
Research article

Architecture and depositional dynamics of Miocene carbonate buildups: A case study of the Jhil member, Southern Kirthar Fold and Thrust Belt, Pakistan

Syed Haroon Ali^{1,2,3}, Mehmood Iqbal^{4,*}, Yasir Bashir^{5,*}, Noreen Shoukat⁶ and Amir Asghar⁷

¹ Department of Earth Sciences, University of Sargodha, Punjab 40100, Pakistan

² Interdisciplinary Research Center for One Health, University of Sargodha, Punjab 40100, Pakistan

³ School of Earth Sciences, University College Dublin, Dublin, Ireland

⁴ School of Marine Science and Engineering, Nanjing Normal University, China

⁵ Geophysical Engineering, Faculty of Mines, İstanbul Technical University, Türkiye

⁶ Department of Petroleum Geoscience, Universiti Teknologi PETRONAS, Malaysia

⁷ Institute of Geology, University of Poonch, Rawalakot, Azad Jammu & Kashmir, Pakistan

* **Correspondence:** Email: roohmehmood98@gmail.com; ybashir@itu.edu.tr; Tel: +90 5366 224 503.

Abstract: Miocene carbonates are important hydrocarbon reservoirs, yet the structural characteristics of carbonate reefs in Pakistan's Miocene remain poorly documented. Along the coast west of Karachi, the Miocene carbonates of the Karachi Arc, particularly between Sono Pass and Allah Bano, offer a valuable opportunity to study these rocks, with exposed thicknesses of 110 m and 150 m, respectively. In this research, we focused on a detailed analysis of the lithostratigraphy, facies, and diagenetic processes of the Jhil Member within the Gaj Formation in the Karachi Arc region, based on sedimentary features. The lithological sequence began with nodular argillaceous limestone exhibiting notable porosity, followed by limestone rich in large benthic foraminifera, corals, and red calcareous algae. The Sono Pass section was dominated by corals and red calcareous algae, while the Allah Bano section featured bryozoans alongside red calcareous algae. These Miocene carbonates recorded tectonic events such as uplift and subsidence phases, reflecting dynamic geological processes. Importantly, these carbonate deposits provide valuable insights into the final closure of the Tethys Sea following the collision between the Indian and Eurasian plates. Additionally, the Miocene carbonates of this region contribute to understanding extensive carbonate sedimentation across Turkey, Saudi Arabia, Iraq, Iran, Pakistan, and India, highlighting their regional geological significance.

Keywords: Miocene carbonates; Sequence stratigraphy; paleoclimate; architecture; heterogeneity; reservoir quality

1. Introduction

Miocene carbonate build-ups represent important hydrocarbon reservoirs with considerable economic implications [1–3]. A significant portion of global hydrocarbon reserves is located in carbonates, comprising 60% of oil and 40% of gas reserves. Hydrocarbons are generated from these carbonates in regions such as Central Asia, South Asia, and Southeast Asia, which encompass countries like Iran, Turkmenistan, Azerbaijan, Saudi Arabia, Iraq, Malaysia, Indonesia, the Philippines, and Vietnam [3–5]. Reef talus deposits, associated with reefs in moderate to high-energy environments, experience significant impacts due to reef erosion [5]. For instance, the dimensions and properties have been recorded from Permian formations in the USA [6], Devonian carbonates in Australia, and Permo-Triassic deposits of the Great Bank in the Nanpanjiang Basin and Miocene fault bound carbonates in the western part of Saudi Arabia.

The environments of the Jhil Member of the Gaj Formation from the Miocene epoch have not been thoroughly examined in prior studies. Our key aim is to examine and comprehend the lithostratigraphy, facies, and diagenetic processes related to Jhil, a component of the Gaj Formation. The Gaj Formation, initially referred to as the “Gaj Series”, was first introduced by Blanford [7] for its composition of shale, sandstone, and limestone.

Work on the Gaj Formation in the Kirthar Fold and Thrust Belt has largely proceeded along two separate sections that have not been incorporated [8–10]. Some generalized sedimentological and geochemical studies of the Jhill limestone at Cape Monze and the Karachi Arc were carried out in [11,12]. The exposed rocks in the region consist of the Nari and Gaj formations, which are dated to the Oligocene and Miocene epochs, respectively. The anticlinal structure has been shaped by tectonic and erosional episodes [4]. The Formations of Nari and Gaj in Karachi consist of limestones, shales, and sandstones, which are divided into numerous smaller sections according to their lithologic sequence and paleontological characteristics [13]. The Calcareous Zone of the Northern Axial Belt exhibits characteristics that make it challenging to distinguish it from the Nari Formation. The upper contact and the lowest portion of the Gaj Formation align with the Muncher Formation and the Nari Formation, respectively [14].

Niamatullah and Imran [13] categorized the Gaj Formation into three distinct members: Metan, Jhil, and Talawa, with an overall thickness reaching up to 1000m. Metan is composed of shale and limestone; Jhil is made up of reefal limestone, whereas Talawa includes sandstone, shale, and conglomerates (Figure 1d and e). The Jhil Member exists in the middle unit of the Gaj Formation, formed along the eastern flank of the Kirthar Fold and Thrust Belt. The Jhil Limestone is a prominent, dense, nodular, and thick-bedded component of the Gaj Formation, characterized by coralline features and large benthic foraminifera, exhibiting a color range from creamy white to light brown. Here, northward-propagating compressional tectonics formed a series of intervening synclines and asymmetric anticlines. This controlled the accommodation space across a distally steepened carbonate ramp transitional between the Arabian Platform interior and the proto-Indus foreland basin.

Moreover, geographically, the member crops out discontinuously along a NNW-SSE trending belt in Sindh Province, Pakistan. It is spread between the towns of Sehwan in the north and Khuzdar in the

south. However, erosional windows through Pliocene–Pleistocene cover expose reef-bearing carbonate successions at elevations ranging from 200 to over 900 m above sea level.

The study area is along the western coastline near Karachi, specifically through Sono Pass (24.8997664, 66.7986017) and Alla Bano (24.9082572, 66.8147767). This represents the southernmost extension of the Pab Range. The Sono Pass area, northwest of Karachi in the southern part of the Kirthar Fold Belt, presents a unique geological configuration (Figure 1c). According to the report by Hunting Survey Corporation in 1960 and the documentation by Kazmi and Rana in 1982, the structures in the area predominantly exhibit a north-south alignment south of Pir Mangho, with a gradual shift to a southwest orientation as one nears the coast. The structural change observed is linked to the location of the area at the southern end of the Karachi Arc, which is defined by its eastward convex curvature. The Sono Pass and Alla Bano are separated by a dextral strike-slip fault, with a distance of approximately 5 to 7 kilometers between them [13,14].

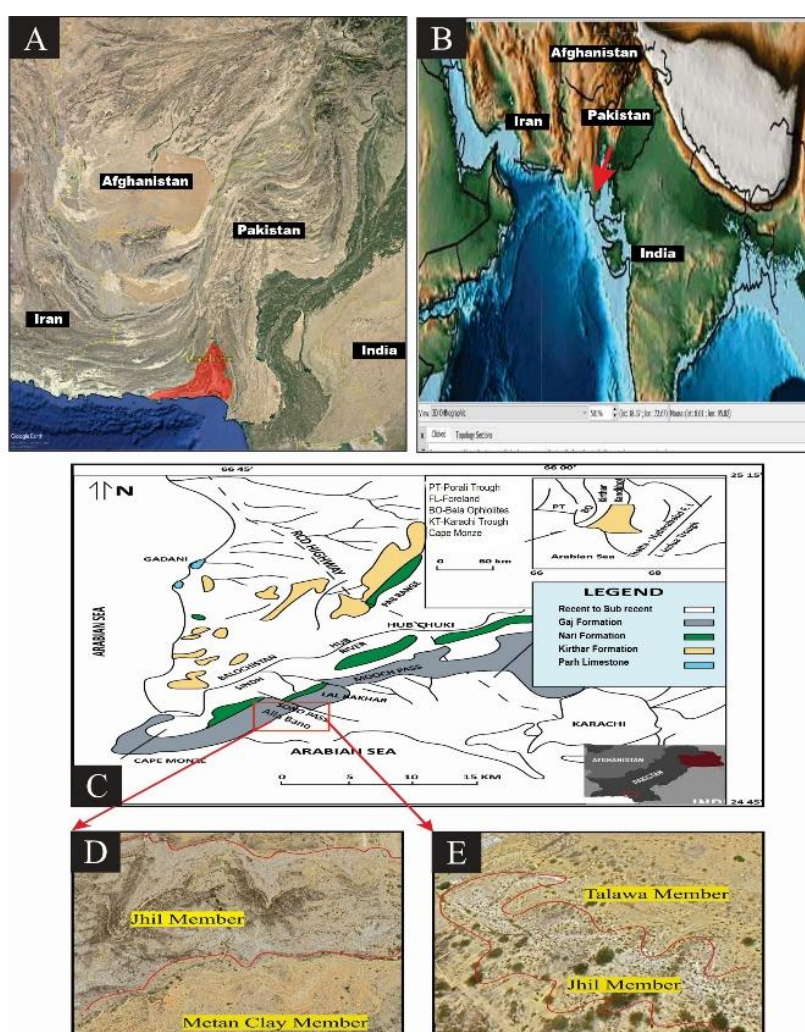


Figure 1. (a) Google earth image of parts of Pakistan with focus on Karachi arc. (b) Early Miocene time reconstruction of Indian plate, indicating presence of open sea condition with probable deposition of carbonates (Courtesy: G-Plates). (c) Geological map of Jhil Member of Gaj Formation Karachi arc, Pakistan. (d) Satellite image of Gaj Formation showing Jhil Member overlying the Metan clay. (e) Satellite image of Gaj Formation showing Jhil Member underlying the Talawa Member.

Despite the widespread occurrence of Miocene carbonate buildups along the western Tethyan margin, the internal stratigraphic architecture, reef-to-off-reef facies transitions, and depositional controls of these systems in the Kirthar Fold and Thrust Belt remain poorly constrained, largely because outcrop-based studies integrating microfacies analysis with sequence stratigraphic frameworks are absent for this sector of the Indo-Pakistan passive margin.

The Karachi trough area presents an opportunity to observe carbonates, specifically the Jhil Limestone, which contributes to the sedimentological and tectonic significance of this region. The Karachi Arc is bounded by a dextral strike-slip fault system that imposes a north-south to southwest structural deflection across the study area, yet how this fault-controlled accommodation influenced the nucleation and growth route of Miocene carbonate buildups in the Jhil Member remains unaddressed. Researchers have documented the structural geometry independently of facies architecture, leaving the tectonic forcing on reef initiation, lateral buildup asymmetry, and drowning events unresolved. In this study, we evaluate whether fault-controlled differential subsidence governed the heterogeneity, spatial thickness, architecture, and distribution variability of Jhil Member carbonate buildups between the Sono Pass and Allah Bano sections.

We address this gap by documenting the three-dimensional buildup geometry, facies associations, and diagenetic overprinting of the Jhil Member carbonates:

1. To reconstruct the depositional dynamics and platform evolution during the Miocene,
2. To provide direct implications for carbonate reservoir characterization in analogous subsurface plays across the broader Arabian Plate foreland.

1.1. Regional framework

The Indian Plate, having separated from the African Plate during the Jurassic to early Cretaceous period, initiated a northeastward movement from the Paleocene to early Eocene, ultimately colliding with the Eurasian Plate. From a global tectonic perspective, the Indian Plate is one of three lithospheric plates that converge in Pakistan, alongside the Eurasian Plate and the Arabian Plate [15]. This collision involved intercontinental interactions, including obduction and thrusts, and is regarded as the model for the orogeny of the Himalayas and Alps [2]. The Indus Basin and the Baluchistan Basin are two geologically distinct sedimentary basins in Pakistan, each showcasing unique tectono-sedimentary histories and depositional patterns. A notable and geologically important fault zone defines the boundary between these basins. The structural divide serves to separate the unique lithostratigraphic successions of each basin while illustrating the intricate tectonic evolution of the region. The region that includes both basins spans approximately 553,200 square kilometers [16], positioning it as one of the largest and geologically varied areas in South Asia.

In the Eocene epoch, the tectonic framework of the region experienced considerable reorganization as a result of increased interaction between the tectonic plates. During the process of convergence, strain was managed not only via folding and thrusting but also through the formation of extensive transform fault systems [17]. In this context, carbonate sedimentation was either minimal or absent, primarily as a result of tectonic uplift, erosion, and the introduction of significant amounts of terrigenous clastic material originating from swiftly elevating orogenic belts. Fluvial, deltaic, and shallow-marine siliciclastic systems were predominant, resulting in the deposition of sandstones, siltstones, and shales [13,14].

The significant north–south variation in sedimentation observed during the Eocene highlights the intricate interactions among tectonics, paleogeography, and depositional environments [11]. The southern Indus Basin served as a location for carbonate accumulation in relatively stable shallow-marine environments, whereas the northern regions experienced the effects of active orogenesis, significant clastic influx, and rapidly evolving basin physiography [4,18,19].

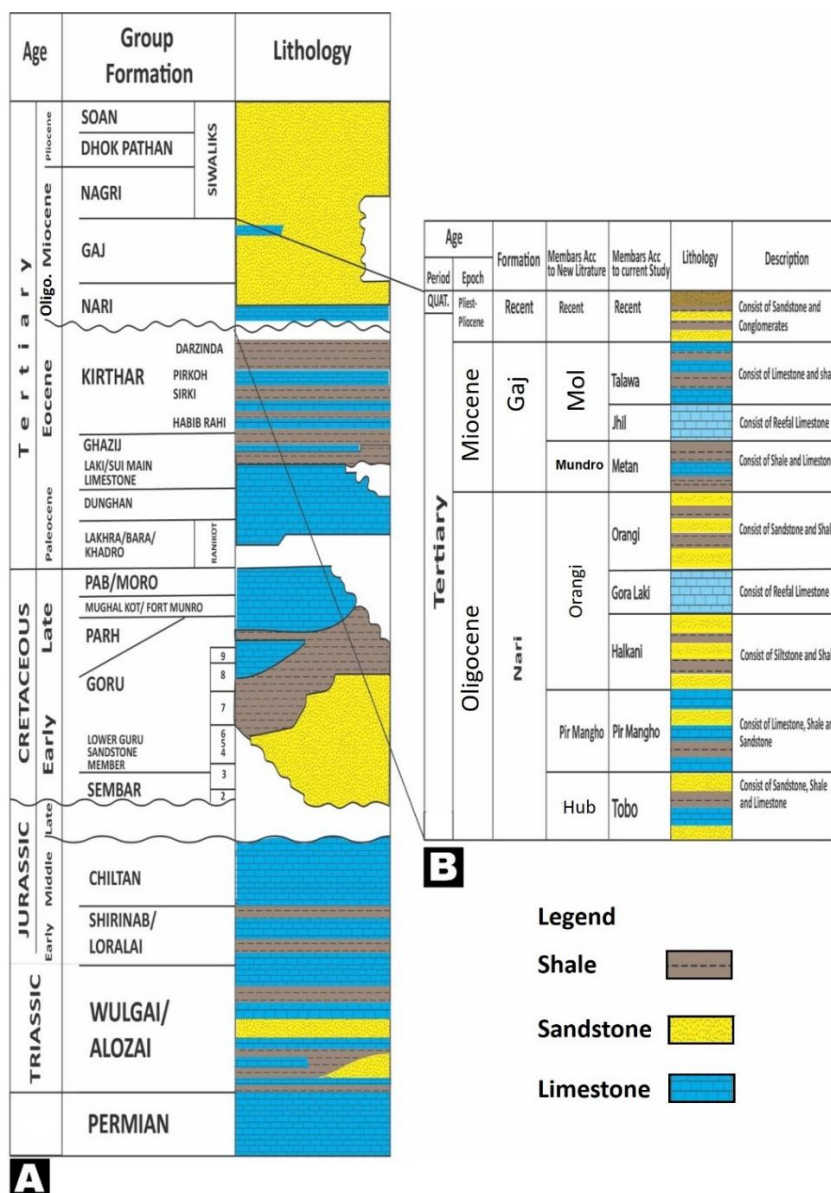


Figure 2. (a) Stratigraphic column of the Lower Indus Basin after [13,16]. (b) Stratigraphic Column of the area of interest with emphasis on Gaj Formation [13].

The Miocene successions of the northern Arabian Plate show significant stages of basin evolution, carbonate platform formation, and tectono-sedimentary interaction. In this regional context, the Gaj Formation, specifically the Jhil Member, serves as a significant Miocene carbonate buildup in the southern area of the Kirthar Fold and Thrust Belt (KFTB) [13]. Comprehending its lithofacies, depositional architecture, and diagenetic modifications is crucial for reconstructing regional paleoenvironments and evaluating reservoir potential in structurally intricate terrains. The fault-

controlled platform geometry and accommodation utilize a primary influence on the facies partitioning and stratigraphic architecture of Tertiary carbonate systems, as demonstrated by outcrop and forward modeling studies of Miocene platforms in extensional tectonic settings [18,19].

The Lower Indus Basin (Figure 2) encompasses several geological features, including the Karachi Trough, Deep Kirthar Fore, Sukkur Rift Zone, Thar Platform, Kirthar Fold Belt, and Indus Offshore [4]. The Kirthar Fold Belt extends in a north-south direction, measuring over 800 km in length and approximately 200 km in width, situated between Quetta and Karachi. However, certain deformations of the thick skin tectonics have also been associated with its southern region of the Kirthar fold belt, Karachi Arc [13,16].

2. Database, workflow, and methods

The fieldwork for this study took place from 2022 to 2023, concentrating on two representative outcrops of the Jhil Member: The Sono Pass and Alla Bano sections, located in the Southern Kirthar Fold and Thrust Belt, Pakistan. The Sono Pass section exhibits an exposed stratigraphic thickness of about 150 meters, while the Alla Bano section has a measurement of approximately 110 meters. The southernmost side of both outcrops has a relatively gentle slope, which facilitates easier access for measurement and sampling. In contrast, the northern side features cliff faces, creating logistical challenges that necessitate careful climbing and safety precautions during the sampling process. The Alla Bano section features a contemporary karst cave at its upper stratigraphic level, offering significant insights into current karstification processes and their potential implications for paleoenvironmental interpretations.

A vertical stratigraphic logging method was utilized to document lithological variations and heterogeneity present within the carbonate sequence. Comprehensive lithological descriptions were documented at specified intervals, capturing texture, color, sedimentary structures, fossil content, and diagenetic alterations. Facies classification relied on field observations combined with petrographic data to create a comprehensive facies model for the Jhil Member.

A total of 45 hand samples were collected systematically from both sections to cover the complete spectrum of lithological and textural variations. Samples were analyzed in the laboratory for their carbonate composition, lithology, and classification, employing the carbonate rock classification system. Grain size analysis was conducted to quantify textural parameters. Diagenetic features, including cementation, dissolution, compaction, and recrystallization, were meticulously examined. In the course of petrographic analysis, a total of 33 thin sections were meticulously prepared following established laboratory protocols. Thin sections were examined using a polarizing petrographic microscope to determine microfacies, fossil assemblages, allochem types, and matrix composition. Diagenetic features such as neomorphism, micritization, and fracturing were also documented. High-resolution field photographs were taken at different scales, from panoramic outcrop views to detailed close-up textures, and subsequently assembled into photomosaics to visually represent stratigraphic architecture. The combination of field observations, petrographic analysis, and photographic documentation facilitated a thorough characterization of the Jhil Member's lithofacies, depositional environments, and diagenetic history.

Figure 3 illustrates the comprehensive workflow implemented in this study, encompassing fieldwork and laboratory analyses. The process initiates with comprehensive field investigations at the chosen outcrops, during which stratigraphic measurements, photographic documentation, and sample collection

were conducted. The samples were subjected to a methodical process of petrographic preparation, followed by thin section analysis and classification in accordance with Dunham's scheme. This was further enhanced by a grain size evaluation and classification. The concluding phase encompassed the integration of field and laboratory data to delineate lithofacies, depositional environments, and diagenetic characteristics, thus facilitating a thorough characterization of the Jhil Member.

Our approach was organized as a multi-phase geological investigation centered on the Jhil Member (Figure 3). The initial fieldwork took place from 2022 to 2023 at the Sono Pass and Alla Bano outcrops, where vertical sections of 150m and 110m were logged, respectively. This phase involved the integration of slope and cliff observations with the documentation of modern karst caves to establish a geomorphological context. Subsequently, comprehensive outcrop documentation was conducted to identify vertical stratigraphic heterogeneity and distinct facies types, supported by systematic photography. A total of 45 rock samples were collected from both sections for high-resolution analysis to assess carbonate composition, lithology, and diagenesis, employing the Dunham classification method. The laboratory preparation consisted of producing 33 thin sections through the application of standard petrographic techniques. For the following petrographic analysis, we employed microscope-based evaluation to categorize lithofacies, recognize diagenetic features, and assess grain size. Ultimately, field and laboratory data were combined to create a thorough geological interpretation of the Jhil Member.

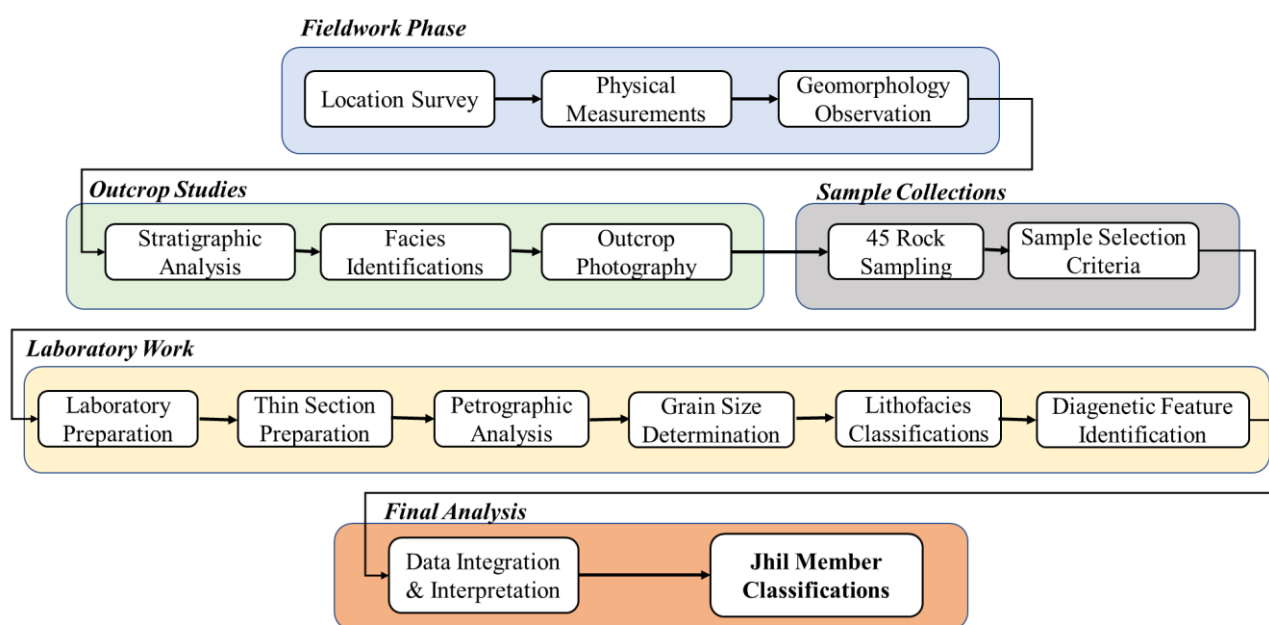


Figure 3. Detailed schematic methodology workflow diagram for the Jhil Member study, showing the sequential steps from fieldwork to final interpretation.

3. Results

A lithofacies study was conducted based on the lithology and composition of the rock [20,21]. The Jhil member of the Gaj Formation constitutes a geological rock unit situated within the Karachi Arc in Pakistan. This indicates the section of the Miocene sedimentary deposit found in the area. The Jhil member is composed of various lithofacies, which represent distinct rock types or sedimentary units

that exhibit different characteristics. Presented below are the specifics regarding the nine lithofacies commonly observed in the Jhil member of the Gaj Formation (Figure 4).

These lithofacies were identified during the current study.

- (a) Nodular Argillaceous Limestone Lithofacies
- (b) Framestone Lithofacies (Coral)
- (c) Grainstone Lithofacies (Foraminifera)
- (d) Floatstone to Rudstone Lithofacies (Algal)
- (e) Packstone Lithofacies (Red Calcareous Algae)
- (f) Argillaceous Limestone and Shale Lithofacies
- (g) Rudstone to framestone Lithofacies (coral)
- (h) Peloidal Grainstone Lithofacies
- (i) Pelecypod Rudstone Lithofacies

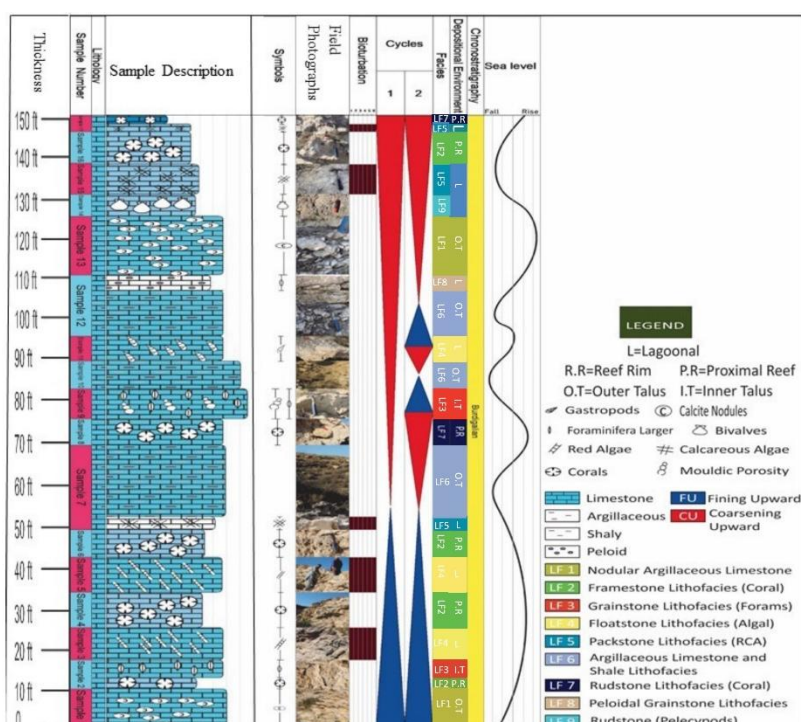


Figure 4. Lithologic log presenting various facies with depositional settings and cycles in the Jhil Member.

Figure 5 illustrates the macroscopic architecture of the Jhil Member within the Gaj Formation. A field photograph captured from the northern perspective showcases the significant carbonate reef formation within its natural environment. To enhance the understanding of the observed geometry, this view is supported by a schematic diagram in Figure 5b, which offers a structural interpretation of the internal organization of the reef buildup.

3.1. Lithofacies analysis

This lithofacies consists of nodules of concretion, commonly composed of calcium carbonate and featuring an argillaceous clay-rich matrix (Figures 5 and 6a). Nodules are generally composed of

calcium carbonate and exhibit a range of sizes and shapes within the limestone lithofacies. The argillaceous matrix consists of clay minerals and fine-grained sediments that originate from terrigenous material input or organic matter. The lithofacies indicate that deposition took place in a marine setting characterized by carbonate precipitation, along with intermittent influxes of clay. The lithofacies were formed in conditions conducive to the development of the nodules and the argillaceous matrix. The text indicates the correlation between carbonate production and clay sedimentation within a marine environment during the Miocene epoch [17].

This lithofacies is characterized by a framework of coral colonies embedded within a limestone matrix (Figure 6b). Coral framestones indicate development in warm, shallow marine environments, particularly in coral reef ecosystems. Coral colonies within framestone lithofacies typically exhibit a branched or mound-like morphology and demonstrate excellent preservation. These may encompass various types of corals, including those that contribute to reef formation. The coral framework provides structural support to the limestone and imparts a unique texture to it. Lithofacies suggest that deposition occurred in shallow, warm marine environments, such as coral reefs, which are conducive to coral growth. This indicates that the environment during the Miocene was conducive to the development and proliferation of coral colonies, characterized by clear and warm seas, appropriate substrate, and sufficient light availability [17].

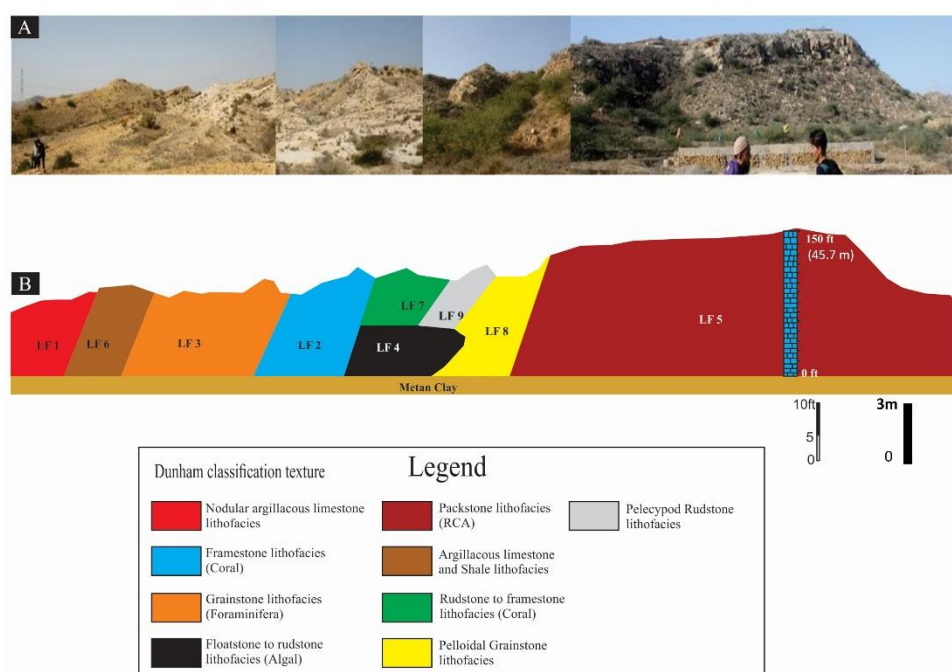


Figure 5. The architecture of the Jhil Member. (a) view taken from the northern side of the carbonated reef buildup of the Jhil Member of Gaj Formation. (b) Schematic diagram of the reef carbonate buildup.

This lithofacies is primarily composed of a foraminiferal shale matrix that is supported by grains. Foraminifera are unicellular organisms characterized by shells composed of calcium carbonate (see Figure 6c). The presence of foraminifera shells is significant, suggesting deposition in a highly dynamic marine environment characterized by strong currents. The process of dissolution and

subsequent filling of foraminiferal tests or shells leads to the formation of foraminiferal stylolites, which are a distinct category of stylolites that occur within limestone lithofacies. In sedimentary rocks, stylolites manifest as irregular, frequently undulating surfaces due to the process of pressure solution and the dissolution of minerals when subjected to pressure. In sedimentology, the phrase “foraminiferal stylolite lithofacies” denotes a limestone rock unit characterized by the presence of stylolites and an abundance of foraminiferal remains. The calcareous shells of foraminifera, single-celled marine organisms, can be found preserved within the limestone matrix. Grainstone lithofacies exemplify high-energy environments, including shallow marine or reef areas, characterized by the influence of currents or waves on sediment transport and deposition [22]. Grainstone lithofacies typically exhibit a structured arrangement of rounded grains that are primarily made up of carbonate minerals. The classification is further substantiated by the presence of foraminiferal remains identified within the grainstone lithofacies [23,24]. The grainstone matrix can preserve foraminifera shells either as distinct grains or as fragments, providing insights into the biological composition and paleo-environmental conditions during deposition [25]. Additionally, the foraminiferal stylolite lithofacies characterize limestone rock units that contain stylolites. Stylolites form through the pressure solution of foraminiferal shells, whereas grainstone lithofacies refer to limestone rocks that consist of well-sorted carbonate grains, which may include foraminiferal remains. The lithofacies provide significant insights into the diagenetic history and paleo-environmental conditions associated with their formation.

These lithofacies are characterized by a significant presence of algal fragments embedded within a carbonate mud or micrite matrix. Calcareous algae, including green algae, red algae, and stromatolites, are present in algal fragments (Figure 6d). Algal fragments are found within the lithofacies ranging from floatstone to rudstone. These fragments are frequently preserved as structures of algal colonies or as skeletal remains. Limestone exhibits a distinctive texture and morphology attributed to its algal constituents. The lithofacies indicate that the sediments were deposited in shallow marine environments characterized by conditions conducive to algal growth, including warm, clear water and adequate light availability. Extensive algal blooms indicate a highly productive ecosystem during the Miocene epoch [25].

This lithofacies is characterized by an abundance of red calcareous algae and a packstone texture. The presence of areas rich in algae frequently results in a mottled appearance. The packstone texture of the lithofacies reveals a significant abundance of grains, including algal fragments and carbonate particles, embedded within a fine-grained matrix (Figures 5 and 6). Red calcareous algae, known for their role in imparting the distinctive hue of limestone, frequently exhibit excellent preservation. The presence of abundant algae can result in a mottled appearance of lithofacies. The occurrence of red calcareous algae suggests deposition during the Miocene in warm, shallow marine environments where sufficient light was available to support algal growth. Red algae produced and contributed carbonate sediments to the atmosphere with significant productivity, as evidenced by the prevalence of algal lithofacies [14].

This lithofacies consists of alternating layers or interbeds of shale, clay-rich sedimentary rock, and limestone. This lithofacies presents a sedimentary unit characterized by the integration of clay-rich (shale) and carbonate-rich (limestone) components (Figure 6f). The shale fractions comprise fine-grained clay minerals, including illite, kaolinite, and smectite, whereas the limestone fractions are characterized by the presence of carbonate minerals like calcite and aragonite. The properties of carbonate- and clay-rich components within lithofacies can be influenced by sedimentary environments and regional geological conditions. A lithofacies represents a depositional environment

shaped by the interaction of carbonate and siliciclastic sediments. This pertains to scenarios where the formation of carbonate occurs alongside the incorporation of fine-grained detrital substances, such as clay, silt, or organic matter. Examples of these mixed depositional environments include deltaic systems, lagoons, and near-marine ecosystems [17].

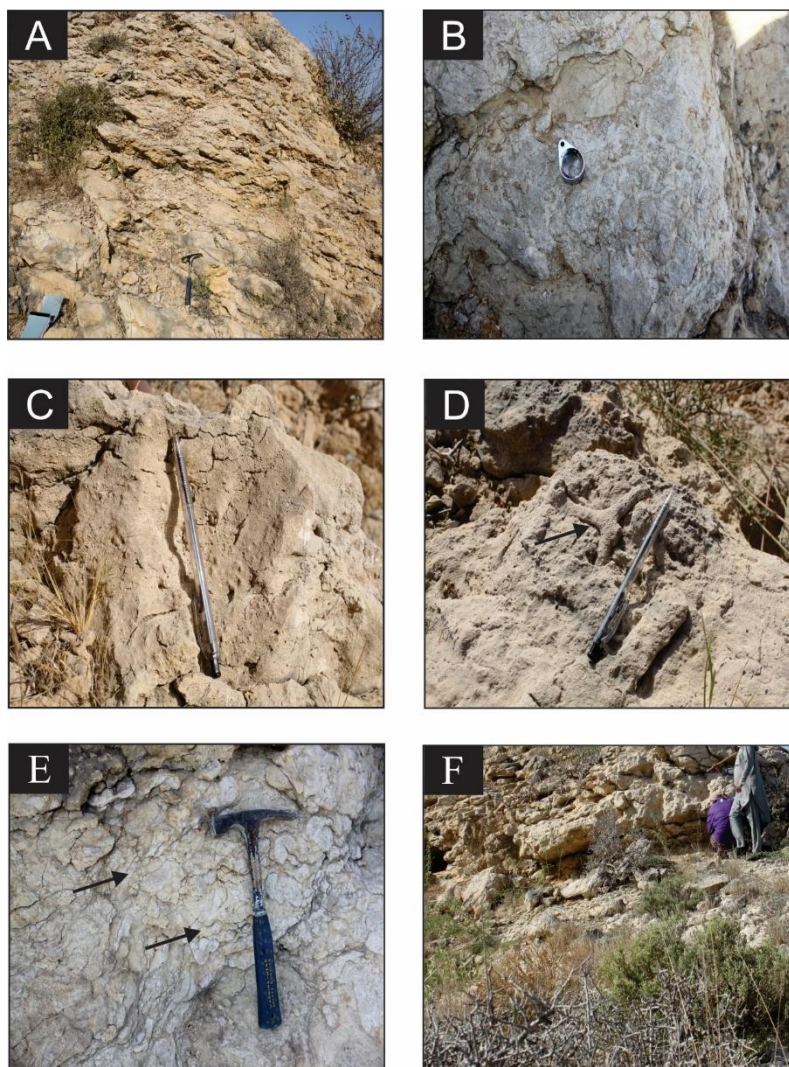


Figure 6. The outcrop field photographs illustrate the facies of carbonate reef buildup. (A) Nodular Argillaceous Limestone Lithofacies. (B) Framestone Lithofacies (Coral). (C) Grainstone Lithofacies (Foraminifera). (D) Floatstone to Rudstone Lithofacies (Algal). (E) Packstone Lithofacies (Red Calcareous Algae). (F) Argillaceous Limestone and Shale Lithofacies.

The coral lithofacies are characterized by isolated coral colonies dispersed throughout the limestone matrix. Framestone corals do not establish a permanent structure characteristic of coral framestone lithofacies. A specific category of sedimentary rock characterized mainly by isolated coral remains is referred to as the rudstone to framestone lithofacies (Figure 7a). Solitary corals, which are individual polyps, create smaller reef structures compared to their colonial counterparts. Lithofacies are typically characterized by the presence of distinct coral fossils that exhibit excellent preservation within the surrounding rock matrix. The fossils exhibit a range of shapes and structures, including

distinctive tubular, conical, and irregular forms, among others. Additional associated skeletal fragments, including shells and bryozoans, are also identified within the lithofacies. The occurrence of individual corals within lithofacies suggests deposition in marine environments conducive to their growth, including deep water and shallow nearshore settings. The lithofacies indicate a palaeoenvironment characterized by numerous isolated corals that played a crucial role in carbonate deposition. This indicates a marine environment characterized by intermittent coral colonies [26,27].

This lithofacies is characterized by limestone that is abundant in peloids. Peloids are small, spherical carbonate grains that result from chemical precipitation or the byproducts of an organism's activity. Peloids constitute the predominant component of peloidal grainstone lithofacies and serve as the main rock element (Figure 7b). Peloids exhibit concentric or radial internal structures and display a range of sizes, shapes, and compositions. The cement or micritic matrix is commonly utilized to fill the gaps between the peloids. "Peloidal Grainstone Lithofacies" includes peloids within the rock matrix. Peloids are small, spherical carbonate grains that vary in size from silt to sand. These materials frequently include carbonate microcrystals or micrite, characterized as a fine-grained carbonate clay. The lithofacies reveal multiple locations where deposition likely took place, including shallow marine, lagoonal, or marine flat environments characterized by the prevalence of carbonate mud. The accumulation of carbonate mud particles frequently leads to the development of peloids, which are indicative of sedimentation occurring in low-energy environments and areas with minimal hydrodynamic activity. The dimensions, configuration, and composition of peloids serve as criteria for the further classification of pelloid limestone lithofacies, which exhibit a range of textures. The observed variations could result from differing collection processes and settings [25].



Figure 7. The outcrop photos show the facies of the Carbonate Reef build-up. (A) Rudstone to framestone Lithofacies (coral). (B) Peloidal Grainstone Lithofacies. (C) Pelecypod Rudstone Lithofacies.

This lithofacies is differentiated from calcic green algae by the presence of traces or pelecypods. Pelecypods are diminutive organisms that bear resemblance to bivalves. Pelecypod fossils identified within lithofacies indicate a marine habitat characterized by a significant presence of bivalves, likely representative of a shallow marine or nearshore environment. The green color of lithofacies can be attributed to various factors, such as the presence of green algae, chlorite minerals, or organic material (Figure 7c). Lithofacies can encompass numerous dichotomous species, with shells exhibiting a range of preservation states, from fully intact to fractured. The presence of bivalves in lithofacies provides insights into the palaeoenvironment, indicating suitable substrate for colonization and nutrient availability in the water column. The distinctive lithofacies variations provide further insights into the depositional settings and the species that inhabited the Karachi Arc during the Miocene. The lithofacies of this rock indicate deposition in a shallow marine environment conducive to pelecypod activity and the proliferation of green algae. Each lithofacies indicates distinct sediment sources, energy levels, and environmental conditions, thereby enhancing our comprehension of the area's geological history [26].

3.2. Quantitative analysis

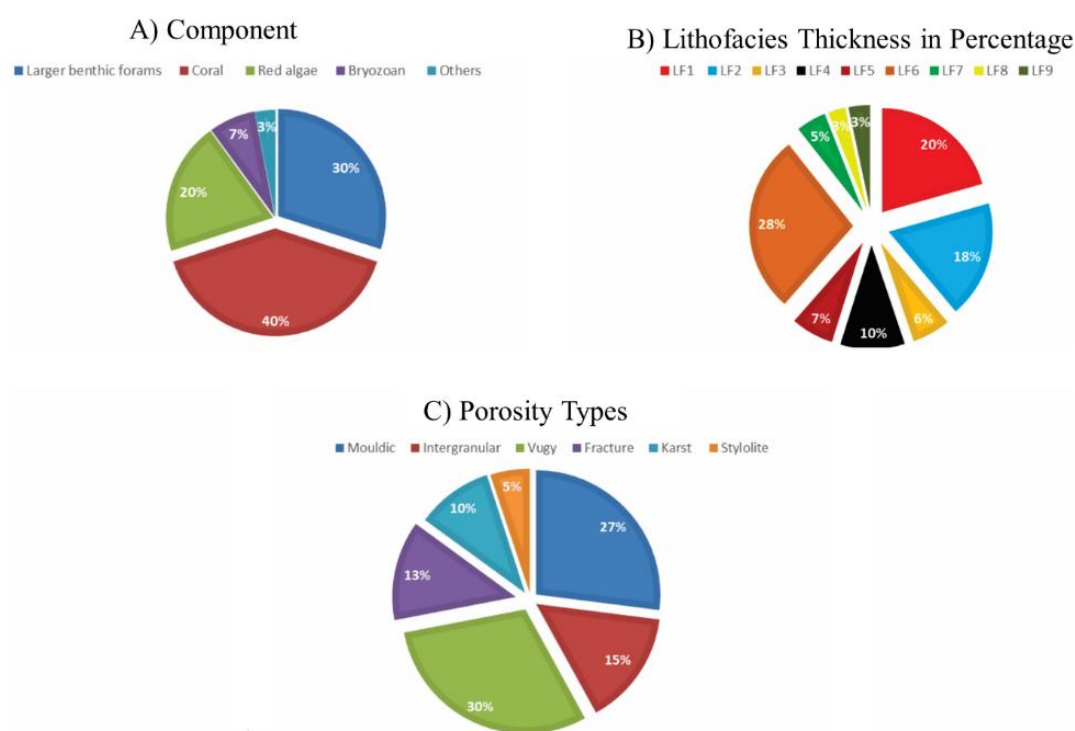


Figure 8. Quantitative description of Carbonate reef build-up based on A) Component, B) lithofacies thickness in percentage, and C) porosity types available.

The quantitative analysis of the carbonate reef build-ups was conducted by integrating the field and laboratory data obtained through the methodology explained earlier. Figure 8 presents a comprehensive analysis of these build-ups, concentrating on the distribution of individual components and the comparative thickness of recognized lithofacies represented in percentages. This figure categorizes the different types of porosity identified through petrographic microscope analysis, an essential process in assessing the reservoir potential of the Jhil Member. The integration of vertical

stratigraphy recorded during fieldwork with high-resolution data from the 33 thin sections provides a statistically supported perspective on the internal architecture of the reef.

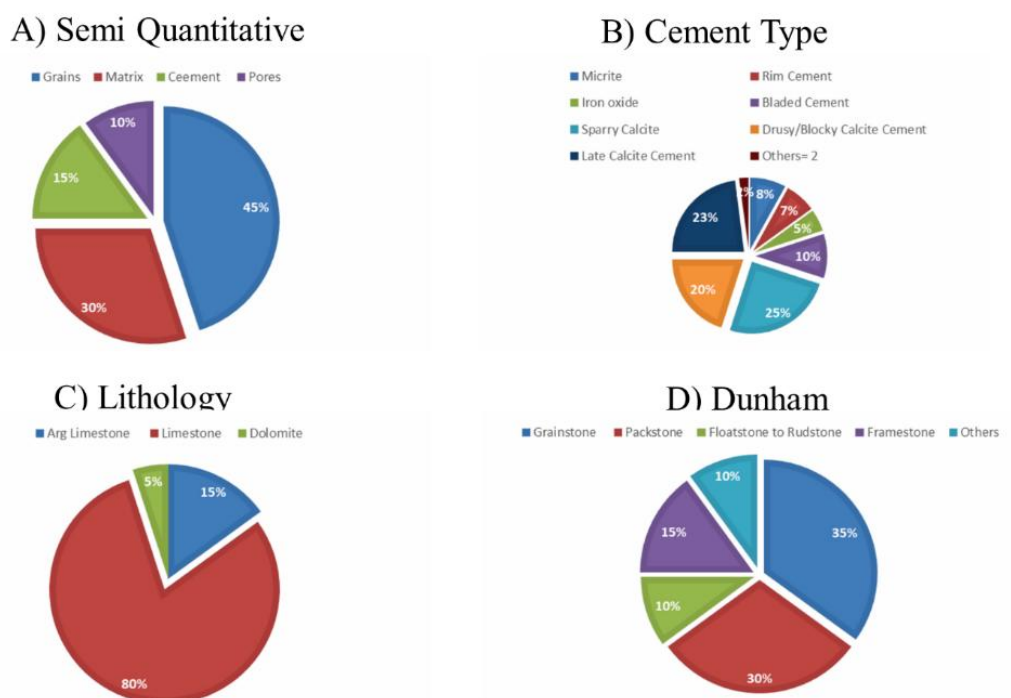


Figure 9. Quantitative description of Carbonate reef builds up based on A) semi-quantitative, B) cement type, C) lithology, and D) Dunham's name.

Expanding on the component-based analysis, Figure 9 offers a more comprehensive characterization of the reef build-ups via semi-quantitative assessments and lithological classifications. In this section, we focus on the distribution of cement types and the overall lithology, as identified during the phase of laboratory work dedicated to recognizing diagenetic features. Furthermore, the build-ups are categorized, which ensures that the terminology is aligned with the established petrographic techniques described in the methodology. For this detailed quantitative description, we aim to confirm the initial outcrop observations by offering a thorough, lab-verified framework for identifying facies types and integrating data.

4. Discussion

Studies on Miocene carbonate buildups globally show that these formations generally occur on structural highs, platform edges, or as standalone bio-constructive mounds, where conditions such as accommodation, water energy, and nutrient flow support abundant carbonate-producing organisms. The principles outlined are relevant to the Jhil Member, as field-based and outcrop-analogue observations indicate that it consists of heterolithic carbonate lithofacies. These lithofacies vary from grain-dominated packstones and grainstones to matrix-supported boundstones, as well as microbial- to bioclastic-rich rudstones [6]. The variations in vertical and lateral characteristics within buildups indicate changes in energy conditions, intermittent siliciclastic contributions, and ecological differentiation from the outer edges to the center.

Facies mapping at outcrop scale frequently uncovers lateral transitions spanning tens to hundreds of meters, suggesting patchy reefal or bioconstructive growth as opposed to uniform, continuous platform deposition. Lithofacies analyses typically delineate distinct facies belts within Miocene buildups: An outer high-energy rim, which is characterized by coarse grainstones and cross-bedded bioclastic shoals; an intermediate flank composed of packstones containing abundant benthic foraminifera and fragments; and a sheltered core featuring boundstones, wackestones, and, in some areas, peloidal or micritic deposits. In the Jhil Member, analogous facies stacking patterns have been deduced, supported by evidence of episodic exposure surfaces or hardgrounds that document relative sea-level fluctuations and subaerial diagenetic processes [14,15]. The reconstructions of the depositional environment for the Jhil buildup highlight shallow, warm marine settings, which span from intertidal to shallow subtidal zones, characterized by predominantly normal marine salinities. Hydrodynamic indicators, including grain orientation, abrasion textures, and the presence of ooids or pisoids, suggest varying energy conditions that are affected by local bathymetry and potentially by concurrent tectonic relief. Intercalated thin siliciclastic horizons indicate episodic influxes from adjacent terrestrial sources, likely influenced by local uplift, erosion, and sediment supply driven by climate factors.

Nine distinct lithofacies have been identified, encompassing a range from distal outer to inner talus deposits, as well as proximal reef, reef rim, and lagoonal deposits [26]. The Jhil Member primarily consists of grain-bearing limestone, with a grain content ranging from approximately 45% to 70%. Facies LF3 exhibits the highest grain content, primarily composed of foraminifera. The Jhil Member of the Gaj Formation is defined by its hard limestone composition, exhibiting minimal pore spaces [27]. Fractures related to the uplift of the formation are filled with calcite cement, likely as a result of exposure to weathering processes. The upper stratigraphic layers of the Allah Bano section exhibit enhanced dissolution, resulting in the development of caves. The caves, also known as underground sinkholes, intersect bedding planes and fractures, resulting in a deep vertical karst system. No dolomite was observed in the outcrop; only minor amounts were identified in thin sections within the outer talus deposits [18]. A comparison of textures observed in outcrops and thin sections indicates that the more argillaceous outer-talus argillaceous limestone (LF1, LF6) is characterized by a dominance of benthic foraminifera, while the coral debris-rich inner talus (LF2, LF3), algal-rich lagoonal (LF4, LF5, LF8, LF9), and framestone (LF7) represent proximal reef deposits (Figure 10). Lagoonal deposits display a granular packstone-rudstone texture, which suggests a shallow lagoonal environment, characterized by the presence of coarse coral debris adjacent to the reef edge. Talus deposits are roughly 20 to 60 meters from the reef's edge [19,23].

Reef rim deposits are shaped by the initial processes of sedimentation and the later transformation of corals through neomorphism. The original pore spaces within coral cavities, known as intraparticle pores, are typically occupied by recrystallized calcite, and the preservation of the original framework porosity is uncommon [19]. Furthermore, the aragonitic structures of the corals have undergone dissolution, leading to the formation of casts that are filled with calcite cement. This indicates that reef rim deposits could serve as pathways for fluid movement into the subsurface, attributed to their elevated permeability. Lagoonal facies exhibit horizontally bedded rocks, predominantly consisting of large benthic foraminifera, red algae, and bryozoans in the upper section. The reservoirs exhibit a high grain content, such as rudstone and packstone. Given the presence of reworked secondary porosity, internal talus, and lagoonal deposits, they demonstrate certain reservoir potential. The Sono Pass Section's lower region primarily consists of argillaceous and nodular limestone characterized by cavernous porosity, which serves as a habitat for larger benthic foraminifera. As one progresses upward

through the section, there is a notable increase in the presence of red calcareous algae and corals, alongside a reduction in larger benthic foraminifera and a small quantity of bryozoans.

The Alla Bano Section exhibits a dominance of bryozoans and RCA, featuring cavernous porosity and karst topography due to the dissolution of limestone, which is primarily composed of calcite with minor dolomite content. The microfacies observed in the Miocene buildup carbonates are predominantly influenced by tectonic activities, resulting in variations in relative sea levels. A buildup dominated by coral foraminifera, classified into nine microfacies, develops on a structural high, experiencing changes in deposition from shallow to deep lagoon and returning to shallow lagoon conditions. The Dolomites are present in limited quantities within the carbonate accumulation, providing superior reservoir quality characterized by intercrystalline pores, which indicates potential for hydrocarbon development. Following burial beneath clastic sediments approximately 5 million years ago, particularly during that interval, stylolite formation and mechanical compaction occurred, modifying pore structure as a result of continuous subsidence during the final phases of carbonate accumulation.

The compaction trends perceived in the Jhil Member are analogous to those reported for Miocene carbonates off the west coast of Australia, indicating similar diagenetic and burial-related porosity reduction processes [28].

The facies heterogeneity, architecture, and diagenetic overprinting found in the Jhil Member carbonates reflect a complex interplay between relative sea-level fluctuations, antecedent topography, and syndepositional tectonic subsidence [25,29]. The vertical transition from open-marine wackestones and packstones in the lower Jhil Member to high-energy grainstone shoals and boundstone-dominated reef cores in the middle succession records a deepening-upward then shallowing-upward motif that mirrors third-order sequence stratigraphic cycles identified in the Gaj Formation by previous workers [30,31]. Although the internal reef geometry and off-reef apron facies documented here add considerably finer resolution to that framework. The control of larger benthic foraminifera, particularly *Nummulites* and *Operculina* assemblages, in the peri-reefal facies is consistent with photic zone deposition in oligotrophic, warm-water conditions analogous to those reconstructed for Miocene carbonate factories along the northern Tethyan margin [32,33]. This supports the isolated pinnacle reef geometry from outcrop analogues that was inferred from subsurface data alone. The diagenetic sequence includes pervasive meteoric and burial diagenesis, expressed as fabric-selective dolomitization, neomorphic aragonite replacement, and fracture-controlled cementation. It substantially modified primary porosity networks and must be accounted for in any reservoir quality prediction derived from Jhil Member analogues. A point highlighted by comparable diagenetic complexity reported from Miocene carbonates in the Central Luconia Province of Malaysia and the Dam Formation of Saudi Arabia [34,35]. Collectively, these results demonstrate that the Jhil Member records a tectonically modulated, high-frequency carbonate system. Its facies heterogeneity, buildup architecture, and diagenetic evolution are directly comparable to productive Miocene carbonate reservoirs across the broader Indo-Arabian domain. This gives the outcrop record of the southern Kirthar Belt substantial value as a surface analogue for subsurface exploration targets in the region.

The distinct facies gap between the Sono Pass section and Allah Bano assemblage is best explained not only by sea level changes alone, but by fault-partitioned subsidence along the dextral strike-slip system separating the two localities. The southwest structural bend imposed differential accommodation space, favoring high-energy reef-crest growth at Sono Pass on the structurally elevated block while promoting lower-energy, deeper-water conditions at Allah Bano in the relatively subsiding hanging wall position. This tectonic dividing, rather than a simple ramp-to-basin bathymetric gradient,

accounts for the lateral diagenetic heterogeneity observed in the Jhil Member. It has direct implications for predicting reservoir quality distribution in analogous fault-bounded carbonate buildups across the Kirthar Fold Belt and beyond.

4.1. Developed tectonostratigraphic model

The application of sequence-stratigraphic frameworks to Miocene carbonate systems reveals that buildups are frequently delineated by flooding surfaces and sequence boundaries, which have significant implications for lateral connectivity and the formation of traps [36,37]. The integration of facies, diagenesis, structural setting, and sequence stratigraphy results in a detailed model for the Jhil Member. This model describes a structurally influenced, heterogeneous carbonate buildup characterized by variable reservoir potential, which is determined by the distribution of facies, fracture networks, and diagenetic history. Future efforts that integrate detailed sedimentology, petrography, and subsurface geophysics will enhance these interpretations and provide quantifiable insights into the hydrocarbon and groundwater significance of the Jhil Member within the Kirthar fold-thrust domain.

The stratigraphic evolution of the Gaj Formation progresses through five distinct and sequential stages, each contributing a unique geological imprint to the depositional history of the region. The initial phase is characterized by the Metan Member, which offers significant evidence of considerable clay deposition, indicating the prevalence of fine-grained siliciclastic sedimentation during this early stage. This stage indicates a depositional environment characterized by low energy, possibly associated with deltaic or distal marine settings where there is a significant accumulation of clay minerals. These conditions suggest a depositional environment that occurred prior to the notable carbonate formation seen in subsequent stages.

The second stage records the formation of the Jhil Member, characterized by substantial limestone layers that are complexly structured and densely inhabited by large benthic foraminifera. The lithological characteristics indicate a warm, shallow marine carbonate platform environment, where clear and nutrient-rich waters promoted extensive carbonate production. The variety and quantity of benthic foraminifera serve as significant indicators of past environmental conditions, indicating favorable circumstances for the thriving of these organisms.

The third stage presents a significant ecological transition in depositional characteristics, with the limestone succession increasingly characterized by coral frameworks. The coral-rich carbonates document the evolution of dynamic reef ecosystems, maintained in their original location, and offer a crucial paleoecological insight into a flourishing Miocene marine environment. The prevalence of coral indicates times of consistent sea levels and elevated carbonate saturation, enabling reef-building organisms to create intricate, wave-resistant formations.

In the fourth stage of the stratigraphic record, the depositional system demonstrates a symbiotic relationship between corals and red calcareous algae, alongside the notable presence of Bryozoans. This collection indicates a transitional phase in the carbonate factory, wherein environmental and ecological interactions led to a more diverse community structure [20]. The red algae played a crucial role in binding and stabilizing sediment, whereas Bryozoans, despite being less abundant, provided a supportive function in framework construction and sediment baffling.

The fifth and final stage of stratigraphic evolution is characterized by the deposition of the Talawa Member, which acts as an indicator of marine flooding events. This phase is marked by the gathering of sediments that reflect a significant transgressive event, leading to the submersion of previous

carbonate formations. The occurrence of this member at the apex of the succession conclusively concludes the depositional narrative of the Gaj Formation, characterized by a clear stratigraphic and environmental signature (Figure 10).

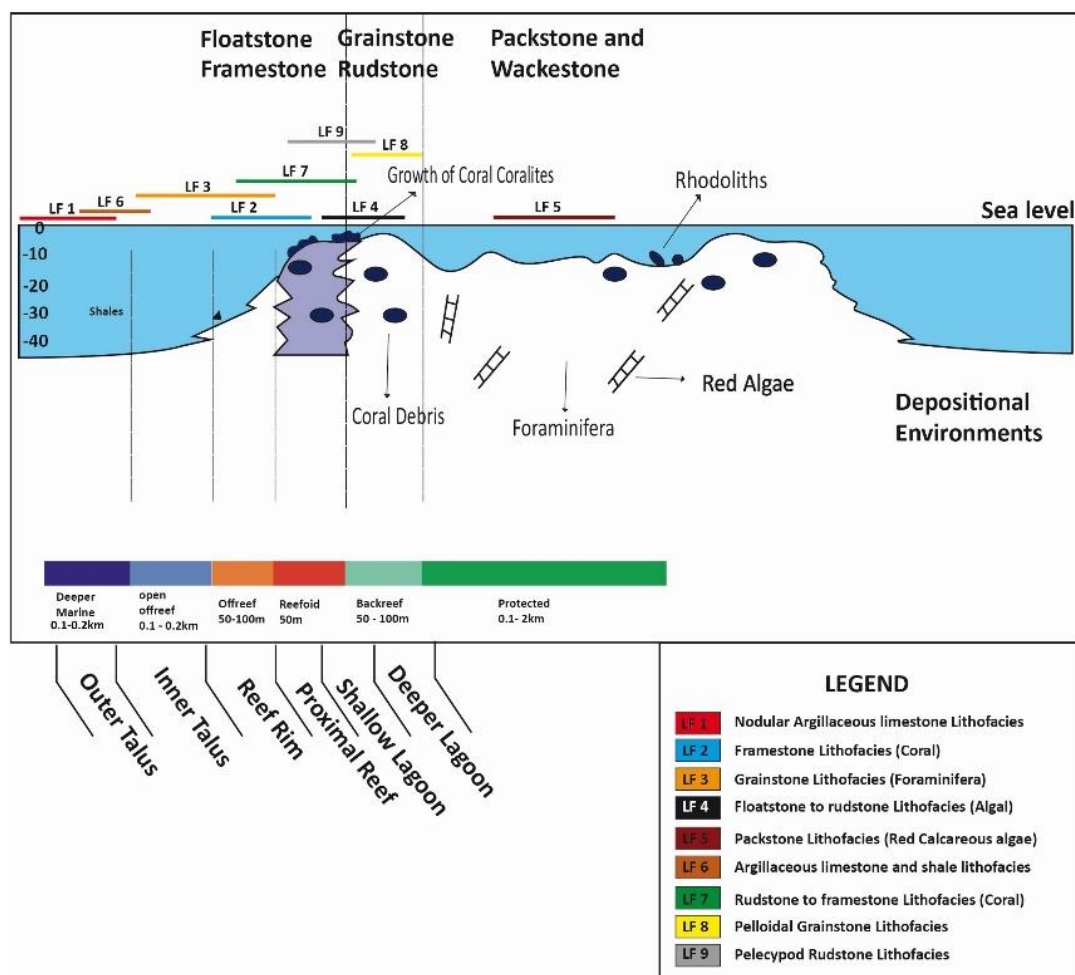


Figure 10. Conceptual tectonostratigraphic model of lithofacies suggesting the diverse carbonate reef setting complex associated with the inner talus to the deeper lagoon.

The cementation processes observed in the carbonate buildups throughout these stages exhibit distinct variations, which correspond to alterations in accommodation space, hydrodynamic energy, and diagenetic pathways. The variations become especially evident during flooding events, as changes in pore-water chemistry and burial conditions lead to the development of distinct cement morphologies. The Jhil Member exhibits notable porosity development, characterized by significant primary porosity derived from depositional textures and secondary porosity resulting from post-depositional dissolution processes. The presence of open and partially filled fractures has significantly increased the permeability of these carbonate units, highlighting their potential as efficient fluid reservoirs. The integrated stratigraphic and diagenetic framework emphasizes the intricate interactions among depositional environment, tectonics, and post-depositional alterations that influence the reservoir properties of the Gaj Formation.

5. Conclusions

The Jhil member of the Gaj Formation demonstrates the principles discussed in this paper, comprising limestone and minor argillaceous components such as clays. The Jhil member is characterized by a diverse range of lithofacies, which include nodular argillaceous limestone, framestone (coral), grainstone (foraminifera), floatstone to rudstone (algal), packstone (RCA), argillaceous limestone and shale, rudstone to framestone (coral), peloidal grainstone, pelecypods, and a combination of rudstone and packstone to framestone (branching coral and algae).

The variations are associated with flooding surfaces induced by tectonic activity, resulting from alterations in sea level linked to subsidence. The carbonates found in the Miocene buildup predominantly display secondary porosity types, including mouldic, microporosity, vuggy, and intercrystalline characteristics within limestone and dolomitic limestone.

Secondary porosity developed as a result of the dissolution of foraminifera and coral fragments. The distribution of pores and cement within the buildup was influenced by several factors, such as the geometry of the buildup size, stratigraphy, time, fluid dynamics, and the depositional environment. Diagenetic activities took place in various environments, including early marine, phreatic mixed meteoric-seawater, and meteoric realms. Flooded surfaces that are impervious primarily influenced subsequent diagenetic stages, resulting in the degradation of reservoirs on these surfaces.

Author contributions

SHA: Supervision, Conceptualization, Methodology, Software, Formal analysis, Writing: Original Draft, MI: Software, Formal analysis, Writing-Original Draft, Data Curation, YB: Methodology, Writing: Review & Editing, Visualization, NS: Conceptualization, Writing: Review & Editing, Project administration, AA: Writing: Review & Editing, Project administration.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Data availability

Data will be available on demand.

Ethics approval

All ethical standards have been followed during this research.

Conflict of interest

The authors declare no competing interests.

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