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GEOLOGY

Sedimentological and sequence stratigraphic analysis of Late Eocene Kirthar Formation, Central Indus Basin, Pakistan, Eastern Tethys

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ABSTRACT

Rakhi Nala (Gorge) section of Eastern Sulaiman Range, Pakistan hosts world-class geological sections from the Cretaceous to the Recent. Here, Late Eocene Kirthar Formation is having a conformable lower contact with the greenish grey massive shale of the Baska Member of the Ghazij Formation. The rusty beds of the Oligocene Chitarwatta Formation are overlying the Kirthar Formation. To understand the detailed microfacies and depositional setting, detailed fieldwork was carried out in the Kirthar Formation in the outer Sulaiman Foldbelt. The late Eocene Kirthar Formation includes Habib Rahi Limestone, Domanda Shale, Pirkoh Limestone, and Drazinda Shale. Domanda Shale Member was deposited in transgression before Habib Rahi Limestone Member was deposited. It was followed up by the deposition of the second member Pirkoh Limestone and Marl Member. Habib Rahi Limestone, Pirkoh Limestone, and Marl Member have catch-up-to-keep-up deposition with rise and fall of sea level. Some facies of Drazinda and Domanda Shales represent a restricted setting supported by the presence of gypsum, while deep sea facies were also identified. This study will provide a guide for evaluating sedimentological concepts and understanding complex facies in highly oil and gas-prone stratigraphic sequences especially in the Eastern Tethys Region.

Keywords: Eocene, Lithostratigraphy, Sea level changes, Carbonates, Eastern Sulaiman Range, oil and gas exploration.

Análisis sedimentológico y de secuencia estratigráfica de la formación Kirthar, del Eoceno Tardío, Cuenca Central Indus, Pakistán, Oeste de Tetis.

RESUMEN

La sección del cañón de Rakhi Nala en las montañas del este de Sulaiman, Pakistán, hospeda secciones geológicas de clase mundial desde el Cretácico hasta el presente. Por ejemplo, la formación Kirthar del Eoceno tardío presenta un contacto en la parte baja con un shale masivo gris verdoso del miembro Basaka, formación Ghazij. Los lechos oxidados de la formación Chitarwatta de Oligoceno se sobreponen a la formación Kirthar. En este estudio se realizó un detallado trabajo de campo en la formación Kirthar, en el pliego extremo de Sulaiman, para entender la configuración de microfacies y deposicional. La formación Kirthar se caracteriza por la piedra caliza en Habib Rahi, esquistos en Domanda, piedra caliza en Pirkoh y esquistos en Drazinda. Los esquistos en Domanda se depositaron en transgresión antes de las calizas de Habib Rahi. Después vino la deposición del segundo miembro de calizas en Pirkoh en el miembro Marl. Las calizas de Habib Rahi, de Pirkoh y del miembro Marl tienen deposiciones configuradas por las subidas y bajadas del nivel del mar. Algunas facies de los esquistos de Drazinda y Domanda representan una configuración restringida apoyada por la presencia de yeso, y que también fue identificada en las facies a mayor profundidad en el mar. Este trabajo provee una guía para evaluar conceptos sedimentológicos y comprender las facies complejas en secuencias estratigráficas altamente propensas en petróleo y gas, especialmente en el oriente de la región de Tetis.

Palabras clave: Eoceno; litoestratigrafía; cambios en el nivel del mar; carbonatos; montañas de Sulaiman; exploración de gas y petróleo.

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1. Introduction

In sedimentary geology, the word facies is used to describe the dimensions, sedimentary Formations, particle kind and sizes, color and biological characters. These characters are further used to describe a Formation (Middleton and Hampton, 1973; Hou *et al.,* 2024). On the other hand, lithofacies is the term for a description that only includes the characteristic physical and chemical properties of a rock (Abdel-Fattah *et al.*, 2022). The physical and chemical mechanisms of sediment movement and deposition influence the lithofacies characteristics (Pettijohn, 1975; Pettijohn *et al.*, 2012; Allen, 1982; Nichols, 2009). To describe the paleoenvironment during the deposition of the Eocene Kirthar Formation, various types of facies were recognized during interpretation and are examined in depth. These facies were characterized based on the variability, each of which is representative of specific environmental fluctuation. The existence of these natural variations in the sedimentary record of any Formation makes it possible to describe it concerning its depositional environment (Miall, 2022).

This paper extensively examines the Eocene succession (Kirthar Formation) in the eastern Sulaiman Ranges and explains the findings of sedimentology and sequence stratigraphic analysis (Figure 1). The Sulaiman Fold belt is in a north-south direction, on the eastern edge of the Sulaiman lobe and spans 400 km from Rajanpur to South Waziristan. Its height rises to a maximum of 3440 meters in the north and drops to a maximum of 1600 meters in the south. It is roughly 20–25 km wide (Kazmi and Jan, 1997). The Kirthar Formation is well exposed in the Rakhi Nala section, which has been chosen for this study (Khan *et al.* 2021; Figure 1). It is located about 40 kilometers south-southwest on Gaj-Fort Munro Road, Dera Ghazi Khan (N-70). The Cretaceous to Recent sedimentary succession is exceptionally well exposed in this area, offering geologists a distinctive research opportunity. The presence of fossils in this area, particularly dinosaur footprints, microfossils, as well as its outstanding sedimentary exposure and features, have drawn geoscientists from all over the world (Malkani, 2023). The Rakhi Nala portion is also significant because it serves as a reference section for numerous Formations in the Sulaiman Range. This study aims to conduct a microfacies analysis, depositional and sequence stratigraphic model of the Kirthar Formation. The members of the Kirthar Formation are also the most significant in terms of hydrocarbon resources in the Sulaiman Foredeep Basin.

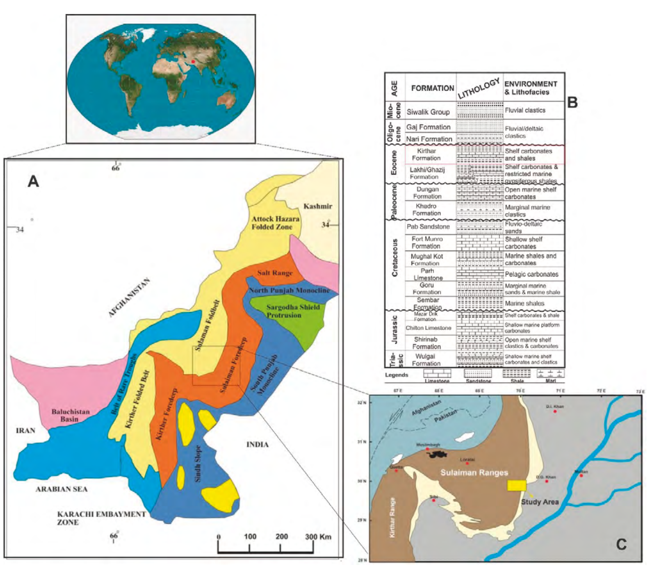

Figure 1. (a) Tectonic framework of the of Pakistan, inset into Sulaiman Range, (modified after Stonely, 1974; Powell, 1979; Kazmi & Rana, 1982), (b) Generalized stratigraphic column of the area (Abbas, 1999), (c) Location and Study area (after Khan *et al.* 2021), showing the location of lobate-shaped Sulaiman Range on the western edge of the Indian subcontinent (Mehmood et al., 2023).

2. Geologic Setting

The eastern Sulaiman Range is situated in the Lower Indus Basin, Pakistan in the Dera Ghazi Khan region. The Lower Indus Basin has been divided into northern and southern subbasins by Jacobabad High. Sedimentary rocks with age ranging from the Cretaceous-recent are present in the eastern Sulaiman Range. The Sulaiman Range is positioned in the NW Indian plate and is placed along the zone of compression. In contrast, the Salt Range, which is situated in a region is associated with the Himalayan collision (Ghazi *et al.*, 2015; 2020; Ahmad *et al.*, 2020; Gong *et al.*, 2021; Javed *et al.*, 2021). According to a study by Allemann (1979), the Afghan block and the Indian plate are compressed together to create the foredeep basin in the East of the Sulaiman lobe (Khan *et al.*, 2021). Arcuate folds and faults east to west which diverts from north to south near the belt's edge make up most of the Sulaiman fold belt structure (Khalid *et al.*, 2012). Imbricate faults can only be detected from the ground in the northern region of the Sulaiman Foldbelt (HSC, 1961; Kazmi and Rana, 1982). They disappear out at the foremost edge of the subsurface fold belt. There are signs of neotectonics activity along tear faults like the Kingri fault, including offset fold axes, faults, raised and tilted gravel beds, and huge bends along the course of streams (Abdel-Gawad , 1971; Rowlands, 1978; Khan *et al.,* 2021; Figure 1).

The Sulaiman fold belt's sedimentary succession is separated into three main groups, each of which has a unique tectonic significance. Molasses deposits from the late Miocene to the present are represented by units 1 and 2, Khojak Flysch from the late Eocene to the early Eocene is represented by unit 3, and marine rocks from the Permian to the Eocene are represented by unit 4 (Lawrence and Khan, 1990). Part of the marine crust was propelled upward onto the Maastrichtian shelf, forming the Muslim bagh ophiolite in the Zhob Valley (Abbas and Ahmad, 1979). The Sulaiman fold belt contains relatively high Bouguer gravity anomalies despite having a deep sedimentary section, indicating that it covers a sizable portion of the crust (Lillie *et al.*, 1989; Jadoon *et al.*, 1994; Figure 1). A rich succession of sedimentary rocks dating from the Cretaceous to the present can be found in the Rakhi Nala Section, Eastern Sulaiman Range. Numerous authors have described the stratigraphy of the Sulaiman Basin (Figure 1D), including Qureshi *et al.* (1987), Raza *et al.* (1989), Shah (2001, 2009), Kazmi and Abbasi (2008), and Malkani (2010).

3. Methodology

The majority of the information needed to achieve these goals was gathered through fieldwork in Pakistan's Rakhi Nala section of the Eastern Sulaiman Range. A variety of laboratory and field techniques were used to obtain a thorough image of the depositional environment and sedimentation patterns. Before beginning fieldwork, a thorough understanding of the previous work was coordinated to familiarize oneself with the geological setting of the project region. The Rakhi Nala's lithostratigraphic sections containing numerous rock units were meticulously examined and measured. To thoroughly analyze the microfacies assemblages of the Formation, microscopic studies were carried out.

3.1 Stratigraphic section measurement

Fieldwork carried out in the Eastern Sulaiman Range served as the foundation for this study project. Both the samples and the measurements were gathered. To prove that the formations exist, pictures and measurements of them were obtained. Rocks that were hard and compact had to be shattered with a geological hammer to acquire representative samples. The study area's lithological variability was employed to direct sample collection. These samples were collected in the field through a variety of techniques, including contact sampling, tagging, labeling, numbering, and proper storage. Using a GPS device, longitude and latitude were verified. Key features in the field were also photographed. After that, samples were taken to the laboratory for evaluation. These variations were documented in the form of a field log. Throughout the entire area, visibility is superb. Where streams and roads have dug through the rock, excellent outcrops can be seen. During this fieldwork, bedding, lithology, rock character and sedimentary structures in the stratigraphic layers were noted. All of the samples were collected from this outcrop.

3.2 Measurement and sampling collection

The area immediately surrounding the selected piece is also examined and measured. Sequence borders, transgressive and regressive surfaces, and measuring the thickness of particular sequences in the Rakhi Nala section through sampling were given priority. Samples from each lithofacies are collected to comprehend the lithological variations recorded in each member of the Kirthar Formation. The thicknesses of the exposed rock are routinely sampled at regular intervals. Transitions in lithology are plotted and sampled to build a comprehensive database of facial traits, in the Rakhi Nala. About twenty-eight samples were collected for testing at the lab. Nineteen samples were selected for thin sections and were subjected to microfacies analysis. To determine the microfacies, the microfossils, matrix kinds, cement types, and clasts were examined.

4. Results

4.1 Lithostratigraphy

Lithostratigraphic relationships among stratigraphic layers have been investigated. Lithology was used to establish this connection. The rock types being researched are marl, gypsiferous shale, limestone, and shale. Within the Rakhi Nala, the lithofacies of the Late Eocene Kirthar Formation, have been studied (Figure 2). These formation members have a total measured thickness of 561 meters (Figures 2 to 4).

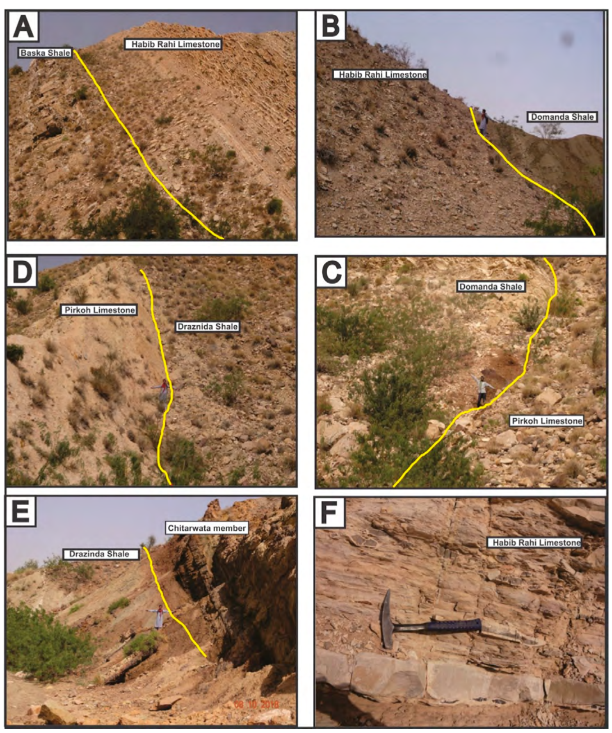

Figure 2. (a), A conformable contact between Baska Shale and Habib Rahi Limestone member (HRLM), (b) Transitional contact between Domanda Shale member and HRLM, (c) Transitional contact between Domanda Shale member and Pirkoh limestone and Marl member (PLMm), (d) Transitional contact between Drazinda Shale member and Pirkoh limestone and marl member, (e) Conformable contact between Drazinda Shale member and Chitarwatta Formation, (f) Medium bedded argillaceous limestone from HRLM.

4.1.1 Kirthar Formation

Blandford, 1876 used the name "Kirthar," which derives from the Kirthar Range, which is located south of the Sulaiman Range. Its reference areas are Rakhi Nala, Zinda Pir, and Spintangi George, which may be found in the eastern and western Sulaiman Ranges, respectively. The Kirthar Formation's dominant lithologies are interbedded of limestone and shale, with only a small quantity of marl. The limestone is a light grey to cream tint that ages to become grey, brown, or cream. The limestone contains thick to massive bedding. Shale is grey, orange, yellow, and olive. It is silky and has an earthy gloss. The southern Indus Basin has a large exposed portion of this formation. It measures 1270 m thick at the Gaj River portion.

In contrast to its transitional contact with the Baska Shale, the Formation's contact with the Chitarwatta Formation is unconformable (Figures 2A and E). There is a healthy fauna in this Formation. It was created between the Early Eocene and the Early Oligocene. It is Middle to Late Eocene in age in the Zinda Pir and Rakhi Nala region (Latif, 1961; Samanta, 1973; Warraich and Natori, 1997). All four of the Kirthar Formation's components are superbly exposed in the Rakhi Nala region.

4.2 Lithostratigraphy of Kirthar Formation in Rakhi Nala Section

Member of the Kirthar Formation from old to young:

- Drazinda Member
- Pir Koh Limestone and Marl Member
- Domanda Member
- Habib Rahi Limestone Member

4.2.1 Habib Rahi Limestone Member

Habib Rahi Limestone is the official name given to it by Pakistan's Stratigraphic Committee. Tainsh *et al.* (1959) neglected to annotate the type location. This member's limestone features fine, platy bedding. Habib Rahi Limestone has nodular chert and thin laminations. There is also some interbedded shale and marl, but an almost negligible amount is found in this member (Figure 2F). Massive shale beds are also located at the top (Figure 3H). In the bottom portion of the limestone strata of this member, Assilina is overly abundant. In the Rakhi Nala portion, the Habib Rahi Limestone Member is 38 meters thick. In conformity with the Baska Formation, this component overlies it (Figure s. 2A, B, & F and Figure 3).

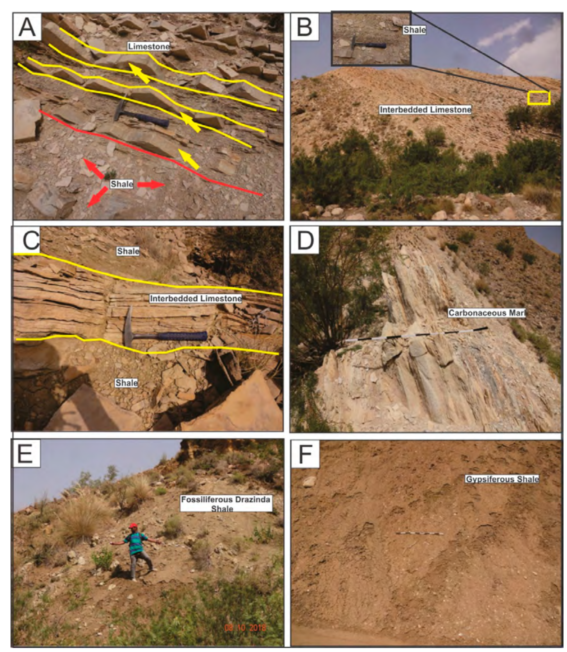

Figure 3. (a) Shale interbedded within the limestone of HRLM, (b) Massive shale at the top of HBRLM, (c) Limestone interbedded in non-gypsiferous shale of Domanda member, (d) Marl and Carbonaceous Marl in the upper part of PLMm, (e) Fossiliferous Domanda shale member, (f) Highly gypsiferous Drazinda Shale.

4.2.2. Domanda Member

The type locality is Dera Ismail Khan Road, which is near Fort Sandeman and situated west of Domanda (Lat. 31°35′30″N: Long. 70°12′E). Hemphill and Kidwai (1973) suggested the name "Domanda Shale Member". It was dubbed "Lower Chocolate Clays" by Eames in 1952. The Domanda Formation is the official name given to it by the Pakistani Stratigraphic Committee. This formation contains claystone and a lesser amount of thinly bedded limestone with shell fragments. In some locations, non-gypsiferous shale contains limestone interbedded inside it (Figure 3C). Additionally, there is fossiliferous shale (Figure 4E). The colour of the claystone ranges from yellow to greenish brown to chocolate. There are also a few weakly bedded, silty claystone beds. Gypsum slices make up the lowest portion of this component. The Rakhi Nala part of the Sirki Member is 225 m thick. Its transitional and conformable interaction with the underlying Habib Rahi, Pirkoh Limestone (Figures 2B, C and Figure 5).

4.2.3 Pir Koh Limestone and Marl Member

The term “Pirkoh Limestone Member” was first coined by Hemphill and Kidwai (1973). It was referred to as a “White marl band” and a “Pirkoh Limestone and Marl Member” by Eames (1952). Pirkoh Anticline (Lat. 29° 7′ N: Long. 69° 8′ E) is the name of its type locality. The predominant lithologies of this deposit are limestone and marl. The limestone has interbeds of marl and ranges in hue from grey to chalky white to reddish (Figure 3D). The distinguished feature that marked this formation are cliffs found in this formation. The Pir Koh Limestone and Marl Member are 13 meters thick in the Rakhi Nala region (Figure 4). This contacts the Domanda member below and the Drazinda Shale above (Figures 2C, D).

4.2.4 Drazinda Shale Member

The name Drazinda Shale came from a Drazinda village. The Stratigraphic Committee of Pakistan has given this name official status. Hemphill and Kidwai (1973) suggested Drazinda village as the species’ type locality (Lat. 31°46′N: Long 70°09′E). This component has claystone, which settles into some strata as silt. The claystone unit comes in the hues of grey, brown, green, and chocolate. This member contains mollusks. There are also some limestone beds, albeit in smaller numbers. These beds are teeming with foraminifera (Figure 3F). The Rakhi Nala part of the Drazinda Member is 285 m thick. The upper contact of the unconformable Kirthar Formation is situated in the “Drazinda Member” and underlying sandstone sequences of the Chitarwatta Formation. One of the largest unconformities in the basin may be found in the Rakhi Nala section, which is marked by a varicolored conglomeratic, hematitic-bed that is rusted dark brown, contains trace fossils, and has rich hematinic and pyritic material on the surface (Figures. 2D, E, and 3D, E).

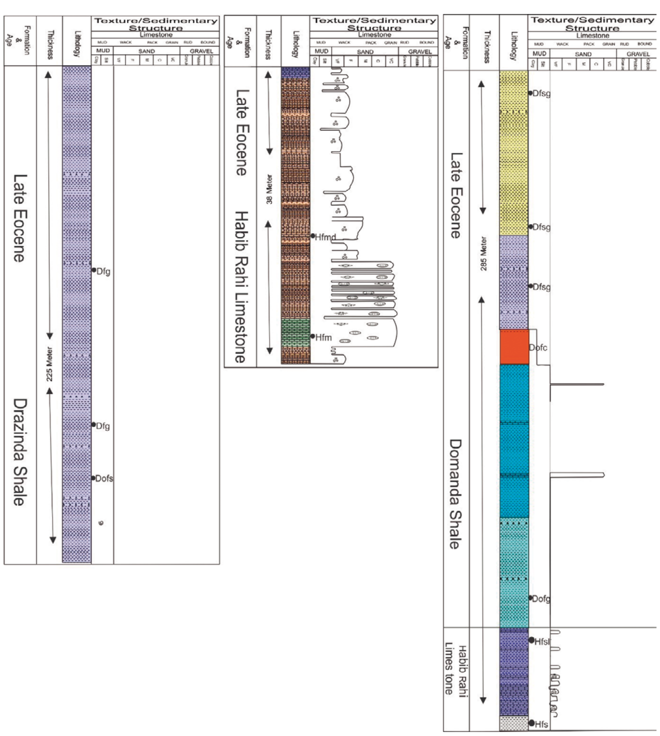

Figure 4. Lithologic log of the Drazinda Shale member, Habib Rahi Limestone member and Domanda Shale member.

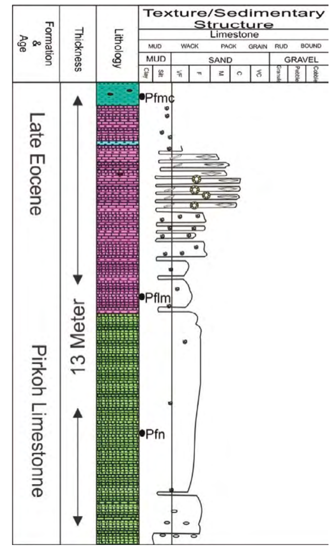

Figure 5. Lithologic log of the Pirkoh Limestone member.

4.3 Microfacies Analysis

Different members of Formation’s microfacies were examined, and they were compared and analyzed by using the facies zones and SMF of Flugel (1982) and Wilson (1975). Different microfacies studied in the Formation are as:

4.3.1 Drazinda Member

Bioclastic Wackestone to Packstone Microfacies (DR-1)

The Drazinda member’s uppermost limestone bed, which is cream in color, and its lowermost, heavily fossiliferous deposit, are examples of the microfacies. Kdr-2 and Kdr-8 are the sample numbers from the top and bottom, respectively, of the Drazinda Member. Kdr-2 is 15 meters thick, while Kdr-8 is 8 meters thick. The bioclastic wackestone facies include Nummulites, Miscella, Ranikothalia, Orbitolites, green algae, and occasional shell fragments (Figure 6C). The microfacies represent FZ-7 of Wilson (1975) and SMF-8 of Flugel (2013). Micrite makes up the matrix. There are only 9% matrix and 11% clasts, mostly bioclastic.

Bioclastic Packstone Microfacies (DR-2)

Limestone with a cream tint serves as a metaphor for the microfacies. Bioclastic packstone microfacies are found below the bioclastic wackestone microfacies in the Drazinda Member of the Late Eocene Succession. Larger benthic foraminifera are represented by bioclasts that contain a significant amount of discocyclina. After Discocyclina, quartz crystals are the second most important clast component. It symbolizes Wilson’s (1975) FZ-8 and Flugel’s (2013) SMF-18. Additionally, there are some bioclast pieces and corallinacean algae (see Figure 6B). The ratio of clasts to matrix in bioclastic packstone microfacies is roughly 33% to 67%.

Bioclastic Mudstone Microfacies (DR-3)

Limestone with a cream colour serves as the microfacies’ representation. The sample from this section of the Drazinda Member is known as Kdr-6b. Mudstone facies are found below the bioclastic packstone facies of the Drazinda Member of the Late Eocene Succession. Kdr-6b has a thickness of 15 m. This microfacies represent Wilson’s (1975) FZ-9. Bioclastic mudstone microfacies contain unidentified bioclasts and bioclastic particles (Figure 6A). 98% is a matrix and only 2% is clasts, mostly bioclastic.

Bioclastic Wackestone to Packstone Microfacies (DR-4)

These microfacies are represented by yellowish brown colored limestone beds. There are many microfacies at the Drazinda Shale Member’s base. The FZ-6 of Wilson (1975) is represented by these microfacies. Micrite represents the matrix, and the sample’s grains are represented by bioclasts (Figure 6D).

4.3.2 Pirkoh Limestone

Bioclastic Mudstone Microfacies (P-1)

Two adjacent beds of cream-colored limestone serve as the symbol for this microfacies. The Pirkoh Limestone's topmost layer has bioclastic mudstone microfacies. The bioclasts are composed of discocyclina, planktonic forams, and algae, and the matrix is micrite (Figure 6E). The FZ-2 of Wilson (1975) is represented by these microfacies. The Pirkoh Limestone's bioclastic mudstone microfacies have 5%–5% clasts and 95%–97% matrix (upper bed, 3% bioclasts). The matrix of the bioclastic mudstone microfacies in the lower bed.

Bioclastic Wackestone-Packstone Microfacies (P-2)

This microfacies has a cream colour. The bioclastic wackestone-packstone microfacies are located inside the Pirkoh Limestone, beneath the bioclastic mudstone microfacies. The bioclastic part of the sample is made up of discocyclina, corallinacean algae, and pieces of fractured shell, whereas the matrix is micrite (Figure 6F). The FZ-2 of Wilson (1975) is represented by these microfacies. In the bioclastic mudstone microfacies of the Pirkoh Limestone, there are roughly 23% clasts and roughly 77% matrix.

Bioclastic Wackestone-Packstone Microfacies (P-3)

The limestone bed in this microfacies is cream in color. Below the bioclastic wackestone-packstone microfacies of the Pirkoh Limestone is the bioclastic wackestone-packstone microfacies. The bioclastic section is made up of discocyclina and pieces of fractured shell, while the matrix is micrite. The FZ-6 of Wilson (1975) is represented by these microfacies. The majority of the microfacies' bioclastic composition is made up of pieces of broken shell (Figure 6G). About 10% of the Pirkoh Limestone's bioclastic mudstone microfacies are made up of clasts, and the remaining 90% is matrix.

Planktonic Mudstone Microfacies (P-4)

Two adjacent beds of cream-colored limestone serve as the representatives for this microfacies. Below the bioclastic mudstone-wackestone microfacies are the bioclastic mudstone microfacies of the Pirkoh Limestone. Planktonic foraminifera and smaller benthic foraminifera make up the bioclastic component of the upper and lower bioclastic mudstone microfacies beds (Figure 7C), respectively, while micrite makes up the matrix (Figure 6H). The FZ-6 of Wilson (1975) is represented by these microfacies. There are roughly 5% clasts and about 95% matrix in the Pirkoh Limestone's upper bioclastic mudstone microfacies. A 3% bioclastic component and 97% matrix make up the basal bioclastic mudstone microfacies bed.

4.3.3. Domanda Member

Bioclastic Packstone Microfacies (DO-1)

Reddish brown limestone is representative of this microfacies. Dasyclad green and red algae, tiny benthic and planktonic foraminifera, and uncommon ostracods make up the majority of the microfacies' bioclastic component (Figure 7A). The FZ-7 of Wilson (1975) is represented by these microfacies. Micrite and rare sparite make up the matrix. Members of the Domanda group have bioclastic packstone-grainstone microfacies with about 40% clasts and 60% matrix.

Algal Wackestone Packstone Microfacies (DO-2)

The reddish-brown limestone beds are hosting these microfacies. Green dasyclad algae is widespread. The bioclastic part of the microfacies consists of planktonic and benthic foraminifera (Figure 7B). Micrite and rare sparite make up the matrix. The FZ-7 of Wilson (1975) is represented by these microfacies. Algal wackestone microfacies have a clast content of about 20% and an 80% matrix.

4.3.4 Habib Rahi Limestone

Bioclastic Mudstone Wackestone Microfacies (H-1)

Beds of limestone that have weathered to a light brown tint indicate this microfacies. The bottom portion of the Habib Rahi Limestone has mudstone microfacies. The clastic section is made up of smaller benthic forams, planktonic forams, and coralline algae, while the matrix is made up of micritic and microspar. The FZ-1 of Wilson (1975) is represented by these microfacies. Habib Rahi Limestone's bioclastic mudstone microfacies have about 17% clasts and 83% matrix (Figure 6I).

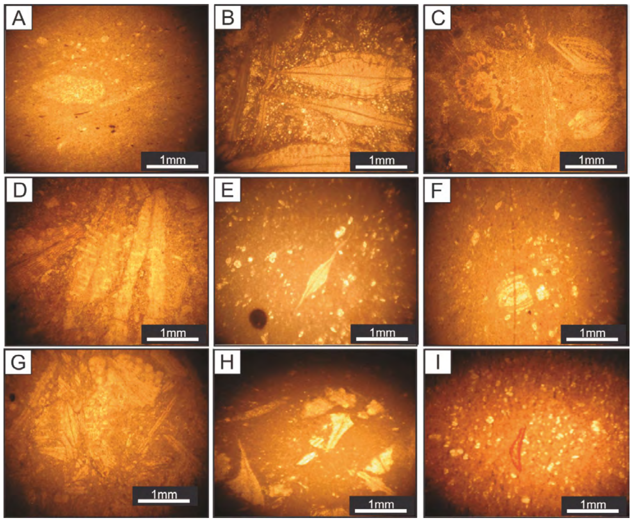

Figure 6. Photomicrographs showing the microfacies of Kirthar Formation (a) Bioclastic mudstone, (b) Bioclastic packstone, (c) Bioclastic Wackstone, (d) Bioclastic Wackestone to packstone, (e) Bioclastic mudstone, (f) Bioclastic mudstone, (g) Bioclastic Wackestone to packstone, (h) Bioclastic mudstone to Wackestone, (i) Bioclastic mudstone with planktons.

Bioclastic Molluscan Mudstone Wackestone Microfacies (H-2)

A bed of limestone that has weathered to a light brown tint represents this microfacies. The bed of limestone is thinly bedded. Above the bioclastic mudstone-wackestone microfacies of the Habib Rahi Limestone are bioclastic molluscan mudstone microfacies. There are bioclasts such as mollusks, globogerinids, planktonic forams, and smaller benthic foraminifera. Microsparite makes up Matrix. The FZ-1 of Wilson (1975) is represented by these microfacies. Habib Rahi Limestone's mudstone microfacies have about 9% clasts and about 91% matrix (Figure 7D).

Bioclastic Nummulitic Packstone Grainstone Microfacies (H-3)

A bed of limestone that has weathered to a light brown colour represents this microfacies. Overlying the bioclastic molluscan mudstone-wackestone microfacies of the Habib Rahi lies nummulitic packstone. The clastic component of this microfacies is made up of Nummulites, Assilina, and shattered foraminifera fragments. The FZ-6 of Wilson (1975) is represented by these microfacies. This facies has a micrite as a matrix. Habib Rahi Limestone's mudstone microfacies contain about 45% clasts and 55% matrix (Figure 7E).

Bioclastic Assilina Packstone Grainstone Microfacies (H-4)

The limestone beds in the formation have a light brown color representing these microfacies. These microfacies are present below the mudstone microfacies. The matrix in these microfacies consists of micrite and the clast in the samples is comprised of Assilina, Nummulites, molluscan and other foraminiferal fragments. The FZ-6 of Wilson JL (1975) is represented by these microfacies. About 40% of the clasts are present and 60% is a matrix in these microfacies (Figure 7A).

Bioclastic Mudstone Microfacies (H-5)

Limestone beds that have weathered to a light brown tint represent this microfacies. Mudstone microfacies developed above the bioclastic Assilina packstone and grainstone microfacies. Veins, certain bioclasts, and coralline algae make up the clastic part. Micrite makes up the matrix. The FZ-2 of Wilson (1975) is represented by these microfacies. Habib Rahi Limestone's mudstone microfacies have about 7% clasts and 93% matrix (Figure 7G).

Bioclastic Wackestone Microfacies (H-6)

The weathered color limestone bed present in the formation represents this facies. Bioclastic mudstone microfacies are present below these bioclastic mudstone microfacies. The major portion of the clast belonging to coralline algae, benthic foram consists of sparite and calcite veins. The FZ-1 of Wilson

(1975) is represented by these microfacies. Micritic matrix is commonly identified. Around 18% of clasts are present in the mudstone microfacies of Habib Rahi Limestone and around 82% of the matrix is present (Figure 7H).

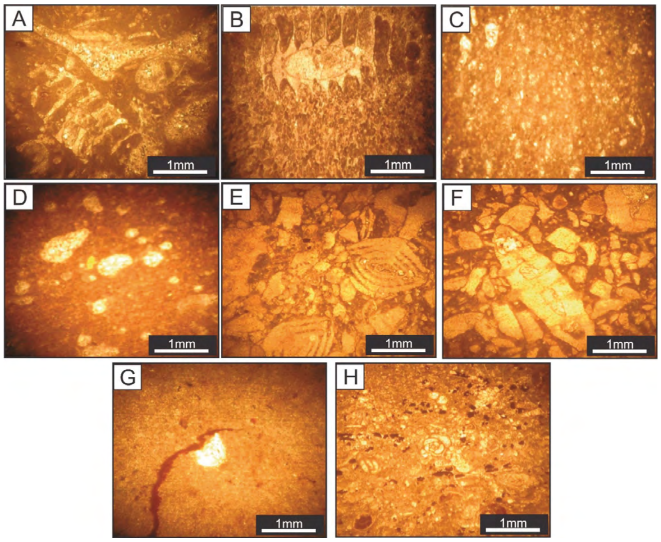

Figure 7. Photomicrographs showing the microfacies of Kirthar Formation a) Bioclastic packstone, (b) Bioclastic Wackestone to packstone, (c) Bioclastic mudstone to Wackestone, (d) Bioclastic molluscan mudstone Wackestone, (e and f) Bioclastic Nummulitic packstone to grainstone, (g) Bioclastic mudstone, (h) Bioclastic Wackestone.

4.4 Facies analysis

4.4.1 Open Sea Facies

The open sea facies is represented by the colours light grey, grey, creamy white, and brown together with a bedded to a thick-bedded sedimentary structure. This sedimentary environment's distinctive microfacies are foraminiferal wackestone through packstone. The Kirthar Formation's Pirkoh Limestone and Habib Rahi Limestone members in the middle represent these microfacies. Another significant sedimentological trait is a microscopic matrix. Additionally, the fauna is very diverse (Rankey *et al.*, 2019; Saw *et al.*, 2019). The larger open sea shelf facies represented by Discocyclina, Nummulites, and Assilina exhibits paleontological traits. The open-shelf facies are also characterized by a greater volume of bio-detritus (Figure 8A).

4.4.2 Carbonate Sand Shoal/Platform Edge Facies

This environment is characterized by minor marl, limestone, and argillaceous limestone lithologies that range in colour from light brown to brownish grey and are bedded to thickly bedded. The green algal packstone and bioclastic foraminiferal packstone to grainstone microfacies serve as representations of this habitat (Ali *et al.*, 2018; Ali *et al.*, 2021a). Paleontological characteristics include bigger benthic foraminifera such Assilina, Nummulites, Discocyclina, Alveolinidae, etc. as well as clasts of larger and smaller benthic foraminifera, green algae, and red algae (Figure 8B).

4.4.3 Semi-protected marine shelf (lagoonal) facies

In the field, marl and marly limestone, which is grey to light grey, serve as representations of these facies. The facies related to this habitat include foraminiferal grainstone, green algal packstone, and wackestone to packstone (Bashir *et al.*, 2021; Ali *et al.*, 2021a; Ali *et al.*, 2021b). The significant sedimentological aspect of this habitat is represented by micritic matrix. This area is distinguished by a diversified fauna in terms of paleontology. This habitat has significant dasycladacean green algae, mollusks, uncommon planktonic forams, some smaller and larger benthic foraminifera (including Nummulites, Assilina, and Discocyclina), and echinoids (Figure 8C).

4.3.4. Restricted Platform Inner Shelf Facies

Brown to brownish grey colored, very thin to medium bedded limestone can be used to identify this facies. Ostracodal grainstone and microcrystalline dolomite are associated microfacies of this environment. Sedimentologically, this area is characterized by winnowed texture and moderate to good sorting. Paleontologically, this environment is characterized by a constrained fauna, thick-walled ostracod abundance, and smaller benthonic forams (Figure 8D).

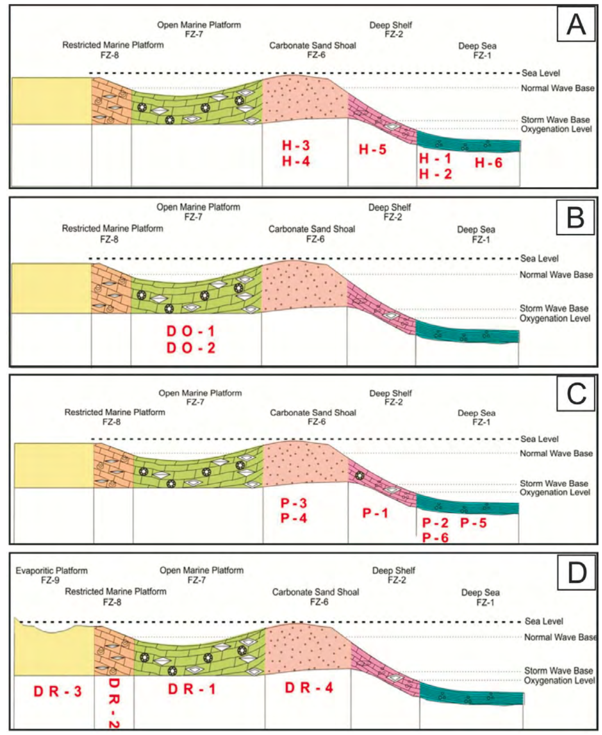

Figure 8. (a) Depositional model of Habib Rahi Limestone member based on microfacies analysis, (b) Depositional model of Domanda shale member, (c) Depositional model of Pirkoh Limestone and Marl member, (d) Depositional model of Drazinda Shale member.

5. Discussion

5.1 Facies and environment interpretation of Kirthar Formation

A deep euphotic open shelf at a depth of 40–130 m has a diverse foraminiferal assemblage. The large, flat discoidal foraminifera, shelf foraminifera, and planktonic foraminifera make up the diverse foraminiferal assemblage (Hallock and Glenn, 1986). With a water depth of 40 to 130 meters, the open sea area offers a low-energy environment. These qualities are represented by sediments that have been deposited in subtidal open sea shelf habitats. The FZ-2 zone of Wilson (1975) and the Z zone of Irwin (1965) are the corresponding models. The marine water was in typical conditions.

Since benthic foraminifera are excellent markers of paleoecology, they can be utilized to investigate paleoecology (Hayans, 1981; Adams, 1989). Rotaliidae, Assilina, and Nummulites imply moderate depth in an environment with a shallow shelf. For green algae to grow in the lower tidal to subtidal environment, a photic zone and a typical marine environment are required (less than 10 m). Dasyclads typically reside at a depth of 3-5 meters, with a few species living as deep as 90 meters or even more (Flugel, 1992). Red algae are common in shallow to deep environments, 250 meters deep (Flugel, 1992). Foraminiferal bioclasts are an example of high-energy current activity. This collection of facies represents a subtidal habitat with moderate to high energy settings that is present on the platform edge, as stated in the preceding paragraph (Y zone of Irwin, 1965 model and SMF-12.FZ-6 of Wilson, 1975). These deposits show that typical marine ecosystems predominated in the photic zone, which was moderately sheltered, well-oxygenated, and located beneath the lower tidal to subtidal shallow platform edge setting.

Dasycladacean green algae is a sign of tropical to subtropical, calm, marine environments with low energy levels below the tidal zone (Flugel, 1992). The presence of a high ratio of micritic matrix indicates the existence of a muddy substrate. This particular type of muddy ground is typical of protected lagoons (Flugel, 1992; Wray, 1977). In low energy (lagoonal), shallow marine, and subtidal environments, these kinds of sediments are deposited. The photic zone may have water depths of 20 meters or less. These facies correspond to Wilson's (1965) FZ-7 zone and Irwin's Z zone, respectively. Water was a typical marine, as evidenced by the facies. Grainstone facies represent deposits with moderate to high energy current-laid rates.

Microfossils called ostracods are quite prevalent in this facies group. Ostracodes are excellent at interpreting salinities. Ostracodes are particularly prevalent in brackish waters. Additionally, ostracodes have been observed in hypersaline lagoons with salinity levels as high as 80% (Dodd and Stantan 1981). The Cytheracea superfamily includes these ostracodes. Cytheracea is typically thought of as the brackish water genus. The genus Cyprideis, which can withstand high salinities, is characteristic of salt marshes, lagoons, and hypersaline oceans (Brasier, 1980).

5.2 Sequence Stratigraphy of Kirthar Formation, Rakhi Nala Section

By combining the relative sea level changes with Tertiary paleogeography, it is feasible to support the hypothesized depositional history of the Kirthar Formation in the Rakhi Nala region. Variations in seal level concerning a certain datum level can be used to describe changes in relative sea level. Tectonic uplift or subsidence, eustatic sea level fluctuations, and sedimentation rate all affect relative sea level changes. Stratigraphic data from interpreted series were checked by Schutter (1998), Haq (1991), and Handford and Loucks (1994).

Early Eocene Regression

The sea stopped moving southward in the late early Eocene. A barred and evaporitic basin was created as a result of this southerly regression, depositing thick gypsum or alabaster in the Baska shale and alabaster component (late HST to early LST). During the late early Eocene, Mari-Kandkot High was a subaqueous island in a stable carbonate platform. In a carbonate-stable platform with contemporaneous facies of the upper Ghazij Formation, shallow open marine, subtidal carbonates were deposited (Saw *et al.*, 2017; Ali *et al.*, 2021a; Figure 9).

Middle Eocene Transgression

The Middle Eocene saw a large transgression event in the Indus basin (Nagappa, 1959). Tectonic action was the cause of this transgression. Numerous local sea level changes during this significant transgression event led to the deposition of different microfacies associations in the Kirthar Formation.

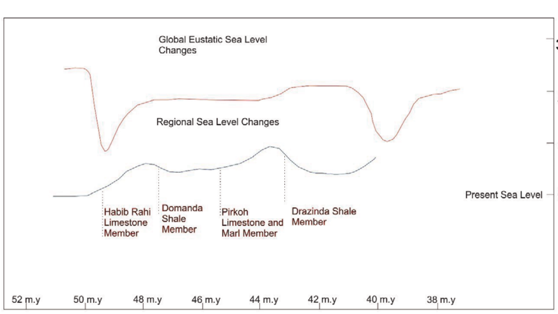

Figure 9. Eustatic Sea Level changes during the deposition of the Kirthar Formation (Modified after Vail *et al.*, 1977).

In the Sulaiman sub-basin, the Kirthar Formation was deposited as a result of four significant tectonic and sea level shifts. The already confined basin changed into the somewhat restricted inner shelf lagoonal basin that constitutes TST during the late early Eocene (Ali and Abdullatif, 2015). Shale from the Ghazij Formation was deposited during this time. The shale in question is from the upper Ghazij Formation.

Due to the ongoing sea level rise, the Kirthar basin was transformed into an open sea shelf platform (Early TST). The submerged paleo highs served as a shoal/platform edge environment with high energy. This environment led to the deposition of the bioclastic packstone-grainstone microfacies of the Habib Rahi limestone on the shelf margin. Pirkoh, Kandkot, and Mari regions served as depocentres in the south. In comparison to nearby locations, the rate of sinking was higher here. Jones and Desrochers (1992) referred to the ongoing and substantial vertical trend as "catch-up deposits." Deep open marine, organically abundant basinal Globogerinids wackestone-packstone microfacies of the Habib Rahi Limestone were deposited as parasequences after the highest sea level rise. Later, the subsidence that had been occurring in the south moved to the north, with Kingri, Pitok Nala, and Drazinda regions emerging as the focal points of these facies. At the summit of the Habib Rahi Limestone, it is discovered that there is an unconformity (sequence boundary) present. Following the relative sea level decline (late HST) (Figure 9).

Regression

The basin became partially constrained during LST as the already existing paleo highs came into effect. Domanda members' shales deposited in and filled this semi-restricted basin. The Indian platform served as a source of clastics in the direction of the east. The centre of the Sulaiman Foldbelt is on the front. Late HST settings with hypersaline, moderate to high energy, warm, and shallow temperatures are where ostracod grainstone microfacies of Domanda members were deposited. The shales are typically taken into account during late HST or cratonic basin LST (Schutter, 1998). A deviation is noted at the top of the Sirki member. With the beginning of the second sea level rise, the influx of clastic material ceased (TST). When the second sea level rise, indicated by the transgression system tract, started, parasequences of the Pirkoh limestone member were deposited in the carbonate factory. Foraminiferal Wackstone to packstone microfacies are deposited in the euphotic zone, shallow subtidal, and low-energy open sea shelf settings. The Jones and Desrochers (1992) "catch-up" deposits can be utilized to explain the continuous and dense vertical sequence of related facies. Following that, sea level rise reached its highest point, which is indicated by the peak of floods in late TST and early HST. In a deep open sea outer shelf environment at this time, laminated and organically abundant pelagic globogerinid wackestone to packstone microfacies were deposited. These circumstances were present in the districts of Rakhi Nala, Zinda Pir, and Drazinda. Comparatively more subsided than surrounding lands were the areas where these circumstances were present. Due to the deposition of organic-rich, anoxic sediments with low oxygen levels. The dense vertical and continuous series of related facies can be explained in this case using "catch up to keep up" depositional theories. An unconformity at the top of the Pirkoh Limestone and Marl Member may be seen (Figure 9).

The paleo highs to the south acted to partially confine the basin as a result of the sea's regression. Reduced bottom water circulation increases the ability of organic stuff to be preserved (Ali *et al.*, 2016). A high rate of terrigenous input once again hindered the deposition of carbonates in the carbonate factory due to the prograding thick shales of the Drazinda Shale component deposited. This clastic inflow is assumed to have originated from the Afghan shield, which is located to the northwest of the research area. It is possible to classify these shales as cratonic LST or HST. The Drazinda members' bioclastic foraminiferal packstone and foraminiferal grainstone microfacies were deposited in high-energy shallow marine conditions with slow sedimentation rates (TST). Marine remnants are recorded for this sedimentation. These parasequences may have a sequence boundary at their base (Figure 9).

In the end, a terrigenous clastic inflow created the HST basin's open sea shelf. Foraminiferal Wackestone to packstone microfacies of Drazinda members were deposited toward the top as a result of this clastic input. Near the top of the Drazinda member, there is a Type 1 unconformity identified (Figure 9). The Type 1 unconformity, which has an erosional hiatus, is defined by a laterite bed at the base of the Oligocene Chitarwatta Formation. The Indian and Eurasian plates collided, causing regional lows and regional highs (Ghazi *et al.*, 2015; Gong *et al.*, 2020). These troughs were filled with clastic sediment. The Indian shield or the recently rising axial belt was the source of this clastic inflow. These clastics made up the Oligocene Chitarwatta Formation. This indicates the presence of an LST-representing marginal marine or maybe deltaic environment in the research area (Figure 9).

6. Conclusions

After conducting robust fieldwork and microfacies analysis in the Rakhi Nala region of the Eastern Sulaiman Range, middle to late Eocene period Kirthar Formation, the following findings were established.

The Domanda shale member, the Pirkoh Limestone and Marl member, and the Drazinda Shale member are the four members of the Kirthar Formation found in the study area. The Kirthar Formation, from the Middle to Late Eocene, rests beneath the Ghazij Formation in a conformable manner. However, the contact between the Kirthar Formation and the Oligocene Chitarwatta Formation in the specific area under study is marked by an unconformity. These four members' measured thicknesses are as follows: Pirkoh Limestone Member: 13m, Drazinda Member: 285m, Domanda Shale Member: 225m, Habib Rahi Limestone Member: 38m. The microfacies H-1, H-2 and H-6 of Habib Rahi Limestone members were deposited in the deep-sea environment (FZ-1). H-3 and H-4 were deposited in a carbonate sand shoal environment (FZ-6). H-5 microfacies of Habib Rahi Limestone Member deposited in deep shelf (FZ-2). DO-1 and DO-2 members of Domanda Shale Member deposited in an open marine platform environment. P-1 microfacies of Pirkoh Limestone and Marl Member deposited in deep shelf environment (FZ-2). P-2, P-5 and P-6 microfacies are deposited in the deep-sea environment (FZ-1). P-3 and P-4 microfacies of this member were deposited in a carbonate sand shoal environment (FZ-6). The limited marine platform (FZ-7) and the open marine platform (DR-1 and DR-2 microfacies of the Drazinda Shale Member, respectively). In an evaporitic platform environment (FZ-9), DR-3 was laid down. DR-4 is deposited in a carbonate sand shoal environment (FZ-4).

The lithological units in the Kirthar Formation were formed as a result of periodic tectonic and sea level changes. As a result of the initial sea level rise, Habib Rahi Limestone members were deposited in a shallow to deeper open marine shelf setting. The Kirthar Formation's Domanda Shale Member was deposited as a result of sea level fall. Domanda members were deposited in inner shelf and semi-restricted shelf lagoonal habitats, as a result of the sea level fall. The second phase of the relative sea level rise resulted in the deposition of the Pirkoh Limestone Member. As a result of sea level rise, Pirkoh Limestone members were deposited in a shallow to deep open marine shelf environment. Due to these repeated sea level fluctuations, environments with facies of the Drazinda member were developed, ranging from a semi-restricted shallow shelf to an open marine shelf.

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