Controls on Hydrocarbon Generation from Eocene Source Rocks in the Ash Shulaydimah Trough, NE Libya

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***Abstract*— In north-eastern Libya, the Eocene succession within the Ash Shulaydimah Trough is not well understood with respect to its potential as a source rock for petroleum, despite the presence of organic-rich shale layers. The geological and geochemical characteristics of the source rocks of the Eocene period in the Ash Shulaydimah trough have been studied, with particular attention to the Lower shale and the Eocene Antelat formation. The assessment is conducted by re-evaluating existing pyrolysis and total organic carbon (TOC) Rock-Eval data from numerous exploration wells. The data is combined with information from burial history analysis, stable isotope data, observations of the rock's texture, information about the environment in which the rocks were formed and a stratigraphic analysis.**

These source rocks are of Eocene age and contain a generally high organic content, ranging from 1.8 to 8.7 percent by weight. In some regions of the basin, organic content was very high, as reflected by high hydrogen index values; this high hydrogen index is characteristic of oil-generating kerogen. It appears that the oxygen levels in the area were low, and the organic matter found is primarily marine life, with low carbon-13 levels and deposited in low-energy environments where oxygen was blocked mainly out, especially in the clayey limestone formations. The quality of the source rock does not appear to limit hydrocarbon production in the Eocene succession.

The majority of source rocks in the Eocene are immature; this is shown by the thermal maturity data which indicate that in many cases, the samples have a Tmax value that is too low to have generated oil. The history of sediment burial suggests hydrocarbons began forming during the Eocene and increased until the sedimentary rocks were exposed in the late Pliocene. In the Ash Shulaydimah trough, hydrocarbon generation seems to be limited to specific areas where expulsion occurs. In the D1-NC129 well, the presence of oil indicates that the Antelat Formation can generate oil if burial is deep enough. The main risk during the exploration of the Eocene petroleum system in western Cyrenaica comes from the effectiveness of the charge rather than from the source rock's quality.

Keywords—: Ash Shulaydimah Trough, Rock-Eval pyrolysis, Total organic carbon, Kerogen type. Thermal maturity

I. Introduction

North Africa has one of its largest oil-producing systems in Libya, where a significant proportion of the country's crude oil comes from shales that date back to the upper Cretaceous and Silurian periods.

Libya is situated within the Tethyan sedimentary mega-basin system which contains most of the world's hydrocarbon reserves - 70% according to Baudin [1]. It is estimated that nearly 85% of Libya's discovered hydrocarbons come from Upper Cretaceous source rocks. In northeastern Libya the importance of a potential source rock system in the Ash Shulaydimah trough has mainly been overlooked up to this point. Regional geochemical studies by Ghori et al. [2], [3] and Burwood et al. [4]. Most recent research on (Cretaceous) petroleum in the Sirte Basin has focused on the Cretaceous petroleum systems. The geochemical and maturity assessments, though noting possible local contributions of the Eocene units to hydrocarbon generation by these authors, lacked thoroughness. Because of this, the Eocene succession in eastern Cyrenaica has so far been poorly dated in terms of its source rock quality, maturity and the overall effectiveness of the petroleum system.

Regional reviews of hydrocarbon potential have concluded that Eocene source rocks account for only approximately 4.4% of Libya's hydrocarbon reserves [5]. The Eocene succession in western Cyrenaica, preserved in specific locations, is of a clayey-carbonate type. This could represent an effective, though limited-in-scope, oil source rock. A detailed geochemical evaluation of the Eocene petroleum system is presented, concentrating solely on the Lower Shale and the Antelat Formation. This assessment is based on previously gathered geochemical data.

A. Geologic Setting

Stretching along the Mediterranean Sea's southern shoreline, the western part of Cyrenaica is found on the northern edge of the African continental shelf. The area is divided into four main tectonic units: the Cyrenaica Platform, the Al Jabal al Akhdar Uplift, the Marmarica trough and the Ash Shulaydimah Trough [6]. A complex evolution of tectonic domains occurred during late Cretaceous extension, Paleogene subsidence and late Miocene to Pliocene uplift and inversion. This has controlled burial history, sedimentation and the overall petroleum systems.

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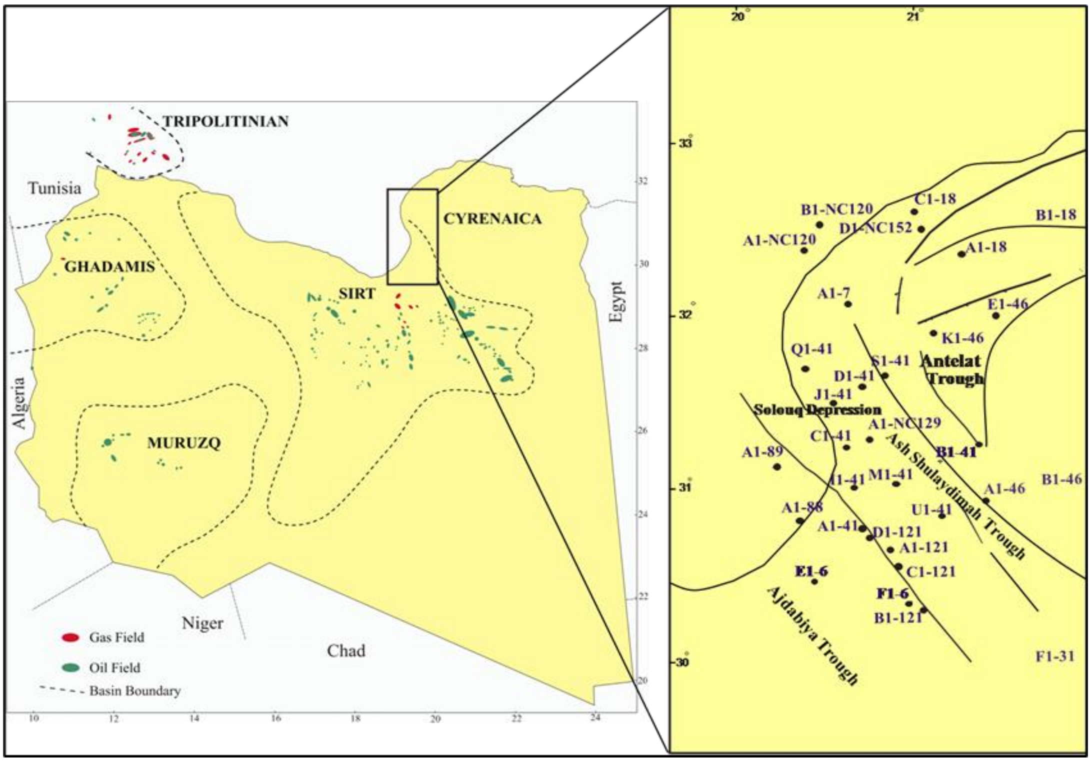

Figure 1. The study area is situated in a region of northeastern Libya, as shown by the map of the area below. The map illustrates the position of the Ash Shulaydimah trough within the Cyrenaica. On the detailed map, the structural framework of western Cyrenaica and the distribution of wells used in this research are displayed.

Western Cyrenaica's Eocene main basin is known as the Ash Shulaydimah Trough or the Soluq/ Antelat trough. The Eocene age sediments here reach a depth of over 4,000 feet, suggesting that there was considerable subsidence in the middle Eocene period. The isopach maps show Tertiary formations deepening in a southerly direction, reaching an extreme thickness of nearly 5,500 ft in the Ash Shulaydimah trough, where subsidence was most significant. This structural configuration facilitated the preservation of fine-grained carbonate and shale strata, which in turn were characterised by elevated organic content.

Since the late Cretaceous, the general layout of troughs and platforms in northeastern Libya has been broadly consistent. They faced the Mediterranean and periodically allowed marine floods to enter. The region's basin-specific stratigraphic patterns were the result of interplay between tectonic subsidence and uplift, changes in sea level and sediment supply.

B. Depositional Environment of Eocene Rocks

The stratigraphic sequence in the north-east of Libya extends from the Upper Cretaceous to the Miocene. The area's geology is primarily made up of carbonates. Shales appear at intervals due to subsidence as well as the sea advancing further inland. The collapse of the Sirt Arch and the Cenomanian transgression over the region largely controlled deposition during the Upper Cretaceous. The Antelat Formation in western Cyrenaica was deposited predominantly in a hemipelagic outer-shelf to open-marine environment and contains argillaceous limestones with wackestone to packstone textures and abundant planktonic foraminifera, indicating conditions favorable for the preservation of marine organic matter [7].

Throughout the region, there are noticeable variations in thickness across the geological formations. These variations are attributed to a shift in platform settings from the southern and western regions to the basinal environments in the northern and eastern areas. This shift is exemplified in the uppermost Cretaceous Maastrichtian dolomitic and chalky limestones.

Throughout the Libyan study area the Tertiary strata are found and date from the Paleocene to the Late Miocene periods. This region's uppermost Tertiary succession comprises a series of dolomite and chalk units. Over these rocks there is a sequence of both marl and limestone, together with shale. During the Tertiary, the Ash Shulaydimah and northeastern Ajdabiya troughs served as carbonate platforms. These developed in shallowing up sequences which include the Al Bayda and Harash formations. In the areas immediately to the west and south of the Ash Shulaydimah Trough, conditions allowed for organic matter to be better preserved, as indicated by the increased content of total organic carbon.

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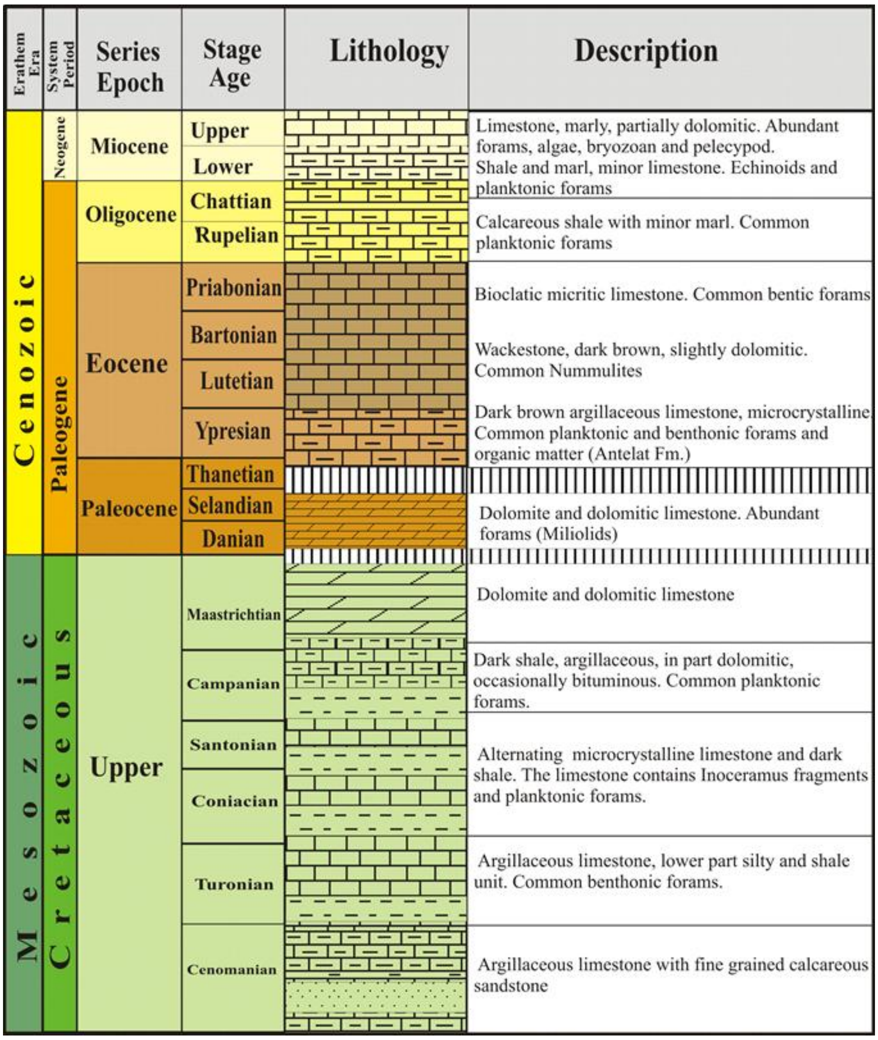

Figure 2. Generalized subsurface stratigraphic column of western Cyrenaica showing the Cretaceous to Neogene succession, lithology, and depositional characteristics, with emphasis on the Paleocene-Eocene carbonate units including the Antelat Formation and associated organic-rich intervals

The period which is Late Paleocene to Early Eocene is marked by a thick sequence of three equivalent strata. These are the dolomite, the argillaceous limestone and the bioclastic limestone formations. Together they form the Antelat Formation.

The distribution of the dolomite facies and pictures shown in figure 3 show a development of dolomite from shallow water areas to limestones deposited in open sea and in areas where limestone sediment accumulated with a lot of clay. This suggests that a period of tectonic activity in the Eocene controlled the formation of the area's carbonate rocks. This situation resulted in the formation of small basins where organic material could be preserved. The western part of the Cyrenaica Platform is composed of dolomitic facies, consisting of finely to microcrystalline light-grey dolomite with minor anhydrite. These rocks show rhomb-shaped crystals and holes between the crystals, as one would expect from sediments deposited where the sea meets the land during a rise in sea level. The rock units that exhibit these facies here are considered to be effective reservoir units in the local area.

This part of the study area is mainly composed of a bioclastic facies. It is characterised by wackestones that are rich in nummulites and this type of rock is often found interbedded with a type of limestone which has chalky properties. In northwards advancing marine conditions of Late Paleocene-Early Eocene times these sediments were deposited; they correspond to the Apollonia Formation's lower strata.

The subject of this research is the clayey limestone series of the Antelat Formation. It is mainly found in the western and southwestern parts of Cyrenaica in Ash Shulaydimah Trough. The lithology and layer relationships of the underlying Paleocene dolomite and the Antelat sandstone are shown in the D1-41 well log (figure 4). The sequence comprises repeated layers of limestone argillaceous, mudstone and minor dolomite. Such conditions are typical of low-energy marine environments. According to the analysis of fossils within the concession NC 129, the formation, dated by Abuessaoud and Muftah [7], is considered to have originated during the Late Paleocene to Early Eocene era. It consists of argillaceous limestones, wacke and mudstones. Characterised by its rare dolomite grains and thin-shelled

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planktonic foraminifers. Many indications of organic-rich rock are observed from drilling in several wells, including H1-41 and C1-41.

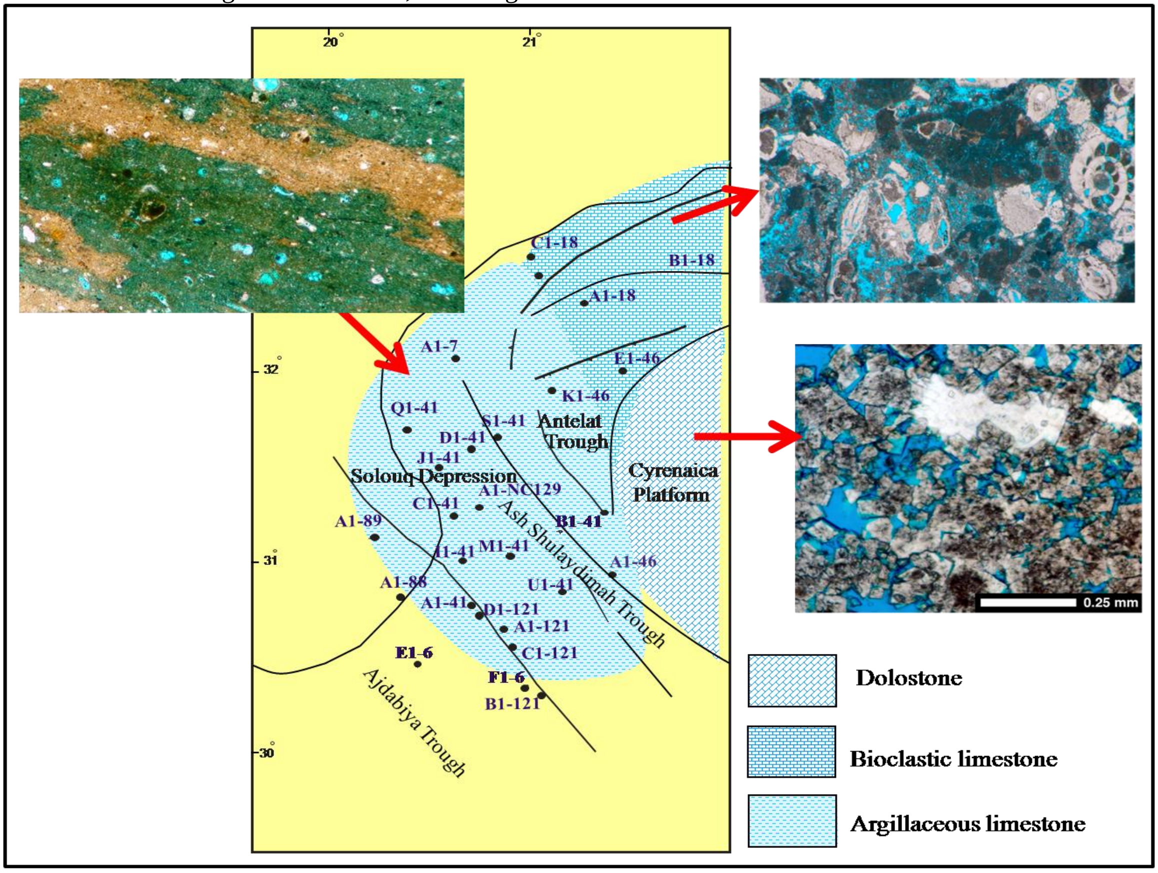

Figure 3. Facies distribution of Late Paleocene - Early Eocene strata in the study area, showing the spatial relationship between dolomitic platform facies, bioclastic limestone, and argillaceous limestone of the Antelat Formation.

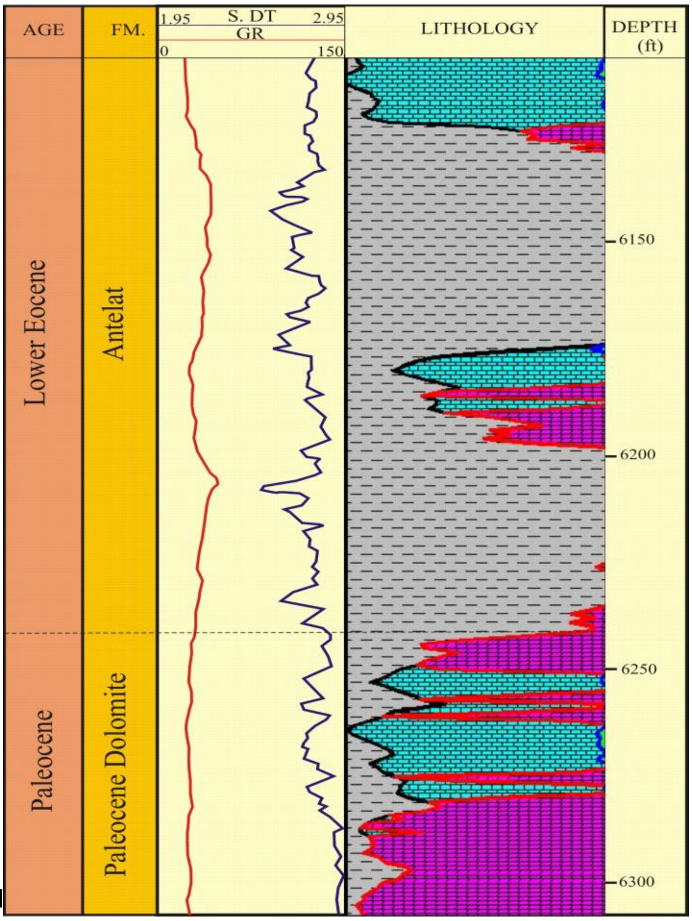

Figure 4. Lithologic section of the Antelat Formation in well D1-41, constructed from density and gamma-ray log responses. The section illustrates interbedded argillaceous limestone, carbonate-rich intervals, and organic-rich layers within the Lower Eocene succession, highlighting vertical lithologic variability and intervals favorable for organic matter preservation.

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The Antelat Formation becomes deeper as it moves southwestwards towards the Ajdabiya trough where it reaches a maximum thickness of around 750 feet in well A1-41. It decreases in thickness as it moves eastward and can locally cease to exist.

A trough in the studied area has a southwest-north east trend as shown by thickness data and the eastern side of the trough is steeper than the western side. This steepness is thought to be due to tectonic activity which controls where sediment is deposited and what type of sediment is found there. The Antelat Formation has characteristics indicating it was formed in a low-energy, anoxic environment with low water circulation. This made it ideal for preserving organic material likely to become oil.

II. Materials and Methods

A comprehensive review of geochemical and petrographic data obtained from more than 15 exploration and appraisal wells in the Eocene succession of the western region of Cyrenaica has been conducted. The drilling project used information from Rock-Eval pyrolysis and total organic carbon (TOC) data obtained from drilling cuttings and composite chip samples. The samples were collected from the Eocene geological periods, including the Antelat Formation and shale. These data were gathered from previous drilling operations and laboratory studies conducted prior to the present exploratory project.

The parameters evaluated in this study by Rock-Eval pyrolysis are Tmax, S3, S2, S1 and total organic carbon (TOC). The hydrogen and oxygen indices, calculated as HI = 100(S2 / TOC) and OI = 100(S3 / TOC), provided a means to assess the depositional redox conditions, organic matter quality and kerogen type. The quality of source rocks and kerogen can be interpreted from the Rock-Eval results in accordance with established criteria [8]. This interpretation covers the thermal maturity of these source rocks. Kerogen type and quality are crucial in determining the petroleum potential of a region. Rock-Eval is a tool used to determine source-rock properties, and its results must be interpreted in the context of other geological data [9].

Petrographic analysis, supported by geochemical data from the cores, has been used to characterise lithofacies and determine the depositional mode [10]. Using a transmitted light microscope, a petrographic analysis was done to examine features including clay content, the textures of carbonates, diagenetic features and fossil populations. This type of analysis proved helpful in understanding how organic matter was preserved and helped explain variations in geochemical factors [11]. By integrating petrographic observations with geochemical data, the depositional settings of the Eocene formation can be better understood as well as controls influencing the enrichment of organic material in this formation.

Each cuttings sample was scrutinized for evidence of contamination and examined for analytical anomalies. Samples that belong to the Eocene stratigraphic section were the only ones that were utilised for interpretation. A multi-disciplinary study combining petrography and geochemistry has been conducted to assess the potential of Eocene source rocks in western Cyrenaica.

III. Results

The Eocene source rocks in northwestern Cyrenaica hold greater potential than the rest of the Cyrenaica succession, as shown in Table 1. The Lower Shale and Antelat Formations show high organic content and geochemical properties. Rich in organic material, the Antelat Formation has good to excellent organic content, with carbon ranging from 1.8 to 8.7 percent by weight, as illustrated in Figure 5. This is reflected in its carbon content, which ranges from 1.8% to 8.7% by weight. Here, rock samples from this part of Libya contain large oil deposits. The rock samples from this part of Libya contain over 80 milligrams of hydrocarbon per gram.

The hydrogen index typically ranges from 630 to over 950 mg HC/g TOC. The organic material in question is oil-rich. Under low oxygen index values, generally below 15 mg CO_2 per gram of organic carbon, there are sediments which were laid down in a low oxygen sea environment. The carbon isotope ratio indicates that the source rocks were formed in a marine environment. The δ13th carbon isotope value of the organic material in the Antelat Formation is low in comparison with Cretaceous source rock intervals as shown in figure 6. The fact that conditions at the time of burial were more restrictive, contributing to the preservation of the organic marine material.

Conditions here are well-suited for preserving organic material containing fats and for reducing oxidative degradation during burial. The Lower Shale has an organic content of 3.6-3.9 weight percent. This compost has a high hydrogen content of 960 to 970 milligrams of organic compound per gram of organic matter. The kerogen from this northeastern Libyan location contains a high proportion of hydrogen. This is comparable to the hydrogen in Type I-II kerogen. Compared to the Antelat, the Lower Shale Formation is thought to be more hydrocarbon-rich and to have a greater capacity to generate oil and gas.

TABLE I. Summary of Rock-Eval geochemical data from selected wells in north-western Cyrenaica

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Well Name	AVE Depth (ft)	Formation	TOC	S1	S2	S3	Tmax	HI	OI
D1-41	6109.3	Antelat	2.40	1.04	18.50	0.29	427	770	12
D1-41	6715	Antelat	1.86	1.22	13.20	0.09	429	708	5
C1-41	7067	Antelat	8.74	3.72	80.65	0.42	436	923	5
C1-41	6715	Antelat	3.03	2.46	28.87	0.15	429	953	5
C1-41	6725	Antelat	2.66	2.64	23.45	0.08	431	880	3
D1-41	6108	Antelat	1.99	0.88	12.62	0.29	430	634	15
B1-33	10761	Barremian	0.53	0.31	0.48	0.14	437	91	26
E1-NC152	11980	Barremian	0.29						
H1-41	7403	Lower Shale	3.59	2.02	34.92	0.19	425	972	5
H1-41	7419	Lower Shale	3.90	2.18	37.47	0.08	425	961	2
B1-33	11885	Neocomian	0.53	0.12	0.27	0.04	442	51	8
A1-NC152	9446.9	Ceno.-Turonian	0.58	0.04	0.32	0.08	429	55	14
D1-NC152	6110	Turonian	0.46						
A1-19	6600	Lower Cretaceous	0.41						
A1-19	5640	Lower Cretaceous	0.43						
A1-NC-129	10810	Cretaceous	0.51	0.17	0.60	0.21	443	118	41
A1-NC-129	10783	Cretaceous	1.29	0.47	1.95	0.22	445	151	17
A1-NC-129	11136	Cretaceous	2.17	1.54	3.93	0.33	448	181	15
A1-NC-129	11151	Cretaceous	1.88	1.73	3.43	0.35	448	183	19
A1-NC129	10792	Cretaceous	1.63	0.87	2.81	0.30	443	173	18
A1-NC152	10500	Cenomanian	0.62	0.15	1.10	0.13	432	179	21
B1-NC152	12303	Cenomanian	0.43						
B1-NC152	12286	Cenomanian	0.28						
B1-NC152	12418	Cenomanian	0.44						
B1-NC152	12009	Cenomanian	0.57	0.35	1.00	0.16	439	176	28
D1-NC152	7110	Cenomanian	0.54	0.10	0.82	0.10	433	151	18
D1-NC152	7500	Cenomanian	0.43						
I-41	14150	Coniacian	0.40						
A1-NC152	11880	Daryanah	0.64	0.09	0.53	0.38	438	82	59
A1-NC152	11940	Daryanah							
A1-18	2250	Albian-Aptian	0.28						
A1-18	2970	Albian-Aptian	0.38						
F1-41	8862	Tanezzuft	1.12	0.29	2.23	0.14	430	199	12
A1-31	9601	Tanezzuft	0.59	0.27	1.01	0.02	440	171	3
F1-42	8855	Tanezzuft	1.62	0.56	4.40	0.08	428	271	5

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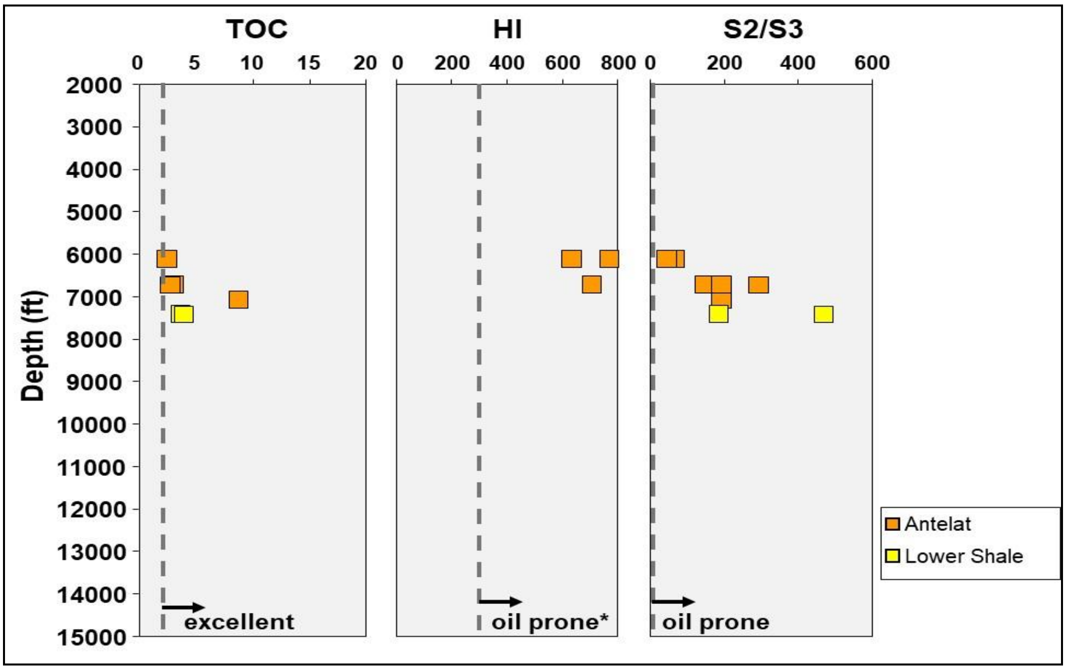

Figure 5. Depth versus total organic carbon (TOC), Hydrogen Index (HI), and S2/S3 ratios for Eocene source rocks in western Cyrenaica. Data are shown for the Antelat Formation and the Lower Shale, highlighting excellent organic richness, oil-prone kerogen characteristics, and strong hydrocarbon generative potential.

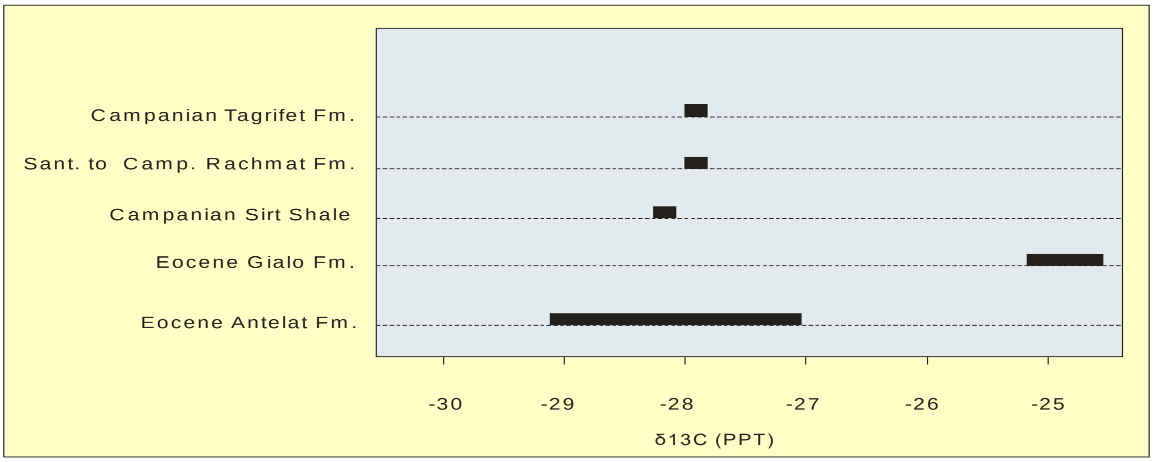

Figure 6. The $\delta^{13}C$ (PDB) value for the carbon in the organic material from the Eocene Antelat Formation in northern Libya is lower compared to that of Cretaceous source rock layers. This shows organic material from marine environments is preserved more under certain conditions when being deposited.

In the lower shale the mean values for the total organic content, S2, and HI are greater compared to the Antelat formation with values of 3.75 percent for the total organic content, 36.2 milligrams of HC for every gram of rock for the S2 and 966 milligram HC/g TOC for the HI. The OI was found to be 3.5 mg CO2/g TOC in the lower shale. The variations suggest that there was less deposition and more preservation of the oilbearing organic matter within the Lower Shale.

For all Eocene samples, hydrogen index-oxygen index cross-plots (Figure 7) reveal a distinct oil-prone kerogen population. In the HI vs. OI plot, both Antelat Formation and Lower Shale samples fall into the Type I–II kerogen category, showing high HI values (greater than 600 mg of HC/g of TOC) and very low oxygen indices (less than 15 mg of CO_2/g of TOC). The Lower Shale is the most gas-rich part of the field.

The good generative potential of the Eocene source rocks is illustrated by TOC/S2 relationships (figure 5). The organic richness and source-rock qualities of both intervals fall into the excellent-to-good class of oil-prone source rocks.

Across the study area, Tmax values vary between roughly 425 to 436 degrees Celsius, pointing to thermal maturity that falls in the immature to early oil window category. The majority of the oil samples collected in the Eocene are beneath the maximum levels of oil production, suggesting that the oil could not have been produced under the current depth. The lowest area in the Ash Shulaydimah Trough appears to be where the local sedimentation is oldest.

Further thermal history modelling of the petroleum system in western Cyrenaica confirms the geochemical conclusions that the source rocks were confined to the Eocene kitchen area. Within the Ash Shulaydimah Trough, the burial and thermal maturity of the one dimensional Antelat Formation suggests hydrocarbons began generating in the Eocene with production peaking at the periods when the trough was at its maximum burial before the Neogene uplift. The history, as modelled, of hydrocarbon expulsion indicates that such expulsion was restricted in time and space; this is consistent with the limited volumes of migrating charge suggested by Rock-Eval pyrolysis data.

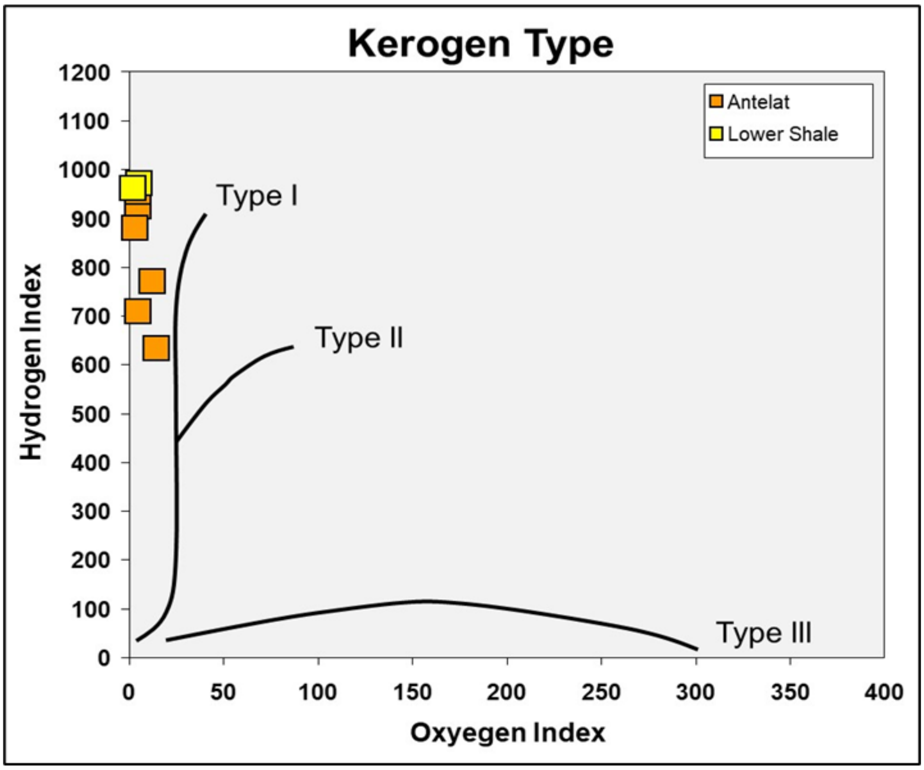

Figure 7. Hydrogen Index (HI) versus Oxygen Index (OI) diagram for Eocene source rocks in western Cyrenaica, showing samples from the Antelat Formation and the Lower Shale. Most data plot within the Type I and Type II kerogen fields, indicating highly oil-prone marine organic matter deposited under restricted conditions.

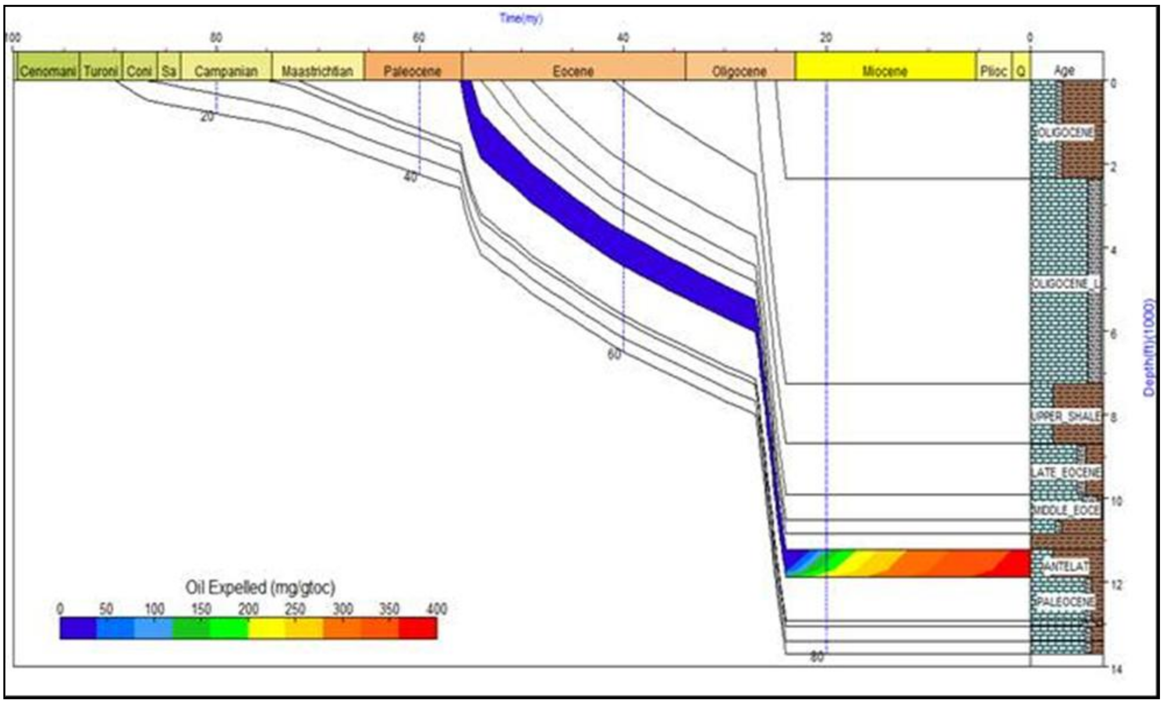

Figure 8. One-dimensional burial and thermal maturity model showing hydrocarbon generation and expulsion history of the Antelat Formation in the Ash Shulaydimah Trough. Colour shading indicates cumulative oil expelled (mg/g TOC), highlighting localized Eocene hydrocarbon generation prior to Neogene uplift.

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IV. Discussion

A. *Source Rock Quality and Depositional Controls*

The Eocene source rocks of western Cyrenaica have represented the best-quality source-rock interval for petroleum in the area. Under conditions typical of the restricted marine environment the organic matter prone to forming oil was preserved. This is shown by both the exceptionally high values for the HI and the very low OI values combined with a TOC figure that is high. Characteristically, these geochemical signatures are indicative of environments at the water-sediment interface that have limited oxygen availability, and environments which have reduced bioturbation and in which organic matter has been preserved.

In the Antelat Formation, sediments of a low energy marine environment were deposited. The conditions were such that they allowed organic material to settle on the sea bed. Under different circumstances, the Lower Shale shows more persistent reducing conditions. This is shown by its mean HI value being greater and its OI value being smaller. In the northeastern region of Libya, specific conditions led to a higher preservation of hydrogen, resulting in kerogen rich in hydrogen, among the richest in the region. Key differences in the geochemistry of the two sequences indicate there were slight changes in the manner in which the sediments were deposited.

B. *Kerogen Type and Thermal Maturity*

The HI - OI diagram reveals that both Eocene intervals contain mainly kerogen of the oil-prone type I and II. The HI-OI plot (figure 7) illustrates that kerogen for Lower Shale samples and Antelat Formation samples is primarily composed of Type I and Type II kerogen. The kerogen types in question have a high atomic ratio of hydrogen to carbon and a low atomic ratio of oxygen to carbon. This type of kerogen is frequently found in North African oil fields where there is an abundance of liquid hydrocarbons [12]. In this area post-Cretaceous strata show occurrences which are uncommon. High initial production rates were recorded in the Lower Shale; in some instances these rates reached or exceeded 970 milligrams of hydrocarbon per gram of organic content. Located in one of the region's most prospective source rock reservoirs for oil, this well sits.

The relationship between total organic carbon content and oil saturates indicates that the organic richness of the rock is a direct indicator of its hydrocarbon generation potential. In the area of Cyrenaica, the source rock itself does not appear to pose a limitation to the generation of oil from the Eocene age.

While most of the region exhibits geochemical characteristics of mature Eocene source rocks, they are immature, almost maturing. This maturation profile indicates that almost all samples are below the oil window. Given the current depth at which the samples are buried, hydrocarbon generation is reduced significantly. The reservoir's oil has low degrees of maturity. This is largely because of two reasons; The area, geologically speaking, is very young, having been only lightly buried. There has been considerable progress made in the past. With this process oil has been formed at lower temperatures than would otherwise be the case. The oil did not reach the formation temperature.

It is thought that hydrocarbon generation in the Ash Shulaydimah trough took place at its base. Here, the rocks which are the source of the hydrocarbons are buried deeply. In these areas with limited storage space, the petroleum reservoir was split into different sections and the oil was stored for a relatively short period. This may have lessened the effectiveness of oil release and the overall oil supply.

C. *Implications for Exploration*

The lack of commercial Eocene oil and gas in western Cyrenaica is best attributed to limitations in the charge. This is more so than a lack of good quality source rocks in the area [13]. The Eocene petroleum system has been hindered by limited thermal maturity, restricted kitchen volumes and structural complexity. While the region's source rocks appear to be less oil-prone than initially thought, certain structural depressions may still be worth exploring for oil.

Investigations into hydrocarbon potential should centre on detecting, within the Ash Shulaydimah trough, buried or structural Eocene sediment traps which might possess sufficient thermal maturity to produce oil and gas. In western Cyrenaica Eocene petroleum systems, integrating basin modelling, structural restoration and a more detailed maturity model should be crucial for reducing exploration risks.

V. Conclusions

The petroleum source rock potential of the Eocene deposits in the western Cyrenaican Ash Shulaydimah Trough was examined by combining geochemical, petrographic and modelling techniques. The top-level source rock in this region is the Early Eocene Antelat Formation and the Lower Shale Series.

The samples are both very rich in organic matter and contain a high proportion of Type I or Type II kerogen, which can form oil. The low oxygen index and depleted carbon-13 isotope levels in the core suggest marine organic matter deposited under low-energy conditions and low-oxygen conditions. The fact that source rock is of good quality shows that it is not a limiting factor in the Eocene petroleum system of the region of western Cyrenaica.

Although the source rock's qualities are highly beneficial, most Eocene intervals are immature to early-mature. It appears that Neogene uplift and erosion reduced the oil window's residence time and maximum burial depth, thus limiting hydrocarbon production. Hydrocarbon generation is restricted to areas of the Ash Shulaydimah Trough where the Eocene source rock is located at its deepest.

The oil discovery by the AGOCO in well D1-NC-129 independently confirms that the Eocene source rock in the area is able to generate oil under the correct burial conditions. In this Eocene petroleum province the significant exploration risk is the charge, rather than the presence of the source rock. Further research should focus on stratigraphically more complex depocentres with adequate preservation of the burial history and the integrity of post-generation traps.

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