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Accepted Manuscript

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DOI: 10.22059/geope.2025.401107.648839

Receive Date: 21 August 2025
Revise Date: 13 November 2025
Accept Date: 29 November 2025

Source rock characterization of shale deposits (Eocene) of Kohat Basin, Pakistan

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Received: 21 August 2025, Revised: 13 November 2025, Accepted: 29 November 2025

Abstract
Kohat Basin is a well-known petroliferous basin of Pakistan. The current study emphasizes the origin and source rock characterization of Eocene shale deposits in three surface outcrops in the Kohat Basin. Problem statements include limited data availability, understanding complex depositional environments, accurately measuring thermal maturity, and resolving the influence of drilling contaminants on geochemical parameters. The main objectives of the current study were to evaluate the source rock characteristics and geochemical properties of organic matter contained in Eocene shale deposits. These objectives were fulfilled by X-ray diffraction (XRD), total organic carbon content (TOC), Vitrinite Reflectance (R_O), and Rock-Eval Pyrolysis analyses of shale samples collected from the Dharangi, Naripanos, and Karak sections of the Kohat Basin. XRD analysis shows that the Eocene shale of the Kohat Basin is rich in clay minerals, such as illite-smectite and kaolinite, with smaller amounts of quartz, plagioclase, and K-feldspar. Gypsum, halite, chlorite, and pyrite were present as minor constituents. The TOC values range from 1.60 wt. % to 2.90 wt. %, indicating a good to very good potential source rock. The Oxygen Index (OI), Hydrogen Index (HI), and T-max parameters from Rock-Eval pyrolysis indicate that the Eocene shale comprises type II and type II/III Kerogen, which can generate oil and gas-oil at appropriate temperatures. Vitrinite Reflectance (R_o) values ranged from 0.42 % to 1.28 %, indicating the immature to mature zone of thermal maturity. Overall, it has been evaluated that the Eocene shale of the Kohat basin has good potential for hydrocarbon generation, which can play a significant role in hydrocarbon prospectivity within the Kohat Basin.

Keywords: Source Rock, Eocene Shale, Rock-Eval Pyrolysis, Vitrinite Reflectance, Kohat Basin.

Introduction

The Kohat Basin is a significant geological region owing to its rich deposits of oil, gas, gypsum, and salt (Ahmad et al., 2024). These resources play a substantial role in the regional economy. The Kohat Basin is famous for its hydrocarbon resources owing to its notable oil fields, including Nashpa, Chanda, Makori, Shakardara, and Gurguri (Nawaz et al., 2015), making it a strategic area for hydrocarbon exploration. In addition to hydrocarbons, the Kohat Basin comprises gypsum and salt deposits that support various industrial and local livelihoods. Hence, these resources drive the region's economic development. Source rocks are fundamental components of petroleum system. Therefore, it is essential to examine the source rock and its characteristics to identify the petroleum system in a petroliferous basin. The Eocene shale can act as a good source rock in the Kohat Basin because of its black color in the outcrop. However,

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the organic content and thermal maturity of these shales have not been investigated in the Kohat Basin. The degree of thermal maturity plays a pivotal role in determining whether a source rock generates oil, gas, or enters the condensate window, which is evaluated by the chemical characteristics and distribution prediction of the source rock (Chen et al., 2024; Xiao et al., 2024). The types of organic matter also play a significant role in defining the petroleum products (Alipour, 2025). The Kohat-Potwar Fold and Thrust Belt (Fig. 1a) is located north of the Lakki Marwat and Bannu Districts, and south of the Kohat District, along the Indus Highway (lat. 33º 09′ 54″ N and long. 70º 59′ 53″ E). This basin boasts 48% of the world's acknowledged petroleum potential owing to its location along the continental margin, which has accumulated thick sedimentary deposits within the depression. This basin is characterized by a thick sequence of fluvial sedimentary layers, creating ideal geothermal conditions due to the depth of burial. This depth allows for the maturation of hydrocarbons and their eventual migration within the basin (Khan et al., 1986). The Kohat sub-basin is a highly productive region for oil and gas exploration because of its unique geological characteristics. The hydrocarbon potential is evaluated based on the abundance of organic matter, degree of maturity, and quality of rocks (Li et al., 2023; Siyar et al., 2023; Yang et al., 2024).

Previously, Porth and Raza (1990) revealed that a high-quality oil shale layer was present approximately between 27m to 30m located at the bottom of Jatta Gypsum (Eocene) within the Kohat Basin. However, these authors did not conduct geochemical analyses on oil shales to evaluate the quantity, quality, and maturity of the organic matter contained therein. Fifty surface channel and composite samples were collected from selected sites to determine the total organic content and other geochemical parameters. Due to the complicated structural deformation of the area and salt diapirism of variable intensities, carbonaceous Eocene shale deposits are widely dispersed and infrequently exposed.

Petroleum geoscientists evaluate the volume to measure the source rock potential, hydrocarbon potential, and geochemical characteristics (Reda et al., 2022; Abdel-Fattah et al., 2024; Zhao et al., 2025).

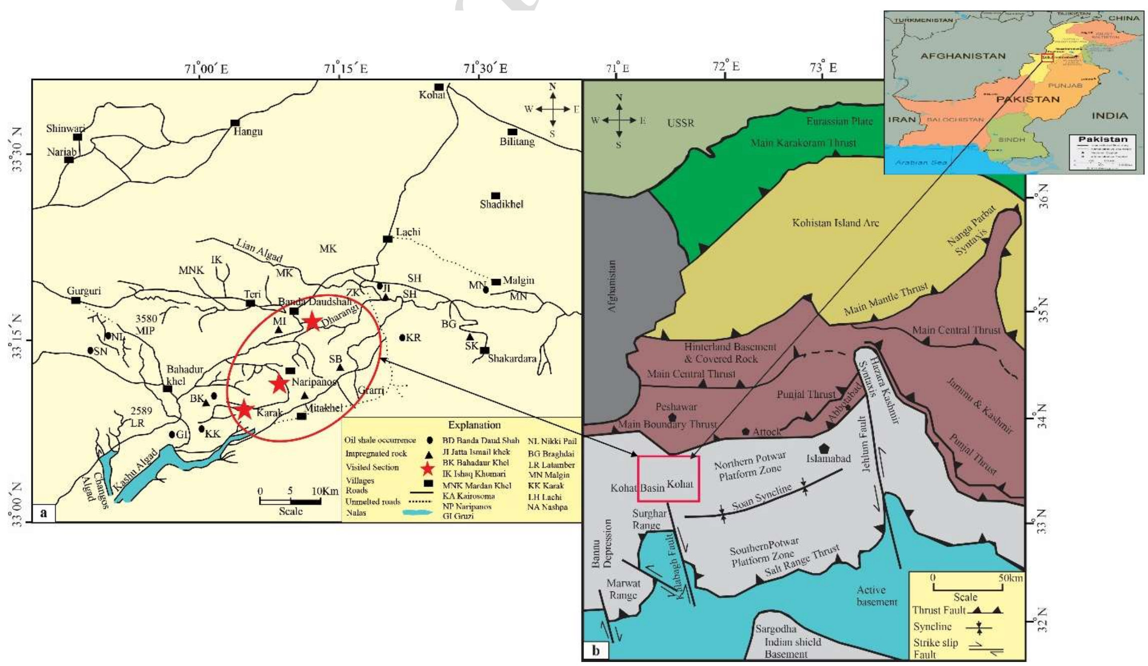

Figure 1. a. Show the location map of the study area, Kohat Basin, KPK, Pakistan; 1b;Showing tectonic map of Northern Pakistan, with subdivisions of the Himalaya (after Chaudhry and Ghazanfar, 1997)

Occasionally, the shale horizons exhibit minimum thickness or may not be present at all, revealing a clear and distinctive boundary between the carbonaceous shales and gypsum beds. Eocene shale has a thickness ranging from 0.5 to 1.5m, containing total organic carbon (TOC) of up to 25 %, accompanied by an oil yield of 20 % (Khan et al., 2020; Ahmad et al., 2022; Al-Eid et al., 2025). Problem statements associated with source rock characteristics focus on the accurate identification, quantification, and understanding of factors that affect the hydrocarbon generation potential. The main objectives of the current study are as follow: 1) to evaluate the geochemical properties of the organic matter contained in shale deposits; and 2) to assess the source rock characteristics.

Regional geology

Pakistan is situated in a prominent and distinctive worldwide structural system (structural plates). This system comprises the Indo-Pakistan, Eurasian, and Arabian Plates (Molnar et al., 1975). According to Kazmi and Jan (1997), the Himalayan orogenic belt in northwestern Pakistan was created by the collision of the Indian and Eurasian Plates, which began approximately 55 million years ago. The Kohat Basin (KB) is the western part of the Himalayan Foreland Folds and Thrust Belt, which is 70 km wide in the north-south direction. Geographically, the KB is restricted in the north by the Main Boundary Thrust (MBT), the Surghar Range in the south, and the Kurram Fault demarcates the western boundary (Khan *et al*., 1986)(Fig. 1b). The Kalabagh strike slip fault separates the Surghar Range from the Salt Range (Fig. 1b). Towards the south, the Bannu Basin demarcates undeformed sediments from the southern boundary of the basin.

The Kohat Sub-Basin is situated within the northern Foreland and Thrust Belt of the Himalayan Range. The unique characteristic of the Kohat Basin is its specific thrust system, which is partially influenced by the presence of an evaporite sequence serving as a base decollement (Jaume and Lillie, 1988). Several detachments below the Kohat Basin have been identified using various data sources, from both the surface and subsurface. The detachment layer primarily consists of evaporates, specifically Jatta Gypsum and Bahadur Khel Salt, extending from its base to an intricate duplex structure at its uppermost part. The duplex structure involves the overlapping of Mesozoic-Paleozoic successions. The complex structural geometry within the basin is due to thrust faults, as well as oblique and high-angle reverse faults (Ahmad et al., 2024). This complex tectonic environment and the presence of thrust sheets have contributed to the favorable thermal maturity and good source rock potential exhibited by shales within the Jurassic and Eocene rock units (Fig. 2). Generally, all the structures show an E-W orientation and southward vergence. Deformation is manifested in fan folds, isoclinal folds, thrust faults, drag folds, diapiric movement of salt, flowage of clay, and expression of gypsum beds. The structural complexities are more severe due to widespread salt diapirism in the studied basin. The Eocene strata are typically found at the core of tight, narrow, and thrusted anticlines. The structures associated with salt diapirism are tight anticlines separated by broad synclines. Synclines are open, have a wide aerial extent, and are generally accompanied by major faulting. They are covered by Miocene and Plio-Pleistocene sediments (Raza et al., 1993).

The well-exposed sedimentary deposits found in the studied area comprise deposits from the Paleocene to Pliocene (Fig. 2). The Jurassic to Triassic rock units are present in the subsurface but are not well exposed in the study area. The Paleocene rocks (Hangu Formation, Lockhart Limestone, and Patala Formation) present in the studied area comprise of clastic and carbonates. The Hangu Formation consists of sandstone and shale intercalations with subordinate limestone. Generally, medium to thickly bedded sandstone with shale intercalation is predominant in the upper parts. The Lockhart Limestone consists of grey to medium-grey limestone characterized by medium to thick-bedded fossiliferous limestone at the base. The

Patala Formation consists of shale and marl with limestone and sandstone, as well as minor constituents of coal seams in some places. The Eocene succession consists of carbonates and evaporite deposits in a marine environment (Pivnik and Wells, 1996) (Figs. 3a, b, e). Bahadur Khel Salt is composed of massive bedded white to pink salt, with dark colored bituminous material that emits an unpleasant odor and may contain traces of pyrite in places. The Jatta Gypsum consists of green to white massive gypsum, and the Kohat Formation consists of interbedded limestone and shale.

The Miocene to Pliocene molasses strata consist of clastic deposits: the Rawalpindi Group, including the Murree and Kamlial Formations (Early to Middle Miocene), and the Siwalik Group (Middle Miocene to Pliocene)(Fig. 2). The Murree Formation consists of purple to dark red clay, and medium to coarse-grained purple-grey sandstone with subordinate conglomerates. The Kamlial Formation consists of medium to coarse-grained grey to dark brick red spheroidal sandstone (Fig. 3c) with purple shale and conglomerates.

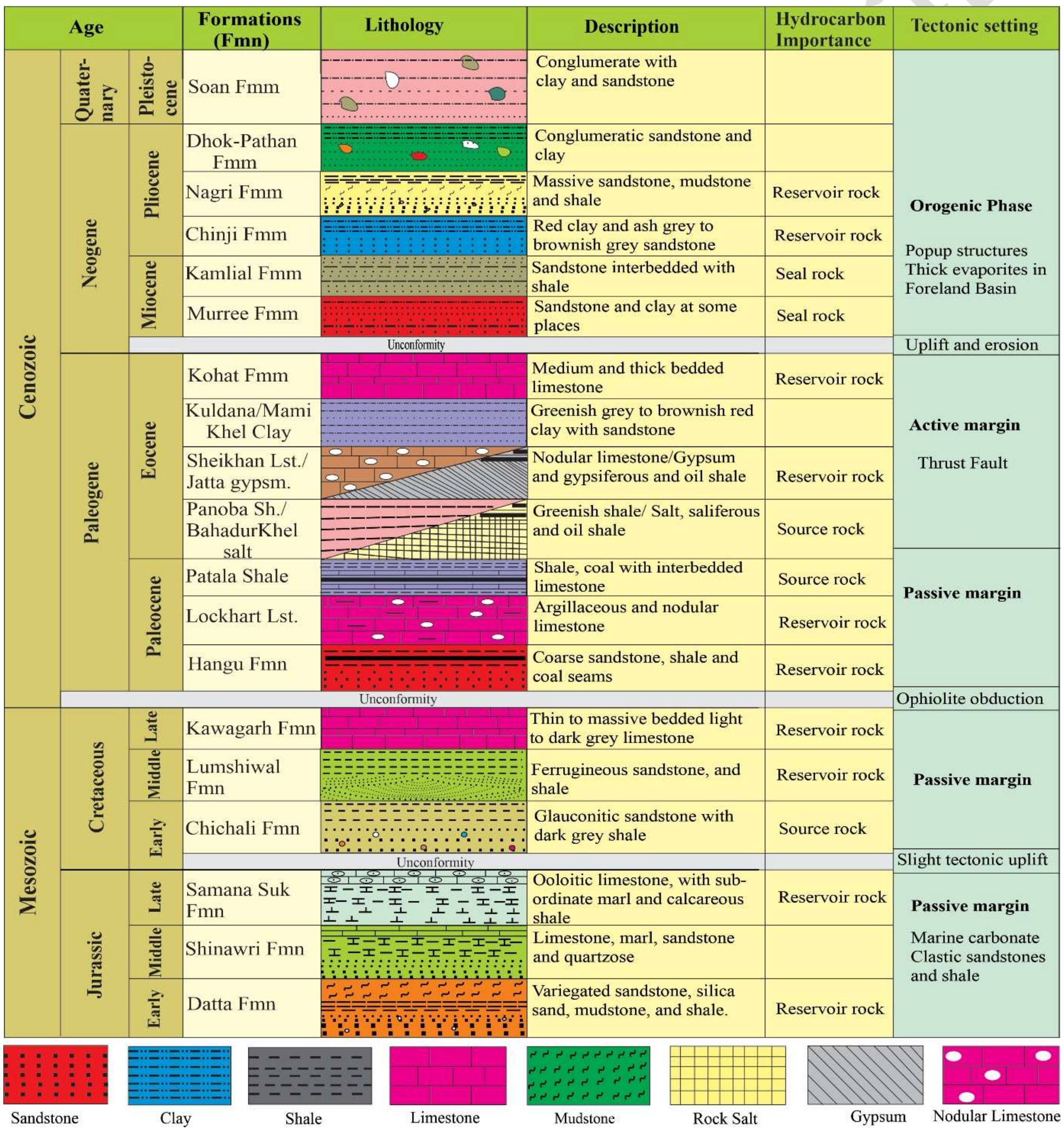

Figure 2. Stratigraphic section of the study area, Karak, KP, Pakistan

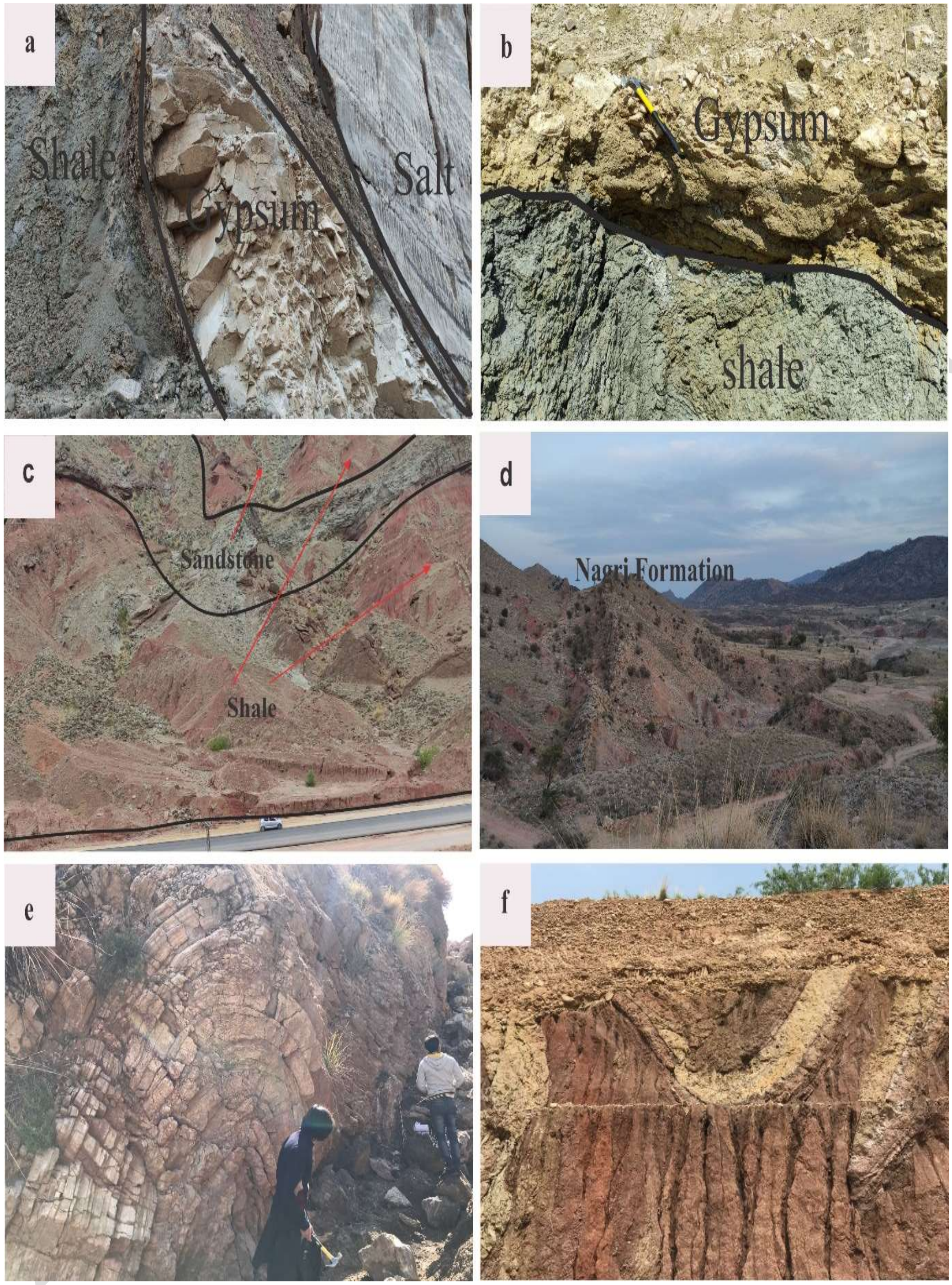

Figure 3. a). Contact between Kerogen Shale, Jatta Gypsum, and Bahadur Khel Salt; (b) Contact between Kerogen Shale and Jatta Gypsum; (c) Chinji Shale with subordinate Sandstone; (d) Nagri Formation; (e) Anticline fold in Jatta Gypsum, which shows angular unconformity; (f) Syncline fold

The Chinji Formation comprises red clay, with sporadic occurrences of grey or brownish grey ash, along with sandstone. The sandstone is fine to medium-grained with occasional gritty, cross-bedded structures. The Nagri Formation consists of massive and thick-bedded pebbly sandstones with claystone and siltstone (Fig. 3d). The Dhok Pathan Formation is composed of brownish claystone and hematic sandstones. The clay within the formation shows variegated color, characterized by its calcareous and sandy composition.

Methodology

Three well-exposed sections from the Kohat Basin were selected for detailed analysis to evaluate the source rock potential of carbonaceous Eocene shale from Dharangi (5ft), Naripanos (6ft), and Karak (5.5ft) areas. A total of 45 samples were collected from the three studied sections (15 samples from each section)(Fig.4), from which 15 rock samples (5 samples from Dharangi and Naripanos and 3 from Karak section) were selected from the outcrop for Total Organic Carbon (TOC), Rock-Eval Pyrolysis (Delsi-Nermag Rock Eval II Plus TOC module), and Vitrinite Reflectance, and 9 (3 from each) samples from the Dharangi, Naripanos, and Karak sections were selected for X-Ray diffraction (XRD). X-ray diffraction is the primary tool used to obtain chemical composition and mineralogical examinations, especially for fine-grained sediments. A diffractometer was used to conduct XRD analysis on powdered samples of 1-50 µm. XRD is used to generate a diffraction pattern by exposing a crystalline sample to X-rays, and analyzing the resulting peaks to determine the phase identification, crystal structure, lattice parameters, crystallite size, and texture. The selected XRD samples were arranged for XRD examination in the XRD laboratory CRL (Central Resource Laboratory) at the, University of Peshawar.

Figure 4. a). Presence of Kerogen Shale on Eocene evaporites in Karak Section; (b)Sampling from Karak Section; (c) Sample collection from Naripanos Section; (d) Sample collection in Dharangi Section

In total organic carbon (TOC) analysis, a 300 mg pulverized rock sample was subjected to controlled and programmed heating (combustion that oxidized carbon to CO_2 at high temperature) in an inert helium environment, yielding the TOC (using the LECO-CS 300 TOC analyzer) values expressed in weight percentages. After conducting a TOC analysis, the rock samples with TOC values >0.50% were chosen for additional geochemical examination such as Rock-Eval pyrolysis. The Rock-Eval Pyrolysis was used to evaluate the source rock potential for generating hydrocarbons. Rock eval pyrolysis heats the powdered rock sample under an inert gas to assess its organic matter content and thermal maturity for petroleum exploration. The process involves measuring the release of hydrocarbons and carbon dioxide during the heating stages to calculate various parameters. The key parameters assessed by Rock-Eval pyrolysis are S_1 (free hydrocarbons), S_2 (hydrocarbons produced during the thermal cracking of kerogen), and S_3 (release of oxygen) yields. The Rock-Eval method includes the determination of the maximum temperature (T-max, in ^{0}C) at which the S_2 peak exhibits its maximum generation rate, making it a valuable parameter for evaluating organic matter thermal maturity. The Oxygen Index (OI), Hydrogen Index (HI), and Production Index (PI) are useful for evaluating the potential of source rocks. Vitrinite reflectance (VR_o%) was used to evaluate the thermal maturity of the organic matter. The utilization of vitrinite reflectance (VR_o%) measurements is widely acknowledged as a reliable and standardized technique for measuring the thermal maturity of source rocks. Rock Eval Pyrolysis, TOC, and VR_o% measurements were performed in the laboratories of HDIP Islamabad, Pakistan.

Results

Geochemical analysis to evaluate the source rock characteristics

The source rock evolution process relies on the measurement of three main geochemical parameters: organic matter richness (i.e., quantity of organic matter), thermal maturation (i.e., maturity of organic matter), and type (i.e., quality of organic matter) (Tissot and Welte, 1984). The most commonly used techniques for evaluating these parameters are Rock-Eval Pyrolysis, and organic petrography.

TOC values

The studied samples showed moderate to very good source rocks. In the Dharangi section, the TOC values vary between 1.6 wt.% to 2.9 wt.% (with an average of 2.2 wt.%) (Table 1a). In the Naripanos section, TOC values vary between 0.60 wt.% to 2.6 wt.% (average 1.7 wt.%). In the Karak section, TOC values vary between 1.6 wt. % to 2.0 wt. % (an average of 1.8 wt.%). The maximum TOC value indicates very good hydrocarbon potential, and the minimum TOC value indicates fair to good hydrocarbon potential of the source rock **(**Fig. 5**)**.

Mineralogy by XRD analysis

The XRD analysis showed that the studied samples of Eocene shale were rich in clay minerals that is illite-smectite and kaolinite, with smaller amounts of quartz, plagioclase, and k-feldspar. Gypsum, halite, chlorite, and pyrite were present at minor concentrations (Fig. 6). Clay minerals play a significant role in preserving organic matter, manipulating porosity (pore structures that impact hydrocarbon migration), and affecting hydrocarbon preservation within sedimentary rocks. These minerals can act as physical and chemical shields that protect organic matter from decomposition and endorse its accumulation. The presence of gypsum and halite in the Eocene shale indicates that it was deposited in lagoon environments by evaporation of saline water. It is possible that the basin experienced an influx of water, followed by evaporites, leading to the deposition of gypsum in Eocene shale. Similarly, the presence of halite can also be suggested to have been deposited in evaporites of water in arid or semi-arid environments. These salt deposits could be carried by water into the basin and then concentrated through evaporation, leading to their incorporation into the shale. Overall, it can be concluded that the presence of gypsum and halite can be attributed to the geological history of the basin, changes in environmental conditions, tectonic, and climatic conditions. Chemical composition of the studied shale samples consists of K^+, Al^{3+}, Mg^{2+}, SiO_4^{4-}, SO_4^{2-}, Ca^{2+} as major ions, followed by Na^+, Cl^-, CO_3^{2-}, as well as it consisting of Fe^2, Mn, Sr, Ba as trace elements (Tables 2a-e).

Rock Eval pyrolysis

The Rock-Eval pyrolysis (Table 1a) evaluates the significant indices, that is the S_1 (0-2.1) peak, S_2 (0.4-12) peak, and S_3 (0.1-1.2) represent the amount of emitted carbon dioxide. T-max values range from 411-446°C, and the Hydrogen Index (HI) ranges from 215-380, expressed hydrogen to Total Organic Carbon (TOC=0.6-2.9) ratio, represented as $100 \times S_2$ / TOC (Table 1a). The HI is correlated with the quantity of hydrogen in kerogen; high HI indicates a high potential for oil generation. This can provide details regarding the kerogen type. The Oxygen Index (OI) ranged from 16.6-55, and the production index (PI) ranged from 0-0.4.

Vitrinite Reflectance ($VR_{O\%}$)

Vitrinite reflectance ($VR_{o\%}$) is a key parameter for evaluating the maturation of source rocks. R_o measurements play a significant role in petroleum exploration by helping assess whether source rocks contain organic matter that has undergone sufficient thermal maturation to produce hydrocarbons (Dembicki, 2017; Hackley et al., 2018; Javed et al., 2024). In the Dharangi section, the R_o data ranged from 0.53% to 0.69%, with an average of 0.60 % (Table 1b).

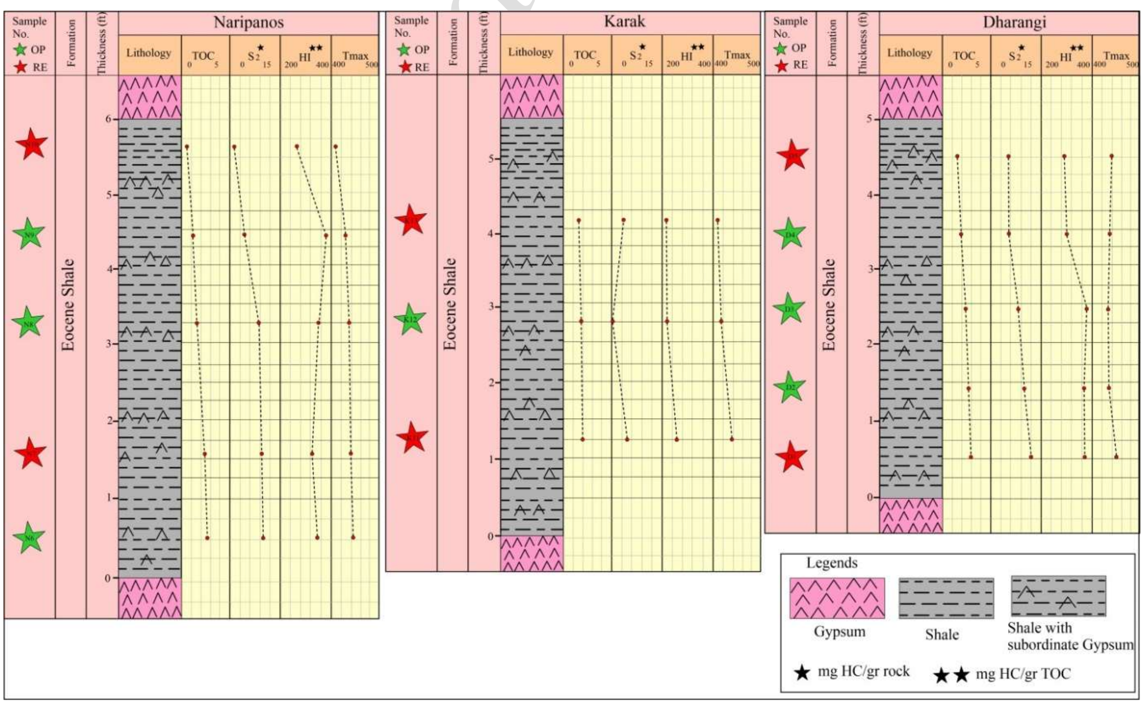

Figure 5. Showing the comparison of different stratigraphic sections with Indices of Rock-Eval Pyrolysis of Narpanos, Karak and Dharangi section

Table 1a. Rock Eval Pyrolysis indices (Eocene shale) of Dharangi, Naripanos and Karak sections, Kohat area, Pakistan

Indices/Component	Dharangi Section					Nari Panos Section					Karak Section		
	D1	**D2**	**D3**	**D4**	**D5**	**N6**	**N7**	**N8**	**N9**	**N10**	**K11**	**K12**	**K13**
TOC (wt%)	2.9	2.7	2.3	1.9	1.6	2.6	2.4	1.7	1.2	0.6	2	1.8	1.6
S1 (mg HC/g rock)	2.1	1.8	0.9	0.6	0.5	1.7	1.3	0.8	0.5	0.6	0.5	0	0.3
S2 (**mg HC/g rock**)	12	10	8.7	5.8	5.3	10	9.3	8.5	4.6	1.6	4.7	0.4	3.4
S3(mg CO_2/g rock)	1.2	0.8	0.8	1	1	0.8	0.7	0.5	0.4	0.1	0.6	0.4	0.3
GP (**mg HC/g rock**)	14.1	11.8	9.6	6.4	5.8	11.7	10.6	9.3	5	2.2	5.2	0.4	3.7
Tmax (°C)	446	432	432	435	439	442	439	435	426	416	437	417	411
HI (mg HC/g rock)	368	365	377	306	292	346	330	351	380	267	253	222	215
OI (mg CO_2/g TOC)	32	29	37	55	51	47	41	38	29.1	16.1	24.6	22.2	20.3
PI	0.4	0.2	0.1	0.1	0.1	0.3	0.2	0.1	0.1	0.3	0.1	0	0.1

Table 1b. Vitrinite reflectance (Eocene shale) of Dharangi, Naripanos and Karak sections, Kohat area, Pakistan

Section name	Sample no	Mean vitrinite Reflectance (VRo%)	Standard Vitrinite Descriptor (SDVE)	Number of readings	Range
Dharangi Section	D1	0.69	Peak Oil Window		0.6-1
	D2	0.55	Early Mature		0.5-0.65
	D3	0.53	Early Mature		0.5-0.65
	D4	0.61	Early Mature	5	0.5-0.65
	D5	0.65	Early Mature		0.5-0.65
Naripanos section	N6	0.64	Early Mature		0.5-0.65
	N7	0.62	Early Mature		0.5-0.65
	N8	0.60	Early Mature		0.5-0.65
	N9	0.60	Early Mature	5	0.5-0.65
	N10	1.23	Late Oil Window		0.9-1.35
Karak Section	K11	0.61	Early Mature		0.5-0.65
	K12	1.26	Late Oil Window		0.9-1.35
	K13	0.42	Immature	3	0.-0.5

Table 2a. Showing the chemical composition of D1, Dharangi section, Karak, KPK, Pakistan

Element	Weight %	Atomic %
K	31.55	35.90
Al	24.80	25.20
Si	22.89	21.46
Mg	15.17	13.35
Ca	1.60	1.10
Na	0.90	0.76
Fe	0.46	0.35
S	0.25	0.16
O	2.40	1.20
Cl	0.98	0.52
Total	100	100

Table 2b. Showing the chemical composition of D2, Dharangi section, Karak, KPK, Pakistan

Element	Weight %	Atomic %
K	29.98	34.12
Al	23.75	24.45
Si	23.54	20.5
Mg	15.80	13.32
Ca	1.92	2.10
Na	1.31	1.26
Fe	1.37	1.98
S	0.27	0.15
O	1.80	1.30
Cl	0.26	0.82
Total	100	100

Table 2c. Showing the chemical composition of NP7, Naripanos section, Karak, KPK, Pakistan

Element	Weight %	Atomic %
K	28.90	33.10
Al	22.70	23.41
Si	24.50	20.5
Mg	16.70	13.22
Ca	1.88	2.12
Na	1.34	1.28
Fe	1.40	1.96
S	0.29	0.17
O	1.80	1.30
Cl	0.26	0.82
Total	100	100

Table 2d. Showing the chemical composition of Np 1, Naripanos section, Karak, KPK, Pakistan

Element	Weight %	Atomic %
K	26.84	27.13
Al	24.45	24.85
Si	22.63	22.81
Mg	16.30	16.79
Ca	2.12	2.48
Na	2.01	1.6
Fe	1.63	1.73
S	0.72	0.85
O	2.70	1.50
Cl	0.60	0.38
Total	100	100

Table 2e. Showing the chemical composition of K6, Karak section, Karak, KPK, Pakistan

Element	Weight %	Atomic %
K	32.45	30.10
Al	23.40	25.40
Si	21.70	21.50
Mg	16.19	12.30
Ca	1.50	2.10
Na	0.87	1.22
Fe	0.45	1.92
S	0.23	0.17
O	2.20	1.30
Cl	0.89	0.84
Total	100	100

The highest value (0.69%) shows high maturation, indicating the presence of wet gas. The lowest reflectance values (0.53%) show an immature to maturation zone. In the Naripanos section, the R_o values vary from 0.60% to 1.23% with average of 0.80 % (Table 1b). The highest reflectance values (1.23%) indicate a late maturation zone with gas (above 1.1% and 2%). The lowest reflectance values (0.60%) represent the early maturation zone of the oil window. Whereas in the Karak section, the R_o data show variation range from 0.48% to 1.28% (Table 1b; Fig. 5) with an average of 0.70 %. The highest reflectance values (1.28%) represent the late mature zone with gas. The lowest value of reflectance, 0.48% shows the immature zone.

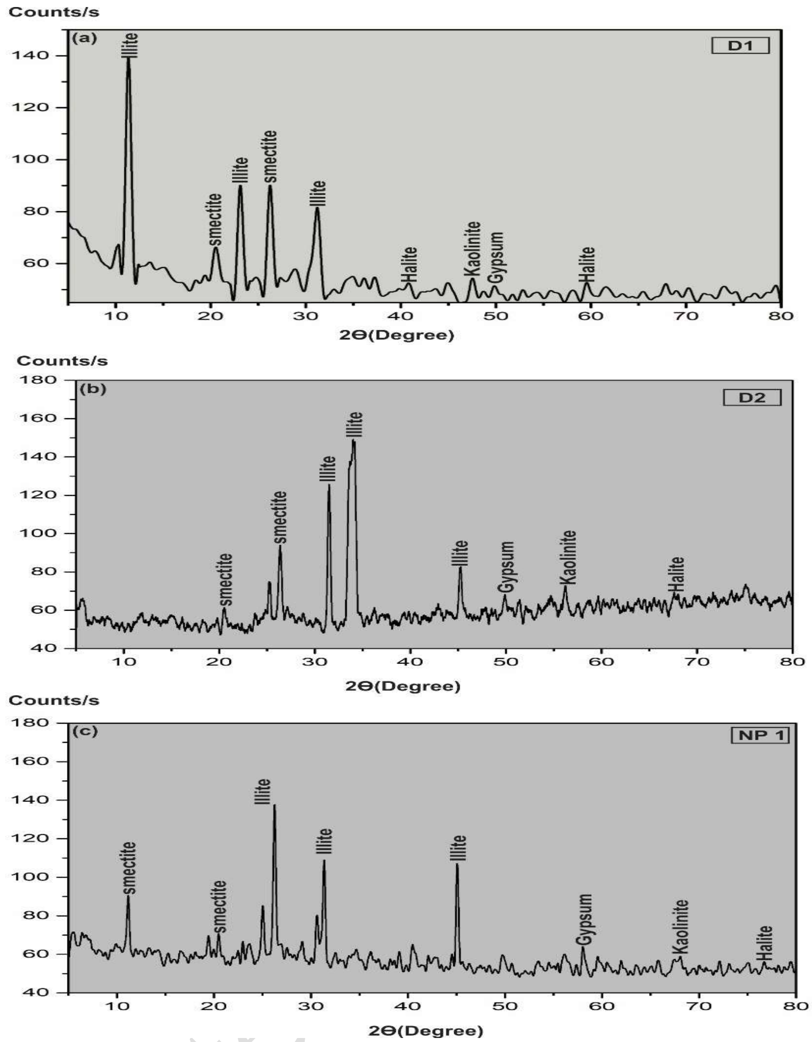

Figure 6. Shows the XRD graphs; (a) dominant mineral present in the sample D1 is illite and smectite; (b) the main mineral present in the sample D2 is illite and smectite; (c) the dominant mineral present in the sample NP1 is illite and smectite

Discussion

Source rock maturation and richness

The Dharangi section has average TOC and S_2 values of 2.2wt% and 8.3mg/g respectively, indicating good to very good hydrocarbon potential (Fig. 7). In the Naripanos section, average TOC and S_2 values are 1.7 wt% and 6.8mg/g respectively, suggesting poor to very good hydrocarbon potential. The Karak section averages of 1.8 wt % TOC and 2.8 mg/g S_2, also reflecting good to very good potential. The TOC vs S_2 plot confirms moderate to good hydrocarbon potential.

Relative Investigation of Hydrocarbon source rock indicators

Organic matter types and quality

Organic matter types are critical for assessing source rock generation potential and hydrocarbon characteristics. It is evaluated using Hydrogen index (HI: 215-380), T-max (411-446°C), and oxygen index (OI= 16.6-55). HI vs OI plot determines kerogen types (Fig. 9). In the Dharangi section, the HI ranges from 292 to 377 mg HC/g. The lowest value (292 mg HC/g, D5) indicates mixed kerogen type II/III (oil and/or gas), while other samples above 300 mg HC/g indicate type II kerogen with high oil potential. In Naripanos, the HI ranges from 267 to 380 mg HC/g; the lowest values (267 mg HC/g; NP5) suggests type II/III, while higher values indicates oil-prone type II kerogen.

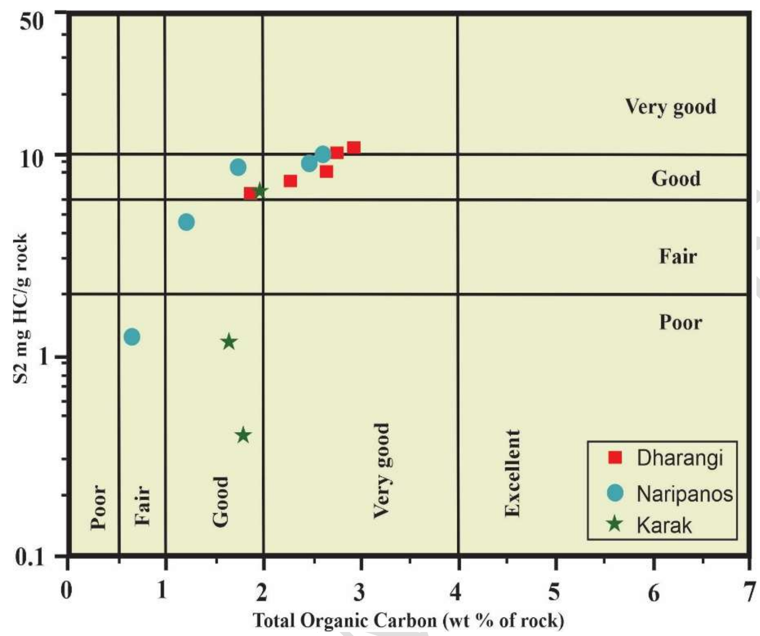

Figure 7. Shows S_2 mg HC/g rock and TOC showing organic richness

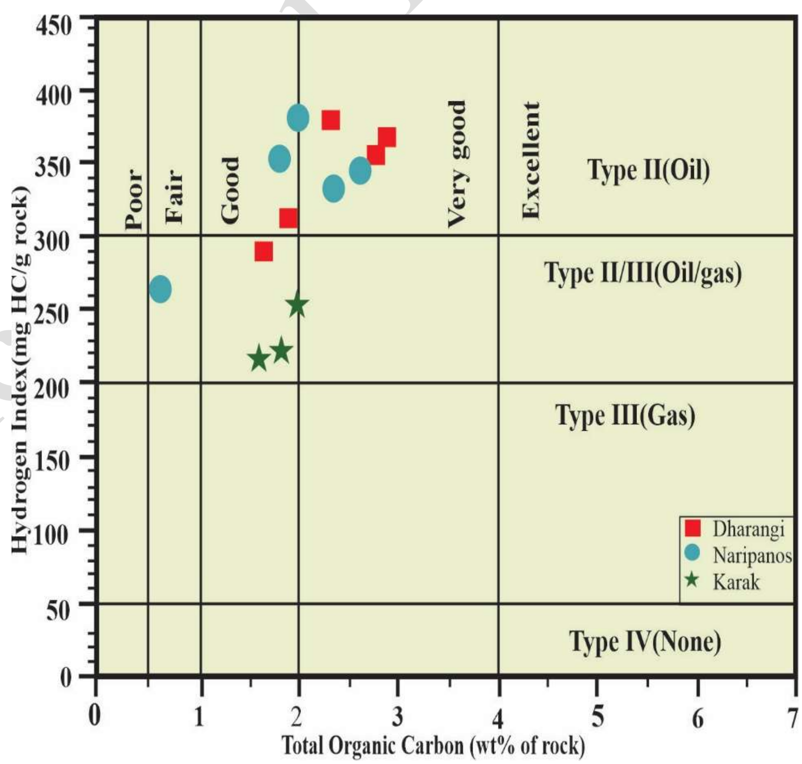

Figure 8. Plot of Hydrogen index (mg HC/g rock) and TOC representing the kerogen types and generation potential

In Karak, HI ranges from 215 to 253 mg HC/g, indicating Type II/III kerogen (oil and gas) (Fig. 9). The Van Krevelen diagram (Fig. 9) shows most samples are type II or II/III, suitable for oil and gas generation at appropriate temperatures. HI vs T-max plot (Fig. 10) confirm mix oil-gas and oil-prone in Dharangi and Naripanos, and oil-gas prone kerogen in Karak section. Overall, the source rock quality is moderate to high.

Thermal evolution characteristics

Organic matter maturation can be evaluated by critical Rock-Eval parameter, T-max, and the estimated Rock-Eval parameter (production index (PI). R_o values ranges from 0.50% to 0.70%, and 0.70% to 1.0% and 1.0% to 1.3%, indicates low-grade, medium-grade and high grade source rock respectively. In Dharangi section R_0 values ranges from 0.53 % to 0.69%, and T-max ranges from 432ºC to 446 ºC, indicates immature to mature stage (low-grade source rock) (Fig. 11). In Naripanos section the R_o and T-max values ranges from 0.60% to 1.23%, and 416ºC and 442ºC respectively, indicating immature to early mature stage (low to high grade source rock) (Fig. 11). In the Karak section, R_o and T-max values ranges from 0.42% and 1.28 %, and 411 ºC and 437 ºC respectively, indicating an immature to early mature zone (low to high grade source rock) (Fig. 11).

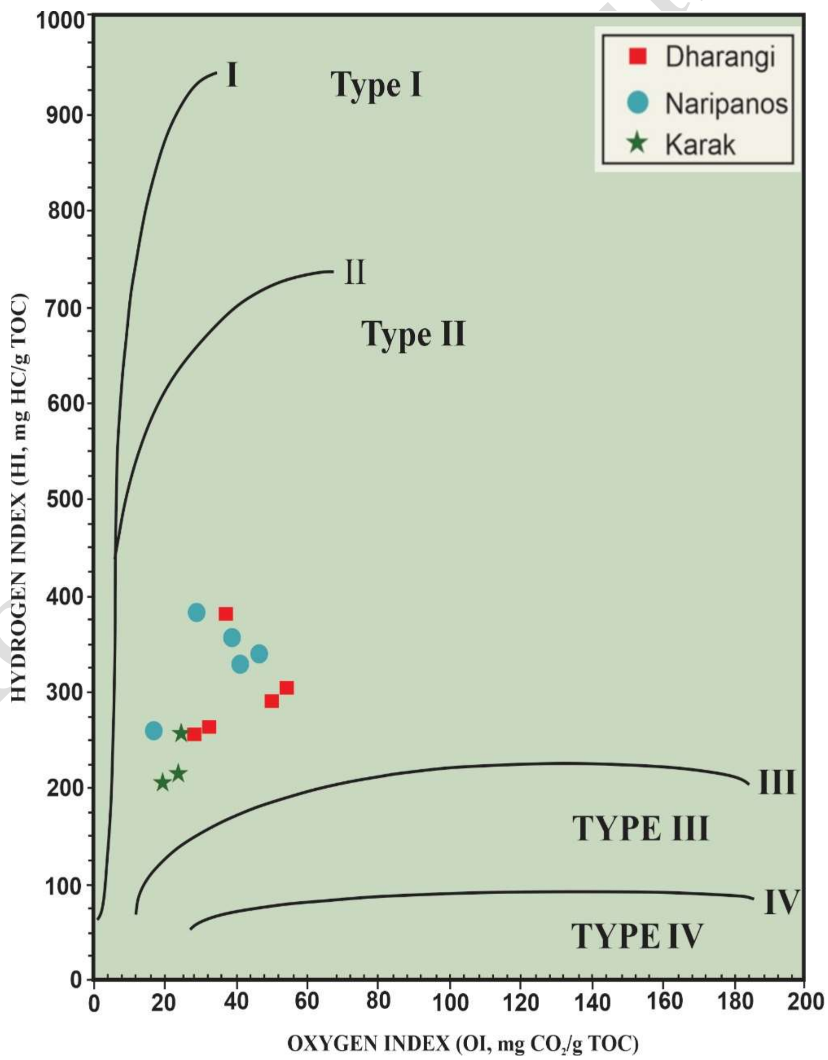

Figure 9. Pseudo-Van Krevelen diagram representing the kerogen type of the studied samples

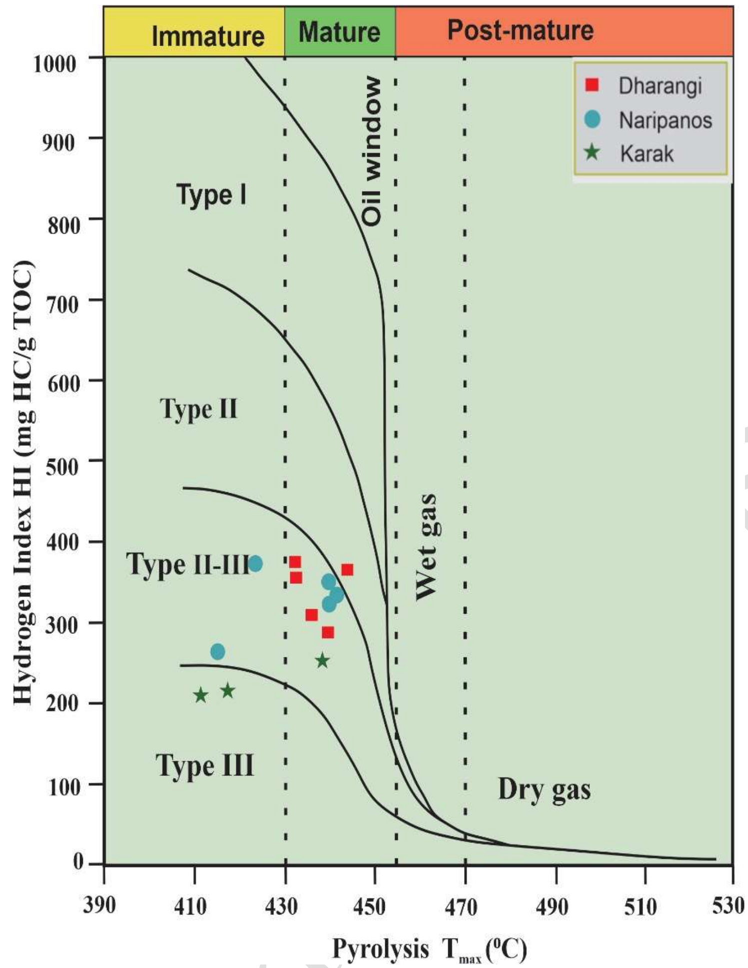

Figure 10. Shows hydrogen index vs T-max, displaying the relationship of kerogen type and maturity level

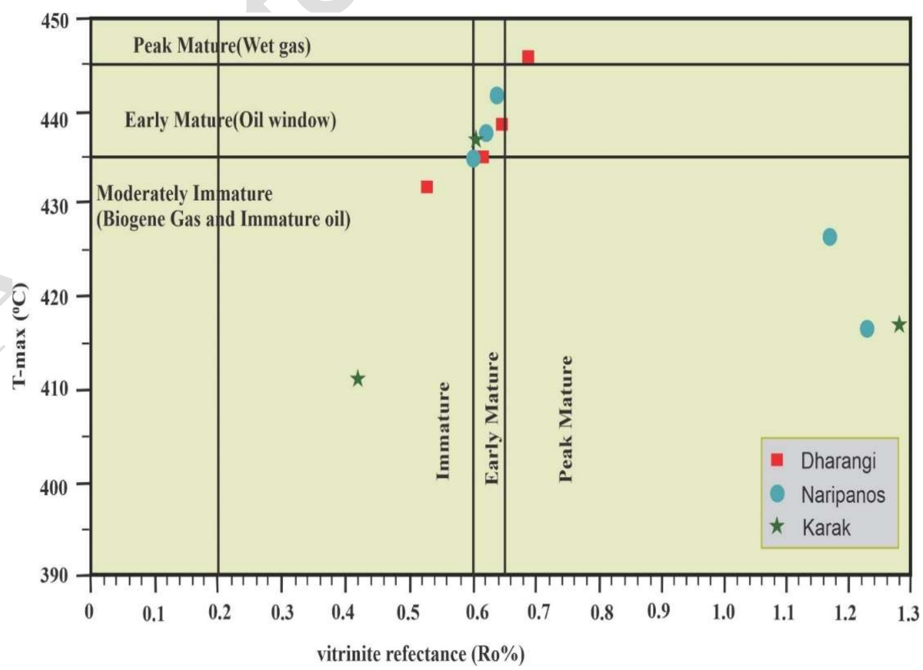

Figure 11. Vitrinite reflectance vs T-max showing the thermal maturity of organic matter

The production index (PI), T-max, and Rock-Eval pyrolysis parameters are correlated for thermal maturity and hydrocarbon generation zone. The characteristics of organic matter vary with its maturity level. T-max values below 430°C and PI values less than 0.10 indicating immature organic matter and PI ranges from 0.10 to 0.40 indicating mature organic matter, within the oil window, the T-max and PI ranges 460°C and 0.40 respectively. At post-mature stage, organic matter tends to have a high PI value greater than 1.0 as it nears the end of the dry zone (Bacon, 2000). The Kohat region displays geographic variations from the Kohat Plateau to the folded and faulted Kohat Foreland Basin, bordered by Salt Range and Trans-Indus Ranges. Geologically, the area is characterized by a thick sequence of sedimentary rocks, including Eocene limestones and shales, and the younger Miocene-Pliocene Siwalik Group, which have been heavily deformed by compressional tectonics. This deformation manifests as intense folding, faulting, and the creation of complex structural features. T-max data shows the variation from region to region. The geothermal gradient in the Kohat region is variable such as a ~20-25°C/km gradient recorded in nearby fold belts, suggesting heat flow is influenced by sedimentary basin structure and depth.

A wide variation in T-max values within a single shale section is due to the heterogeneity in burial history, variations in mineralogy, differences in organic matter type, and variable thermal gradients. These factors can lead to different levels of thermal maturity, resulting immature to mature stages within the same area. In Dharangi section T-max values greater than 430 °C, PI from 0.10 to 0.40, indicates early mature stage (oil window), where all other samples falls in the hydrocarbon generation zone. In Naripanos section, the T-max values varies from 416 °C to 442 °C, and PI values varies from 0.10 to 0.30, indicating immature to mature source rock, similarly the samples with T-max greater than 430 °C, and PI ranges from 0.10 to 0.30, indicates hydrocarbon generation zone, except the samples NP-4 with T-max 426 °C and PI 0.10, and NP-5 with T-max 416°C and PI 0.30, are non-indigenous (migrated hydrocarbon). In the Karak section, the T-max values range from 411°C to 437 °C and PI ranges from 0 to 0.10 indicates an immature to mature source rock. KK-1 sample, having T-max and PI values of 437 °C and 0.10 respectively, indicates a hydrocarbon generation zone, while the other two samples with T-max values below 435 °C, indicating the immature source rock (Fig. 12).

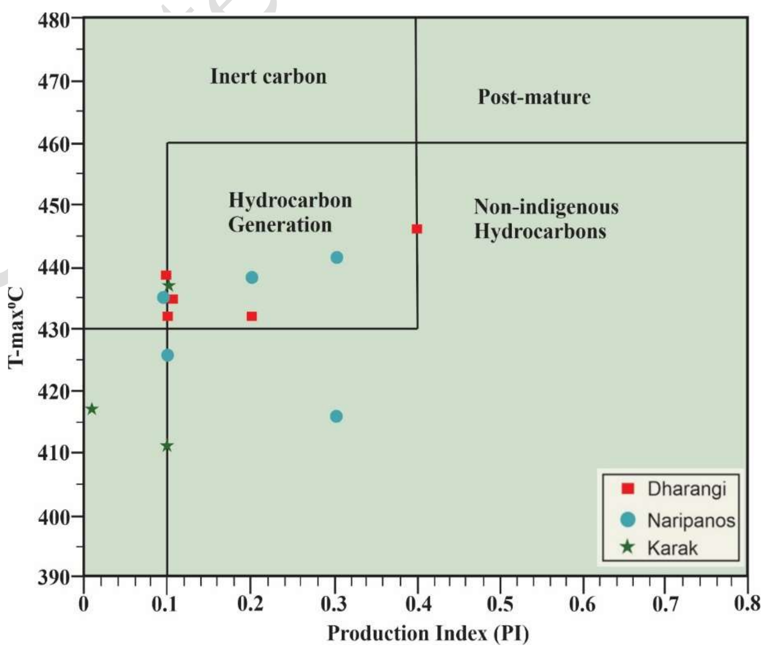

Figure 12. Shows production index (PI) vs T-max display the nature and maturation of the hydrocarbon products of oil shale of Kohat Basin, Khyber Pakhtunkhwa, Pakistan

Conclusions

In the Dharangi section, the TOC values ranges from 1.60 wt% to 2.90 wt%, and the S_2 ranges from 5.30 to 12mg/g (with average TOC=2.2 wt%, and S_2=8.3 mg/g), indicates good to very good source of hydrocarbon potential. In the Naripanos section, the TOC values ranges from 0.60 wt% to 2.60 wt%, and S_2 ranges from 1.60 to 9.6 mg/g (with average TOC=1.70 wt%, and S_2= 6.80 mg/g), indicating a fair to good source rock. In the Karak section, the TOC values ranges from 1.60wt % to 2.00 wt%, and S_2 ranges from 3.40 to 4.70 mg/g (with average TOC = 1.80 wt%, and S_2= 2.83 mg/g), indicating organic matter with promising source rock potential (good to very good).

In the Dharangi section, HI (hydrogen Index) vs OI (Oxygen Index) shows type II/III (oil and/or gas) and type II kerogen with a high oil source. Similarly, the plot of T-max vs HI shows an immature to mature nature for generating oil and gas. In Naripanos section, plotting of HI vs OI indicates Kerogen type II/III (oil/ gas) and type II (oil). Whereas the Plot of HI vs T-max show an immature to early mature nature of oil and gas generation. In the Karak section, the HI vs OI plot shows mix of kerogen type II/III (oil/ gas), and the HI vs T-max shows an immature to early mature nature to generate oil and gas.

Vitrinite reflectance (R_o) and T-max were used to assess the thermal maturity of the source rock. In the Dharangi section, the Eocene shale R_o indicating an immature to mature stage, whereas in the Naripanos section, the R_o and T-max shows an immature to early mature stage, and in the Karak section, R_o and T-max values showing immature to early mature zone of maturation. Plotting T-max vs PI values in the Dharangi section indicates an early mature (oil window) stage, falls hydrocarbon generation zone, whereas in the Naripanos section, the PI values indicate an immature to mature nature of the source rock. The PI and T-max values indicate a hydrocarbon generation zone. In the Karak section, the PI values indicate immature to mature source rock. The T-max and PI values indicate immature nature of source rock with the hydrocarbon generation zone. Overall, the Eocene shale of Kohat Basin has good potential for hydrocarbon production, which can play an important role in hydrocarbon production. All results may be helpful in future for hydrocarbon exploration strategy, such as target depth zones, expected maturity windows, or potential for unconventional development in the Kohat Basin.

Acknowledgments

The authors acknowledged the Department of Earth Sciences for providing the basic facilities, as well as the Center of Excellence, University of Peshawar, Pakistan, and Hydrocarbon Development Institute of Pakistan (HDIP), Islamabad for providing experimental facilities. This research work was funded by ourselves. Comments from anonymous reviewers of this manuscript are gratefully appreciated.

Author contribution: All authors contribute to the writing, interpretation; remove grammatical mistakes, and software work.

Data availability: All data included in this study are available upon request by contacting with the corresponding author. Data is transparent and available to the first author.

Declarations Ethics approval: Work is original and not submitted to any other journal.
Conflict of interest: The authors declare no competing interests.

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