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Geochemical Evaluation of Source Rocks in the Sirte Shale Formation, Concession NC98, Southeastern Sirte Basin, Libya

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Abstract

This project presents a geochemical study aimed at evaluating the source rocks of the Sirte Shale Formation within the NC-98 Concession, located in the southeastern part of the Sirte Basin, Libya. The main objective was to assess the hydrocarbon source potential of these rocks. The Sirte Basin is one of the most important oil basins in Libya and Africa. It contains vast high-quality oil reserves and thousands of productive wells, making it a major center for exploration and production activities. This study analyzed 15 rock samples collected from three different locations within the concession area, using advanced techniques such as Total Organic Carbon (TOC) analysis and Rock-Eval pyrolysis. These analyses provide valuable information on organic matter content, kerogen type, and thermal maturity, which are essential factors in determining the capability of rocks to generate hydrocarbons. The study concluded that the rocks of the Sirte Shale Formation, particularly the upper part, possess favorable characteristics as hydrocarbon source rocks. This indicates that the area is promising for future exploration. The study recommends intensifying research and exploration efforts in the region using modern and advanced techniques to identify optimal production sites, thereby enhancing investment opportunities in the Libyan oil sector and supporting the sustainability of national resources.

Keywords: *Total organic carbon (TOC) analysis, Rock-Eval pyrolysis, Source rock, Sirte Shale Formation, Sirte Basin, Libya..*

الملخص

تناول هذا البحث دراسة جيوكيميائية لتقييم صخر المصدر في تكوين سرت شيل بمنطقة الامتياز NC-98 جنوب شرق حوض سرت - ليبيا، بهدف التعرف على مدى كفاءة هذه الصخور كمصدر للهيدروكربونات. يُعتبر حوض سرت من أهم الأحواض النفطية في ليبيا وأفريقيا، حيث يمتلك احتياطيا ضخما من النفط عالي الجودة، ويضم آلاف الآبار المنتجة، ما يجعله مركزًا محوريًا في عمليات الاستكشاف والإنتاج. تركزت الدراسة على تحليل خمس عشرة عينة صخرية مأخوذة من ثلاث آبار مختلفة داخل منطقة الامتياز، باستخدام تقنيات متقدمة مثل تحليل الكربون العضوي الكلي (TOC) والانحلال الحراري Rock-Eval،هذه التحاليل وفّرت معلومات مهمة عن محتوى المادة العضوية في الصخور، ونوع الكيروجين الموجود،

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ومستوى النضج الحراري، وهي عناصر رئيسية لتحديد قدرة الصخور على إنتاج النفط أو الغاز. خلصت الدراسة إلى أن الصخور في تكوين سرت شيل تمتلك الخصائص المثالية كمصدر للهيدروكربونات، خاصة في الجزء السفلي من التكوين، ما يجعلها منطقة واعدة للاستكشاف المستقبلي. وأوصت الدراسة بضرورة تكثيف الجهود البحثية والاستكشافية في هذه المنطقة، باستخدام تقنيات حديثة ومتطورة لتحديد أفضل المواقع الممكنة للإنتاج، مما يعزز من فرص الاستثمار في قطاع النفط الليبي ويدعم استدامة الموارد الوطني.

الكلمات المفتاحية: *تحليل (TOC)، الانحلال الحراري الصخري، صخور المصدر، تكوين سرت شيل، حوض سرت، ليبيا .*

Introduction

Introduction

The Sirte Basin is one of the geologically youngest and most economically important basins, ranking first in Africa and thirteenth in the world in terms of oil reserves. The basin contains 16 giant oil fields and more than 6,000 producing wells and includes approximately 36.7 billion barrels of crude oil(equivalent to 83% of Libya’s total reserves) and 37.7 billion cubic feet of natural gas. Basin oil is characterized by its high quality, with API gravity ranging from 32° to 44° and low sulfur content (0.15–0.66%).

The NC98 Field, operated by the Waha Oil Company, is located in the southeastern part of the Sirte Basin in north-central Libya. The formation of oil and gas in the Sirte Basin is attributed to several source rocks, the most important of which is the "Sirte Shale Formation,” which is distinguished by its dark gray to black laminated shale interbedded with limestone and calcareous shale. This formation is a prime target for geochemical studies because of its high hydrocarbon generation potential.

Organic Geochemistry of the "Sirte Shale Formation"

Organic geochemistry is an essential tool for understanding the properties of source rocks and evaluating their potential to generate hydrocarbons. The Sirte Shale Formation is a typical example of a thermally mature organic-rich unit.

This study was based on fifteen samples collected from three wells (O1, G1, and H1) in the NC-98 concession in the eastern part of the Sirte Basin, using the following techniques:

- Total Organic Carbon (TOC): Used to determine the organic matter content.
- Rock-Eval Pyrolysis: Used to assess kerogen type and thermal maturity.

Study Area Location

The NC-98 concession is located in the Mar Trough between the Cyrenaica Platform and the Gialo-Sarir High in the southeastern part of the Sirte Basin between latitudes 28° 30' to 29° 15'N and longitudes 21° 25' to 22° 25'E (Figure 1). Based on the structural setting of the Sirte Basin, the southern portion of Block NC98 is mostly situated in the Mar Trough, whereas the northern portion of the block is partly situated on the Rakb High. The concession area is approximately 2,653 km², equivalent to approximately 1.15% of the total basin area of 230,000 km².

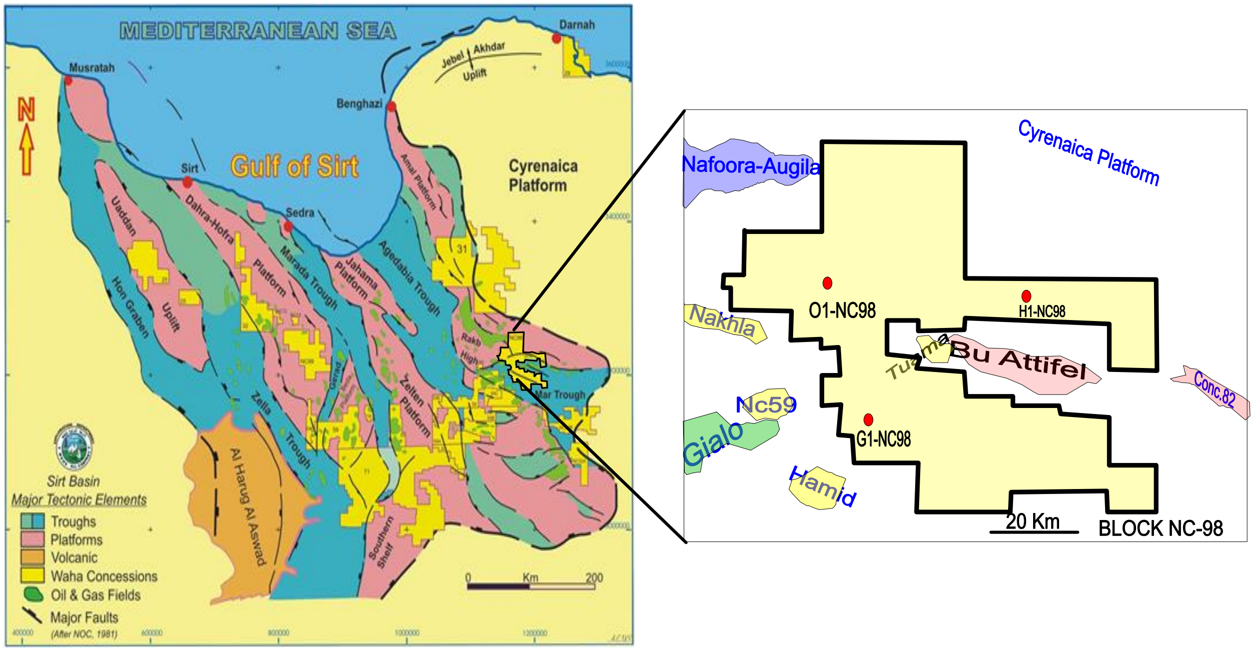

Figure 1: shows the locations of the studied wells (H1, G1, and O1) within the NC-98 concession.

Study Objectives

1. Analyzed the quantity and quality of organic matter in the Sirte Shale Formation using TOC and Rock-Eval.
2. The dominant type of kerogen was determined, and its potential for generating hydrocarbons was evaluated.
3. Evaluated the thermal maturity of the source rocks and its impact on oil and gas generation.

Previous Studies

Several studies have investigated the geochemical characteristics and hydrocarbon potential of the Sirte Shale and related formations within the Sirte Basin. Albriki et al. (2022) applied Rock-Eval pyrolysis and reported that the studied rocks fell within the early to middle stages of oil generation, indicating favorable thermal conditions for hydrocarbon generation. Similarly, Dieb (2015) found that the Sirte rocks contain high percentages of organic matter and exhibit a high level of thermal maturity, supporting their effectiveness as hydrocarbon source rocks.

The roles of depositional environments and regional variations have also been emphasized in earlier research. Meinhold et al. (2021) focused on the influence of depositional environments on geochemical transformations, highlighting the strong control of sedimentary conditions on petroleum potential. In addition, Albaghdady (2018) demonstrated significant regional differences in thermal maturity and confirmed the ability of the Sirte Formation to generate high-quality oil, further emphasizing the spatial variability within the basin.

Detailed assessments of source rock quality and kerogen type were provided by Aboglila and Elkhalgi (2013), who reported that the studied rocks ranged from fair to excellent source quality, with TOC values reaching up to 5.16 wt%. They identified predominantly oil-prone Type II and II/III kerogen, with hydrogen index (HI) values between 115 and 702 mg HC/g TOC. Their results also indicated that the Sirte and Rachmat formations are mature to post-mature, based on production index (PI) values of 0.07–1.55 and Tmax values of 425–440°C. Furthermore, El Diasty et al. (2016) reported moderate TOC content and early mature thermal conditions for the Sirte Formation, with HI values ranging from 60 to 341 mg HC/g TOC, suggesting predominantly gas-prone Type III or mixed Type II/III kerogen.

Data Sources and Methodology

The data for this study were obtained from the National Oil Corporation and Al-Waha Oil Company. This study involved the analysis of of fifteen rock-cutting samples from the Sirte Shale formation using the following methods:

1. TOC Analysis: To estimate the organic matter content.
2. Rock-Eval Analysis: To determine the kerogen type and thermal maturity.
3. Graph Preparation: Graphs were generated using Surfer 13 software.

Regional Geology

General Geology of the Sirte Basin

Sirte's basin ranks 13th among the world's oil-producing regions in terms of known reserves, containing approximately 36.7 billion barrels of oil and 37.7 trillion cubic feet of natural gas reserves.

Reservoirs in the basin consist of approximately 58% clastic deposits (mainly from the Mesozoic) and 42% carbonate rocks (mainly from the Cenozoic). The basin also contains additional lithologies, including limestone, evaporites, and clastic sediments.

Geological History of the Sirte Basin

The Sirte Basin is one of the youngest sedimentary basins in Africa and is structurally distinct from the surrounding basins. It is characterized as a rift basin, with most geological structures stretching from the northwest to the southeast.

Its formation is likely to have begun during the Early to Late Cretaceous due to tectonic extension, which created complex structures of **horsts and grabens**(figure 2) (Conant and Goudarzi, 1980).These rifting activities may have continued until the Miocene or **Holocene** epochs (Selly, 1985).

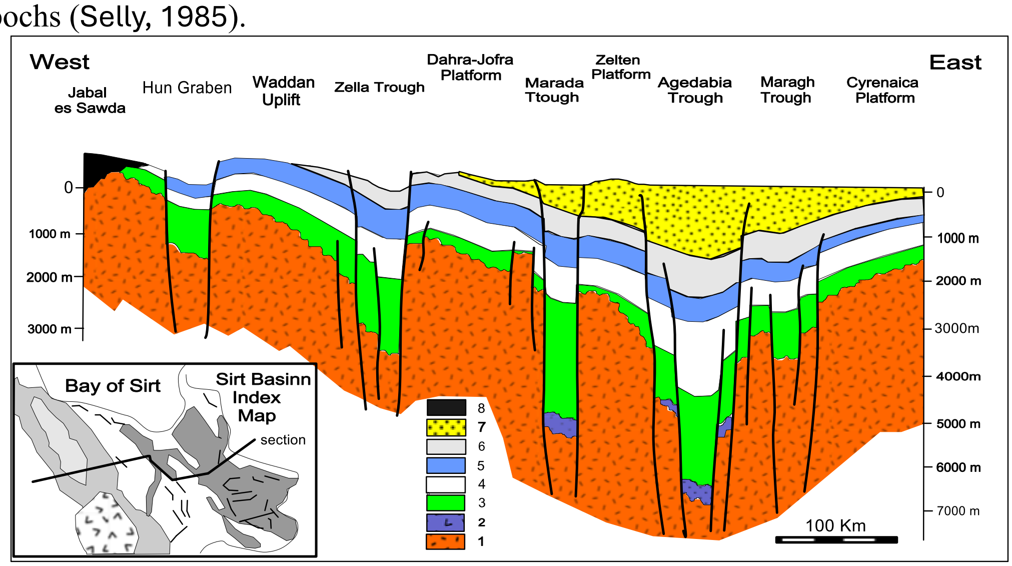

Figure 2: Schematic geological cross-section of the Sirt Basin, modified from Abuhajar and Roohi (2003). (1) Precambrian and Paleozoic (2) Lower Mesozoic (3) Upper Cretaceous (4) Paleocene (5) Lower Eocene (6) Middle Eocene (7) Upper Eocene to Recent (8) Cenozoic volcanic.

According to Burke and Dewey (1974), uplift and erosion have removed most Paleozoic sediments. Later, tectonic extension during the Mesozoic Era caused deep faults and sub-basins aligned NW–SE.

Stratigraphy of Southeastern Sirte Basin

The basin has a diverse and rich sequence of clastic sedimentsthat extends from the **Cenozoic**Era; we mentioned the most important of them as follows, which was formed by intensive tectonic activity and sedimentation (figure 4).

1. Nubian Formation

a. Middle Shale Member: Pre-Upper Cretaceous. Dark, fine-grained shale rich in organic matter with interbedded sandstone. These deposits indicate variable depositional environments (Smith 1985).

b. Upper Nubian Sandstone: Quartz-rich, medium-to coarse-grained, high porosity, and permeability. This unit represents fluvial to continental depositional environments (Bell & Ward, 1970).

2. Transitional Beds Formation

Upper Cretaceous. Claystone and shale with overlapping sandstone layers. These deposits reflect changing depositional environments, from quiet to more active conditions.

3. Lower Sirte Shale Formation

Upper Cretaceous. Laminated shale with interbedded siltstone, dolomite, and anhydrite.

Deposited in **low-energy marine and evaporitic environments**, this formation is a major source rock in the Sirte Basin.

4. Tagrifet Formation

Chalky carbonate with shale interbeds This unit represents war,m **shallow marine environments** with organic-rich conditions.

5. Upper Sirte Shale Formation

It is rich in organic matter and is considered a **major source rock** in the Sirte Basin (Barr and Weegar, 1972).

6. Lower Sabil Formation

Paleocene. Alternating limestone and clay layers were observed. It acts as a **primary reservoir** in lowland areas.

7. Upper Sabil Formation

Dolomite and anhydrite with some clay were also present. Variable thickness. It was found in the Zaqout and Al-‘Aoura fields.

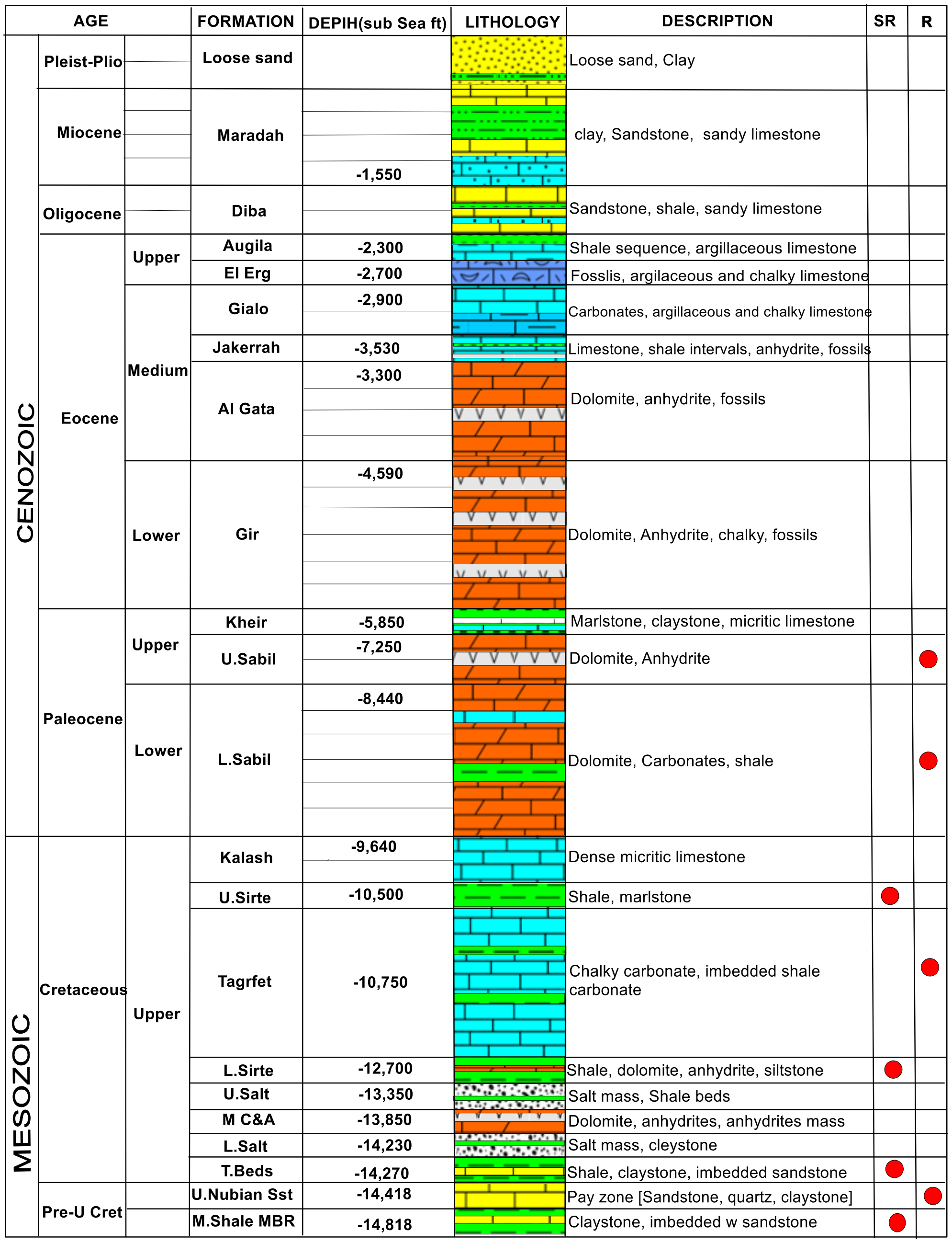

Figure 4: Stratigraphic column of the NC-98 concession (Waha Oil Company).

Source Rock Evaluation

TOC and Rock-Eval are widely used as reliable methods to provide fundamental data on the presence of hydrocarbons (oil and gas) and to identify organic richness, kerogen type, thermal maturity, and hydrocarbon generation potential.

According to Waples (1985), source rocks are classified based on their hydrocarbon potential into potential and confirmed source rocks. These parameters were evaluated by focusing on quantity (organic richness), quality (kerogen type), and maturity (Tables 1–3).

Table 1 lists the significance of the Rock-Eval pyrolysis peaks (Peters, 1986; Tissot and Welte, 1984).

Peak	Significance	Comment
S_1 mg HC/g rock	The sample's free hydrocarbons prior to analysis.	Considered a residual hydrocarbon phase. An alternate source, such as migrated hydrocarbons or contamination, should be suspected when S_1 is high in comparison to S_2.
S_2 mg HC/g rock	The amount of hydrocarbons produced when the sample was thermally pyrolyzed.	used to calculate the rock samples' residual capacity to produce hydrocarbons.
S_3 mg CO2/g rock	the CO_2 produced when the rock's kerogen breaks down thermally.	Most common in source rocks that are calcareous.
T_{max}	Correlates to the Rock-Eval pyrolysis oven temperature at maximum S_2 generation and measures thermal maturity.	T_{max} is a kerogen-dependent maturation parameter. The type of organic matter has an impact on T_{max}.

Table 2:Rock-Eval pyrolysis measurements (Peters and Moldowan, 1993)

Measurement Peak	Significance	Comment
Hydrogen index (HI) (S_2/TOC) x 100	Measurements of the source rock's hydrogen content.	An initial evaluation of the petroleum generative potential in a source rock can be obtained by plotting the HI against the OI.
Oxygen index (OI) (S_3/TOC) x 100	It can be used in conjunction with HI to estimate the quality of source rocks by measuring their oxygen richness.	This index is not accurate for rocks with high carbonate content. High OI values (>50 mg/g) are characteristic of immature hydrocarbon.
Production index (PI) $S_1/[S_1 + S_2]$	Low ratios indicate either immaturity or extreme post-mature organic matter. High ratios indicate the mature stage or contamination by migrated hydrocarbons or drilling additives.	The production index is the ratio of the generated hydrocarbons to the potential hydrocarbons. The PI increases steadily with depth and is associated with hydrocarbon generation.

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Table 3a**:** Geochemical parameters that describe the quantity of petroleum potential in an immature source rock (Peters and Cassa, 1994)

Petroleum potential	**Organic matter**			**Hydrocarbons (ppm)**
	TOC (wt%)	**Rock-Eval pyrolysis**		
		S_1	**S_2**	
Poor	0-0.5	0-0.5	0-2.5	0-300
Fair	0.5-1	0.5-1	2.5-5	300-600
Good	1-2	1-2	5-10	600-1200
Very good	2-4	2-4	10-20	1200-2400
Excellent	>4	>4	>20	>2400

Table 3b: Characteristics of expelled products and geochemical parameters characterizing kerogen type (quality) (Peters and Cassa, 1994)

Kerogen type	**Kerogen composition**	**HI (mg HC/g TOC)**	**S_2/S_3**	**Atomic H/C**	**Main expelled product at peak maturity**
I	Amorphous/alginite	>600	>15	>1.5	Oil
II	Exinite	300-600	10-15	1.2-1.5	Oil
II/III	Exinite/vitrinite	200-300	5-10	1.0-1.2	Mixed oil and gas
III	Vitrinite	50-200	1-5	0.7-1.0	Gas
IV	Inertinite	<50	<1	<0.7	None

Table 3c**:** Geochemical parameters that describe the degree of thermal maturation (Peters and Cassa, 1994)

Stage of thermal maturity for oil	**Maturation**			**Generation**
	R_o (%)	**T_{max} (^{O}C)**	**TAI**	**PI [$S_1/(S_1+S_2)$]**
Immature	0.2-0.60	<435	1.5-2.6	<0.10
Early mature	0.60-0.65	435-445	2.6-2.7	0.10-0.15
Peak mature	0.65-0.9	445-450	2.7-2.9	0.25-0.40
Late mature	0.9-1.35	450-470	2.9-3.3	>0.40
Postmature	>1.35	>470	>3.3	–

Evaluating Source Rocks Using TOC/Rock-Eval Data

Rock-Eval pyrolysis provides information on the quantity and quality of organic matter in sedimentary rocks and their thermal maturity (Espitalie et al., 1977).Total Organic Carbon (TOC) represents the amount of organic matter in a rock sample (Figure 5).

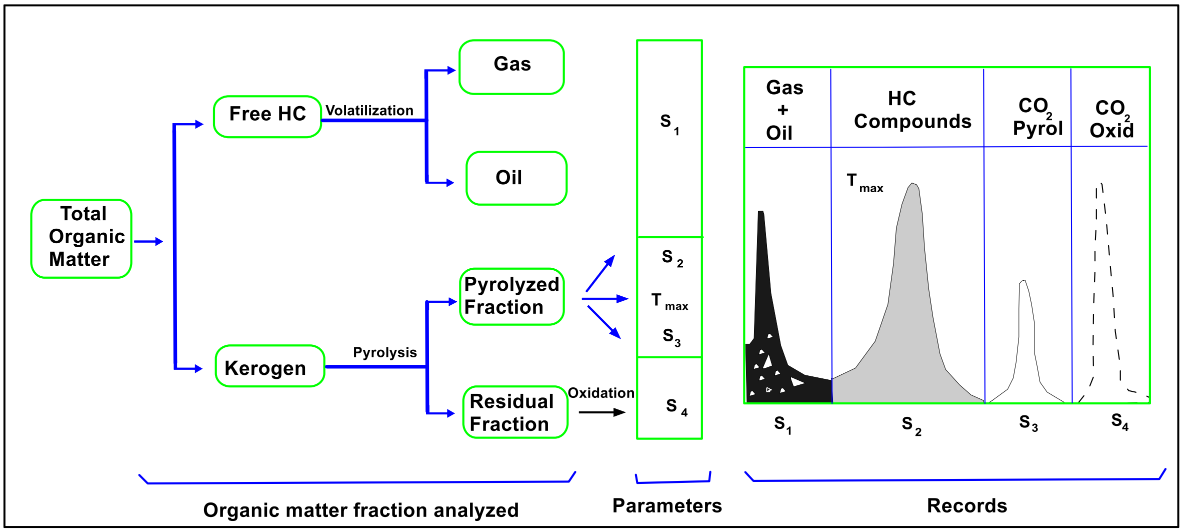

Figure 5: A general diagram displaying the various fractions of the total organic matter of the rocks under analysis, along with the associated parameters and their recordings (Lafargue et al., 1998).

The TOC and Rock-Eval parameters (S2, Tmax, Hydrogen Index [HI], Oxygen Index [OI], and Production Index [PI]) for 15 samples from the Sirte Shale Formation are listed in Table 4.

Table 4: Results of TOC/Rock-Eval pyrolysis data from wells retrieved from the NC98 Concession, Southeast Sirte Basin – Libya

Table 4: Results of TOC/Rock-Eval pyrolysis data from wells retrieved from the NC98 Concession, Southeast Sirte Basin – Libya

PI	OI	HI	$T_{max}C^0$	S_2	%TOC	Sample Type	Sample Depth	Formation	Well name	.no
0.03	35	139	438	1.87	1.35	Cuting	11250	U_Sirt SH	**O1-NC98**	**1**
0.03	53	170	439	2.04	1.2	Cuting	11280	U_Sirt SH	**O1-NC98**	**2**
0.02	56	154	439	1.69	1.1	Cuting	11310	U_Sirt SH	**O1-NC98**	**3**
0.03	53	158	439	1.75	1.11	Cuting	11400	U_Sirt SH	**O1-NC98**	**4**
0.04	56	166	441	1.86	1.12	Cuting	11450	U_Sirt SH	**O1-NC98**	**5**
0.03	50	165	441	2.05	1.24	Cuting	11480	U_Sirt SH	**O1-NC98**	**6**
0.03	21	372	439	1.14	3.06	Cuting	11470	L-Sirt SH	**G1-NC98**	**7**
0.19	105	118	438	0.73	0.62	Cuting	11530	L-Sirt SH	**G1-NC98**	**8**
0.22	100	154	437	0.8	0.52	Cuting	11560	L-Sirt SH	**G1-NC98**	**9**
0.22	150	194	438	1.05	0.54	Cuting	12070	L-Sirt SH	**G1-NC98**	**10**
0.19	144	187	445	0.97	0.52	Cuting	12550	L-Sirt SH	**H1-NC98**	**11**
0.09	29	239	446	4.3	1.81	Cuting	12640	L-Sirt SH	**H1-NC98**	**12**
0.16	106	279	449	1.04	0.66	Cuting	12670	L-Sirt SH	**H1-NC98**	**13**
0.34	109	173	438	0.97	0.56	Cuting	12940	L-Sirt SH	**H1-NC98**	**14**
0.23	135	197	436	1.52	0.77	Cuting	13330	L-Sirt SH	**H1-NC98**	**15**

TOC= Total organic carbon; S2= Remaining hydrocarbon generative potential; Tmax = Temperature at maximum of S2 peak; HI: Hydrogen index= S2×100/TOC; OI= Oxygen index =S3×100/TOC; PI= Production index= S1/ (S1+S2)

Organic Richness (Quantity)

Organic richness is a prerequisite for hydrocarbon generation (Peters and Moldowan, 1993). TOC is a primary factor in determining the organic content of source rocks. Batten (1996) recommended minimum TOC values of over 0.5% for shale and 0.3% for carbonates. Peters and Cassa (1994) suggested a minimum threshold of 1–2% for effective source rocks.

In the Upper Sirte Shale, TOC values range from 1.1% to 1.35% with an average of 1.18%, and S2 values range from 1.69 to 2.05 mg HC/g, with an average of 1.87, indicating acceptable organic richness.

In the Lower Sirte Shale, TOC values range from 0.52% to 1.81%with an average of 0.75%, (except one high value of 3.06%) and S2 values range from 0.73 to 4.3 mg HC/g, averaging 1.39, suggesting that moderate hydrocarbons can be generated (Figure 6).

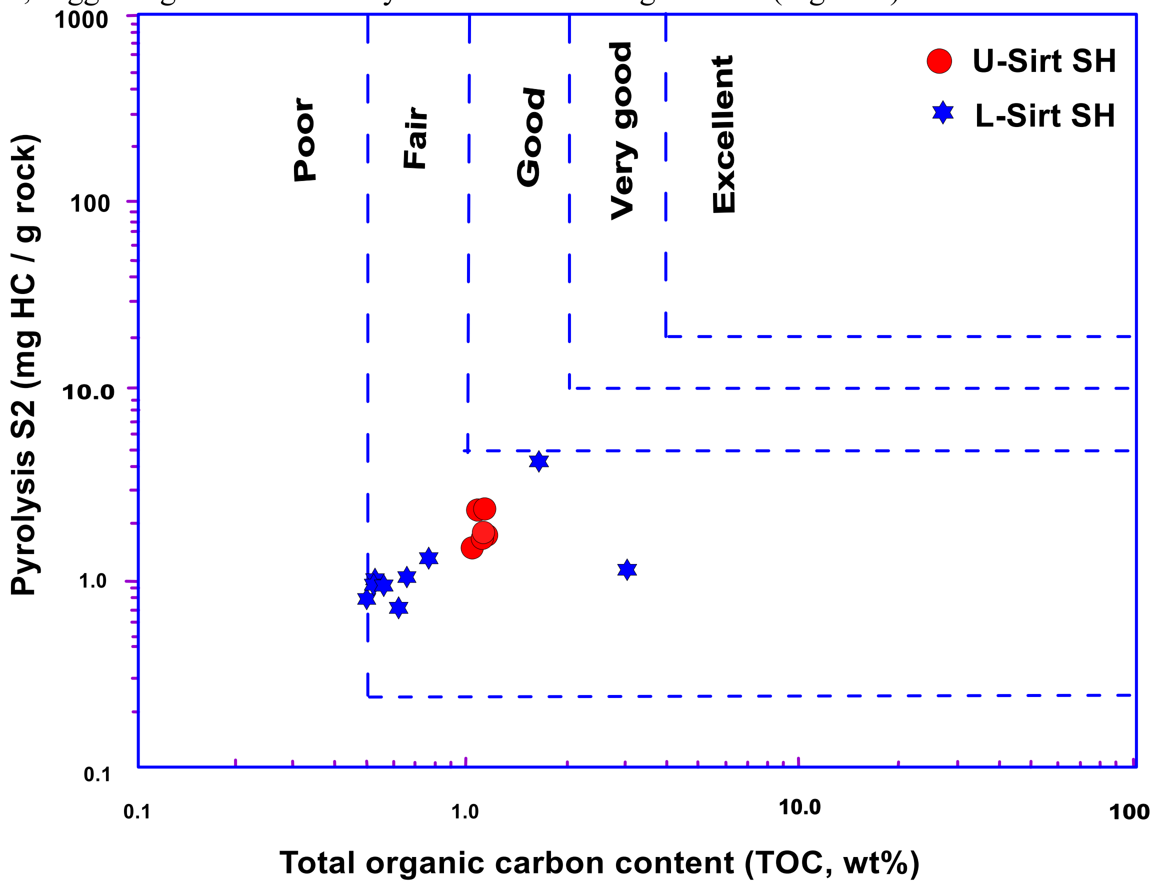

Figure 6: TOC vs. S2 cross-plot for samples from the Sirte Shale, Southeast Sirte Basin.

Organic Matter Type and Kerogen Quality

The hydrogen index (HI) versus oxygen index (OI) is shown in (Figure 7).

In the Upper Sirte Shale, HI values range from 139 to 170, indicating Type III kerogen (continental depositional environment, gas-prone). The OI values ranged from 35 to 56, with an average of 50.5.

In the Lower Sirte Shale, HI values range from 118 to 372, indicating Type II/III kerogen (mixed marine-terrestrial origin, capable of generating oil and gas). The OI ranged from 21 to 150.

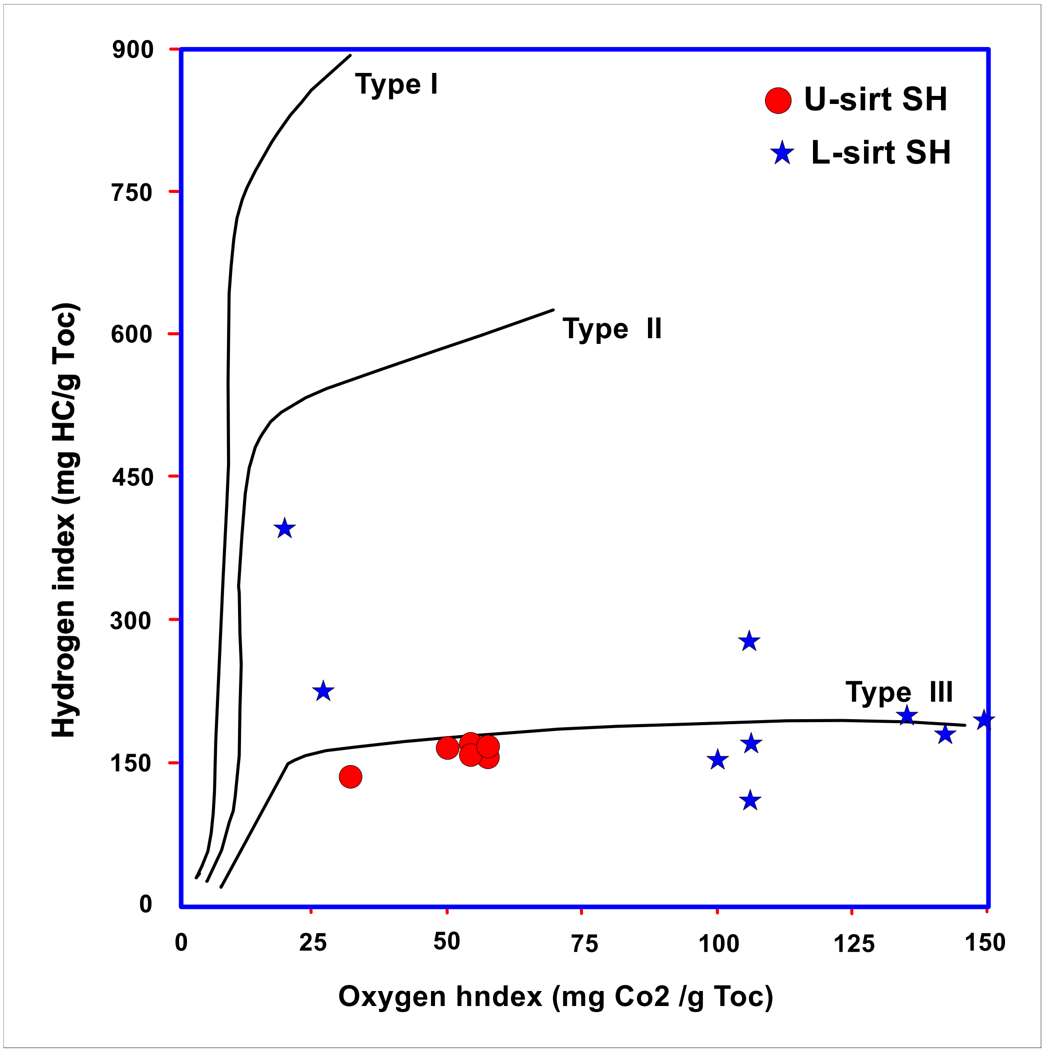

Figure 7: Van Krevelen diagram (HI vs. OI) for the Sirte Shale samples from the Southeast Sirte Basin.

Thermal Maturity

In the Upper Sirte Shale, Tmax values range from 438°C to 441°C, with an average of 439.5°C, and PI values range from 0.02 to 0.04, indicating that all samples fall within the early mature oil window.

The Lower Sirte Shale has relatively high Tmax data, ranging from 436 to 449°C, with an average of 400°C, and PI values ranging from 0.03 to 0.34, indicating the early to main stage of the oil generation window (Figure 8).

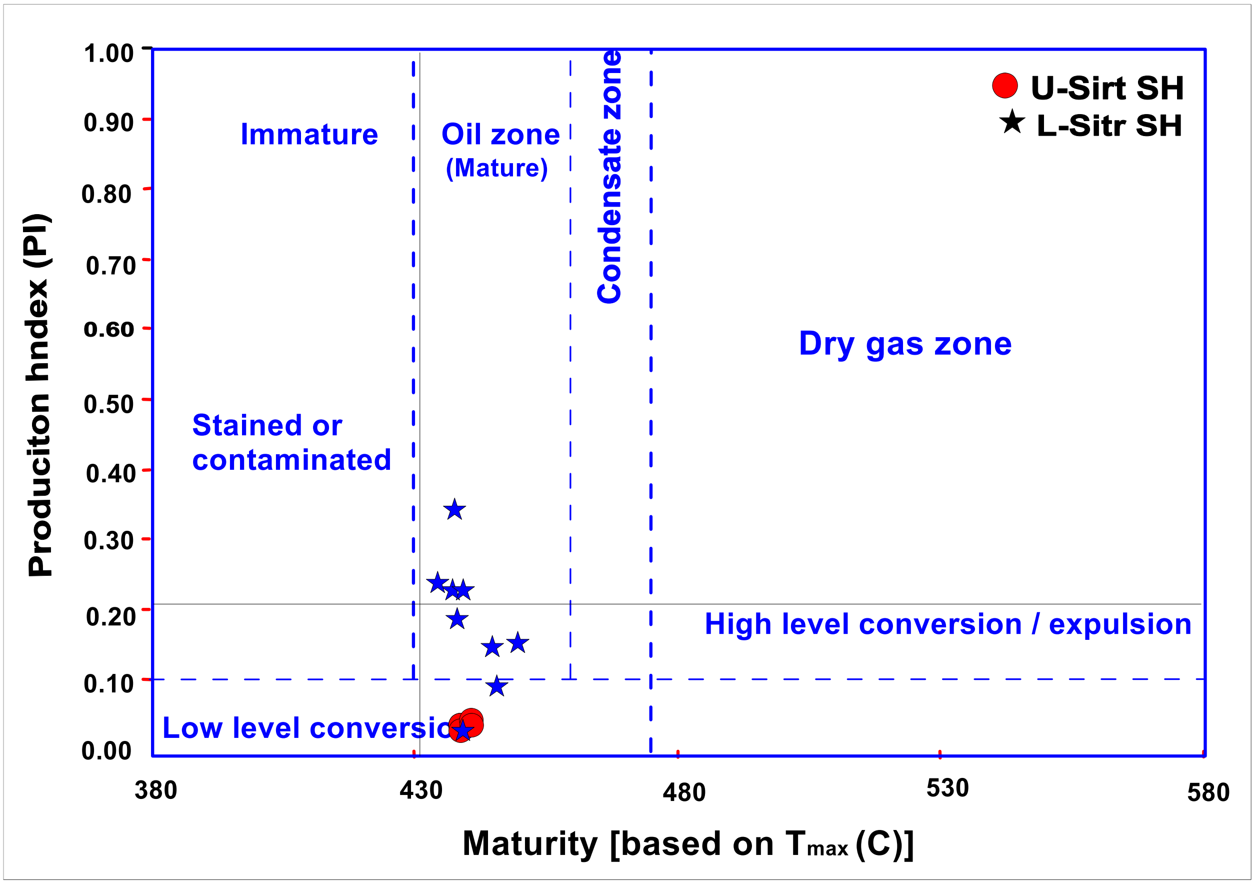

Figure 8: Tmax vs. PI plot for the Sirte Shale samples from the Southeast Sirte Basin.

Geochemical Log

The geochemical log (Figure 9) shows the distribution of TOC, HI, and PI values, highlighting the zones of oil and gas potential. Tmax profiles show rocks at various stages of thermal maturity, suggesting that these formations are promising targets for future exploration and production efforts.

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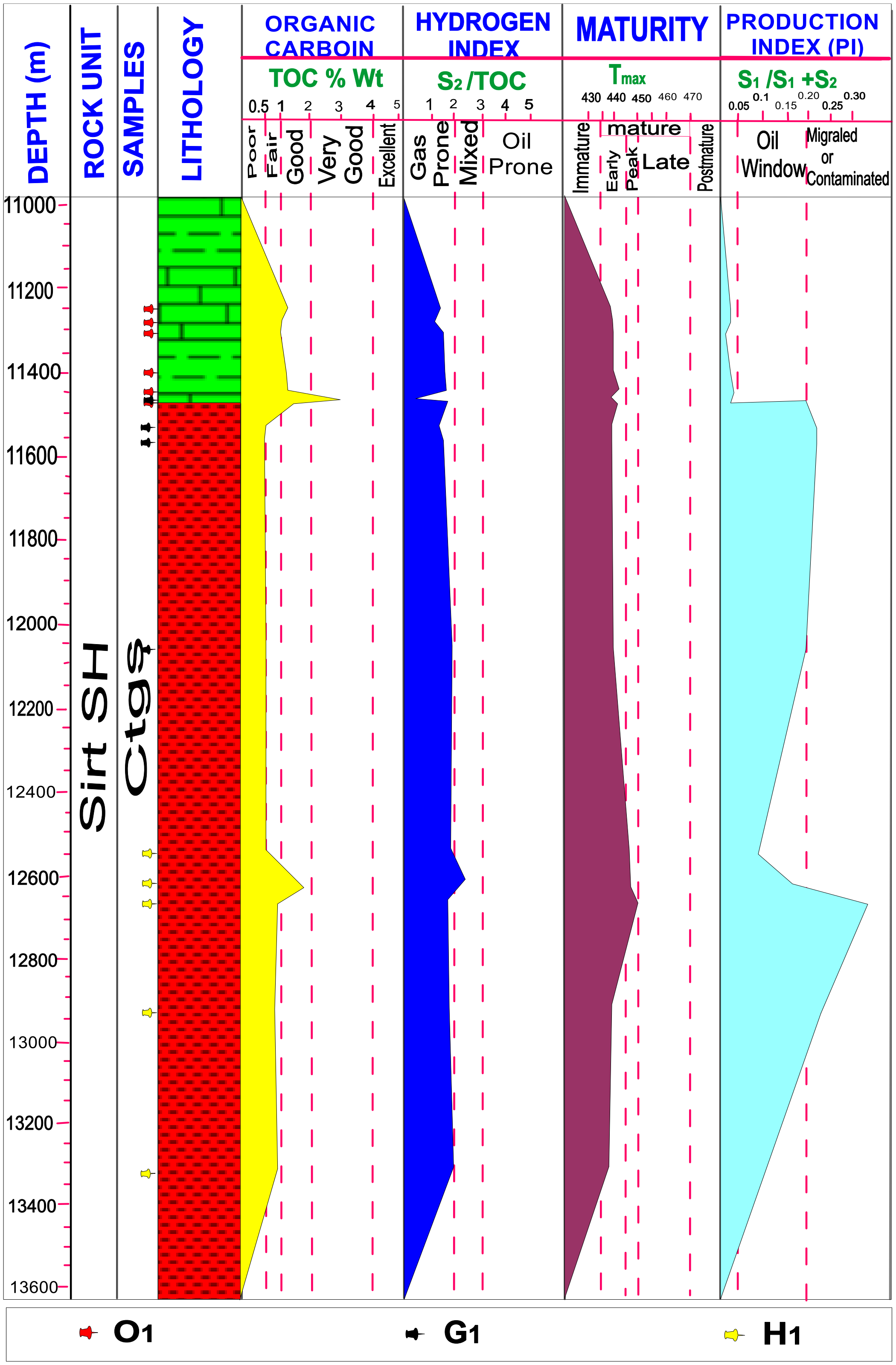

Figure 9: Composite geochemical log for the Sirte Shale samples from the Southeast Sirte Basin.

Discussion

The geochemical characterization of the Sirte Shale Formation in the NC-98 concession provides important insights into its effectiveness as a hydrocarbon source rock and improves our understanding of petroleum system development in the southeastern Sirte Basin. Integrated TOC and Rock-Eval pyrolysis data indicate that the formation possesses adequate organic richness, favorable kerogen composition, and sufficient thermal maturity to generate hydrocarbons, consistent with the study objectives and regional geological framework.

The TOC results show that the Upper Sirte Shale consistently exceeds the minimum thresholds for effective source rocks defined by Peters and Cassa (1994), whereas the Lower Sirte Shale exhibits greater vertical variability in organic carbon content. This heterogeneity reflects changing depositional conditions during sedimentation and agrees with the findings of Aboglila and Elkhalgi (2013), who reported wide TOC ranges within the Sirte Shale Formation. Although the average TOC of the lower section is moderate, localized organic-rich intervals suggest episodic conditions favorable for organic matter preservation, likely related to reduced oxygenation and lower sedimentation rates. Similar vertical and lateral variations were reported by Albriki et al. (2022), who linked them to fluctuations in subsidence and Late Cretaceous paleoenvironmental conditions.

S2 values support the source rock potential inferred from the TOC data. Higher and more uniform S2 values in the Upper Sirte Shale indicate a more reliable hydrocarbon generation capacity than in the lower section, where S2 values are dispersed. This contrast suggests more stable depositional conditions and sustained organic input in the upper unit, whereas the lower unit reflects variable sedimentary regimes, consistent with the observations of El Diasty et al. (2016).

Kerogen type differentiation based on the HI and OI values revealed clear vertical variations. The Upper Sirte Shale is dominated by Type III kerogen, indicating a strong terrestrial organic matter contribution and deposition under relatively oxic conditions influenced by continental inputs. This interpretation is consistent with that of Meinhold et al. (2021), who emphasized the control of depositional environment on organic facies development. In contrast, the Lower Sirte Shale contains mixed Type II/III kerogen, reflecting combined marine and terrestrial sources and the potential to generate both oil and gas, as reported by Aboglila and Elkhalgi (2013) and Albaghdady (2018). Elevated HI values in some lower-section samples indicate improved preservation of hydrogen-rich organic matter during the more reducing depositional phases.

Thermal maturity indicators confirmed the effectiveness of the Sirte Shale as a hydrocarbon source rock. Thermal maturity analysis of the Upper Sirte Shale (Tm_{ax} between 438 and 441°C) confirmed that these samples fall within the early mature oil window. In contrast, the Lower Sirte Shale exhibits relatively higher Tmax data, ranging from 436 to 449°C, which correspond to the early to main stage of the oil generation window, in agreement with the maturity levels reported by Albriki et al. (2022) and Aboglila and Elkhalgi (2013). Variations in the PI values suggest different degrees of hydrocarbon generation and expulsion, reflecting spatial differences in burial history, heat flow, and structural evolution within the NC-98 concession, consistent with the regional maturity trends described by Albaghdady (2018).

Overall, the geochemical results indicate that the Upper Sirte Shale represents the most laterally consistent and effective source rock interval in the study area, despite its predominantly gas-prone kerogen content. The Lower Sirte Shale remains a viable secondary source rock owing to its mixed kerogen type and mature thermal conditions, particularly where organic-rich intervals occur. These findings reinforce regional petroleum system models for the Sirte Basin and highlight the strong control of the depositional environment and thermal evolution on source rock quality. The integration of this geochemical dataset with existing geological and geophysical data provides a solid basis for refining exploration strategies within the NC-98 concession.

Conclusion

This study provides an integrated organic geochemical evaluation of the Sirte Shale Formation in the NC-98 concession in the southeastern Sirte Basin using TOC and Rock-Eval pyrolysis data from 15 samples. The results confirm that the formation represents an effective and thermally mature hydrocarbon source rock with distinct vertical variations in organic richness, kerogen type, and generation potential. The Upper Sirte Shale exhibits relatively consistent TOC and S2 values and is dominated by Type III kerogen, indicating a predominantly gas-prone character. In contrast, the Lower Sirte Shale shows greater heterogeneity in organic content and contains mixed Type II/III kerogen, reflecting the potential for oil and gas generation. Thermal maturity indicators (Tmax and PI) placed all samples within the early to main stage of the oil generation window, confirming favorable conditions for hydrocarbon generation. Overall, the results demonstrate that depositional environment and thermal evolution exert strong control on source rock quality, with the Upper Sirte Shale representing the most laterally consistent and prospective source interval within the NC-98 area.

Recommendations:

Future exploration activities within the NC-98 concession should prioritize the Upper Sirte Shale interval, as it exhibits relatively high organic richness, consistent hydrocarbon generation potential, and favorable thermal maturity. Targeting this interval is expected to improve exploration success and reduce geological risks.

To support sustainable development, the results of this study should be incorporated into regional evaluation frameworks to highlight the proven hydrocarbon potential of this area. This will assist decision-makers in optimizing exploration strategies and allocating investments more effectively.

It is recommended that existing geochemical datasets be integrated with detailed geological, geophysical, and structural analyses to establish a comprehensive petroleum system model for the NC-98 concession. Such integration will enhance the understanding of source-to-reservoir relationships, improve well placement, and increase the drilling efficiency.

Finally, strengthening the collaboration between academic institutions and the petroleum industry is essential. Joint research programs, data sharing, and applied studies will facilitate the effective translation of scientific findings into practical exploration and developmental strategies.

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