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Organic geochemical assessment of black shales: case study of Oued Soura, Tamtret region, Algeria

Abdelghani Kadou[a], *Boudjema* Rebhi[b]

[a] University Tahri Mohammed,
Laboratory of Chemistry and Environmental Science, Béchar, Algeria;
e-mail: kadouabdelghani@gmail.com,
ORCID iD: https://orcid.org/0009-0004-8053-4455

[b] University Tahri Mohammed,
Laboratory of Chemistry and Environmental Science, Béchar, Algeria;
e-mail: rebhibouj@gmail.com,
ORCID iD: https://orcid.org/0009-0002-6793-1603

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Abstract:

Introduction/purpose: Black shales are increasingly recognized as significant unconventional hydrocarbon sources due to their organic richness and potential for oil and gas generation. However, their complex geochemical nature, especially in underexplored regions such as Tamtert in southwestern Algeria, poses challenges to accurate evaluation. This study aims to assess the hydrocarbon potential of black shales from the Djebel-Zereg area using advanced organic geochemical methods.

Methods: Five black shale samples were collected from Djebel-Zereg, Tamtert region. Total Organic Carbon (TOC) content was determined, and Rock-Eval 6 pyrolysis and elemental analysis were conducted. Parameters measured included TOC, S1, S2, Tmax, Hydrogen Index (HI), Oxygen Index (OI), and vitrinite reflectance (Ro), providing data on organic matter type, thermal maturity, and hydrocarbon generative capacity.

Results: TOC values ranged from 0.51 to 2 wt.% with an average of 1.33 wt.%, indicating acceptable to very good source rock quality. S2 values ranged from 0.45 to 4 mg HC/g rock, and the average Production Index (PI) was 2.23. HI values (51–233 mg HC/g TOC), along with OI and Tmax, indicated the presence of type II and III kerogen, suggesting

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potential for both oil and gas generation. Tmax values (435–465°C, average 447°C) and vitrinite reflectance (0.68%–1.19%) confirmed thermal maturity. A positive correlation between TOC and S1 values supported the presence of indigenous hydrocarbons.

Conclusion: The integrated geochemical approach confirms that the Djebel-Zereg black shales are thermally mature, organic-rich rocks with promising oil shale potential. These findings support further exploration and development of unconventional hydrocarbon resources in the Tamtert region.

Keywords: Black shale, Djebel-Zereg, elemental analysis, hydrocarbon potential, organic matter, Rock-Eval pyrolysis, source rock evaluation, total organic carbon.

Introduction

The growing demand for energy has made unconventional hydrocarbon resources, particularly black shale, a key focus of exploration efforts (Feng et al., 2024; Qin et al., 2022). These formations, rich in organic matter have the potential to generate significant amounts of oil and gas through thermal and biological processes (Zhao et al., 2022). However, assessing the hydrocarbon potential of black shale requires accurate and effective geochemical methods to evaluate organic richness, thermal maturity, and generative capacity (Carvajal-Ortiz & Gentzis, 2015; Liu et al., 2022). Traditional methods for evaluating black shale typically involve geochemical tools such as kerogen analysis, bitumen extraction, and Ro measurement. These methods have been used for decades to estimate the organic content and thermal maturity of shales (Hackley & Cardott, 2016). However, they often fall short in providing a complete picture of the shale's potential, particularly in terms of spatial heterogeneity and the complexity of organic matter composition. For instance, bitumen extraction may not fully account for the variation in organic matter types within a shale formation, while vitrinite reflectance primarily estimates maturity but does not provide in-depth insights into the generation capacity of the shale (Hackley et al., 2021).

In this context, we intend to review some recent related work in an attempt to more clearly identify research gaps, thereby setting the stage to highlight and justify the contributions of this study. Furthermore, by situating our analysis within both the specific geographical distinctions of Tamtert and the broader methodological landscape, we aim to demonstrate how this work not only addresses unresolved challenges but also offers a novel perspective that enhances the current body of knowledge. This dual emphasis on regional specificity and methodological innovation reinforces the relevance and necessity of our approach. For instance, in (Akintola, 2023), authors proposed a systematic evaluation of unconventional shale gas reservoirs in Permian Bini River Formation of Gongola Sub-basin, Northern Benue Trough, Northeastern Nigeria, focusing on shale lithologies as the primary material of interest. They employed a combination of petrographic, mineralogical (X-ray diffraction), and geomechanical (i.e., uniaxial compressive strength and Schmidt rebound hardness tests) methods to characterize the shale's mineral composition, textural features, and mechanical properties. The study's main advantages lie in its detailed site-specific analysis, which provides foundational insights into the mechanical suitability and frackability of the shales for unconventional resource development, particularly in a relatively underexplored region. However, the study's limitations arise from its exclusion of more comprehensive geochemical assessments that would provide a fuller understanding of the shale's hydrocarbon generation potential, thermal history, and elemental distribution, parameters that are critical for more robust reservoir characterization and resource estimation. The authors in (Chabalala et al., 2023), evaluated the thermal maturity of black shale samples from the Karoo Basin in South Africa using traditional petrographic techniques and Raman spectroscopy. The materials studied include shale samples from Ripon, Whitehill, Collingham, and Prince Albert Formations of the Karoo Supergroup, as well as comparative samples from the Berea Sandstone project in the USA. The methods employed were organic petrology, including Ro and maceral analysis, programmed pyrolysis, and Raman spectroscopy. A key advantage of this study is its integration of Raman parameters with vitrinite reflectance to offer a more detailed understanding of molecular transformations in overmature shales, thereby enhancing thermal maturity assessments. However, the study's limitation lies in its lack of broader geochemical profiling techniques that could provide a more holistic view of the shale's hydrocarbon generative capacity, organic content variability, and elemental composition, which are factors essential for comprehensive resource evaluation. In (Zhang et al., 2024), authors investigated the geochemical properties and gas-bearing characteristics of lower Cambrian black shales, specifically from the Niutitang, Wunitang, and Liuchapo Formations, in Western Hunan Province, China. Utilizing core samples from the

XAD1 exploratory well, they employed a combination of geochemical techniques including TOC analysis, Rock-Eval pyrolysis, bitumen reflectance, Soxhlet extraction, and GC-MS, complemented by Grand Canonical Monte Carlo (GCMC) molecular dynamics simulations to model methane adsorption under varying geological conditions. A key strength of the study is its integration of burial history reconstruction with advanced adsorption simulations, which allowed for a dynamic understanding of how tectonic events and changes in temperature and pressure influenced shale gas enrichment and loss over geological time. However, the work is limited by its relatively narrow analytical focus, as it omits a broader set of geochemical tools that could offer more comprehensive insights into the shale's organic richness, maturity evolution, and elemental composition, factors that are critical for a fuller evaluation of shale gas potential. In (Gao et al., 2024), the authors developed a comprehensive analysis of the geochemical characteristics and shale oil occurrence in Qingshankou Formation, Gulong Sag, Songliao Basin, focusing on mature to high-maturity shale resources. The materials discussed include shale samples from Qingshankou Formation, analyzed for TOC, Rock-Eval pyrolysis parameters, Ro, kerogen elemental composition, chloroform asphalt A, and Gas Chromatography (GC) to evaluate organic matter abundance, type, and maturity. The methods employed involve Rock-Eval pyrolysis, TOC determination, Ro measurements, kerogen carbon isotope analysis, and biomarker studies to assess shale oil occurrence and sweet spot evaluation. The advantages of this study lie in its systematic approach to correcting light-hydrocarbon loss and heavy hydrocarbons, providing a more accurate representation of in-situ retained hydrocarbons, and establishing geochemical criteria for sweet spot identification. However, limitations include the reliance on specific analytical techniques that may not fully capture the heterogeneity of organic matter or the broader geochemical context, potentially overlooking variations in thermal maturity and elemental composition that could further refine the evaluation of shale oil potential. In (Shi et al., 2024), the authors investigated the sedimentary paleoenvironment and organic matter enrichment mechanisms in Ying 4 Member of southern Shuangcheng area, Songliao Basin, focusing on black laminated and massive mudstone samples. The materials discussed include source rocks characterized by TOC content, kerogen types, and trace elements such as Sr, Cu, Ba, V, Ni, and P, which were used to infer paleoclimate, paleosalinity, redox conditions, and paleoproductivity. The methods employed encompassed organic carbon content measurement, kerogen microscopic examination, Rock-Eval pyrolysis, Ro analysis, and major/trace element geochemistry to reconstruct the sedimentary environment and identify controlling factors of organic matter enrichment. The advantages of this study lie in its integrated approach, combining multiple geochemical proxies to establish a productivity model for organic matter enrichment, highlighting the role of warm, humid paleoclimate and volcanic activity in enhancing lake productivity. However, limitations include the reliance on specific elemental ratios and localized sampling, which may not fully capture the broader geochemical variability or the interplay of additional factors such as sedimentation rates or diagenetic alterations that could further refine the understanding of organic matter preservation and distribution.

Table 1 in this case summarizes the key aspects of each study, highlighting their materials, methods, advantages, and limitations while maintaining a focus on geochemical gaps.

Table 1 – Comparative analysis of shale reservoir studies: materials, analytical methods, strengths, and research gaps

Ref.	Year	Materials	Methods	Advantages	Limitations (Gaps)
(Akintola, 2023)	2022	Shale lithologies from Permian Bini River Formation, Gongola Sub-basin, Nigeria	Petrographic, mineralogical (XRD), geomechanical (uniaxial compressive strength, Schmidt rebound hardness)	Detailed site-specific analysis; foundational insights into mechanical suitability and frackability	Lacks comprehensive geochemical assessments (hydrocarbon potential, thermal history, elemental distribution)
(Chabalala et al., 2023)	2023	Black shale samples from Karoo Basin (Ripon, Whitehill, Collingham, Prince Albert Formations), Berea Sandstone (USA)	Organic petrology (vitrinite reflectance, maceral analysis), programmed pyrolysis, Raman spectroscopy	Integration of Raman with vitrinite reflectance for molecular-level thermal maturity assessment	Limited broader geochemical profiling (hydrocarbon generation, organic content variability, elemental composition)
(Zhang et al., 2024)	2024	Lower Cambrian black shales (Niutitang, Wunitang, Liuchapo Formations), XAD1 well, Western Hunan, China	TOC, Rock-Eval pyrolysis, bitumen reflectance, Soxhlet extraction, GC-MS, GCMC molecular dynamics simulations	Burial history + adsorption modeling for dynamic gas enrichment insights	Narrow analytical focus; lacks broader geochemical tools (organic richness, maturity evolution, elemental composition)
(Gao et al., 2024)	2024	Shale samples from Qingshankou Formation, Gulong Sag, Songliao Basin	Rock-Eval pyrolysis, TOC, vitrinite reflectance, kerogen isotopes, chloroform asphalt "A," biomarker studies	Corrects light-hydrocarbon loss; establishes sweet spot criteria	Overlooks broader geochemical context (thermal maturity, elemental composition heterogeneity)
(Shi et al., 2024)	2024	Black laminated/massive mudstone (Ying 4 Member), southern Shuangcheng area, Songliao Basin	TOC, kerogen microscopy, Rock-Eval, Ro, major/trace element geochemistry	Integrated proxies for productivity model; links paleoclimate/volcanism to enrichment	Relies on localized sampling/elemental ratios; misses sedimentation/diagenetic factors

To address these gaps, this work employs a refined geochemical toolkit, including TOC analysis, Rock-Eval pyrolysis, and elemental analysis, to deliver a more comprehensive and quantitative assessment of the black shale's hydrocarbon potential. These methods were selected because:

- TOC analysis provides direct measurement of organic richness, a metric often underreported in studies relying solely on Ro or petrography (Chabalala et al., 2023; Shi et al., 2024).
- Rock-Eval pyrolysis quantifies both hydrocarbon yield (S1, S2) and thermal maturity (T_{max}), addressing limitations in studies like (Gao et al., 2024) that lacked correction for light-hydrocarbon loss.
- Elemental analysis (e.g., Sr/Cu, V/Ni) deciphers paleoenvironmental controls on organic matter enrichment, a factor overlooked in localized studies (Shi et al., 2024).

This research targets the Djebel-Zereg region in southwestern Algeria, a previously unexplored basin within Wadi Saoura area (coordinates: X1 = 1° 49' 30", Y1 = 29° 54' 30"). As the first organic geochemical study in this region, it aims to:

- Assess energy production capacity by correlating TOC and Rock-Eval data with generative potential (cf. (Gao et al., 2024)).
- Delineate thermal maturity using pyrolysis and Ro, bridging gaps in overmature shale analyses (Chabalala et al., 2023).
- Evaluate paleoenvironmental influences (redox, productivity) via elemental ratios, expanding on models in (Shi et al., 2024).

Following such a methodological approach, the study attempts to fill regional knowledge gaps and also advances methodological rigor beyond prior works (Table 1), offering a template for understudied shale basins. The findings will directly inform sustainable hydrocarbon exploitation strategies in Algeria's Beni Abbas Basin.

The remainder of this paper is organized as follows: Section 2 outlines the materials and methods used, including the geological setting of the study area, the sampling process, and the geochemical analysis techniques applied, such as TOC, elemental analysis, and Rock-Eval pyrolysis. Section 3 presents the results and discussion, focusing on organic matter richness, quality, and thermal maturation, with insights into the hydrocarbon potential of the Djebel-Zereg black shale. Finally, Section 4 provides the conclusion, summarizing the findings and suggesting areas for further research.

Materials and methods

This section outlines the geological context of the study area and details the materials and analytical methods used to investigate the geochemical characteristics of the sampled black shales. The analyzed samples were collected from the upper Devonian 'Argiles de Marhouma' Formation, exposed in Djebel Zereg area near Tamtert in the Saoura Valley, southwestern Algeria. Understanding the stratigraphy and sedimentology of this formation is essential for interpreting the organic geochemistry and thermal maturity of its shales. This multidisciplinary approach combines field observations with laboratory analyses, including TOC, elemental composition, and Rock-Eval pyrolysis, to comprehensively characterize the depositional environment and hydrocarbon potential of the formation.

Geological setting

The Saoura Valley in southwestern Algeria extends from the Ouarourout region in the north to the Idhir area in the south. Bounded by the Hercynian Ougarta Mountains to the west and the expansive Great Western Erg to the east, the valley features well-exposed upper Devonian outcrops. Within this framework, the 'Argiles de Marhouma' Formation forms the principal unit of interest, lying stratigraphically below the 'Grès de Ouarourout' Formation. The Tamtert region, located centrally within the valley, provides excellent exposures of these formations, enabling detailed field observations and sampling, as shown in Figure 1 (Malti, 2012).

The 'Argiles de Marhouma' Formation has been subdivided into four lithologically and paleontologically distinct members, as depicted in the stratigraphic column of Figure 2 (adapted from (Malti, 2012)). These members reflect variable sedimentary environments and depositional dynamics over time. The lowermost member, cropping out exclusively in Gara Diba area, is composed of laminated limestones within a calcareous clay matrix. These fossiliferous limestones, which contain *Manticoceras* sp., mark the member as belonging to Frasnian I γ interval. Its restricted lateral distribution suggests localized depositional settings, potentially controlled by paleotopography or sediment supply limitations.

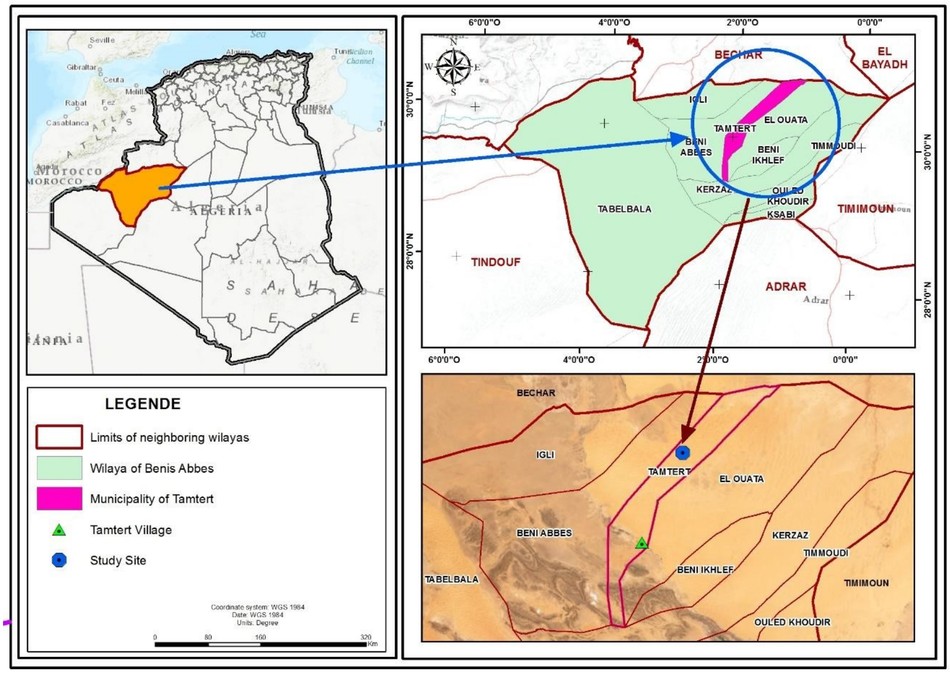

Figure 1 – Geographical location of the Tamtert region (Malti, 2012)

Above this lies a more heterogeneous unit composed predominantly of red clays with silty and calcareous intercalations. This member is subdivided into two segments. The first features thick, schistified red clays interbedded with thin flakes of silty sandstone, topped by a reddish micritic limestone. Beneath this lies a clay-rich interval punctuated by sporadic nodular limestone layers, including a prominent, weathered, nodular bed indicative of periodic carbonate deposition under oxidizing conditions. The second segment is composed primarily of clay enriched with hematitic 'griotte' limestone levels and capped by thin blue-gray limestone beds, the uppermost containing abundant fossil remains such as crinoid stems and bivalves. These lithological features point to changing sedimentation rates and intermittent oxygenation during deposition.

The third member is dominated by thick-bedded 'griotte' limestones alternating with greenish clays. Its base consists of slumped, dark clays with silty concretions, transitioning into distinctive limestone beds with spherical, ball-like structures similar to those of overlying Ouarourout Formation. The recurrence of these alternating lithologies, some with meter-scale thickness, suggests periodic carbonate sedimentation, possibly influenced by sea-level fluctuations or regional climatic changes. The lithological diversity and slumping structures reflect a dynamic and unstable depositional setting.

The uppermost member, from which the samples for this study were taken, shows the greatest lithological variation. It consists of red and green clays with interspersed silty beds and discrete nodular levels of 'griotte' limestone. The lower portion includes red clays forming a trough-like structure interbedded with dark, organic-rich layers and small silty nodules. Higher up, the succession reaches a thickness of approximately 62 meters, comprising alternating greenish clays, silty terracotta horizons, and ferruginous nodular levels, likely recording redox fluctuations during deposition. The uppermost segment is a deeper clay-dominated trough with abundant greenish silts and scattered 'griotte' limestone nodules. These dark clays, rich in organic matter, were the target of geochemical sampling and analysis.

Together, the four members of the 'Argiles de Marhouma' Formation provide a record of shifting depositional environments in Saoura Basin during the late Devonian, capturing both marine incursions and periods of continental influence, as detailed in Figure 2.

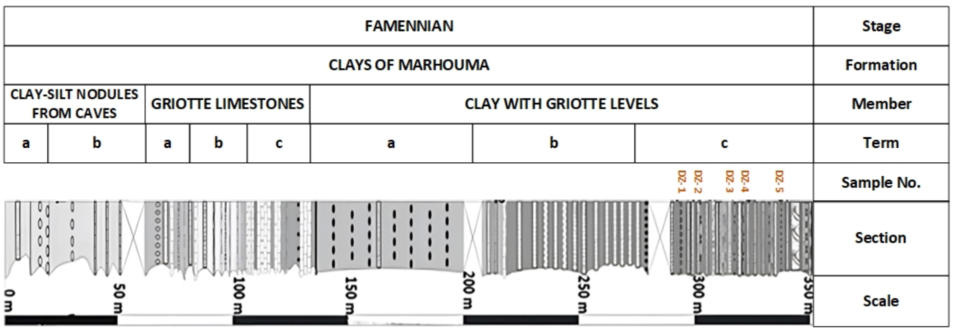

Figure 2 – Modified lithostratigraphic columnar section of 'Argiles de Marhouma' Formation in Saoura Valley (Tamtert-Zereg). Reproduced from (Malti, 2012)

Samples and methods

The methods used in this study are primarily geochemical techniques that provide insights into the organic content, hydrocarbon potential, and thermal maturity of shale samples. These methods rely on quantitative measurements and data interpretation, involving both chemical and mathematical processes to extract meaningful geochemical information.

Elemental analysis

To better understand the geochemical characteristics and organic matter quality of the collected shale samples, elemental analysis was conducted as a foundational component of this study. This procedure enables a precise assessment of major elemental constituents, which is essential for interpreting the depositional environment and diagenetic evolution of organic-rich rocks.

Each shale sample was first ground to a fine powder (<80 μm) to ensure homogeneity and improve reaction efficiency during subsequent treatments. Bitumen extraction was then performed over a 60-hour period using a solvent mixture of 93% dichloromethane (DCM) and 7% methanol (MeOH). This step was critical for removing free hydrocarbons, thereby isolating the mineral matrix and kerogen-bound organic matter for more accurate elemental characterization. Following extraction, residual material was subjected to acid demineralization using 6N hydrochloric acid (HCl) and a 1:1 hydrofluoric acid (HF:HCl) mixture. This treatment dissolved carbonate and silicate phases, respectively, leaving behind the acid-insoluble organic fraction. Special care was taken during this step to minimize loss of organic material while ensuring complete removal of mineral content that could skew the elemental analysis.

Elemental composition was determined using a Thermo Finnigan EA1112 Flash Analyzer. Approximately 1 mg of the demineralized sample was encapsulated in a tin capsule and combusted in an oxygen-rich environment. The resulting gases (i.e., carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), and sulfur dioxide (SO_2)) were separated and quantified using a scatterometer detector system. The concentrations of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) were calculated from signal intensities, with calibration performed against certified reference standards to ensure analytical precision and accuracy.

Although the method is primarily chemical in nature, it incorporates quantitative analytical techniques to determine elemental concentrations. These values are fundamental in assessing the kerogen type, thermal maturity, and redox conditions of deposition, offering valuable insights into both the paleoenvironment and hydrocarbon potential of the shale units studied.

Total organic carbon

In evaluating the hydrocarbon potential of sedimentary rocks, TOC content serves as a primary indicator of organic matter richness and preservation. As such, TOC analysis was carried out to complement elemental data and provide a more comprehensive understanding of organic geochemistry of the shale samples. Prior to TOC measurement, the finely powdered samples were subjected to acid treatment to eliminate any inorganic carbon (primarily carbonates) that could interfere with the analysis. This was achieved by using a diluted hydrochloric acid solution ($HCl:H_2O$ = 1:4), applied until effervescence ceased, indicating the complete removal of carbonate phases. The samples were then thoroughly rinsed with deionized water and dried to ensure accurate TOC determination without dilution or contamination.

The remaining material, containing only organic carbon, was analyzed using a LECO carbon analyzer that is a combustion-based system capable of high-precision carbon quantification. During the analysis, samples were oxidized at high temperatures in an oxygen-rich environment, and the evolved CO_2 was measured using an infrared detection system. The resulting signal was calibrated against known standards, ensuring the reliability and repeatability of the TOC values obtained. Although the overall procedure is relatively straightforward, TOC analysis is a critical quantitative technique in organic geochemistry. It reflects the abundance of preserved organic matter and provides input for the calculation of important indices, such as the HI and OI, when integrated with pyrolysis data. These parameters collectively inform interpretations of source rock quality, depositional conditions, and the potential for hydrocarbon generation.

Rock-Eval Pyrolysis

Rock-Eval pyrolysis is a well-established analytical technique used to evaluate the quantity, type, and thermal maturity of organic matter in sedimentary rocks. In this study, the method was employed to derive several geochemical parameters that are essential for classifying kerogen, assessing hydrocarbon-generating potential, and reconstructing depositional environments. Prior to analysis, the powdered and decarbonated samples were placed in a programmed pyrolysis chamber and gradually heated under an inert nitrogen atmosphere. This stepwise heating induces the thermal decomposition of organic constituents, allowing the quantification of various hydrocarbon fractions and associated gases.

The following primary outputs were obtained:

- S1: Represents the quantity of free hydrocarbons (in mg HC/g rock) that volatilize at low temperatures without cracking.
- S2: Measures hydrocarbons generated from the thermal breakdown of kerogen during progressive heating.
- Tmax: The temperature at which S2 peak occurs; used as a proxy for the thermal maturity of the organic matter.
- S3: Reflects the amount of CO_2 released during pyrolysis, related to oxygenated functional groups in the kerogen.

From these measurements, several critical geochemical indices were calculated:

- PI = S1 / (S1 + S2), indicating the extent of hydrocarbon generation.
- HI = (S2 / TOC) $\times$ 100, providing insight into the type and quality of organic matter.
- OI = (S3 / TOC) $\times$ 100, reflecting the relative oxygen content and depositional redox conditions.

These indices are instrumental in characterizing kerogen types (I, II, III, IV), assessing thermal evolution, and distinguishing between oil- and gas-prone source rocks. For instance, higher HI values typically indicate oil-generative potential, while OI can be used to infer the oxidative conditions under which the organic matter was deposited. The Rock-Eval procedure followed standard protocols as outlined in established methodologies (Espitalie et al., 1977; Peters & Cassa, 1994), ensuring consistency and comparability with previous studies. The analysis combines direct thermal measurements with mathematical interpretation, providing a multidimensional view of organic matter characteristics. The results, summarized in Table 2, form a cornerstone of the organic geochemical framework used in this study and serve as a basis for further interpretation of petroleum potential, thermal maturity trends, and paleoenvironmental reconstructions.

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Table 2 – Results of TOC, Ro, and Pyrolysis data (Rock-Eval 6) analyses for Djebel-Zereg samples

Sample No	S1 (mg/g)	S2 (mg/g)	GP	S3 (mg/g)	TOC Wt.%	HI (mg/g)	OI (mg/g)	Tmax (°C)	R0	PI	C (wt%)	H (wt%)	H/C
1	0.57	0.62	1.19	0.56	0.51	125	114	455	1.03	0.68	20.12	0.59	0.35
2	0.05	0.45	0.50	0.02	0.92	51	22	445	0.85	0.10	35.52	2.04	0.68
3	0.20	3.48	3.68	0.10	1.50	233	8	436	0.68	0.05	55.25	5.06	1.21
4	0.76	4.00	4.76	0.16	2.00	192	8	440	0.76	0.15	54.12	2.68	0.59
5	0.20	1.05	1.05	0.39	0.75	140	52	464	1.19	0.16	49.27	2.81	0.68

Results and Discussion

This section presents and interprets the geochemical data obtained from elemental analysis, TOC measurements, and Rock-Eval pyrolysis to assess the hydrocarbon potential of Djebel-Zereg shale samples. The analysis focuses on key parameters such as organic matter richness, quality, and thermal maturity, each of which plays a critical role in determining the generative capacity of source rocks. The integration of these results allows for a comprehensive evaluation of the samples' suitability as petroleum source rocks and provides insights into the paleoenvironmental and diagenetic history of the organic matter. The discussion is structured into subsections to address each aspect in detail.

Organic Matter Richness

The richness of organic matter in black shale plays a critical role in assessing the hydrocarbon-generating potential of source rocks. For clastic shale source rocks to be effective, TOC value should exceed 0.5 weight percent. In this study, TOC values ranged from 0.51% to 2%, with an average of 1.33% (Table 2). This suggests that samples contain a substantial amount of organic matter capable of hydrocarbon generation. According to the classification system proposed by (Peters & Cassa, 1994; Landais, 1997), these TOC values range from fair to excellent, indicating the presence of a potentially viable source. However, reliance solely on TOC values to assess the generative capacity of source rocks can be misleading, as TOC measures both hydrocarbon-generative organic matter and inert organic matter, leading to an imprecise evaluation of rock potential (McCarthy et al., 2011).

To further evaluate the hydrocarbon potential, generative potential (GP), calculated as the sum of S1 (free hydrocarbons) and S2 (hydrocarbons generated from kerogen cracking), was assessed. GP values ranged from 0.50 to 4.76 mg/g (average 2.23 mg/g) (Table 2). According to (Tissot &

Welte, 1984), rocks with a GP of less than 2 mg/g are typically gas-prone or non-generative, whereas rocks with a GP between 2 and 6 mg/g exhibit moderate source rock potential, suggesting reasonable gas/oil generation. Samples with a GP greater than 6 mg/g are considered good source rocks. Based on these GP values and the HI versus TOC plot (Figure 3), samples 3 and 4 exhibit fair genetic potential with acceptable gas/oil presence, while the remaining samples are categorized as gas-producing rocks.

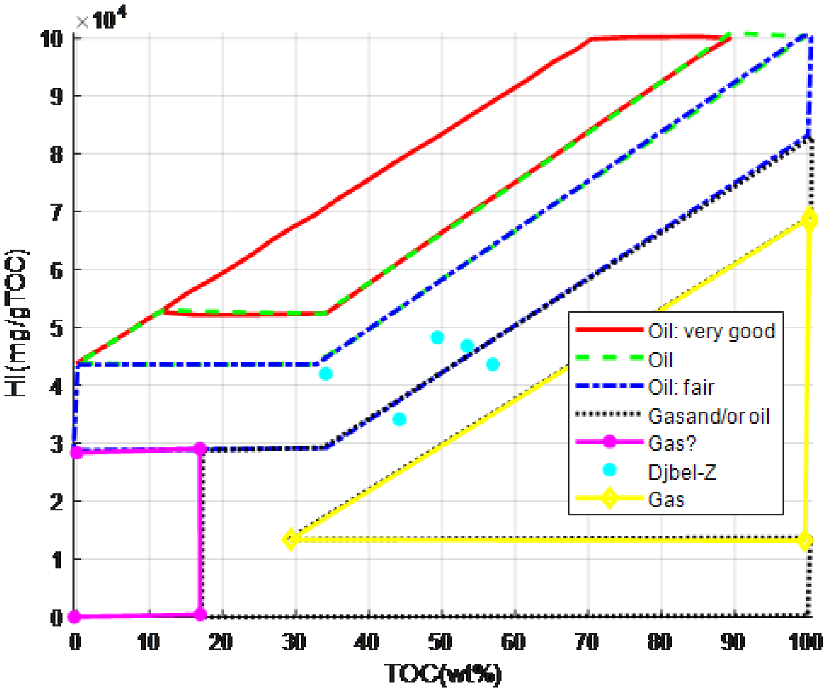

Figure 3 – Cross plot of HI versus TOC for Djebel-Zereg samples. Reproduced from (Sohail et al., 2024)

The migration index (S1/TOC) was calculated to distinguish migrating hydrocarbons from indigenous hydrocarbons. A high TOC with low S1 values suggests the presence of indigenous hydrocarbons (Landais, 1997). The S1 versus TOC plot (Figure 4) further confirms that the studied samples contain indigenous organic matter.

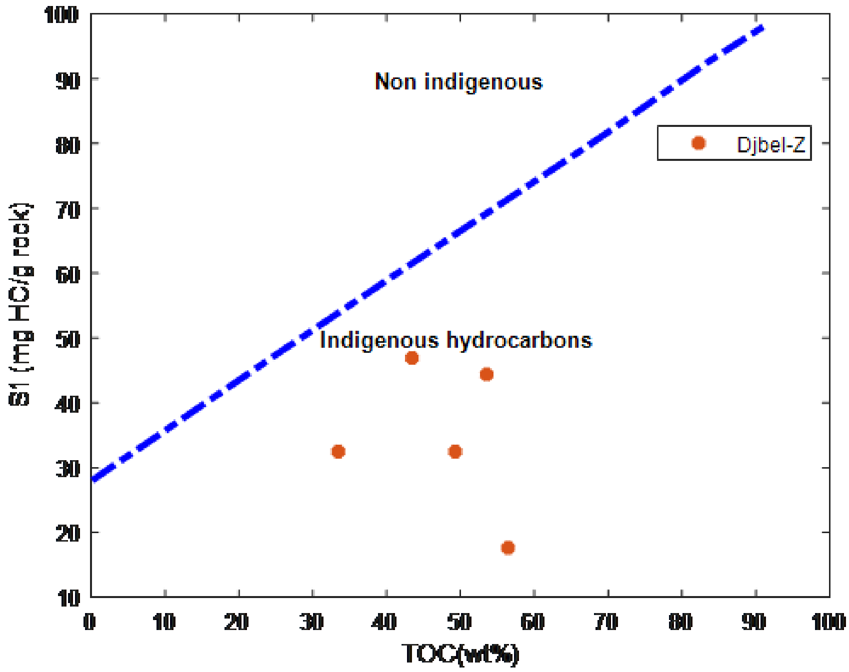

Figure 4 – Cross plot of S1 versus TOC for Djebel-Zereg samples. Reproduced from (Edress et al., 2022)

Organic Matter Quality

The hydrocarbon potential of source rocks depends on the richness of organic matter and on the type of organic materials present. The classification of organic matter is typically informed by HI and OI values. Organic materials with HI values below 150 mg/g correspond to type III organic matter, which is primarily gas-generative. HI values ranging from 150 to 300 mg/g suggest a mixture of type II and type III organic matter, indicating a significant gas generation capability with a minor oil component. HI values exceeding 300 mg/g indicate type II organic matter, which is particularly efficient in generating oil with lesser amounts of gas, while values exceeding 600 mg/g are typically associated with type I or II organic matter, both of which are potent oil producers (Waples, 1985).

In this study, HI values ranged from 50 to 233 mg/g, and OI values varied from 8 to 114 mg/g. These measurements suggest that the majority

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of black shale samples are predominantly composed of type III and type II organic materials, indicating a preference for gas generation, with only trace amounts of oil. This finding is further supported by the HI vs. OI plot (Figure 5), which shows that the samples are predominantly composed of a mixture of type III and type II organic materials.

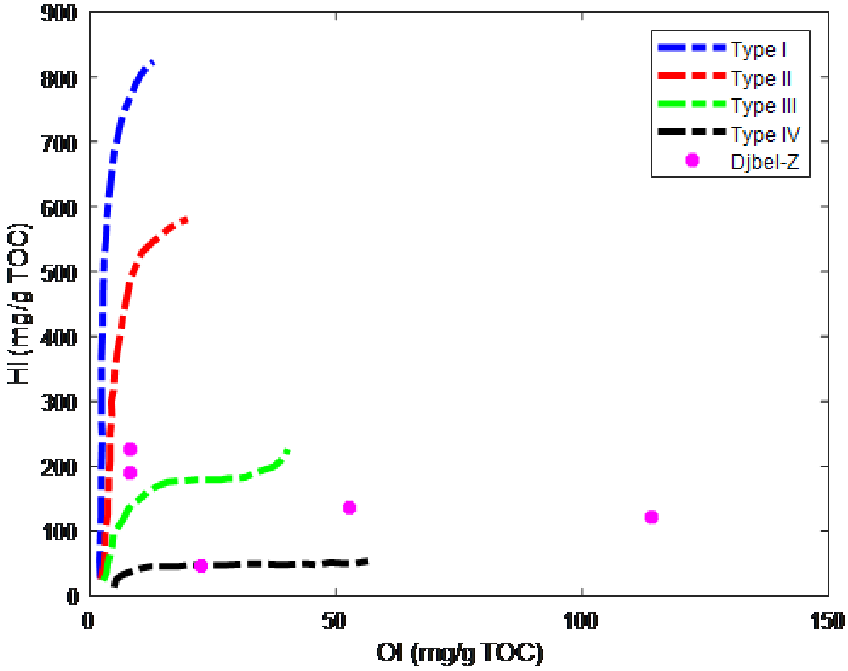

Figure 5 – Cross plot of HI versus OI for Djebel-Zereg samples. Reproduced from (Akinwumiju & Satterfield, 2024)

To refine the classification of organic materials present, H/C atomic ratio was also considered. The H/C ratio is a key factor in determining the quality of organic matter and, consequently, the hydrocarbon potential of source rocks. Organic matter is categorized into three types based on the H/C atomic ratio: type I and II organic matter with H/C ratios $\geq$1.5, type II organic matter with ratios between 1.2 and 1.5, and type III organic matter with ratios typically below 1.0. The H/C ratios in this study ranged from 0.35 to 1.21, with an average of 0.70, suggesting that the samples contain both type III and type II organic materials. This further corroborates the potential for gas generation with minimal oil production.

3.3. Thermal Maturation Stage

Thermal maturity is an essential factor in evaluating the hydrocarbon potential of source rocks. It provides insight into the extent to which organic matter has been converted into hydrocarbons due to heat-driven processes (Peters & Cassa, 1994). The degree of thermal maturity can be evaluated using Tmax values obtained from Rock-Eval pyrolysis. In this study, Tmax values ranged from 436 to 464°C, with an average of 447°C, indicating that the organic matter in these samples has achieved early maturity. These values are typical for both oil and gas generation, as confirmed by the Tmax versus HI plot (Figure 6).

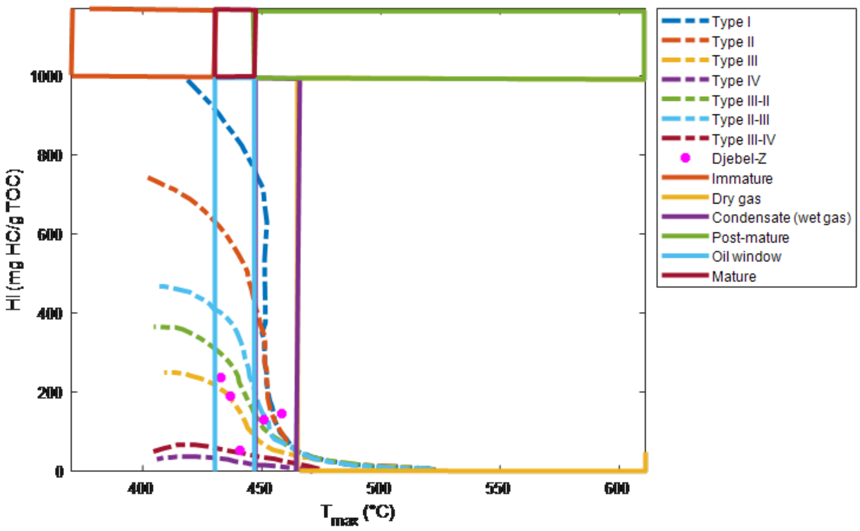

Figure 6 – Cross plot of (HI) versus (Tmax) for Djebel-Zereg samples. Reproduced from (Hong et al., 2021)

Vitrinite reflectance (Ro) is another key indicator of thermal maturity, particularly for organic matter types II and III. Ro is sensitive to the temperature and pressure conditions experienced by the organic material, making it a reliable gauge for assessing thermal maturity (**?**). The Tmax values from Rock-Eval pyrolysis were used to calculate Ro using the formula: Ro

= (0.018 × Tmax) - 7.16 (Dembicki, 2009). The Ro values for Djebel-Zereg samples ranged from 0.68 to 1.12, with an average of 0.90. These relatively high values indicate that the majority of the samples have reached the necessary maturity stage for hydrocarbon generation.

Conclusion

This research offers a comprehensive evaluation of the organic matter characteristics within Djebel-Zereg oil shale, providing valuable insights into its hydrocarbon generation potential. Based on a rigorous series of organic geochemical analyses, including Rock-Eval pyrolysis and elemental analysis, the study reveals several important findings. Djebel-Zereg black shale demonstrates an organic richness that ranges from acceptable to very good, with TOC contents between 0.51% and 2%, averaging 1.33%, and GP values ranging from 0.50 to 4.76 mg/g, with an average of 2.23 mg/g. These findings are consistent with established criteria for source rocks with significant hydrocarbon potential. Additionally, HI values, ranging from 51 to 233 mg/g, alongside OI and HI versus Tmax plots, confirm the presence of type II and III organic matter, indicating a strong potential for both gas and oil generation. Furthermore, the TOC and S1 values across all samples suggest that the hydrocarbons present in the Djebel-Zereg black shale are indigenous, free from external contamination or migration, which underscores the integrity of the source rock. The thermal maturity indicators, such as Tmax values (435–464 °C) and vitrinite reflectance (Ro) values (0.68%–1.19%), indicate that the shale has reached the necessary maturity for hydrocarbon production. These results position the Djebel-Zereg oil shale as a promising resource, characterized by its high TOC content, the presence of type II and III organic matter, and sufficient thermal maturity. While this study provides a solid initial assessment using a range of analytical techniques, further investigation is needed to broaden the sample set and include advanced methodologies such as gas chromatography, gas chromatography–mass spectrometry, carbon isotope analysis, and mineralogical studies through scanning electron microscopy, X-ray diffraction, and X-ray fluorescence. Such analyses will offer a deeper understanding of the geochemical and mineralogical properties of these black shales and their full potential as an unconventional energy resource.

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Organsko-geohemijska procena crnih škriljaca: Studija slučaja doline Saoura, region Tamtert, Alžir

Abdelghani Kadoua, **autor za prepisku**, *Boudjema* Rebhib

University Tahri Mohammed, Laboratory of Chemistry and Environmental Science,
Béchar, Algeria

OBLAST: hemijska tehnologija i materijali
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Crni škriljac se sve više prepoznaje kao značajni nekonvencionalni izvor ugljovodonika zbog svog bogatstva organskom materijom i potencijala za proizvodnju nafte i gasa. Međutim, njegova složena geohemijska priroda, posebno u nedovoljno istraženim regionima poput Tamerta u jugozapadnom Alžiru, predstavlja izazov za preciznu procenu. Cilj ovog istraživanja je procena potencijala crnih škriljaca iz oblasti Džebel-Zereg korišćenjem naprednih metoda organske geohemije.

Metode: Prikupljeno je pet uzoraka crnog škriljca iz Džebel-Zerega, region Tamert. Određen je sadržaj ukupnog organskog ugljenika (eng. TOC), a sprovedene su i Rock-Eval 6 piroliza i elementarna analiza. Mereni parametri uključivali su TOC, S1, S2, Tmax, Indeks vodonika (HI), Indeks kiseonika (OI) i refleksivnost vitrinita (Ro), što je omogućilo analizu tipa organske materije, termalne zrelosti i kapaciteta generisanja ugljovodonika.

Rezultati: Vrednosti sadržaja ukupnog organskog ugljenika kretale su se od 0,51 do 2 %, sa prosekom od 1,33 %, što ukazuje na prihvatljiv do vrlo dobar kvalitet matičnih stena. Vrednosti S2 kretale su se od 0,45 do 4 mg HC/g stene, a prosečni Indeks proizvodnje (PI) iznosio je 2,23. HI vrednosti (51–233 mg HC/g TOC), zajedno sa OI i Tmax, ukazuju na prisustvo kerogena tipa II i III, što sugeriše potencijal za proizvodnju i nafte i gasa. Vrednosti Tmax (435–465 °C, prosečno 447 °C) i refleksivnost vitrinita (0,68–1,19 %) potvrđuju termalnu zrelost. Pozitivna korelacija između TOC i S1 vrednosti podržava prisustvo endogenih ugljovodonika.

Zaključak: Integrisani geohemijski pristup potvrđuje da su crni škriljci iz Džebel-Zerega termalno zreli i bogati organskom materijom, sa obećavajućim potencijalom za proizvodnju naftnih škri-

ljaca. Ovi rezultati podržavaju dalja istraživanja i razvoj nekonvencionalnih izvora ugljovodonika u regionu Tamert.

Ključne reči: crni škriljac, Džebel-Zereg, elementarna analiza, potencijal ugljovodonika, organska materija, Rock-Eval piroliza, procena matičnih stena, ukupni organski ugljenik.

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