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Rock Typing, Diagenesis and Paleoenvironment of Middle Jurassic Tethys Ramp Carbonates, Sub-Himalayas, Pakistan

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Abstract

The Samana Suk Formation is extensively exposed across the Sub-Himalayan region of Pakistan, notably within the Salt Range and the Trans-Indus Ranges, where Jurassic carbonates dominate the stratigraphy. Although localized studies have been conducted, a comprehensive understanding of the link between exposures in these two regions has remained elusive. This study identifies five primary lithologies: limestone (78%), marl/shale (10%), dolomite (9.5%), irregular quartz-bearing limestone (1.5%), and sandstone (1%). Limestones in the Salt Range exhibit a range of textures, including fine- to coarse-grained, nodular, skeletal, micritic, oolitic, and intraclastic varieties. Seven distinct microfacies have been classified: mudstone, dolo-mudstone, bioclastic peloidal wackestone, bioclastic intraclastic grainstone, sandy echinoderm packstone, ooidal peloidal bioclastic grainstone, and peloidal grainstone. Stratigraphic sections in the Trans-Indus Ranges reveal considerable variability in thickness, facies composition, dolomitization intensity, quartz content, and diagenetic features. X-ray diffraction and scanning electron microscopy analyses confirm a predominantly carbonate mineralogy with well-developed microporosity. Above this Jurassic carbonate platform, the upper Paleocene Hangu Formation records a shift to subaerial depositional conditions. These findings collectively highlight the Samana Suk Formation as a valuable archive of Middle Jurassic paleoenvironments and suggest its potential as a hydrocarbon reservoir and a source of raw materials for the cement and construction industries.

Keywords: *Sedimentology; Sequence; Paleogeography; Salt Range; Depositional Environment*

1. Introduction

Several studies conducted by reservoir modellers have recognized the application of conceptual geological models (Abd El Aal et al., 2023; Teles et al., 2023; Brandano et al., 2022). The recent conjectural shift began with the application of conventional field data for on-site documentation of depositional structures and facies geometries, combined with paleogeographic datasets that were previously difficult to obtain. The deposition of the Samana Suk Formation was influenced by paleogeography, regional tectonics, and fluctuations in sea level. The formation has been recognized for approximately a hundred years, with (Cotter 1933; Davies 1993; Gee 1947) the Samana Suk Formation previously referred to as the Kioto Limestone, the Samana Suk Limestone, and the Baroch Limestone, respectively. Samana Suk Formation. exhibits extensive basinal distribution, extending from the Salt Range to the Surghar and Marwat Ranges within the Upper Indus Basin (Shah 1977), as illustrated in Figure 1. This formation is present across various basins and ranges (Sajjad 2020; Saboor et al., 2022; Wadood et al., 2021); however, the connection between the sections in the Salt Range and those in the Trans-Indus Ranges remains unexplored. This entity is extensively distributed across various basins, including the Trans Indus, Kohat, Samana, Hazara, and Kala Chitta Ranges.

Significant events that occurred before and following the breakup of Pangea are described in Figure 1. During the Permo-Triassic period, Gondwanaland initiated rifting, leading to the formation of an Atlantic-type passive continental margin (Searle 1983). The beginning of rifting of the Indo-Australian plate during the Cretaceous period, originating from Madagascar and Africa. An examination of the Tethys Sea reveals its formation during the Paleocene, resulting from the collision of the Indian Plate with the Eurasian Plate as the latter moved in a counterclockwise direction. Consequently, various geological features are situated across their respective locations within the geological formations of Pakistan (Qadri et al., 2010; Mateen et al., 2022; Ali et al., 2022a; Ali et al., 2022b; Naseem et al., 2023). The formation is exposed in the Trans Indus, Western Salt, Kohat, Kala Chitta, and Hazara ranges. The thickness of the

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Samana Suk Formation varies based on the paleogeographic location of the lithostratigraphic section (Ghazi et al., 2015; Ghazi et al., 2020; Ahmed et al., 2020; Ali et al., 2021; Wahid et al., 2022), which dated back to the Middle Callovian (Ali et al., 2021; Figure 2). The fauna indicates that the formation dates back to the Middle Jurassic period (Wahid et al., 2022).

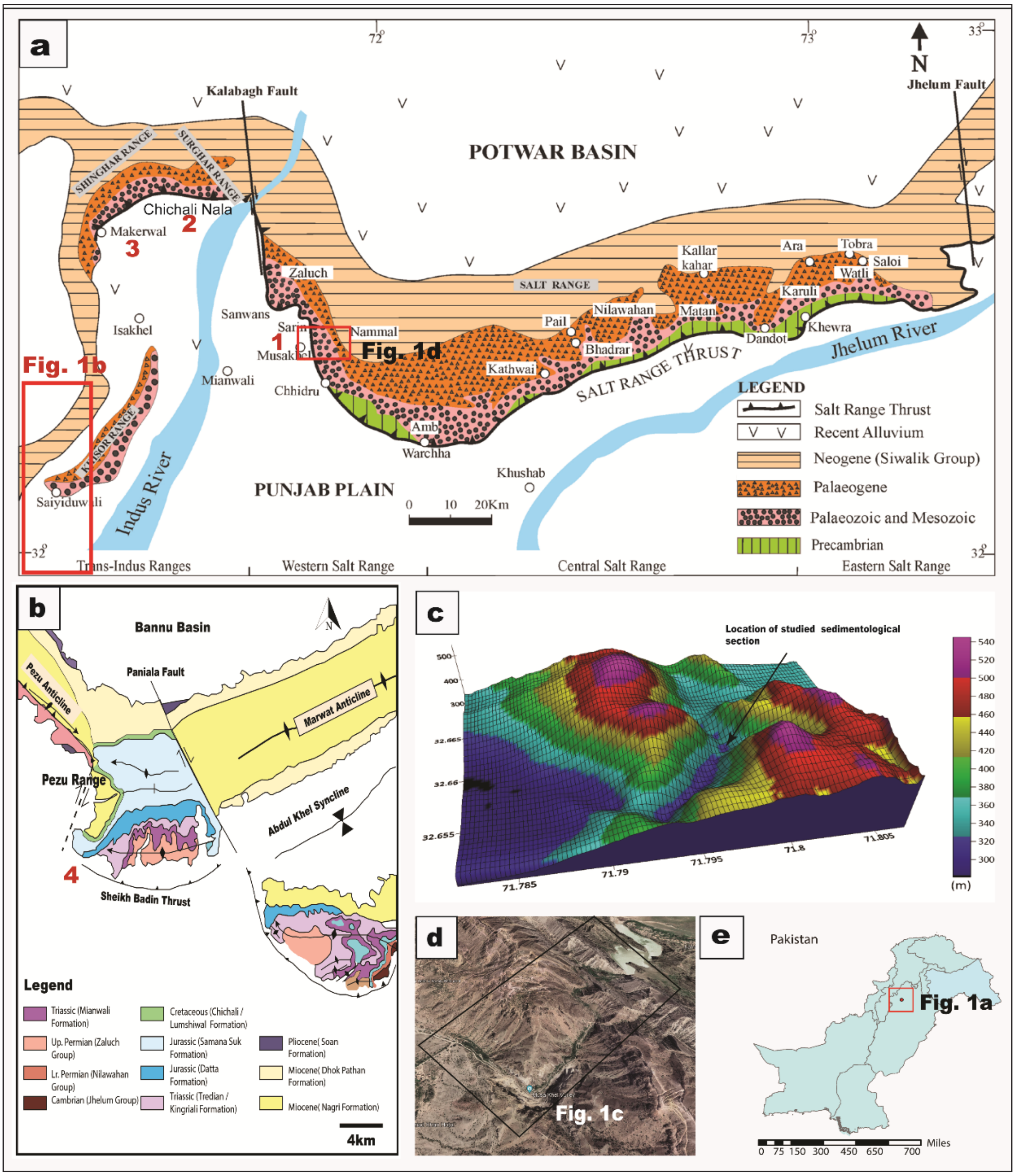

Figure 1. a) Location map of the researched geographical area in the Salt Range, Sub Himalayas, Pakistan: 1-Nammal Gorge, Western Salt Range; 2-Chichali Nala, Surghar Range; 3-Makerwal Section, Surghar Range (Ghazi et al., 2015); (b) Geological map of Marwat Range, 4-Sheikh Badin Hills; (c) Digital Elevation Model (DEM) of Nammal Gorge, indicating the position of the examined stratigraphic section; (d) It marks the DEM location and gorge can be seen, a water reservoir can be noticed near the top; (e) The location of the research area is depicted in the inset.

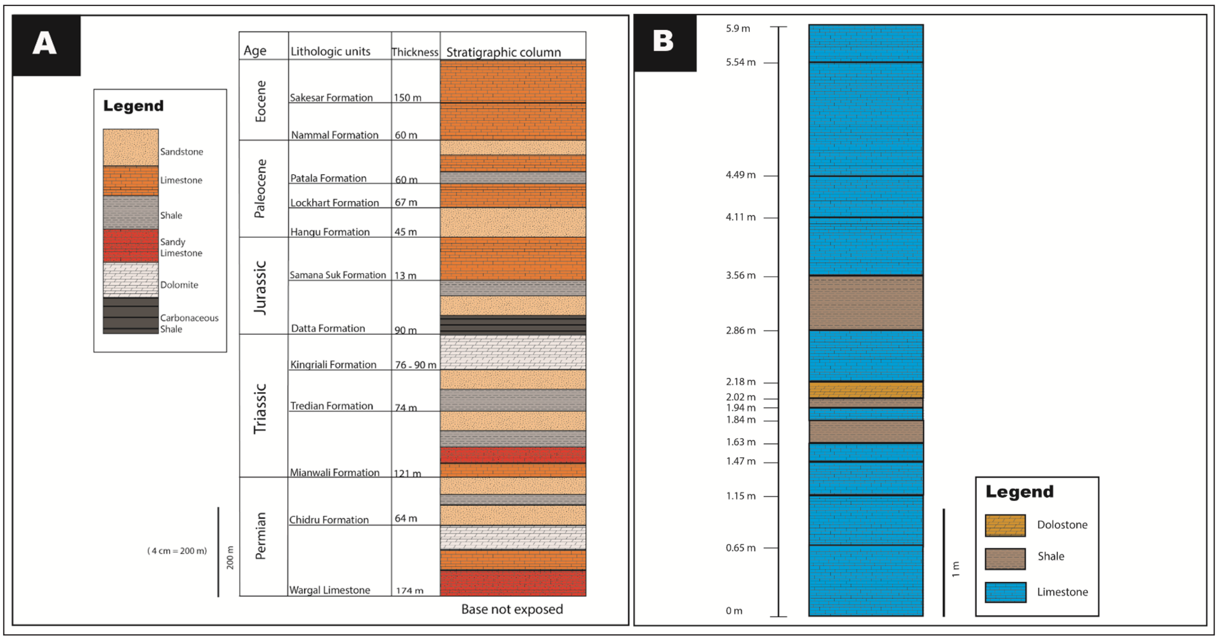

Figure 2. (a) Stratigraphic column of the Western Salt Range, encompassing rocks from the Permian to Eocene epochs; (b) Comprehensive sedimentological log of the Samana Suk Formation, detailing diverse rock types including limestone, shale, and dolomite.

- The Permo-Triassic epoch saw the first rifting of Gondwanaland and the development of a passive continental margin resembling the Atlantic coast.
- Initiation of rifting of the Indo-Australian Plate from Madagascar and Africa during the Cretaceous.
- An in-depth analysis of the Tethys Sea that emerged from the Indian Plate's northward migration, anticlockwise rotation, and eventual collision with the Eurasian Plate during the Paleocene.

The tectonic characteristics have led to various product features being situated in their respective locations within Pakistan. At the transform fault plate boundary, it is essential to highlight the rifled structures, fold-and-thrust belts linked to a foreland depression, and wrench faults. The foreland fold-and-thrust belts have developed from north to south on the Indian Plate, forming the Himalayan Collision Zone in the northwest of Pakistan. The active belts include the Kashmir Mountains, the Salt Range, the Trans Indus Ranges, the Sulaiman Range, and the Kirthar Range. The Kohat and Potwar Plateaus, Salt Range, and Trans Indus Ranges are located on the southern margin of the Himalayan Collision Zone, formed as a result of the underthrusting of the Indian Plate beneath its Phanerozoic sedimentary strata. The decollement of low-strength Pre-Cambrian evaporites from the Salt Range Formation enabled the southward extension zones of this underthrusting over the foreland. The northern fold and thrust belts converge with the Sulaiman Range to the south. The Indian Shield exists in this region as a remnant of Gondwanaland. The Chaman and Ornach-Nal faults define the western boundary of this shield. The extension reaches, at a minimum, the Indus Ophiolitic Belt located beneath the Himalayas in the northeast (Yasin et al., 2021). The stratigraphic column of rocks along the northern boundary of the Indian Plate lies within the southern shelf of the Tethys Ocean.

Tectonic set-up of the Himalayas

The Himalayan orogeny occurred during the Eocene and is defined by a compressional tectonic regime. The Proto-Himalayan zone experienced the emergence of convergent tectonics. A foreland fold and thrust belt developed on the southern margin of this zone due to underthrusting and crustal shortening. According to Kazmi and Jan (1997), the Himalayan orogenic band in northwest Pakistan was formed as a result of the collision between the Indian and Eurasian Plates, which began around 55 million years ago. East-west is the direction of the Himalayas and the related mountain ranges.

The Himalayan Collision Zone, located in northwestern Pakistan, is one of the most extensive active collision zones globally. Active foreland thrusting is taking place on a continental scale, with the Indian Plate underthrusting the Eurasian Plate along its northern margin. This process results in the formation of a series of north-dipping, south-verging thrusts. The process of crustal shortening has led to the development of various folds and thrust belts.

This study incorporated three sections for correlation and comparison regarding basin configuration, thickness, facies changes, and heterogeneity within the facies of the Samana Suk Formation. Two sections are located in the Chichali Nala Section and the Makerwal Section, while one section on Sheikh Budin Hill (7 kilometers from Pezu Pass) is positioned in the Marwat Ranges (Figure 1b).

The objectives of the paper are the following:

- To analyze the rock types and microfacies of the Samana Suk Formation, establish a correlation between the heterogeneity observed from the Salt Range to the Trans-Indus Ranges
- To investigate the paleogeography and depositional environment of the Samana Suk Formation.

2. Database, Materials and Methods

Field Observation and Laboratory Analysis

Three separate geological portions make up the Samana Suk Formation. These are the Sheikh Budin Hill Section in the Marwat Range, the Makerwal Section in the Surghar Range, the Chichali Nala Section in the Surghar Range, and Nammal Gorge in the Western Salt Range. Each image was geo-referenced using high-resolution images. Characteristics of rocks observed in the field include lithology, color, texture, and bed thickness (Figure 1a-c). All samples have been recorded and tagged in the field. Thin sections were prepared in the lab, and microphotographs were taken along with detailed petrographic examination. Thin sections were examined under a Nikon LV100ND polarizing microscope equipped with a digital camera at Quaid-E-Azam University. Photomicrographs were digitized and described. Samples were selected and analyzed by XRD, SEM-EDS, and standard thin-section preparation.

This section's Samana Suk Formation has a measured thickness of 37.98 meters. 114 samples in all were taken from 92 different beds. Most bedding planes in this section exhibit a planar nature, and the bedforms are consistently even. However, some beds exhibit a wavy bedform. The thickness of the bedding ranges from thinly bedded to massive bedding. The large beds, however, are limited in quantity. The section primarily consists of a medium-bedded succession. This section also notes small-scale shallowing-upward sequences (Figure 2b). In this measured section, the count of argillaceous horizons is greater, totaling nine. A significant quantity of dolomite beds has been documented in this section, located at depths of 2.8m, 3.4m, 4.5m, 5.5m, 6.85m, 18.7m, 21.1m, and 28.2m, with the final dolomite bed observed at 29m. The dolomites exhibit thin to medium bedding, pale grey to yellowish grey hues.

The well-developed mud-cracked surfaces, indicative of brief exposure periods and hardened ground conditions, have been documented in this section. The beds indicate the complete retreat of marine water and the occurrence of regressive cycles, resulting in the subaerial exposure of newly deposited carbonate sediments. Two documented instances of older and younger hard grounds from the Makarwal Section are located at depths of 23.8m and 38m, respectively, from the base. The hardgrounds exhibit bioturbation and consist of coarse-grained limestones with iron encrustations, which impart a reddish-grey coloration. The upper, young hard ground delineates the upper stratigraphic boundary of the Chichali Formation. The bioturbated beds observed in certain locations indicate an environment favorable to marine life during their deposition. Skolithos were identified within the strata located in the upper section of the Samana Suk Formation. The presence of these vertical burrows suggests that carbonate deposition occurred in a very shallow aquatic environment, characterized by periodic exposure in the subtidal zone. The occurrence of large fossils, including bivalves, brachiopods, and gastropods, in the uppermost layers indicates a high-energy environment conducive to carbonate sedimentation. Oolitic beds are observed at two distinct levels: 2.4 meters and 9.7 meters. These beds indicate a high-energy environment and are representative of grainstone facies. The sole occurrence of sandstone in this section of the Trans Indus Ranges is located at a depth of 4.7 meters. The depositional synthesis log of the Samana Suk Formation located at the Makarwal Section, accompanied by a comprehensive field description, is illustrated in Figure 2b.

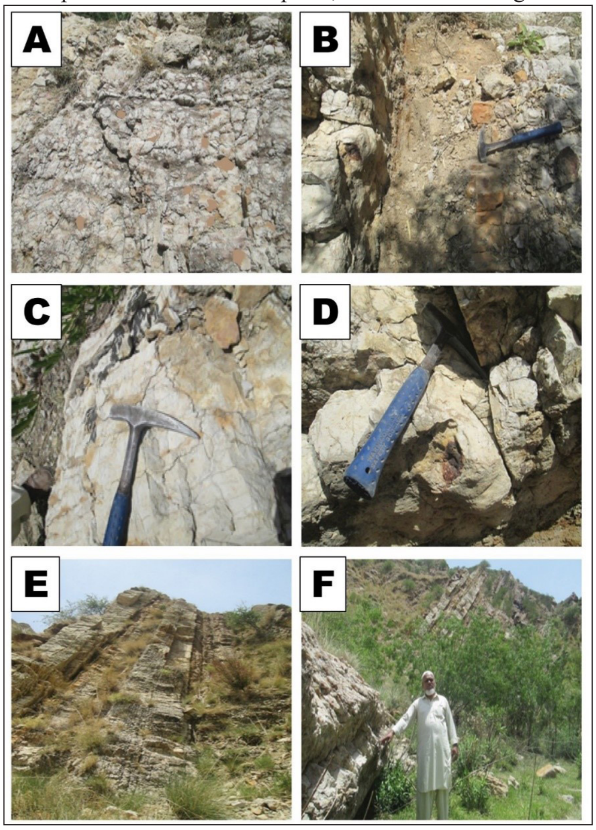

Figure 3. a) Thick-bedded fractured gray limestone with numerous dolomitic patches, showcasing a normal fault and joints; (b) A thick-bedded fractured gray limestone featuring multiple dolomitic patches that illustrate a normal fault and joints; (c) A gray limestone stylolite with a few dolomite patches; (d) The field section displaying iron nodules/concretions; (e) Panoramic view of the outcrop of Samana Suk Formation, Nammal Gorge Section; (f) The Nammal Gorge Section of Pakistan's Western Salt Range demonstrates the lower contact between the Samana Suk Formation and the Lower Jurassic Datta Formation.

3. Results and Discussion

Lithostratigraphy

This study identifies five distinct rock types: limestone (78%), marl/shale (10%), dolomite (9.5%), limestone with irregular quartz (1.5%), and sandstone (1%).

Sheikh Budin Hill Section, Khisor Range

The Sheikh Budin Hill Section is located at a Latitude of 32º17′11" N, and longitude of 70º43′51" E, situated seven kilometers from Pezu Pass in the District of Laki Marwat (see Figure 1). The overall thickness of this section measures 87.57 meters. The formation consists of thick limestone beds, as well as medium- to thick- and thin-bedded limestone, located at Sheikh Budin Hill in the Khisor Range. The bedding geometry, architecture, and heterogeneity of this formation are characterized by vertical stacking, as evidenced by the uneven, wavy beds. This section is characterized by the presence of coarse-grained limestone horizons, indicating the overall grain size. This section is characterized by a predominance of limestone, comprising 86%, followed by dolomite at 8%, and marl/shale at 6%.

Makarwal Section, Surghar Range

The Makarwal section is situated at Latitude of 32º55′35” N, and longitude of 71º08′50” E, along the Mianwali-Bannu Road. The composition consists of thick, medium-to-thick, and thin limestone/dolomite layers, with an approximate thickness of 37.98 meters. This section exhibits heterogeneity through erosive surfaces in the vertical arrangement and the occurrence of different rock types. This section consists of 70% limestone, 15% dolomite, 10% marls/shales, 3% irregular quartz limestone, and 3% sandstone.

Chichali Nala Section, Surghar Range

The Chichali Nala Section of the Surghar Range is approximately located at Latitude of 33º00′38” N, and longitude of 71º24′13” E. The thickness is approximately 43.27 meters, consisting of substantial limestone beds that vary in thickness from medium to thick. This section consists of 86% limestone, 10% marls/shales, and 4% dolomite.

Nammal Gorge Section, Western Salt Range

The Nammal Gorge section, situated at Latitude of 32º39′34” N, and longitude of 71º48′1” E, is situated in proximity to Nammal Dam within the Western Salt Range (refer to Figure 1). This section has a measured length of 5.9 meters (see Figures 3e and 3f). This section exhibits wavy bedforms in certain areas, accompanied by thin to massive beds. Shale breaks, which are typically found in very thin beds, occur at multiple levels within this section (Figure 3e). The observation included the deposition of thin and occasionally very thin layers of shale interspersed within limestone beds, characterized by numerous shale punctuations. The initial shale break is located at a depth of 1.63 meters from the base. The final shale layer is observed at a depth of 2.86 meters. In this section, the older, lower hard ground is observed at depths of 0.6 m and 30.6 m. Several oolitic horizons have been observed, specifically at depths of 26.5 m and 29.6 m within this section. Dolomitization has occurred at two specific levels, ranging from 2.02 m to 2.18 m (Figure 3a, c). Figure 2b presents the depositional synthesis log of this formation, accompanied by a comprehensive field description from the Nammal Gorge section.

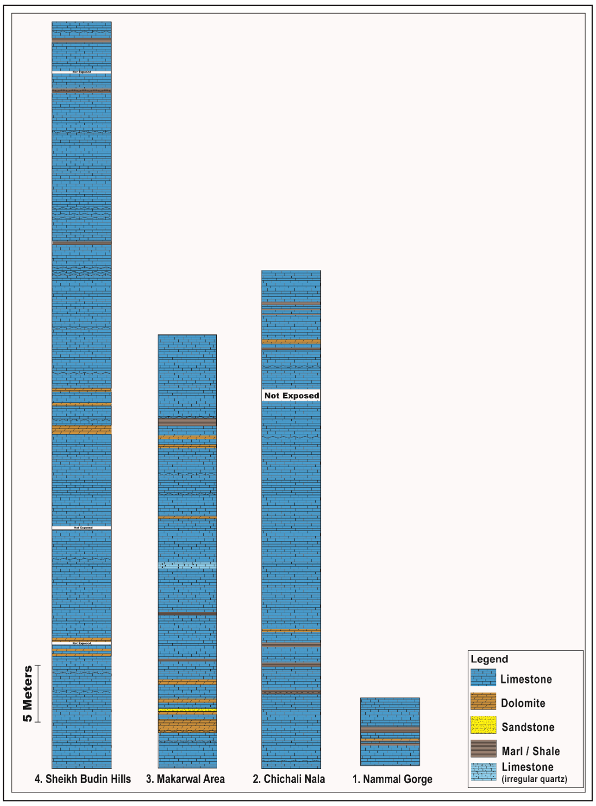

Figure 4. Stratigraphic sections of the Samana Suk Formation in the Upper Indus Basin, Pakistan: 1- Nammal Gorge Section, 2- Chichali Nala Section, 3- Makarwal Area Section, 4- Sheikh Budin Hills Section.

Table 3. Section-wise decadal sinuosity index of Lower Kopili River.

Section Name	Location (Lat- Long)	Thickness (m)	Main Lithology (%)	Features
Sheikh Budin Hill	32º17′11” N, 70º43′51” E	87.57	Limestone (86%), Dolomite (8%), Marl/Shale (6%)	Coarse-grained limestone, vertical stacking, wavy beds
Makarwal Section	32º55′35” N, 71º08′50” E	37.98	Limestone (70%), Dolomite (15%), Marls/Shales (10%), Quartz Limestone (3%), Sandstone (2%)	Erosive surfaces, lithological heterogeneity
Chichali Nala	33º00′38” N, 71º24′13” E	43.27	Limestone (86%), Marls/Shales (10%), Dolomite (4%)	Medium to thick limestone beds
Nammal Gorge	32º39′34” N, 71º48′1” E	5.9	Mainly Limestone with Shale Interbeds	Thin to massive beds, shale breaks (1.63 m to 2.86 m), oolitic horizons, dolomitization (2.02–2.18 m)

Microfacies Analysis

Using 30 thin sections of rock types, textures, pore properties, matrix composition, and mud percentages, the microfacies of the Samana Suk Formation were analyzed. Embry and Klovan's (1971) enlarged framework for further subdividing boundstone microfacies and coquina limestone, as well as Dunham's (1962) method for carbonate rocks, are followed in the classification of microfacies. To examine the coquina limestone facies, Embry and Klovan (1971) further subdivided Dunham's boundstone microfacies. As seen in Figure 4, the microfacies consist of mudstone, bioclastic mudstone, bioclastic wackestone, ooidal grainstone, peloidal grainstone, ooidal packstone, peloidal packstone, bioclastic packstone, and bioclastic mudstone.

Grainstones

Petrographic analysis revealed the subsequent submicrofacies of the grainstone:

- Bioclastic Intraclastic Grainstone

Intraclasts, peloids, cortoids, and ooids may occur together with the skeletal remains of various marine organisms in carbonate sediments. These components are commonly found in shallow marine depositional environments, indicating active reworking and sediment transport. Among these, intraclasts are particularly significant as they are fragments of pre-existing sedimentary material that have been eroded, transported, and redeposited within the same basin. Their presence suggests episodes of sediment disruption and early lithification processes within the depositional setting.

- Peloidal Grainstones

This location exhibits multiple stratigraphic levels where peloidal grainstones are prominently developed. The associated microfacies are primarily composed of fecal pellets and peloidal grains, indicating a high-energy, shallow marine environment with active biogenic reworking. In addition to these components, foraminifera have been observed in close association with the grainstones, further supporting a marine depositional setting. The presence of foraminifera, along with the abundance of peloids, suggests a well-oxygenated environment favorable for benthic organisms.

- Ooidal Peloidal Bioclastic Grainstone

These grainstones are characterized by ooids, peloids, and skeletal fragments from a variety of marine organisms. The ooids typically exhibit microfabrics with distinct radial concentric symmetry, reflecting their formation in high-energy, agitated water conditions. Their nuclei often consist of quartz grains or skeletal debris, around which concentric layers of carbonate have been deposited. These ooidal structures usually appear in a tightly packed arrangement, indicating minimal matrix and a well-sorted, mature grain-supported texture.

Interpretation

These limestones were deposited in a high-energy, shallow marine environment, most likely associated with oolitic shoals, bars, and beach settings. The abundance of ooids, peloids, and well-preserved skeletal grains indicates strong water agitation, typical of wave- and current-dominated zones. The tightly packed nature of the grainstones and the radial concentric cortices of ooids further support deposition under energetic conditions. Fecal pellets and foraminifera within the peloidal grainstones suggest active bioturbation and continuous reworking by benthic organisms. Collectively, these microfacies reflect a dynamic carbonate platform setting favorable for the formation of grain-supported limestone (Ali et al., 2013).

- Packstones

According to ' 'Dunham's classification, packstone microfacies are defined by the presence of more than 50% grains supported by a fine-grained carbonate matrix. These grains typically include a mix of skeletal fragments, peloids, and occasionally ooids, reflecting deposition in moderately energetic environments. The matrix indicates lower-energy conditions than in grainstones, allowing finer material to accumulate between grains. Several distinct packstone microfacies have been identified and documented based on their grain composition and textural features.

- Sandy Echinoderm Packstone

Observations indicate that these packstone microfacies contain echinoderm fragments, including plates and spines, as seen in Figure 5a. Quartz grains are frequently present within the matrix, suggesting some siliciclastic input during deposition. Although echinoderm grains and biodebris are generally present, their occurrence ranges from infrequent to rare across different samples. Peloidal packstone microfacies also include abundant peloids, often associated with skeletal shell fragments and foraminiferal tests, reflecting a mixed biogenic and detrital origin.

- Interpretation:

The depositional environment represented by these Sandy Echinoderm Packstone microfacies is interpreted as a shallow marine shelf setting. This shelf was characterized by moderate water circulation, allowing the accumulation of both bioclastic grains and fine carbonate mud. The presence of diverse skeletal components and peloids suggests a biologically active environment with intermittent energy conditions. Such settings typically lie between high-energy shoals and deeper, low-energy lagoonal areas on the carbonate platform (Flügel 2004).

- Wackestones

Wackestones are carbonate microfacies characterized by more than 10% allochems or grains within a micritic matrix, according to Dunham (1962). These microfacies typically reflect low-energy depositional conditions, with fine carbonate mud dominating. Within the Samana Suk Formation, wackestones are observed at multiple stratigraphic levels. Their distribution is similar to that of other associated microfacies in the formation.

- Bioclastic Peloidal Wackestone

Bioclastic wackestone is characterized by the presence of more than 10% skeletal grains embedded within a micritic matrix (Figure 5b, f, j). In addition to bioclasts, peloids are also observed, indicating a mixed origin of carbonate components. These wackestones exhibit notable faunal diversity, with a fossil assemblage that includes gastropods, pelecypods, sponges, and brachiopods. The studied area contains well-preserved skeletal shells and fragmented remains, reflecting low-energy depositional conditions that favored fossil preservation.

- Interpretation:

The interpreted depositional environment for the wackestone and bioclastic wackestone facies is a shelf lagoon setting. This environment is characterized by low-energy water circulation, allowing the accumulation of fine micrite and delicate skeletal remains. The presence of diverse faunal assemblages and well-preserved shells supports a calm, protected setting with limited reworking. Such conditions are consistent with inner platform lagoons as described by Flügel (2004).

- Mudstone

In this region, mudstones occur at various stratigraphic levels within the Samana Suk Formation. In certain areas, these mudstones exhibit significant fracturing and are infilled with calcite. A heavily fractured mudstone is interpreted as post-dating the fractures, as indicated by a medium-amplitude stylolite that intersects them. Some mudstones also display evidence of at least two stages of fracturing. This microfacies is characterized by unlaminated, homogeneous, unfossiliferous pure micritic limestone.

- Interpretation:

The mudstone facies is interpreted to have been deposited in a low-energy, restricted environment such as a hypersaline tidal pond. The absence of fossils, presence of pure micrite, and lack of lamination support this calm, evaporative setting. Such conditions are consistent with lagoonal-to-supratidal environments described by Flügel (2004), Scholle et al. (2003), and Tucker (2003).

- Dolomudstone

Description:

The mudstone submicrofacies is present at multiple stratigraphic levels within the measured section of the Samana Suk Formation. In certain locations, dolomudstones display fractures that are infilled with calcite, indicating post-depositional diagenetic processes. Bioclastic mudstones, as shown in Figures 5h and 5i, contain minor skeletal components within a micritic matrix.

Interpretation:

These facies are interpreted to have developed near the wave base in shallow marine settings with open water circulation. The presence of bioclastic components suggests periodic faunal activity in a relatively calm but oxygenated environment. Open circulation would have allowed the influx of marine waters, limiting hypersalinity and favoring the preservation of bioclasts. This interpretation aligns with the model proposed by Wright (1992) for inner shelf depositional systems.

- Facies Associations (FA)

Microfacies analysis has led to the identification of four distinct facies associations, each reflecting specific depositional environments as inferred through a comparative study with standard microfacies (SMFs). These include lagoonal and tidal flat facies, hypersaline tidal pond facies, oolitic bar facies, and marine subtidal facies. The depositional settings span a moderate-water-circulation shelf, a low-energy lagoonal shelf, and an intertidal zone influenced by open circulation near the wave base. Within this framework, lime mudstones, bioclastic peloidal wackestones, and peloidal grainstones were deposited.

The limestone facies generally present a fresh, slightly darker coloration compared to their weathered surfaces. Their lithology is typically composed of thinly bedded, unlaminated, homogeneous, and unfossiliferous micritic limestone, interpreted to have formed in restricted, hypersaline tidal ponds. Oolitic limestone occurs at two distinct stratigraphic levels in the upper portion of the studied section, marking high-energy shoal environments. Additionally, facies such as bioclastic wackestone, sandy echinoderm packstone, and grainstone reflect a rich and varied assemblage of benthic fauna and flora. The open marine subtidal zone provided ideal ecological conditions for marine life, as evidenced by the diverse skeletal remains of echinoderms, foraminifera, gastropods, pelecypods, corals, sponges, brachiopods, bryozoans, and calcareous algae preserved within these microfacies.

Petrographic Analysis

The comprehensive petrographic analysis reveals the existence of ooids, peloids, echinoids, intraclasts, and bioclasts. Non-skeletal grains are more prevalent than skeletal grains. Calcite cements are the primary type of cement, with dolomite and pyrite cements following in prevalence. Certain sections are composed of micrite. Dolomite is a well-preserved material recognized as a secondary phase, commonly observed in matrix, fracture filling, and veins. The cementation of carbonate sediments plays a crucial role in providing strength and stability to microfacies, enabling them to endure both physical and chemical compaction.

- Micritic envelopes

Micritic envelopes are typically found on both skeletal and non-skeletal grains within various grainstones and packstones. The cement described in this document includes micritic envelopes, syntaxial overgrowth, poikilotopic cement, blocky cement, drusy cement, fabric-preserved dolomite, fine dolomite cement, dedolomite cement, iron cement, and pyrite.

- Syntaxial rim cement

The syntaxial rim cement forms in optical continuity above the host grain. It generally develops in optical continuity on the shells of echinoderms (crinoids and echinoids) and can be identified by synchronous extinction. Observations have been made on various crinoids and echinoid shells at specific depths within the studied area.

- Blocky to Drusy calcite cement

This material serves to fill cavities and may include sparry calcite as a component. The crystals are located in different microfacies of this formation, beginning small at the cavity boundaries and increasing in size towards the cavity center as accommodation space becomes available.

- Poikilotopic cement

This cement develops after the creation of intergranular cement and extensive dolomitization. This type of cement features fine grains that are encapsulated by larger cement crystals. This phenomenon typically takes place within a burial regime and evolves in a phreatic environment.

- Mechanical compaction

During this phase, the sediments undergo compaction, leading to the initial formation of grain-to-grain contacts. These basic interactions between grains then evolve into sutured grain contacts. The interlocking of one grain with another is sometimes observed as well. Dissolution of grains initiates at these contacts, ultimately leading to the formation of dissolution seams.

- Stylolitization

The formation of stylolites occurs as a later stage in the diagenetic evolution of limestones (Figure 6a). Stylolites represent a diagenetic process characterized by pressure-dissolution or chemical compaction, which can be induced by tectonic pressures, enhanced compaction due to overburden, or a combination of these factors.

- Dolomitization

The dolomitization of limestones during diagenetic processes is a prevalent characteristic of the Samana Suk Formation. This area is developed on various levels, serving both as a substitute and as a binding agent. Dolomitization has been noted in association with stylolites.

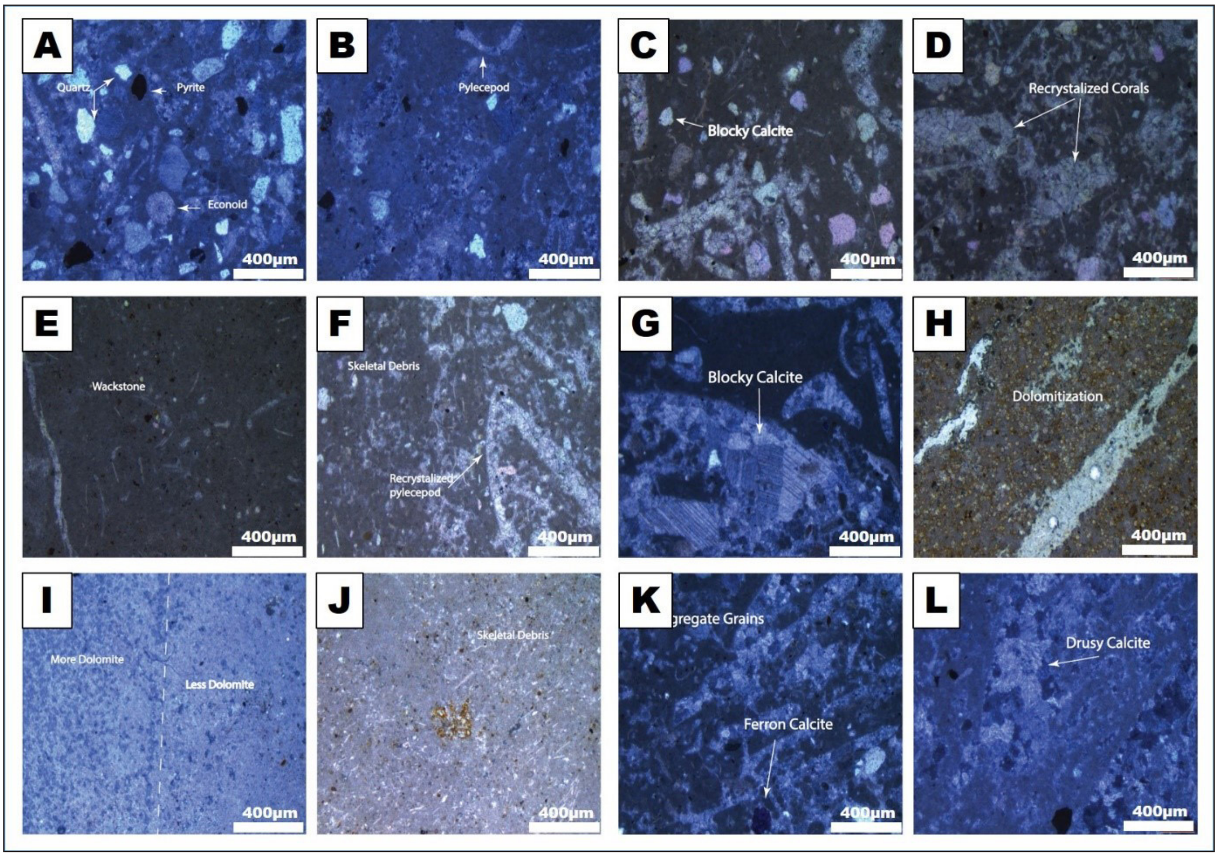

Figure 5. (a) Sandy echinoderm packstone featuring syntaxial overgrowth cements, quartz, and pyrite; (b) Bioclastic peloidal wackestone characterized by blocky calcite cement in pelecypods; (c) Bioclastic peloidal wackestone where most fossils exhibit recrystallization by blocky to drusy calcite cements; (d) Recrystallized corals present in the section, accompanied by large drusy calcitic cements; (e) Dolomudstone containing scattered skeletal debris; (f) Bioclastic peloidal wackestone with recrystallized pelecypods; (g) Poikilotopic cement alongside blocky calcitic cement; (h) Micro-dolomitization observed with very fine crystals of dolomite in dolo-mudstone facies; (i) Dolomudstone facies illustrating the transition between less and more dolomite zones; (j) Skeletal debris found in bioclastic wackestone facies, with visible iron cements; (k) Blocky to drusy calcitic cement within a micritic matrix; (l) Poikilotopic calcite combined with drusy calcitic cements, with minor pyrite also present.

Pervasive dolomitization

This material forms as a result of the prolonged dolomitization of limestones. This process of dolomitization affects the rock's fabric rather than its texture, resulting in complete dolomitization.

- Microdolomitization

During this diagenetic process, dolomite crystals form at very small sizes, requiring higher magnification to observe them effectively.

- Dedolomitization

Certain thin sections that are abundant in dolomite demonstrate dedolomitization processes. During diagenesis, a common reversal process, dolomite undergoes calcitization. This process is considered one of the last stages of diagenesis.

- Fractures

Frequent fractures are observed in the measured section across various levels. The late voids and microfracture-filling spar are associated with deep burial conditions, precipitating between the spalled-off cortices of the ooids.

XRD, SEM, and EDS Analyses

X-ray diffraction (XRD) and scanning electron microscopy (SEM) showed that calcite is the dominant mineral phase within the Samana Suk Formation. The mineralogical composition suggests extensive dedolomitization, as indicated by the presence of calcitic crystal overgrowths and altered textures. Supporting evidence includes minor clay content, intergranular porosity, and hollow grains, as shown in Figure 6c, f, and i. These features reflect post-depositional diagenetic processes that have modified the original dolomitic fabric.

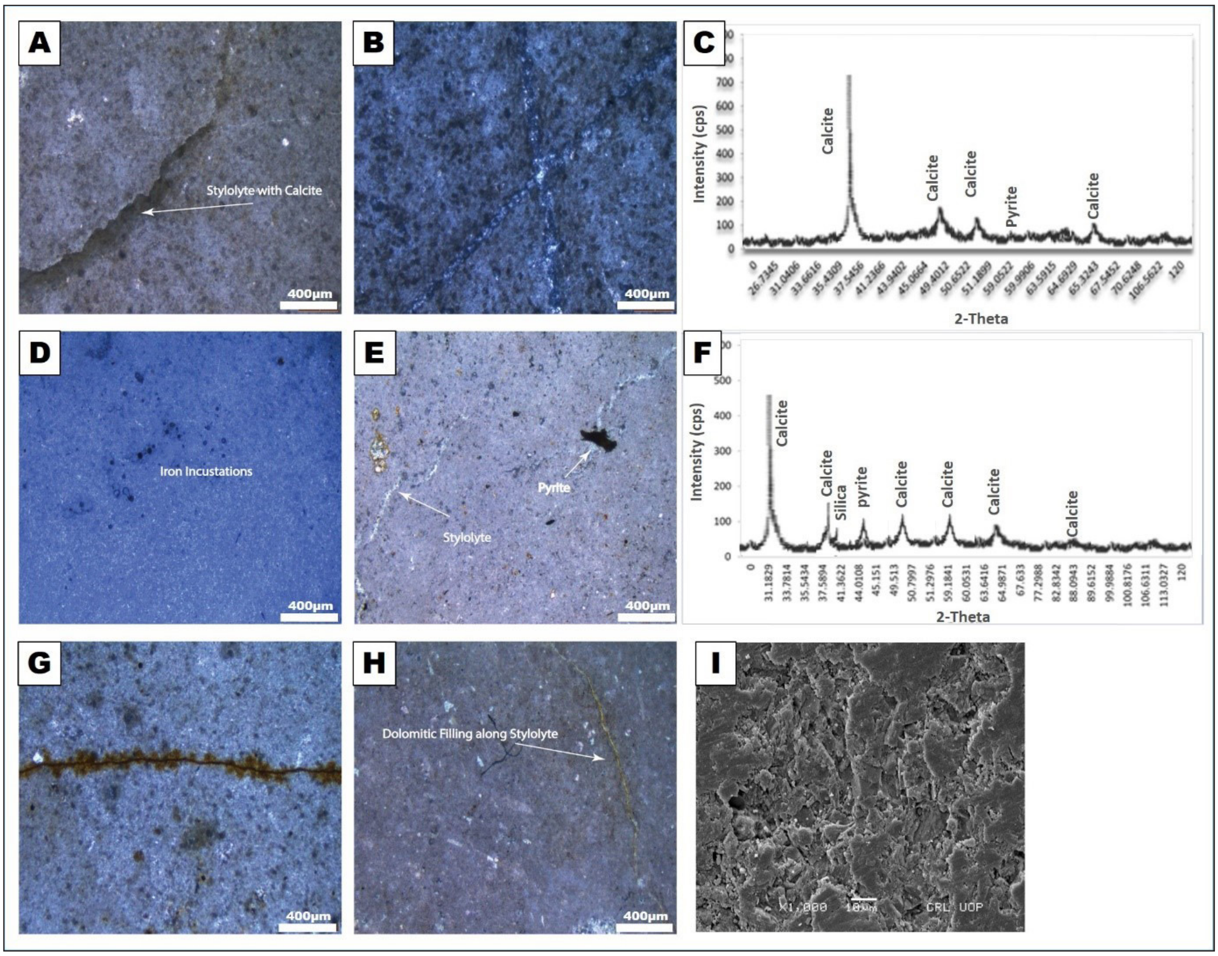

Figure 6. (a) Stylolite observed in mudstone facies; (b) fractures infilled with microdolomite matrix; (c) X-ray diffraction analysis indicates a predominance of calcite in the Samana Suk Formation, with minor pyrite; (d) iron cements identified in the dolomudstone facies; (e) stylolite and pyrite present in the dolomudstone facies; (f) XRD results reveal the presence of calcite, silica, and pyrite; (g) fractures filled with iron mineral growth; (h) Dolomitic mudstone exhibiting dolomite-rich stylolites; (i) Scanning Electron Microscope (SEM) analysis reveals calcitic cements with minor pores, predominantly micropores.

4. Discussion

The Samana Suk Formation represents one of the most extensive and well-preserved Jurassic carbonate successions in northern Pakistan. Deposited along the northern passive margin of the Tethys Ocean, it developed as part of a widespread carbonate platform system, highlighting its significance in the broader context of sedimentology, paleogeography, and tectonic evolution (Shah, 2009; Kassi et al., 2015). The formation predominantly consists of carbonate rocks interbedded with minor siliciclastic components such as marl and shale, suggesting deposition across a range of shallow marine settings, from inner to outer-shelf environments (Kazmi & Jan, 1997; Flügel, 2004). Tectonic activity during the Early Cretaceous, marked by seafloor spreading and rifting, transitioned into a compressional regime in the mid to late Cretaceous, driven by the subduction of Neo-Tethyan oceanic crust (Bender & Raza, 1995). The Samana Suk Formation is characterized by a variety of bioclastic microfacies, including mudstone, wackestone, packstone, and grainstone, indicating dynamic depositional conditions across the carbonate shelf. Key measured sections such as the Chichali Nala, Makerwal, Sheikh Budin Hills, and Nammal Gorge provide a detailed record of lithofacies variability. These include lagoonal and tidal flat lithofacies, hypersaline tidal pond facies, oolitic bar complexes, and open marine subtidal facies, with additional facies such as high-energy tidal channels, restricted shelves, and winnowed platform deposits particularly well-represented in the Makerwal and Sheikh Budin Hill sections (Nizami et al., 2009; Ali & Windley, 2009). Diagenetic processes affecting the Samana Suk Formation are equally diverse and include micritization, dolomitization, mechanical and chemical compaction, as well as the development of ferroan calcite and dolomite phases (Wright, 1992; Flügel, 2004). These features are particularly prominent in the Makarwal and Chichali Nala sections, where multiple stages of diagenetic overprinting have been documented and linked to burial history and tectonic reactivation.

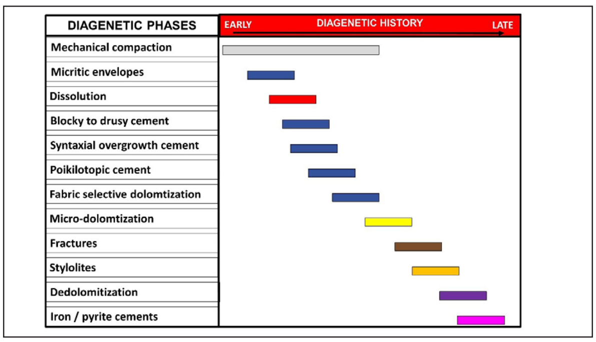

Figure 7. Generalized diagenetic sequence that represents the dominance of mechanical compaction to various types of cements, to fractures, and stylolites.

Deltaic facies replaced the shelf facies of the Mianwali Formation as a result of the tectonic and depositional history of the Indian Plate from the Permian to the Jurassic periods, as shown in Figures 8a and 8 b. This transition is characterized by regressive parasequence sets that indicate a shift from underfill to overfill conditions (Gaetani and Garzanti 1991). The process of dolomitization abruptly halted after the Triassic period, leading to a notable shift towards global cooling and increased humidity (Valdiya and Valdiya 2016). The limited accommodation space and insufficient sediment supply facilitated the formation of laterite beds and their exposure to the atmosphere (Ali et al., 2013). The Jurassic Samana Suk Formation (Figure 8c), along with the Chiltan and Takatu Limestones, represents important sedimentary units within the Sulaiman Foldbelt located in western Pakistan. The Chiltan Limestone consists of substantial layers of light-grey limestone, characterized by a thick, white appearance, and is covered by a thin stratum of dark shale (Siddiqui 2012; Basit et al., 2023). The argillaceous components within the marl/shale are formed by periodic influxes of clay into the area, driven by tectonic uplift, erosion, or small-scale, remote-past climate variations. Cyclic deposition is absent, and the intercalations along with shale/marl fractures, found at various levels, occur randomly. Correlations between them are feasible based on their respective lithologies, thicknesses, and depositional environments.

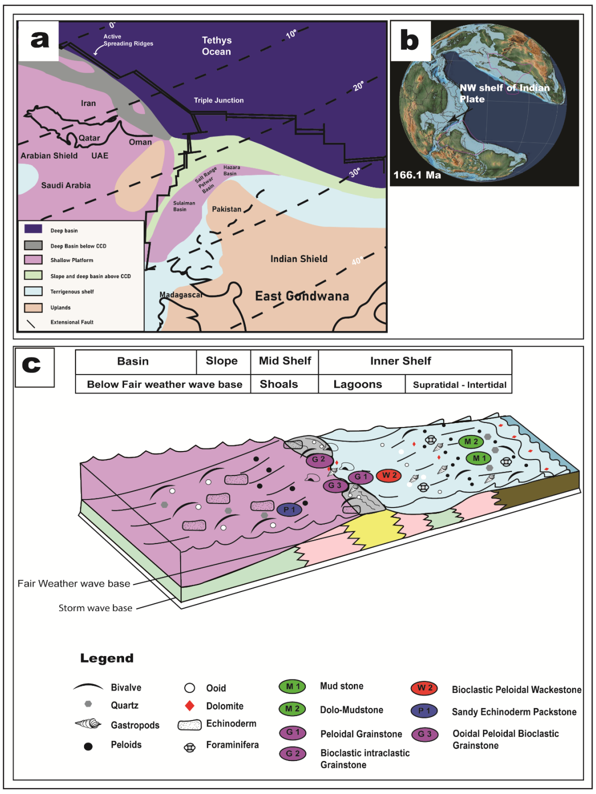

Figure 8. (a) The paleogeographic position of the northwestern section of the Indian Plate; (b) A paleogeographic image produced by Gplates Software illustrates the location of the northwestern shelf of the Indian Plate and the submerged portion of the plate during the Middle Jurassic; (c) The depositional setting of the Samana Suk Formation, featuring proximal mudstone facies adjacent to the outer segments of the oolitic shoals (after Sallam and Ruban, 2020; Wilson 1997).

5. Conclusions

This study investigates the Jurassic carbonates of the Samana Suk Formation (5.9–87.57 m) in the Salt Range, Pakistan, revealing a complex shallow-shelf depositional system characterized by shallowing-upward successions, diverse microfacies, and multiple diagenetic phases. Seven microfacies were identified, representing environments from tidal flats and lagoons to sand shoals and mid-ramp settings, deposited under both restricted- and open-marine conditions. Petrographic and geochemical analyses highlight an intricate paragenetic sequence, including various cement types, dolomitization, dedolomitization, and stylolitization, reflecting a dynamic post-depositional history. Field observations across all four measured sections, from the coarse, vertically stacked limestone beds of Sheikh Budin to the shale-interrupted carbonate layers of Nammal Gorge, reveal a consistent dominance of limestone with variable admixtures of dolomite and marl, highlighting the complex depositional heterogeneity and localized diagenetic overprints that characterize the paleogeographic transitions in northwestern Pakistan. These findings enhance our understanding of Middle Jurassic Tethyan carbonates and demonstrate the Samana Suk Formation's potential as a raw material for cement, construction aggregate, and as a reservoir candidate in petroleum exploration.

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