GEOLOGIJA 69/1, 77-91, Ljubljana 2026

https://doi.org/10.5474/geologija.2026.004

Article

Geochemical Assessment of Liquid Hydrocarbon from the Ormož-1g well (NE Slovenia)

Geokemična ocena tekočega ogljikovodika iz vrtine Ormož-1g (SV Slovenija)

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Prejeto / Received 21. 10. 2025; Sprejeto / Accepted 12. 2. 2026; Objavljeno na spletu / Published online 7. 4. 2026

Key words: Mura-Zala Basin, hydrocarbon, light crude oil, chromatography, mass spectrometry, biomarkers, *n*-alkanes, thermal maturity
Ključne besede: Mursko-Zalski bazen, ogljikovodik, lahka nafta, kromatografija, masna spektrometrija, biomarkerji, *n*-alkani, termična zrelost

Abstract

This study presents the results of an organic geochemical characterisation of a liquid hydrocarbon sample from the Ormož-1g well in the Mura-Zala Basin, north-eastern Slovenia. The main objective was to assess the origin, depositional environment, and thermal maturity using biomarker analysis. The bulk composition of the sample was initially determined by gas chromatography. The hydrocarbon sample was then fractionated into saturates and aromatics. These fractions were analysed by gas chromatography–mass spectrometry (GC–MS) to identify and quantify specific biomarker compounds. Based on an API gravity of 42.53° and biomarker distribution of the saturated fraction, the sample is classified as light crude oil. The dominance of high molecular weight n-alkanes and a Pr/Ph ratio of 1.83 suggests suboxic marine depositional conditions with significant terrestrial organic matter input. The sterane distribution pattern and the isoprenoid/*n*-alkane ratio indicate a mixed origin of organic matter. The uniform distribution of n-alkanes, a CPI value close to 1, a high degree of sterane isomerisation and the relative abundance of 3- and 2-methylphenantherene collectively indicate high thermal maturity. These establish a geochemical framework for further hydrocarbon exploration in the Mura-Zala Basin and enhance the understanding of its petroleum potential.

Izvleček

Študija proučuje organske geokemične značilnosti tekočega ogljikovodikovega vzorca iz vrtine Ormož-1g na severnem obrobju Ormoža (Hardek). Širše območje spada v Mursko-Zalski bazen severovzhodne Slovenije. Glavni cilj je bila ocena izvora ogljikovodika, njegove akumulacije in termične zrelosti z analizo biomarkerjev. Sestava vzorca je bila določena s plinsko kromatografijo. Vzorec ogljikovodika je bil frakcioniran na nasičeno in aromatsko frakcijo. Ti frakciji sta bili nadalje analizirani s plinsko kromatografijo–masno spektrometrijo (GC–MS), da se identificirajo in kvantificirajo specifični biomarkerji. Vzorec smo opredelili na podlagi API gostote 42,53° in analize biomarkerjev v nasičeni frakciji kot lahko nafto. Prevlada *n*-alkanov z visoko molekulsko maso in razmerje Pr/Ph = 1,83 nakazujeta suboksične morske sedimentacijske razmere, na katere je pomembno vplival tudi vnos kopenskega organskega materiala. Porazdelitveni vzorec steranov in razmerje izoprenoidi/n-alkani nakazujeta na mešani izvor organske snovi. Enakomerna porazdelitev n-alkanov, CPI indeks blizu 1, visoka stopnja izomerizacije steranov ter relativna vsebnost 3- in 2-metilfenantrenov skupaj kažejo na visoko termično zrelost. Dobljeni rezultati predstavljajo geokemično osnovo za nadaljnje analize ogljikovodikov v slovenskem delu Mursko-Zalskega bazena ter prispevajo k boljšemu razumevanju naftnega potenciala obravnavanega območja.

Introduction

Petroleum and rock extracts, including light crude oil and gas condensate, are among the most chemically complex mixtures found in nature. To understand their complex composition, advanced molecular analyses such as gas chromatography and mass spectrometry (GC-MS) were introduced as early as the 1960s (Walters et al., 2018). These tools enabled comprehensive characterisation of both major and minor hydrocarbon species in geological samples, along with various trace components. Many of these substances are known as biomarkers – molecular fossils that retain enough of their original biological structure to be linked to specific biological sources. Biomarkers are important tools for reconstructing palaeoenvironmental conditions, assessing biotic input, determining thermal maturity and alteration processes, and establishing correlations between source rocks and hydrocarbons, as well as between hydrocarbons and source rock (Peters et al., 2005).

The hydrocarbon deposits in Slovenia are located in the NE part of the country, in the Mura-Zala Basin, which is a SW part of the larger Pannonian Basin System (Fig. 1A, B). The only commercially gas-producing field in Slovenia is the Petišovci-Dolina oil and gas field, discovered in 1942/43. Gas production over the past two decades has ranged from 2 to 5 kt per year, with condensate production at about 0.15 kt per year (rounded from BMR data, 2023). The low proportion of condensate recovered can be attributed to the high quality of the thermogenic natural gas within the Petišovci-Dolina field, which contains a high concentration of lighter components, notably over 85 % methane (Markič & Kanduč, 2022).

In 1944, and later between 1950 and 1955, six "Kog" wells (620–2180 m deep) (GeoZS; e-vrtine: Internet 1) were drilled in the Kog hills SW of the Petišovci-Dolina field (Fig. 1C). The wells did not reach the pre-Neogene basement, expected at a depth of about 3 km (Mioč & Marković, 1998), nor did they encounter economic quantities of hydrocarbons. However, small amounts of gas were found in the Kog-1 and Kog-2 wells, and traces of oil and saline water were found in the Kog-3 and Kog-5 wells.

This paper presents the first published organic geochemical evaluation of a liquid hydrocarbon sample from the Ormož-1g (Or-1g) well, Slovenia. Although this preliminary work is based on the analysis of a single sample, it provides a detailed and comprehensive assessment of its origin, depositional environment, and thermal maturity through biomarker analysis. The findings of this study aim to establish a solid foundation for further research within the Mura-Zala Basin in Slovenia.

Geological setting

The Mura-Zala Basin is well known for oil and gas production (Šram et al., 2015; Kerčmar, 2018; Tari et al., 2023), thermal water (Lapanje, 2006; Rman et al., 2012, 2015, 2020; Kralj, 2022), coal strata (Markič et al., 2007, 2011; Markič, 2017), potential for underground carbon storage (Lisjak et al., 2011; Lapanje et al., 2011; Orešnik et al., 2011), high geothermal energy potential and use (Rman et al., 2011; Rman, 2014; Rajver et al., 2012), and its extensive groundwater reservoirs (Nador et al., 2012; Tóth et al., 2016).

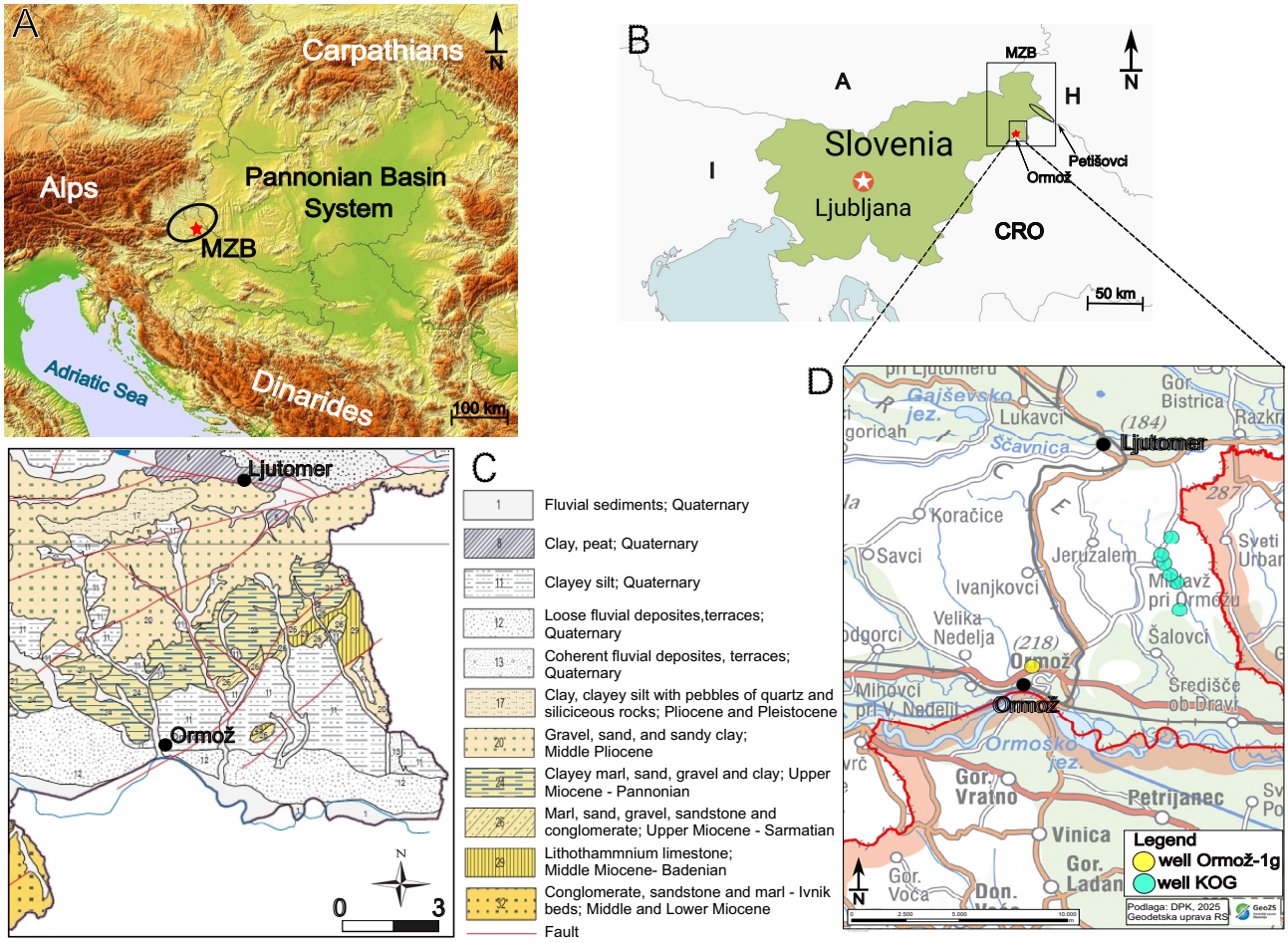

Fig. 1. (A) Position of the Mura-Zala Basin (MZB) in the SW part of the Pannonian Basin System; (B) Position of the Mura-Zala Basin (MZB) in Slovenia; (C) geological map and (D) geographical location of the Or-1g well and KOG wells.

The Ormož-1g (Or-1g) well was designed and drilled in 2005 as a geothermal exploration well in the Hardek area, in the northern part of Ormož in NE Slovenia (Fig. 1C). The drilled successions belong to the Mura–Zala Basin, located in the western part of the Pannonian Basin System (Fig. 1A). The main purpose of the well was characterisation of geothermal and hydrocarbon conditions. One of the targets was to reach the pre-Neogene basement, which was presumed to be composed of a carbonate sedimentary succession (Tancar et al., 2005). The Or-1g well was drilled vertically from the surface, reaching a maximum total depth of 1500 m. The wellhead is located at the following coordinates (EPSG:3794):

N (96): 142,479.55
E (96): 588,516.29
Z: 238.41 m a.s.l.

The wider study area of the Ormož–1g borehole (Mioč & Marković, 1998; Jelen & Rifelj, 2011) (Fig. 1C) consist of Miocene sedimentary successions, including sandstones, marlstones, clayey marlstones, siltstones, limestone breccias, and lithotamnian limestones. These lithologies alternate both laterally and vertically. The structural conditions are controlled by the regional Boč-Ormož-Selnica-Lovaszi-Budafa antiform (Šram et al., 2015), which trends SW–NE and is emplaced between the Ljutomer fault zone to the north and the Donat fault zone to the south. Pliocene sedimentary successions, usually composed of sands, gravely and clays, do not crop out in the study area or have been eroded due to post-Miocene tectonic processes. The Quaternary successions are composed of alluvial gravels, eolian sands, and aeolic silty clays. The contact between Miocene sedimentary successions and the pre-Neogene basement is marked by a regional unconformity (Fodor et al., 2011, 2021; Nador et al., 2012). The pre-Neogene basement of the Slovenian part of the Mura-Zala Basin is most probably composed primarily of eastern-Alpine units, except south of the Ljutomer fault zone, where it is presumably composed of Southern-Alpine and/or Dinaridic tectonic units composed of limestones and dolomites interlayered with Permian and Triassic clastic sequences (Fodor et al., 2011; Nador et al., 2012).

During drilling, the Or-1g well encountered the following main lithological units: the topmost 500 m of the drilled succession are predominantly composed of marly claystones and marly siltstones with thin layers of fine–grained sandstones. This is followed by grey clayey marlstone, which occurs down to a depth of 1200 m. From there to the final depth of the well at 1500 m, silty marlstones predominate, locally interbedded with light-coloured limestones. The limestones occur more frequently between 1310 and 1390 m. The pre-Neogene, basement presumably composed of carbonates, was not reached during drilling.

The main purpose of the Or-1g well was to capture hydrothermal water in the fissured aquifer of Mesozoic carbonate rocks. Drilling revealed that the pre-Neogene basement is located significantly deeper than previously estimated. At a depth of 1500 m, the well reached the Miocene clay-marls of the Murska Sobota formation (old nomenclature). The exact chronostratigraphic and lithostratigraphic constraints of the drilled successions were not reported. The well was tested negative for thermal water and was preserved in 2025. In 2024, the well was temporarily opened for temperature logging to update geothermal potential maps of Slovenia. The bottom hole temperature was measured at 62 °C (Rman et al., 2025). A layer of hydrocarbons was discovered floating on the water column, spanning an approximately 15 m thick interval between 29.7 and 45.2 m. Under static conditions, approximately 1.2 m^3 of liquid was measured and labelled as gas condensate (Rman et al., 2025).

Sampling and Methods

Sampling of the hydrocarbon was conducted by Geogreen d.o.o. Two samples were collected at a depth of 32 m and stored in 0.5 litre dark glass bottles. One of the bottles exploded shortly after collection, so only a single sample was preserved for analysis (Fig. 2). This sample, initially categorised as a gas condensate, was sent to the INA Exploration and Production Laboratory in Zagreb. Comprehensive analytical work was performed, including: total sulphur content analysis, gas chromatography (GC), and gas chromatography-mass spectrometry (GC-MS) of petroleum hydrocarbons, commonly referred to as biomarker analysis.

First, the American Petroleum Institute (API) gravity of the sample was determined. Density is defined as the mass per unit volume of a fluid. The density of crude oil and liquid hydrocarbons is usually expressed in terms of specific gravity (SG). The API gravity is calculated using the following equation:

$$°API = \frac{141.5}{SG_{15.6℃/15.6℃}} - 131.5$$

Fig. 2. Sample of liquid hydrocarbon from the Or-1g well.

The total sulphur content was determined by the wave dispersive X-ray fluorescence spectrometer (WD-XRF). The analysis followed ASTM Standard D2622-24: *Standard Test Method for Sulphur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry*.

Gas chromatographic (GC) analysis of the "whole oil" was performed using an Agilent 7890A gas chromatographer fitted with a 50 m × 0.25 mm i.d. DB-petro column with a film thickness of 0.5 µm and using helium as the carrier gas. A constant flow mode and a flame ionisation detector (FID) were used. The gas chromatography oven temperature was initially held at 35 °C for 10 minutes, then increased to 40 °C at a rate of 1 °C/min, followed by a ramp to 320 °C at 8 °C/min, and held at this final temperature for 20 minutes. The results of the chromatographic composition of the identified components are presented as relative surface percentages. Although the FID detector is mass-sensitive, in complex mixtures such as crude oil and condensate, the percentage of individual components – calculated from the ratio of the area under a given peak to the total peak area – does not correspond to the actual mass percentage.

The condensate sample was fractionated into saturated, aromatic, and polar fractions. Gas chromatography-mass spectrometry (GC-MS) analysis of the saturated and aromatic fractions of the condensate was then performed using an Agilent MS 5975C quadrupole mass spectrometer interfaced with an Agilent 7890A gas chromatograph. The GC 7890A was equipped with an HP-5MS column, 60 m in length, with an inner diameter of 0.25 mm and a film thickness of 0.25 µm. High purity helium was used as the carrier gas. The GC oven temperature was programmed from 60 °C to 315 °C at a heating rate of 2 °C/min, with a final hold time of 15 minutes. The MS was operated at an ionisation energy of 70 eV. The saturated and aromatic fractions were dissolved in isooctane and analysed in full-scan mode over a mass range of 50 to 560 amu. The biomarkers hopanes and steranes were identified using ion chromatograms at m/z 191 and m/z 217 (and m/z 218). Phenanthrene and methylphenanthrene from the aromatic fraction were identified using ion chromatograms at m/z 178 and m/z 192, respectively.

Results and discussion

Bulk properties

Although the sample is distinctly dark in colour, which is generally characteristic of crude oil, its classification cannot be based solely on quantitative bulk parameters, including API gravity. Petroleum fluids are classified by API gravity values as heavy (≤20°), medium (20–40°), and light (40–45°), while condensates have API gravity values >45° (Nasir & Fazeelat, 2013). Based on this scale, the analysed sample, with an API gravity of 42.53° (Table 1), falls within the range of light crude oil. However, since the sample is close to the classification threshold, it may be classified either as light crude oil or as a high-end gas condensate. Additional detailed analyses are required to achieve a more precise characterisation.

Table 1. API gravity and content of total sulphur of the Or-1g sample.

Sample	Sulphur (wt.%)	API (°)
Or-1g	0.049	42.53

Sulphur compounds are undesirable in crude oil and its refined products because they increase the cost of sulphur removal and cause environmental problems. Crude oils are classified as sour or sweet based on their sulphur content, with sour oils containing more than 1 % sulphur and sweet oils less than 1 % (Nasir & Fazeelat, 2013). The sulphur content of the analysed sample is extremely low at 0.049 wt.% (Table 1). Therefore, the sample can be categorised as sweet and commercially valuable. Such low sulphur content is particularly characteristic of gas condensates, however, some crude oils, especially light crude oils, may also exhibit low sulphur content.

Sulphur content also partially indicates the type of organic matter input into the source rock and the environmental conditions during its formation (Gransch & Posthuma, 1973; Al-Khafaji et al., 2018). Carbonate source rocks formed in marine environments under reducing conditions usually have a high sulphur content, while rocks deposited in siliciclastic settings generally contain lower amounts of sulphur (Gransch & Posthuma, 1973; Al-Khafaji et al., 2018). Therefore, the very low sulphur content of the analysed liquid hydrocarbon in this study suggests that it was derived from siliciclastic rocks rather than from carbonate rocks.

Gas chromatography analysis of whole oil

Based on the mass fraction of the identified components (Table 2) and the chromatogram (Fig. 3) of the sample Or-1g, the hydrocarbons range from nC_3 to nC_{33}, with *n*-alkanes constituting the highest proportion of the analysed compounds. This indicates that the sample is normal paraffin-rich ("light") crude oil, which is consistent with its API gravity value of 42.53°. The sample contains a significant proportion of hydrocarbons within the gasoline fraction, up to nC_9. Furthermore, light aromatics such as benzene, toluene, and xylene, as well as hydrocarbons in the range of nC_8 to nC_{16}, are highly represented (Table 2, Fig. 3).

Biomarker distribution

The sample was analysed for *n*-alkanes (*m/z* 99), regular hopanes (*m/z* 191), and steranes (*m/z* 217 and *m/z* 218) in the saturated fraction, as well as for other compounds such as phenanthrene (*m/z* 178) and methylphenanthrene (*m/z* 192) in the aromatic fraction. These compounds are among the most important petroleum hydrocarbons that retain the characteristic structure of the

Table 2. Chromatographic composition (GC) of the Or-1g sample.

Compound	Or-1g (wt. %)	Compound	Or-1g (wt. %)	Compound	Or-1g (wt. %)	Compound	Or-1g (wt. %)
nC_3	0.23	3-MH	0.83	nC_{13}	1.63	nC_{24}	0.37
iC_4	0.18	nC_7	1.58	nC_{14}	1.87	nC_{25}	0.34
nC_4	0.88	ECP	0.07	nC_{15}	1.52	nC_{26}	0.24
iC_5	0.88	2,5-DMH	0.38	nC_{16}	1.24	nC_{27}	0.20
nC_5	1.30	1c2t4-TMCP	0.53	nC_{17}	1.06	nC_{28}	0.16
2,3-DMB	0.42	TOLUEN	1.56	Pr	0.78	nC_{29}	0.16
2-MP	0.77	CHp	0.14	nC_{18}	0.96	nC_{30}	0.13
3-MP	0.53	EBENZ	0.47	Ph	0.43	nC_{31}	0.10
nC_6	1.35	m/p-Xy	2.28	nC_{19}	0.87	nC_{32}	0.07
MCP	1.52	nC_9	1.93	nC_{20}	0.68	nC_{33}	0.06
BENZEN	0.31	nC_{10}	2.10	nC_{21}	0.62		
CH	1.32	nC_{11}	2.19	nC_{22}	0.54		
2-MH	0.61	nC_{12}	2.05	nC_{23}	0.41		

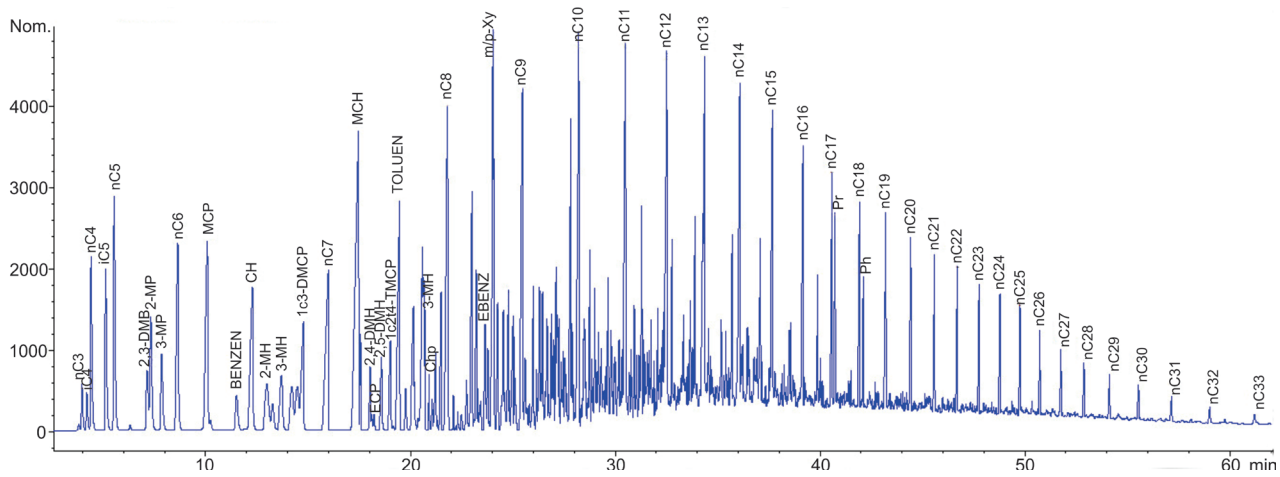

Fig. 3. Gas chromatogram of the Or-1g sample.

original biological material (Lukaye et al., 2017). The origin and maturity of the organic matter in the crude oil were determined based on the abundance and distribution of the biomarkers hopane and sterane from the saturated fraction, while maturity was further assessed using the biomarkers phenanthrene and methylphenanthrene from the aromatic fraction.

Distribution of *n*-alkane

The components most susceptible to biodegradation are the *n*-alkanes (Cheng et al., 2016). Their distribution provides valuable information regarding the source of organic matter, thermal maturity, and extent of biodegradation. As the *n*-alkanes and isoprenoids are fully preserved (complete range from C_{11} to C_{35}), the oil is categorised as minimally biodegraded or non-biodegraded (Peters et al., 2005). Furthermore, the unresolved complex mixture (UCM) is negligible, which is characteristic of a relatively unaltered hydrocarbon composition. The minor apparent enrichment of hopanes is likely a reflection of their intrinsically high concentration relative to *n*-alkanes in the source rock input, rather than being the result of *n*-alkane removal via biodegradation. This preservation pattern is characteristic of a relatively unaltered crude oil (Peters et al., 2005).

The mass chromatogram of *n*-alkanes at *m/z* 99, shown in Figure 5, reveals a distribution pattern with a maximum at high molecular number, specifically at nC_{25}, indicating a significant contribution of terrestrial organic matter to the oil/condensate source. This finding is consistent with the fact that higher land plants typically produce long-chain *n*-alkanes (C_{27}–C_{31}) (Jansen et al., 2006). Furthermore, the analysed sample displays a uniform distribution with no clear dominance of odd or even carbon numbers (Figs. 4 & 5). The absence of a strong odd-over-even preference (low

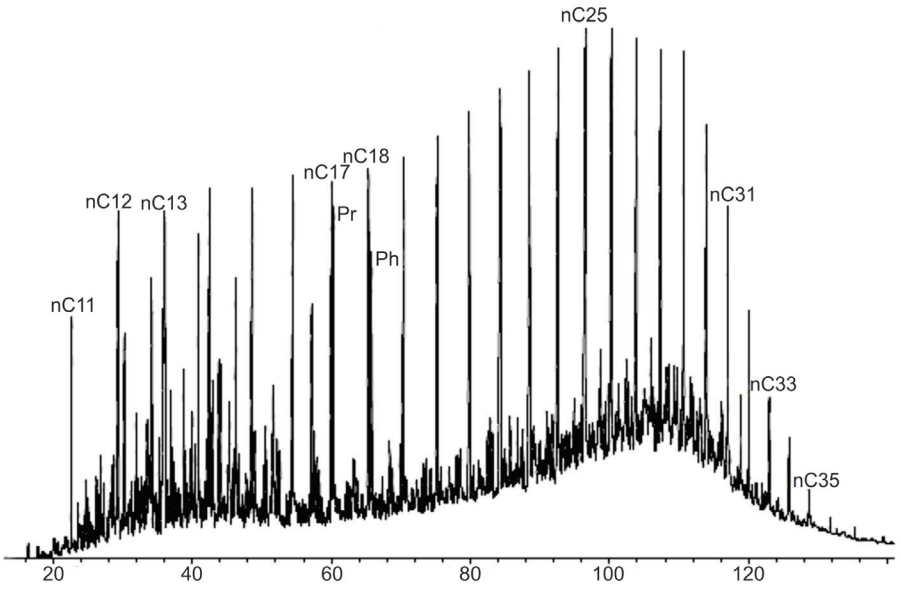

Fig. 4. Total ion current (TIC) chromatogram of the Or-1g sample.

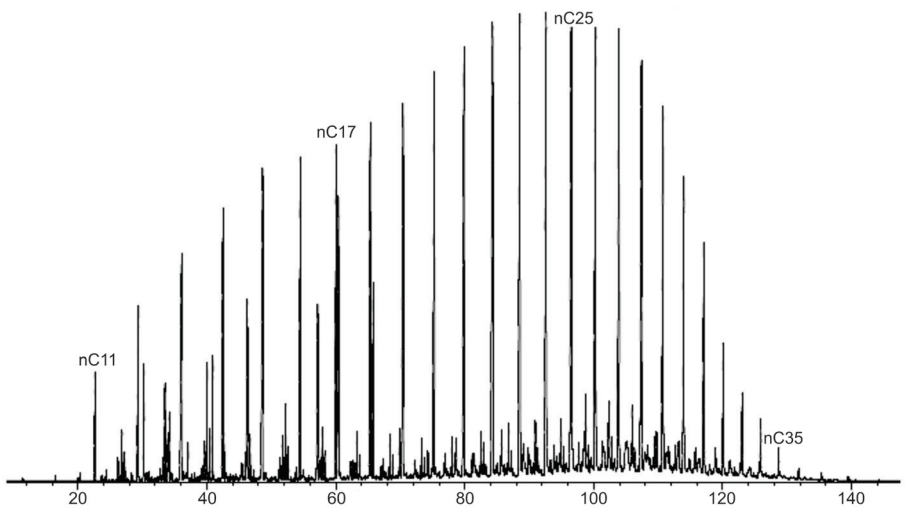

Fig. 5. Mass chromatogram of n-alkanes (m/z 99) of the Or-1g sample.

CPI) is a key indicator of high thermal maturity of the source rock, regardless of the organic matter type.

The distribution pattern described above, with a maximum in high molecular weight *n*-alkanes, is reflected in the carbon preference index (CPI), a valuable parameter for assessing the origin and maturity of organic matter, as well as paleoenvironmental conditions (Peters et al., 2005).Most biologically derived *n*-alkanes, especially those from terrestrial plants, initially exhibit a strong odd-over-even carbon number preference, resulting in high CPI values (Herrera-Herrera et al., 2020). However, as thermal maturity increases, CPI values decrease towards 1.0, reflecting the thermal cracking of the organic matter (Peters et al., 2005; Herrera-Herrera et al., 2020).

The CPI value for the Or-1g sample is 1.18 (Table 3), which is close to 1.0 and indicates a relatively high level of thermal maturity, as shown in Figure 6.

Table 3. Gas chromatography parameters of theOr-1g sample.

Sample	CPI*	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}
Or-1g	1.18	1.83	0.74	0.45

Pristane (Pr; C_{19}) and phytane (Ph; C_{20}) are the most important acyclic isoprenoids, both derived from the microbial or chemical degradation of phytol, the side chain of chlorophyll (Didyk et al., 1978). The redox conditions (oxidation-reduction) of the depositional environment dictate whether phytol is converted into pristane or phytane. Aerobic degradation of plant material in terrestrial, oxygen-rich environments favour the formation of pristane (Pr), with the loss of one carbon atom. In contrast, marine, reducing, oxygen-poor, environments favour the formation of phytane (Ph), where the complete C_{20} structure is retained and preserved (Shanmugam, 1985). The Pr/Ph ratio is a commonly used index to identify the depositional environment of the source rock with higher values indicating more oxidising conditions. This ratio also generally increases with increasing thermal maturation (Peters et al., 2005).

According to the chromatographic composition (GC) in Table 2 and the TIC (Fig. 4), the content of pristane (0.78 wt.%) is higher than that of phytane (0.43 wt.%), resulting in a Pr/Ph ratio of 1.83 (Table 3). The depositional environment can be interpreted based on the following ranges (Chen et al., 2018): low Pr/Ph ratios (<1) indicate anoxic and hypersaline conditions during sediment deposition; intermediate ratios (1–3) are characteristic of suboxic marine environments that may also receive significant terrestrial input; and high Pr/Ph ratios (>3) suggest oxic fluvial or deltaic environments. The Pr/Ph ratio of 1.83 suggests that suboxic conditions prevailed in a marine setting at the time of deposition, with a notable contribution of terrestrial organic matter (Fig. 6).

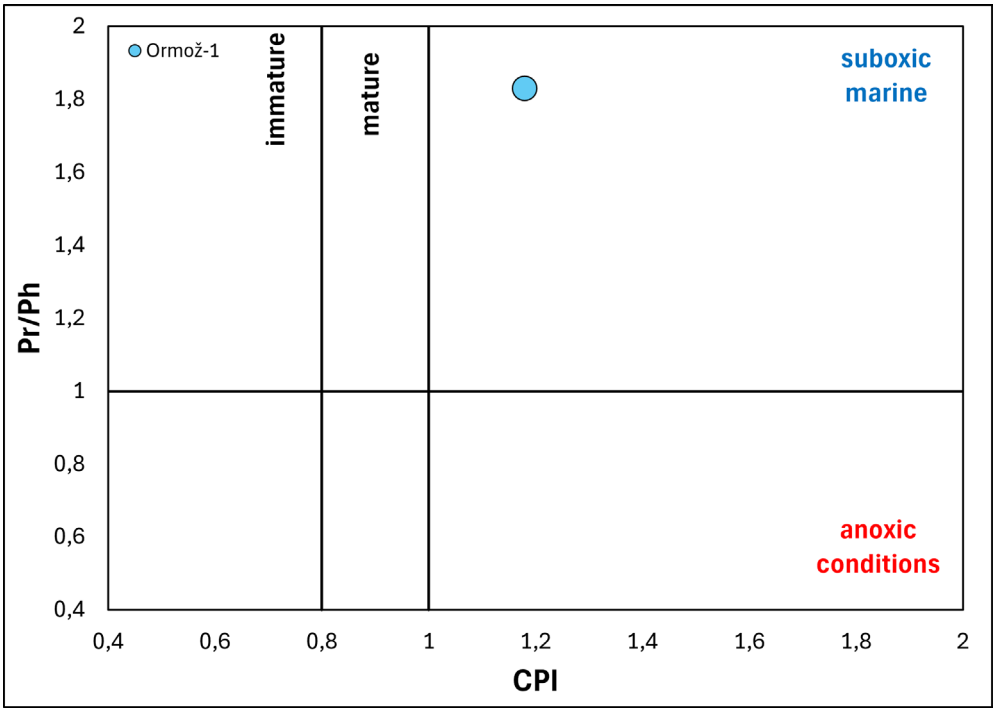

Fig. 6. Pr/Ph vs. CPI, indicating paleodepositional conditions and thermal maturity of the Or-1g sample.

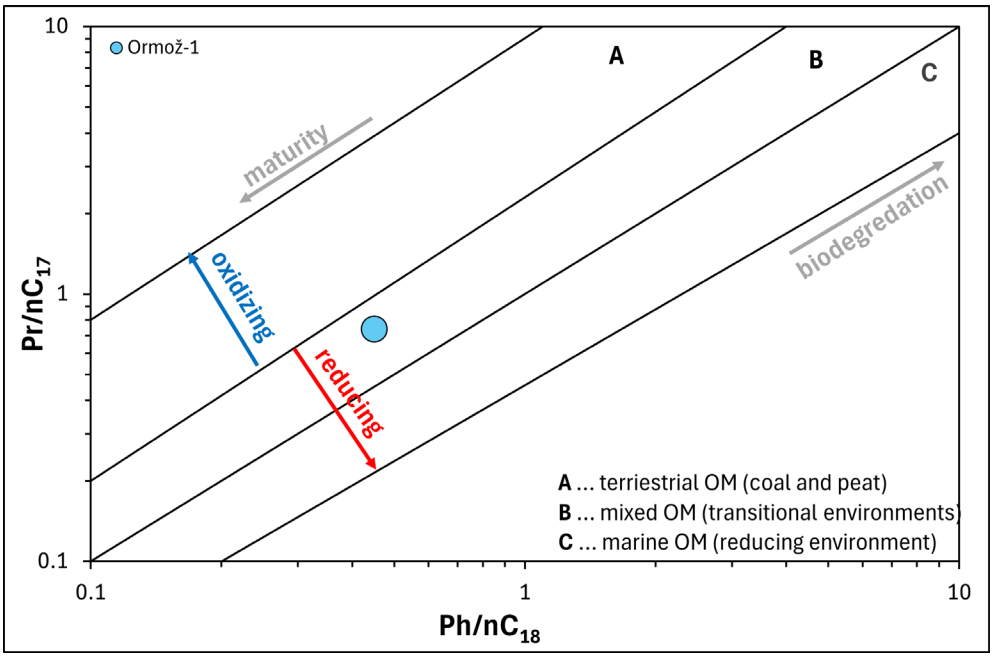

Fig. 7. Pristane/nC_{17} vs. Phytane/nC_{18} for the Or-1g sample.

The isoprenoid content was compared to *n*-alkanes using the Pr/nC_{17} and Ph/nC_{18} ratios, which were determined to be 0.74 and 0.45, respectively (Table 3, Fig. 7). These ratios are primarily used to evaluate thermal maturity and biodegradation. Typically, the ratios decrease as thermal maturity increases, because the isoprenoids (Pr and Ph) degrade more rapidly than the corresponding *n*-alkanes (nC_{17} and nC_{18}) due to their lower thermal stability. Conversely, the ratios increase during biodegradation, as isoprenoids are more resistant to biodegradation (microbial attack) than *n*-alkanes (Peters et al., 2005). Since the sample exhibits a low CPI and a complete *n*-alkane distribution (indicative of high maturity and minimal biodegradation), the values of 0.74 and 0.45 are consistent with high thermal maturity rather than being significantly affected by biodegradation. Furthermore, these specific ratios support the previous interpretation of a mixed organic matter input (terrestrial and marine) into the source rock (Fig. 7).

Hopanes

Hopanes are derived from bacterial membrane precursors and are widely distributed in sediments and petroleum (Ourisson & Albrecht, 1992). They are more resistant to biodegradation than *n*-alkanes, isoprenoids and bicyclic sesquiterpanes (Niu et al., 2021). The *m/z* 191 mass chromatogram of the saturated hydrocarbon fractions clearly shows the presence of both tricyclic terpanes and hopanes (Fig. 8), with hopanes present in a high proportion relative to the tricyclic terpanes. In sample Or-1g, hopanes range from C_{27} to C_{35}, excluding C_{28}, with C_{30} αβ-hopane being the dominant homologue (Fig. 8). The high abun-

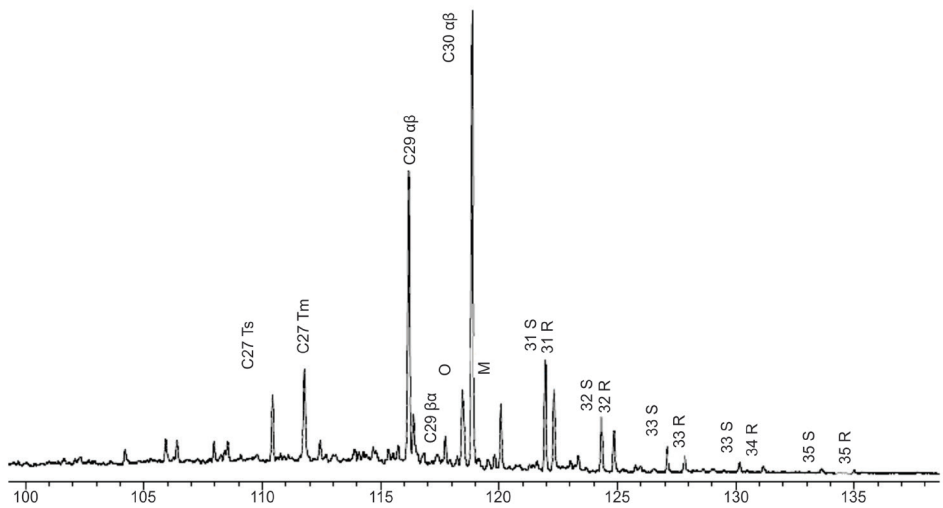

Fig. 8. Mass chromatogram of the hopanes (m/z = 191) of the Or-1g sample.

dance of C_{30} αβ-hopane relative to C_{29} norhopane (17α(H)-trisnorhopane, Tm) suggests an origin from clastic source rocks. This interpretation is consistent with the lithology of the well, which comprises sandstones, marls, clayey marls, siltstones along with limestone breccias and lithotamnian limestones. The clastic source rock trend is further reflected in the homohopane distribution, which is dominated by C_{31} homohopane and decreases progressively towards C_{35} (Fig. 8). Such a declining homohopane pattern is common in clastic, freshwater environments under more oxidising conditions. In contrast, carbonate or evaporitic source rocks often exhibit elevated C_{35} αβ-hopane concentrations (Lukaye et al., 2017).

The thermal maturation of organic matter involves a series of complex reactions, including cracking, isomerisation, and aromatisation reactions, alongside the alkylation and dealkylation of aromatic rings (Stojanović et al., 2007). Hopanes and steranes are essential biomarkers most commonly used for maturity assessment (Peters & Moldowan, 1993). A key metric is the ratio between the thermodynamically stable 22S- and the less stable 22R- epimer of C_{31}–C_{35} homohopanes. This 22S/(22S+22R) ratio increases predictably with thermal exposure until it reaches equilibrium. The evaluation of these homohopane biomarker maturity parameters (Fig. 8; C_{31}–C_{35}) indicates that the Or-1 g sample is characterised by high thermal maturity, consistent with a high-end gas condensate.

Steranes

Regular steranes (C_{27}–C_{29}) are used to distinguish between different biogenic sources of organic matter (Volkman, 2003). As difunctionalised degradation products of sterols, which are essential membrane components of eukaryotic organisms (Grice & Eiserbeck, 2013), their relative abundance pattern is controlled by the contributing photosynthetic organisms. A dominance of C_{27} steranes is typically associated with marine organisms (algae, zooplankton). A dominance of C_{28} steranes is associated with yeast, fungi, algae, and plankton, while a dominance of C_{29} steranes is associated with higher plants (Volkman, 2003). Both sterane and diasterane biomarkers were identified in the Or-1g sample. The mass chromatograms at *m/z* 217 and *m/z* 218 reveal a uniform distribution pattern of regular steranes, confirming a mixed origin of the organic matter (Figs. 9 & 10). While steranes predominate over diasteranes, the relative abundance of diasteranes is noticeably elevated due to the high thermal maturity of the sample, as diasteranes are formed from steranes under thermal stress. The high abundance of diasteranes is also characteristic of clastic depositional environments, further supporting the source rock lithology inferred from the hopane data. Additionally, a high degree of steranes isomerisation, serves as a further indicator of high thermal maturity (Fig. 9).

Gas condensates are highly mature hydrocarbons formed under extreme thermal conditions, where most complex biomarkers have been fully cracked. Consequently, hopane and sterane biomarkers are typically absent in these fluids, as they exhibit lower thermal stability than simpler hydrocarbons. These biomarkers are, therefore, more commonly associated with less thermally altered crude oils.

The Or-1g sample, however, contains both, hopanes and steranes (Figs. 8–10). This evidence indicates that, despite its advanced thermal maturity (as indicated by CPI and isomerisation ratios), the oil has not reached the cracking stage required to destroy thesebiomarkers. Therefore, the preservation of these biomarker molecules, coupled with the API gravity value, strongly suggests that the

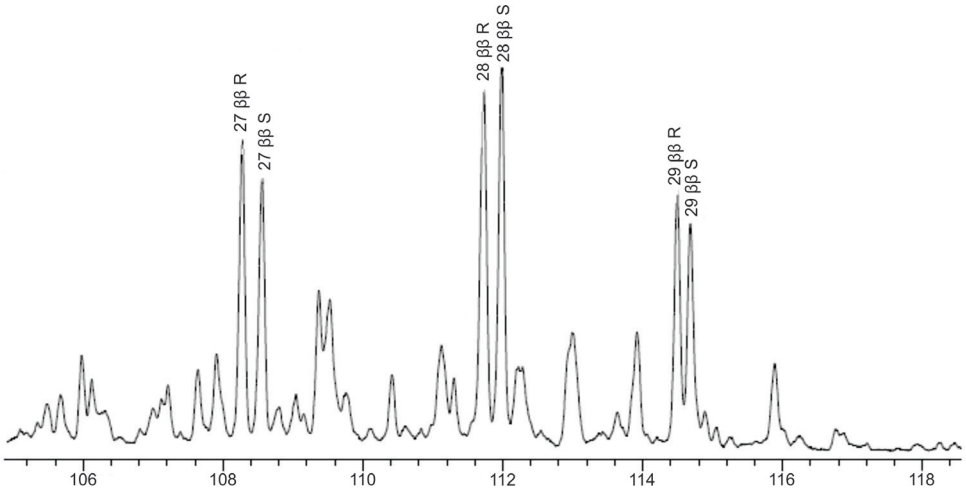

Fig. 9. Mass chromatogram of the steranes (m/z = 217) of the Or-1g sample.

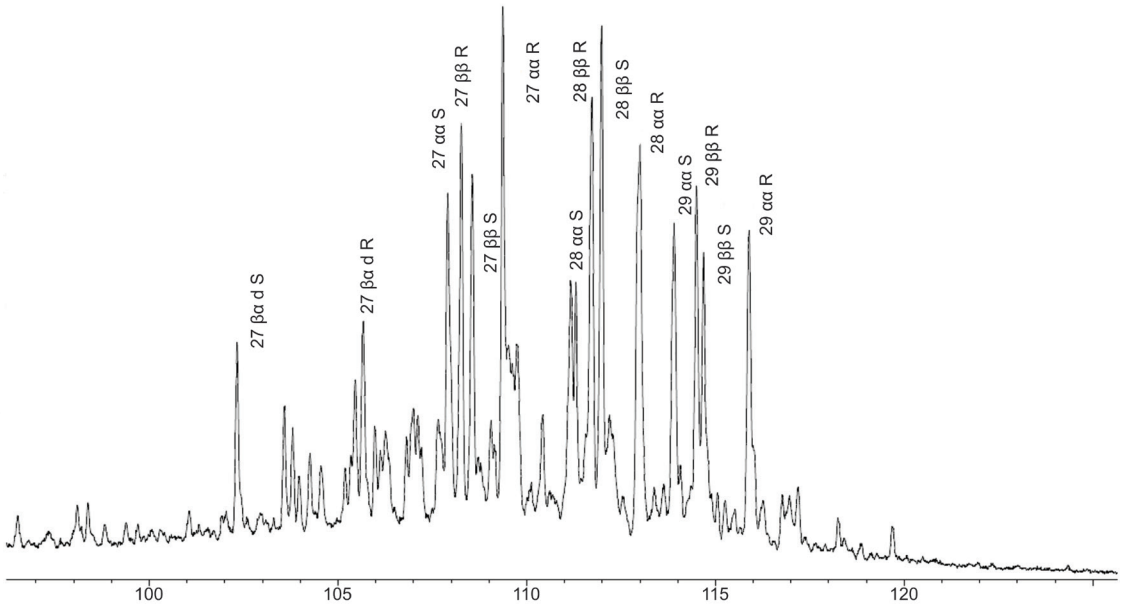

Fig. 10. Mass chromatogram of the steranes (m/z = 218) of the Or-1g sample.

analysed sample is more accurately classified as a light crude oil (or a highly mature, very light oil that has retained its biomarkers) rather than of a typical, fully cracked, gas condensate.

Biomarkers in the aromatic fraction

Aromatic hydrocarbons are important and widespread components of source rocks and crude oils. Their presence and distribution are primarily influenced by the type of organic precursor, depositional environment, and level of thermal maturity during diagenesis and catagenesis. Due to their distinct structural features, these compounds serve as valuable geochemical markers for interpreting the sedimentary environment, sources of organic matter, migration history, thermal maturity and the correlation between oils and their source rocks (Jinggui et al., 2005; Chang et al., 2011; Hakimi et al., 2023). Phenanthrene (P) and its alkylated derivatives, methylphenanthrenes (MPs), are among the predominant aromatic constituents used as molecular indicators in thermal maturity studies (Radke et al., 2000). Selected ion mass chromatograms of *m/z* 178 (Fig. 11) and *m/z* 192 (Fig. 12) show the distribution of phenanthrene and methylphenanthrene.

A comparison of these mass chromatograms reveals that the relative abundance of P is higher than that of MP. Pu et al. (1990) reported that freshwater source rocks typically contain a higher relative concentration of phenanthrenes than marine source rocks. This is inconsistent with the marine origin with terrestrial input inferred from previous parameters. However, this ambiguity is resolved by the findings of Jinggui et al. (2005), who concluded that both marine and freshwater organic matter can produce deposits with relatively high contents of phenanthrene derivatives, making the ratio alone unreliable for distinguishing between marine and freshwater deposits.

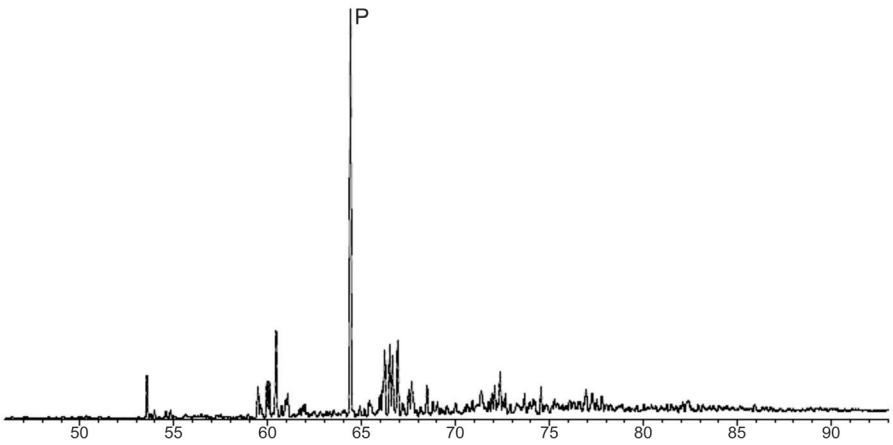

Fig. 11. Mass chromatogram of the phenanthrene (P) (m/z = 178) of the Or-1g sample.

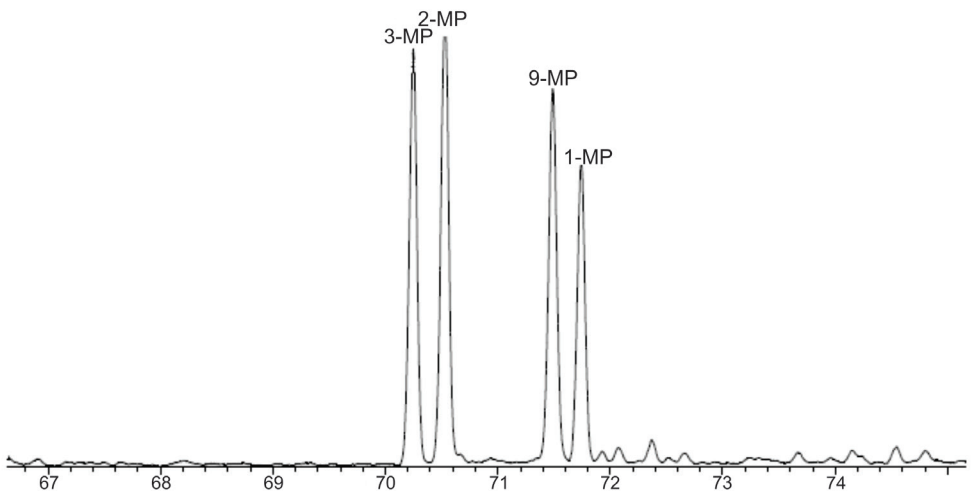

Fig. 12. Mass chromatogram of the methylphenanthrene (MP) (m/z = 192) of the Or-1g sample.

The distribution of alkylated phenanthrenes provides further insights into the type of organic matter and depositional conditions (Budzinski et al., 1995). A high abundance of 9-MP is typically associated with marine organic matter whereas elevated levels of 1-MP and 2-MP are linked to terrestrial plant input (Tupper & Burckhardt, 1990; Heppenheimer et al., 1992). Although the difference in relative abundances between 9-MP and 1-MP is not very significant (Fig. 12), the noticeable relative abundance of 2-MP and 1-MP (Fig. 12) supports the interpretation of a mixed organic matter origin with contributions from both marine and terrestrial sources.

The relative abundances of 9-MP and 1-MP are lower than those of 3-MP and 2-MP (Fig. 12). This is a consequence of thermal maturity, as the less stable isomers (1-MP and 9-MP) are converted into the more thermodynamically stable isomers (2-MP and 3-MP), under increasing thermal stress (He et al., 2019). This isomer shift provides further corroboration of the high thermal maturity previously indicated by the homohopane ratios and the low CPI value.

Conclusion

This preliminary geochemical study of the Or-1g sample from the Mura-Zala Basin provides valuable insights into the origin, depositional environment, and thermal maturity of the source rock organic matter. These findings establish a foundation for understanding hydrocarbon generation and offer basic guidelines for further oil and gas exploration in northeastern Slovenia. Both bulk and molecular (biomarker and non-biomarker) parameters were analysed with the principal findings as follows:

i. Bulk geochemical properties indicate that the Or-1g sample, with an API gravity of 42.53°, is classified as light crude oil. Its low sulphur content categorises it as a sweet crude oil, enhancing its commercial value.
ii. The pristane/phytane ratio (Pr/Ph = 1.83) indicates suboxic depositional conditions, characteristic of marine settings with significant terrestrial organic matter input. This terrestrial organic matter is further supported by the predominance of higher-molecular-weight *n*-alkanes, which exhibit a unimodal distribution pattern from nC_{11} to nC_{35}, peaking at nC_{25}.
iii. A relatively uniform sterane distribution points towards a mixed origin of the organic matter. This conclusion is further supported by the isoprenoid/*n*-alkane ratios and the Pr/n-C_{17} vs. Ph/n-C_{18} cross-plot, both suggesting significant marine and terrestrial contributions typical of transitional depositional environments. The negligible difference in the relative abundance of 9-MP and 1-MP further supports this conclusion.
iv. The uniform distribution of *n*-alkanes, a carbon preference index (CPI) close to 1 (CPI = 1.18) and a high degree of sterane isomerisation collectively indicate high thermal maturity. This is further supported by homohopane biomarkers and methylphenanthrene isomers distributions, particularly the lower abundance of 1-MP and 9-MP relative to 2-MP and 3-MP. These indicators suggest that the sample's generation conditions approach those of a gas condensate, despite its bulk classification as light crude oil.
v. Despite the high thermal maturity, the abundant presence of hopanes and steranes in the saturated fraction clearly confirms a light crude oil signature. Considering the overall biomarker composition, API gravity and low sulphur content, the sample exhibits characteristics consistent with light crude oil rather than a gas condensate.

Data Availability Statement

The research data for this article are available at http://hdl.handle.net/20.500.12556/DiRROS-28553 (Malenšek Andolšek et al., 2026)

Acknowledgment

The authors gratefully acknowledge the financial support of the Slovenian Research and Innovation Agency through Research Core Funding No. P1-0025 "Mineral Resources". The well was opened and the collected as a part of the INRIGeoTeam project, which is co-funded by the Slovenian Research and Innovation Agency within the framework of Development Funding Pillar (DFP).

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