromatic hydrocarbons in crude oils from the Linnan Subsag, Shandong Province China. *Chin J Geochem* 30:132–137

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