Examination of Sedimentary Facies and Diagenesis of the Eocene Deposits in Saravan, Southeastern Iran

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Abstract

The study area is located north of Saravan County, covering the regions from Ghasht toward Sib Soran. Stratigraphic sections of Ghasht and Sib Soran were measured and sampled to describe facies and determine the sedimentary environment. In this area, major clastic and carbonate facies groups were identified. The region includes layers of sandstone, limestone, marl, and shale. The limestones contain benthic foraminifera such as *Nummulites* and *Alveolina*, along with other skeletal and non-skeletal components. Based on the presence of key benthic foraminiferal species, an Eocene to middle Eocene age is proposed for the area. Facies include microconglomerates, sandstones, and shales, exhibiting fining-upward trends in grain size, indicative of a marine setting with turbiditic facies. Microscopic studies further reveal that the sediments in this area are composed of carbonate facies. These facies are associated with the facies belts of lagoon, shoal, and shallow open marine environments. Based on facies characteristics and the abundance of allochems, the depositional environment of this region is interpreted as a shallow marine setting with a gentle slope. Analysis of diagenetic processes in the region highlights various processes such as micritization, cementation, compaction (mechanical and chemical), dissolution, and the filling of fractures and pores. This study, based on fieldwork alongside laboratory results, aims to investigate the sedimentary facies, diagenesis, and sedimentary environment of the Saravan region in southeastern Iran.

Keywords: *Sedimentary facies, Foraminifera, Diagenesis, Eocene, Saravan, Sedimentary environment*.

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1. Introduction

The study area is located north of Saravan County at 28°30'N latitude and 61°30'E longitude, extending from Ghasht toward Sib Soran within part of the region. Geologically, Saravan lies within the Makran zone, which is situated south of the Jazmurian depression. The western boundary of this region is marked by the Minab fault, the southern boundary by the Oman Sea, the eastern boundary by the Chaman fault in Pakistan, and the northern boundary by a series of east-west trending faults and thrusts, with the Bashagard fault being one of the most significant. Along these fractures, extensive outcrops of mélange are visible [1-3].

The oldest rocks in this region are these mélange formations, which date back to the Upper Cretaceous–Paleocene. Over these geological formations, thick flysch-like Eocene and Oligocene sediments occur, comprising alternating layers of shale, sandstone, marl, flysch, and conglomerate. The thickness of these sediments exceeds 5000 meters. These deposits underwent intense folding during the Savian phase before the onset of the Miocene [1-3].

During the Miocene, the Makran region acted as a shallow subsiding basin. This period saw the deposition of alternating marly-shale and calcareous sandstone layers, a mix of sedimentary, metamorphic, and basic rocks, as well as pillow lava deposits forming sedimentary mélange. Additionally, reefal limestone layers, harzburgite conglomerates, and shallow deltaic deposits were formed. According to Shamshaki (2018), the surface deposits from the Plio-Pleistocene primarily consist of conglomerates overlying older units. The deposition of these sediments was influenced by the latest phase of the Alpine orogeny and the onset of new events during the Pasadenian phase [3].

It is hypothesized that from the Upper Cretaceous to the Lower Miocene, the current Makran region contained an oceanic trench, with Jazmurian representing its continental margin. This indicates the presence of an oceanic crust as scattered masses in the region, along with ophiolitic fragments within conglomerate rocks. Thus, the basin floor consists of oceanic crust, and the aforementioned flysch formations resulted from the erosion of older oceanic crust.

The Makran geological region is generally devoid of magmatic activity. However, to the north, there is a series of volcanic mountains. These volcanoes trend approximately east-west and were active during the Plio-Quaternary. Chemically, most of the lava present corresponds to island arc volcanism. The Sistan and Baluchistan Province in southeastern Iran is considered one of the youngest remnants of the Neo-Tethys Ocean, having undergone evolutionary stages from oceanic to continental crust. Based on geological characteristics, this region can be divided into the Makran unit, the Lut and Helmand blocks, and the Iranshahr-Birjand shear zone. The Makran ophiolites, colored mélange, and arc volcanism represent subduction processes of the Neo-Tethys oceanic crust [3].

2. Methodology

To determine facies and interpret the sedimentary environment of the Eocene deposits in Saravan, southeastern Iran, a significant number of hand samples were collected from the Ghasht to Sib Soran region, one of the largest areas in Saravan. Due to facies homogeneity, 200 thin sections were selected for microscopic examination. The prepared thin sections were studied in the laboratory using a polarizing microscope to analyze textural characteristics (e.g., particle size, shape, and arrangement), fossil content, and diagenetic features. The Folk (1962) classification was employed for naming clastic facies, while the Dunham (1962) classification was used for carbonate microfacies.

3. Data and Information

The Saravan region is situated at the eastern edge of the Quaternary alluvial plains of the elongated Saravan Basin. It extends 150 kilometers from eastern Khash to eastern Saravan. The morphology of the area is influenced by the Taftan Volcano to the northwest and extensive Cenozoic flysch in this zone. The predominant facies of the flysch in these areas include sandstone, shale, limestone, and conglomerate (Figure 1 and Figure 2). In the flysch facies of this region, granitic intrusive masses to the north of Ghasht and limestone blocks within the flysch south of Saravan are evident [1]. The two sedimentary zones under investigation include deposits from the Sib Soran Basin in the south, with a thickness of 750 meters, and the Ghasht Basin in the north, with a thickness of 1150 meters. These zones primarily consist of clastic rocks, including shale and sandstone, with varying strata. Based on paleontological evidence observed in the aforementioned sediments through microscopic studies, an early to middle Eocene age has been determined. The identified foraminifera are as follows:

Alveolina spp., Operculina sp., Nummulites spp., Discocyclina spp., Heterillina sp., Rotalia sp., Assilina sp., Discocyclina sp., Litounella spp., Miliolids, Operorbitolites., Litounella sp., Periloculina spp.

In the sedimentary units of the Sib Soran Basin, apart from the foraminifera-bearing limestone units (Figure 3 and Figure 4), other rock units are folded with less elevation compared to the deposits of the Ghasht Basin. They are mostly observed as thin-layered to fine-grained formations. The limestone units predominantly appear as elongated, narrow, and continuous strata within the clastic deposits of

Sib Soran (Figure 6). The stratigraphic column corresponding to the studied section is provided.

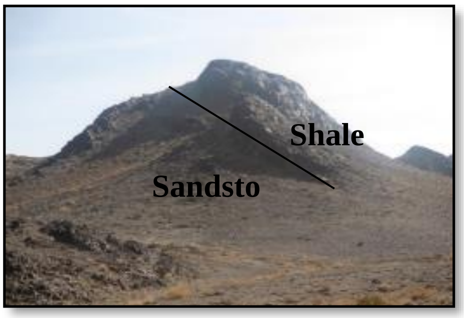


Figure 1. Interval of shale and sandstone in the studied area (View to the north)

Figure 2. View of Eocene limestones (View to the north)

Figure 3. Eocene limestones inside the displacement cores

Figure 4. Limestones within sandy sediments

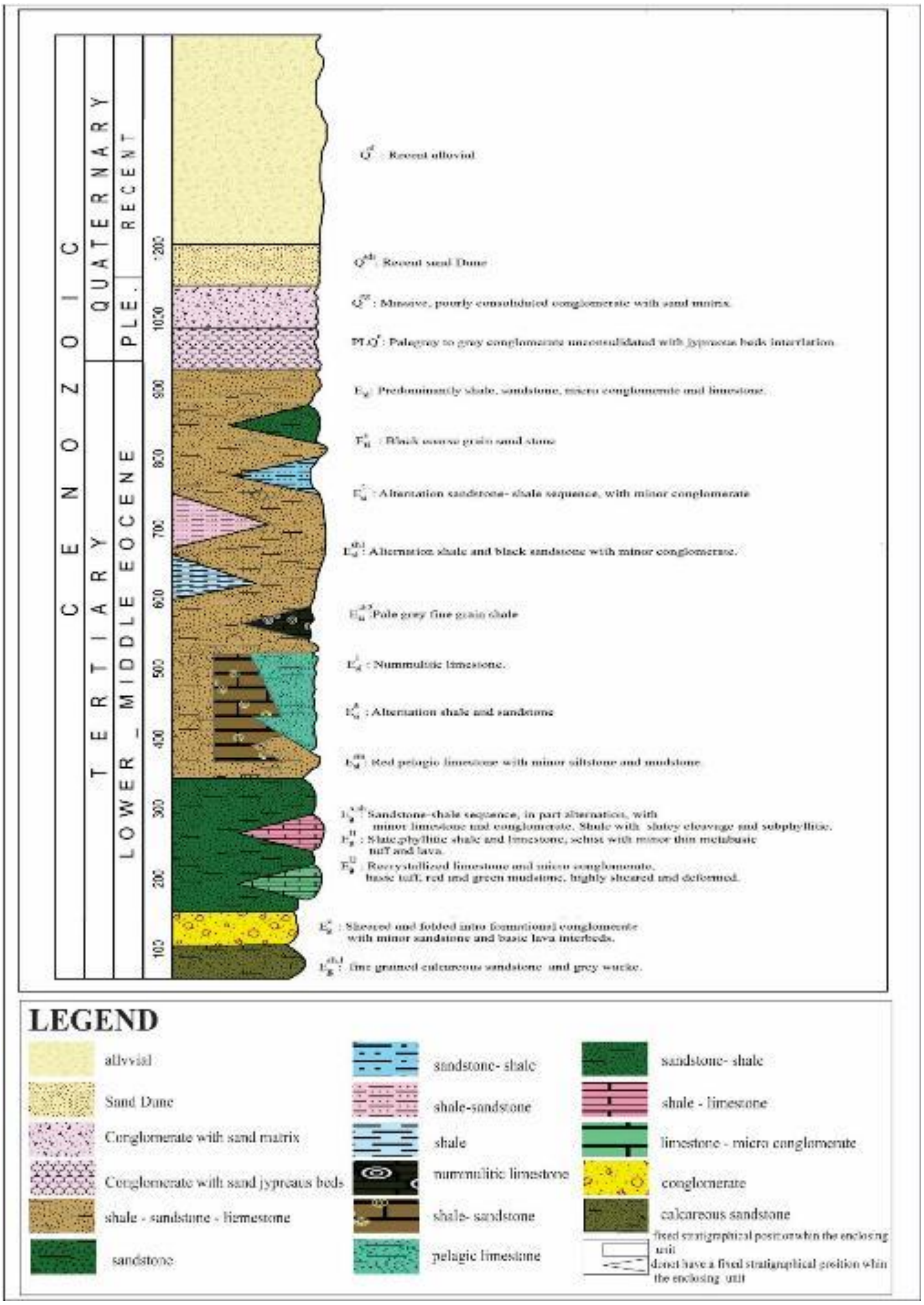


Figure 5. Stratigraphic column of the studied area

4. Discussion

4.1. *Examination of Eocene Facies in the Study Area*

The identified facies in this section include clastic facies and carbonate facies.

4.1.1. *Clastic Facies of Eocene Deposits in the Study Area*

- Subarkose and Arkose Petrofacies: The mineralogical composition of this petrofacies includes quartz, feldspar, calcite, muscovite, mica, biotite, chlorite, sericite, glauconite, mafic minerals, opaque minerals, iron oxides, and hydroxides. The matrix constitutes more than 15%, with feldspar minerals comprising approximately 30% and quartz 70%. Feldspar grains show moderate to poor sorting and are in a texturally immature stage. Quartz grains exhibit relatively good to moderate sorting, with crystal sizes ranging from less than 0.4 mm to 0.5 mm. These quartz grains are monocrystalline with straight extinction, although some display undulatory extinction. The quartz grains are mostly angular to sub-rounded with moderate to good sphericity. Feldspar grains include plagioclase and alkali feldspar with Carlsbad twinning. Some plagioclase grains exhibit albite and polysynthetic twinning, with deformation features suggesting origin-related characteristics rather than diagenetic processes. Feldspar grains are mostly euhedral with moderate sphericity and angularity. Coarse feldspar fractures are often filled with chlorite. Orthoclase shows moderate rounding and relatively good sphericity, occasionally displaying twin remnants. Lithic fragments are observed as fine grains with varying abundances across the rock surface (Figure 7 - Images A, B).

- Sublitharenite and Litharenite Petrofacies: The mineralogical composition includes quartz, feldspar, plagioclase, calcite, sericite, muscovite, mica, biotite (rare), chlorite, sphene, epidote, rutile, lithic fragments, minor zircon, negligible allanite, glauconite, and opaque minerals, along with a siliceous-carbonate matrix exceeding 15%. Quartz occurs as monocrystalline and polycrystalline grains with straight and undulatory extinction. Sorting and rounding range from moderate to poor. Coarse feldspar grains also show moderate to poor sorting and rounding. Lithic fragments are abundant and often rounded, comprising sandstone, shale, siltstone, or volcanic materials ranging from intermediate to basic in composition (Figure 7 - Images C, D, E).

- Calclitite Sandstone Facies: The mineralogical composition includes quartz, feldspar, plagioclase, calcite, epidote, biotite, lithic fragments, iron hydroxides, and opaque minerals, with calcitic cement. The fabric is semi-mosaic. Quartz grains range from fine sand to silt size, showing moderate rounding and sorting, with mostly straight extinction. Feldspar grains exhibit mild sericitization effects. Fossil components include a few *Nummulites* and other bioclasts. Ripple marks, iron oxide coatings, porosity features, and lamination are observed in some sandstone layers. These characteristics suggest a shallow, high-energy, illuminated environment, likely nearshore [4, 5] (Figure 7 - Images F, H).

- Microconglomerate Facies: The mineralogical composition varies in particle size, shape, and type under microscopic observation. Clastic particles range from 0.5 to 1.5 mm, including angular to sub-angular quartz, chert, schist, basaltic rock fragments, and bioclastic limestone with benthic foraminifera such as *Nummulites* and *Discocyclina*. Chert and basaltic lithoclasts constitute about 40% of the matrix. Fossil abundance is low, with identifiable specimens being *Nummulites* and *Discocyclina*. Based on benthic foraminifera, the origin is near a carbonate platform [6]. The presence of foraminiferal and bioclastic fragments indicates transport under high-energy conditions over relatively long distances, suggesting deposition in a shallow, illuminated, high-energy nearshore environment [2]. Diagenetic processes include cementation (Figure 7 - Image G).

Interpretation: The sedimentary environment of these facies, based on field and microscopic studies, indicates microconglomerates, sandstone, and shale, with grain-size fining upwards, pointing to a marine (turbiditic) setting. The boundary between coarse-grained and fine-grained sediments is erosive-depositional. Sedimentary structures in this environment include graded bedding, flow and groove casts, planar cross-lamination, ripple marks, and parallel lamination. Fossils such as *Nummulites*, indicative of marine environments, are occasionally found in these facies. These characteristics suggest deposition by turbidity currents [2].

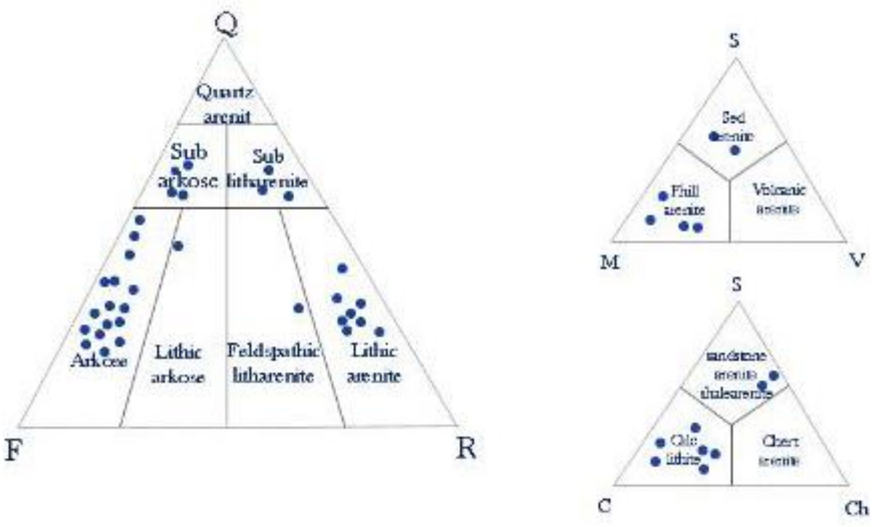


Figure 6. Folk diagram of the composition of sandstones in the study area

4.1.2. Carbonate Facies of Eocene Deposits in the Study Area

The types of limestones in the study area include wackestone, packstone, and grainstone. Carbonate facies are distinguished based on fabric characteristics and fossil content.

- Bioclastic Packstone to Grainstone:

This facies contains micrite as fine and compact grains between allochems, forming a packstone to grainstone with skeletal components, including *Alveolina spp.*, *Nummulites spp.*, *Discocyclina spp.*, *Assilina sp.*, *Rotalia sp.*, and *Quinqueloculina sp.*. Based on the identified fossils, the age is determined to be middle Eocene. This facies includes skeletal components and approximately 15% peloids. Detrital components comprise quartz along with chert fragments and muscovite, with quartz content ranging between 20% and 25%. Quartz grains are monocrystalline and polycrystalline, showing straight to undulatory extinction. Benthic foraminifera are the main components within the micritic matrix.

Interpretation: The presence of foraminiferal shells with porcellaneous textures, such as *Alveolina* and miliolids, suggests a shallow carbonate platform with relatively high salinity [6-9] (Figure 8A). Evidence of dissolution and micritization is observed. The accumulation of biofacies containing *Nummulites* and *Discocyclina* indicates deposition in a shallow marginal reef foreland or a deeper outer shelf at depths of 50–80 meters.

- Bioclastic Packstone:

This facies consists of micrite and is classified as packstone with skeletal components, including *Alveolina spp.*, *Nummulites spp.*, *Discocyclina spp.*, *Rotalia spp.*, *Miliolids*, *Litounella sp.*, coral, bryozoans, and shell fragments. Based on fossils, the age is considered middle Eocene. The main components are *Nummulites* and *Alveolina*, along with other benthic foraminifera. Grain contacts are concave-convex to sutured. *Alveolina* skeletal grains show concave-convex to sutured contacts (Figure 8B).

Interpretation: The presence of *Alveolina* and miliolids indicates a high-salinity, shallow environment, while *Nummulites* and *Discocyclina* suggest a low-energy, photic zone environment with gradually increasing depth and reduced salinity [9].

- Alveolina Wackestone to Packstone:

This facies is composed of micrite, forming a wackestone with skeletal components such as *Alveolina spp.*. The age is considered Eocene based on fossils. The skeletal components include benthic foraminifera (*Alveolina*) of medium to large size within a micritic matrix. This facies shows moderate to good sorting.

Interpretation: The presence of *Alveolina* indicates a high-salinity, shallow environment. These skeletal components typically inhabit the shallow parts of basins [10]. *Alveolina* is more prevalent in lagoonal facies (Figure 8C).

- Bioclastic Wackestone to Packstone:

This facies consists of micrite with skeletal components such as *Alveolina spp.*, *Nummulites spp.*, *Rotalia sp.*, *Operculina sp.*, *Assilina sp.*, *Miliolids*, *Textularia*, *Discocyclina spp.*, echinoid debris, and shell fragments. Based on fossils, the age is middle Eocene. Skeletal *Nummulites* are present in small to medium sizes and are visible within the micritic matrix (Figure 8D). Non-carbonate components include quartz, chert fragments, and muscovite.

Interpretation: Skeletal components, including benthic foraminifera, exhibit poor sorting and angular to sub-angular shapes. The accumulation of *Nummulites* and *Operculina* indicates deposition in deeper waters. The presence of *Discocyclina* and *Operculina* suggests increased depth (Figure 8E, F).

- Assilina Wackestone:

This facies is composed of micrite and is classified as wackestone with skeletal components including *Assilina sp.*, *Nummulites spp.*, and *Discocyclina sp.*. The age is determined to be Eocene based on fossils. Features include fenestral fabric, evaporite molds, and mud cracks (Figure 8H). Fenestral fabric appears as irregular voids, ranging from a few millimeters to several centimeters in size. The dominant skeletal components are benthic foraminifera (*Assilina* and *Nummulites*), exhibiting angular to sub-angular sorting within the micritic matrix.

Interpretation: Fenestral fabric in tidal flat environments reflects depositional and environmental conditions. The presence of *Assilina* and *Nummulites* indicates deposition in the inner ramp environment, with skeletal foraminifera scattered within the micritic matrix [5].

- Dolomitic Wackestone:

This facies includes calcite, dolomite, quartz, and feldspar within a micritic matrix, with scattered biotic and abiotic allochems. The matrix is undergoing replacement by subhedral fine dolomite crystals. Shells show evidence of dissolution and replacement by dolomite, although some biotic allochems resist dolomitization. Quartz and feldspar are scattered in amounts below 10%.

Interpretation: Fine to medium-sized fractures filled with secondary blocky cement are observed. Some fractures in carbonate rocks are filled with micrite (Figure 8G). The main skeletal components are *Nummulites* and *Alveolina*, with few bioclasts. Such deposits typically form in low-energy environments [6].

- Bioclastic Wackestone:

This facies consists of micrite, forming a wackestone with skeletal components such as *Assilina sp.*, *Operculina sp.*, *Rotalia sp.*, *Nummulites spp.*, *Litounella sp.*, *Alveolina spp.*, *Discocyclina sp.*, *Textularia sp.*, *Quinqueloculina sp.*, and shell fragments. Skeletal components primarily include benthic foraminifera with angular to sub-angular sorting. The main components are *Nummulites* and *Alveolina*, accompanied by a few bioclasts.

Interpretation: Such deposits typically form in low-energy environments [11-13]. *Nummulites* are significant contributors to Eocene deposits. Some *Nummulites* show evidence of compaction or contain borings from other organisms. Nummulitic facies are usually found in shallow, middle carbonate platform environments.

4.2. Interpretation of Sedimentary Environment

Based on the identification and differentiation of facies in the study area, as well as the quantity and type of their skeletal and non-skeletal components, the depositional environment and formation conditions of each facies have been interpreted.

- Open Sea

Field observations indicate an open sea environment, represented by alternating marl and thin-bedded limestone layers. The green color of the marl layers suggests reductive conditions and relatively deep formation, supported by the presence of large benthic foraminifera such as *Discocyclina*. Microfacies containing abundant large benthic foraminifera such as *Nummulites*, *Discocyclina*, *Assilina*, and some *Operculina* within a micritic matrix are characteristic of this environment [4].

The presence of abundant carbonate mud indicates deposition in relatively deep and calm parts of the basin. Algal presence in this facies indicates light penetration at these depths. This zone is also within the influence of normal wave activity [9, 14].

- Shoal

Field observations suggest a relatively elevated and mound-like morphology in this zone. The absence of interbedded marl layers indicates a high-energy environment. Facies in this area are characterized by interclasts, peloids, and benthic foraminifera. The absence of micrite and the abundance of interclasts highlight the relatively high energy of this environment. Facies containing interclasts and benthic foraminifera, such as *Alveolina* and

Rotalia, are associated with environments closer to the shore [15, 16].

These facies are located in the central part of the shoal and above the influence of normal wave activity. They also contain conical foraminifera, along with smaller quantities of miliolids and textulariids. The grainstone nature reflects relatively high energy sufficient to wash out carbonate mud. The abundance of foraminifera with agglutinated shells suggests a lagoonal environment closer to the shoreward side of the shoal [4, 7]. The shoal zone lies above the influence of normal waves and within the photic zone, significantly affected by tidal currents [14].

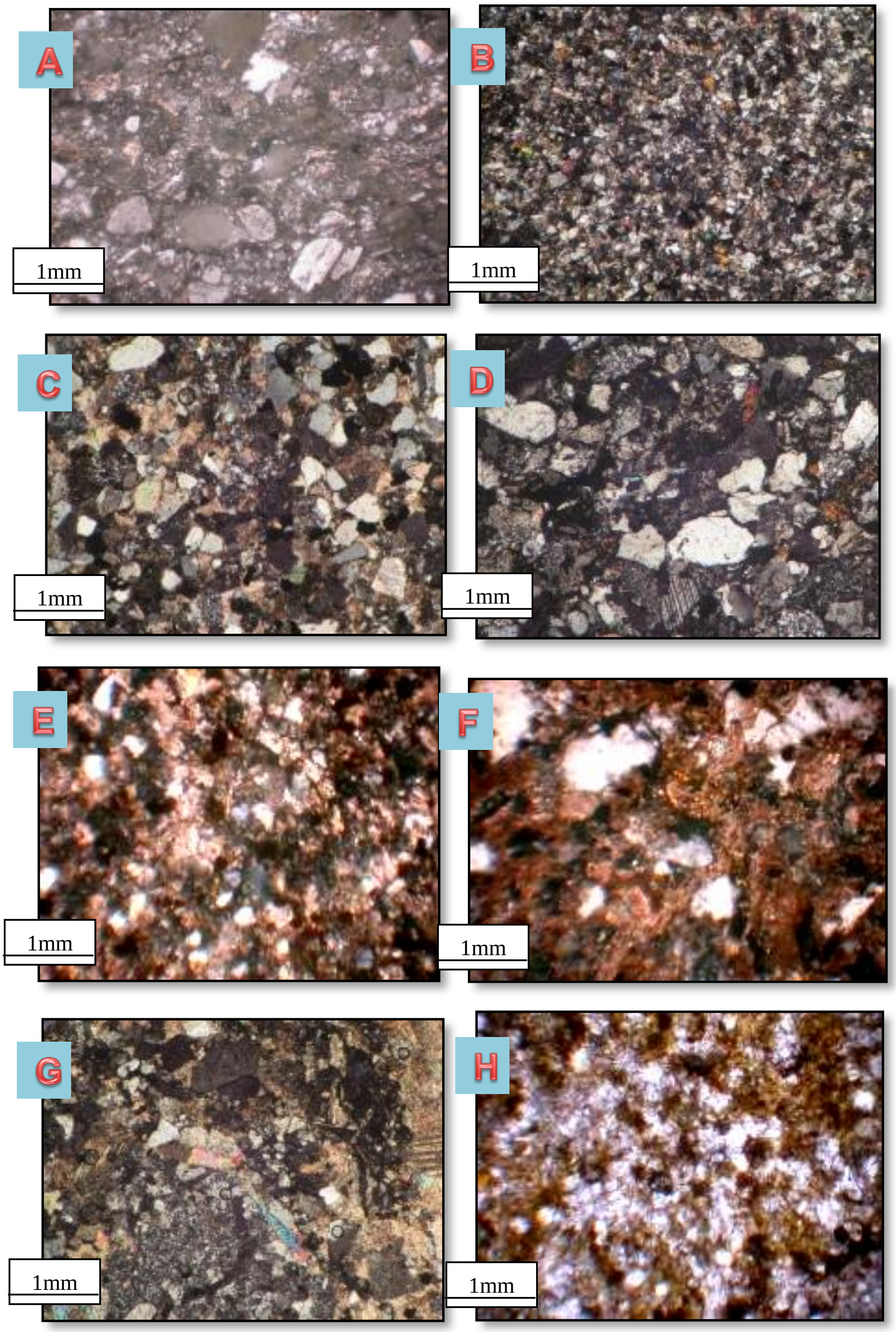
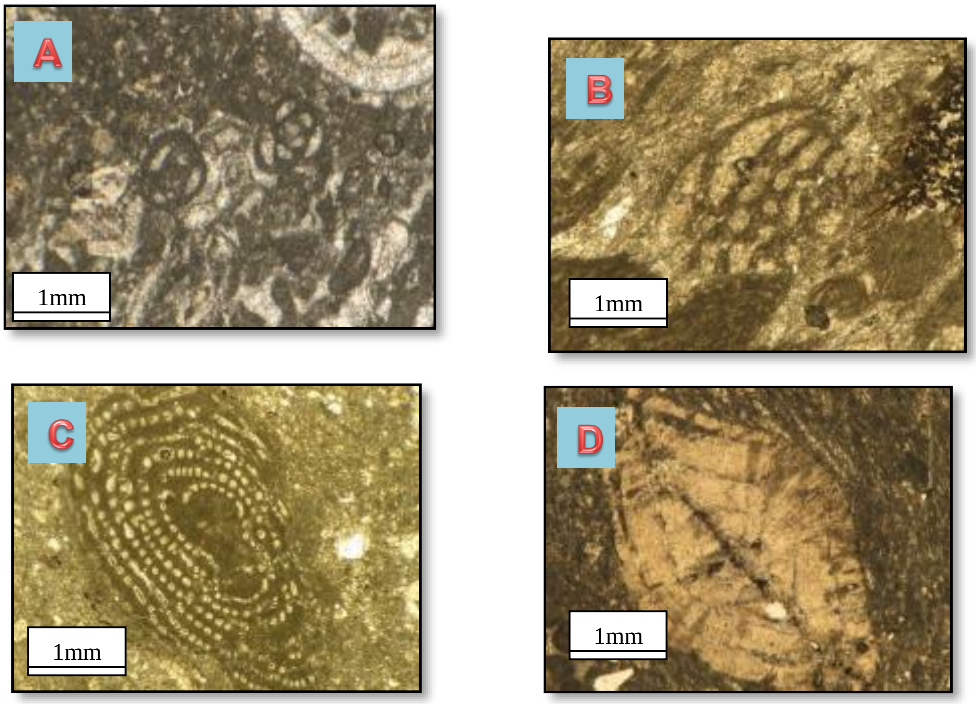


Figure 7. A: Arkose petrofacies (PPL); B: Sub-arkose petrofacies (PPL); C: Lithic petrofacies (PPL); D: Sub-lithic petrofacies (PPL); E: Amorphous quartz minerals in the carbonate matrix of lithic sandstone (PPL); F: Petrofacies of calc-litite sandstone (PPL); G: Microconglomerate (PPL); H: Clay minerals in calc-litite sandstone (XPL).



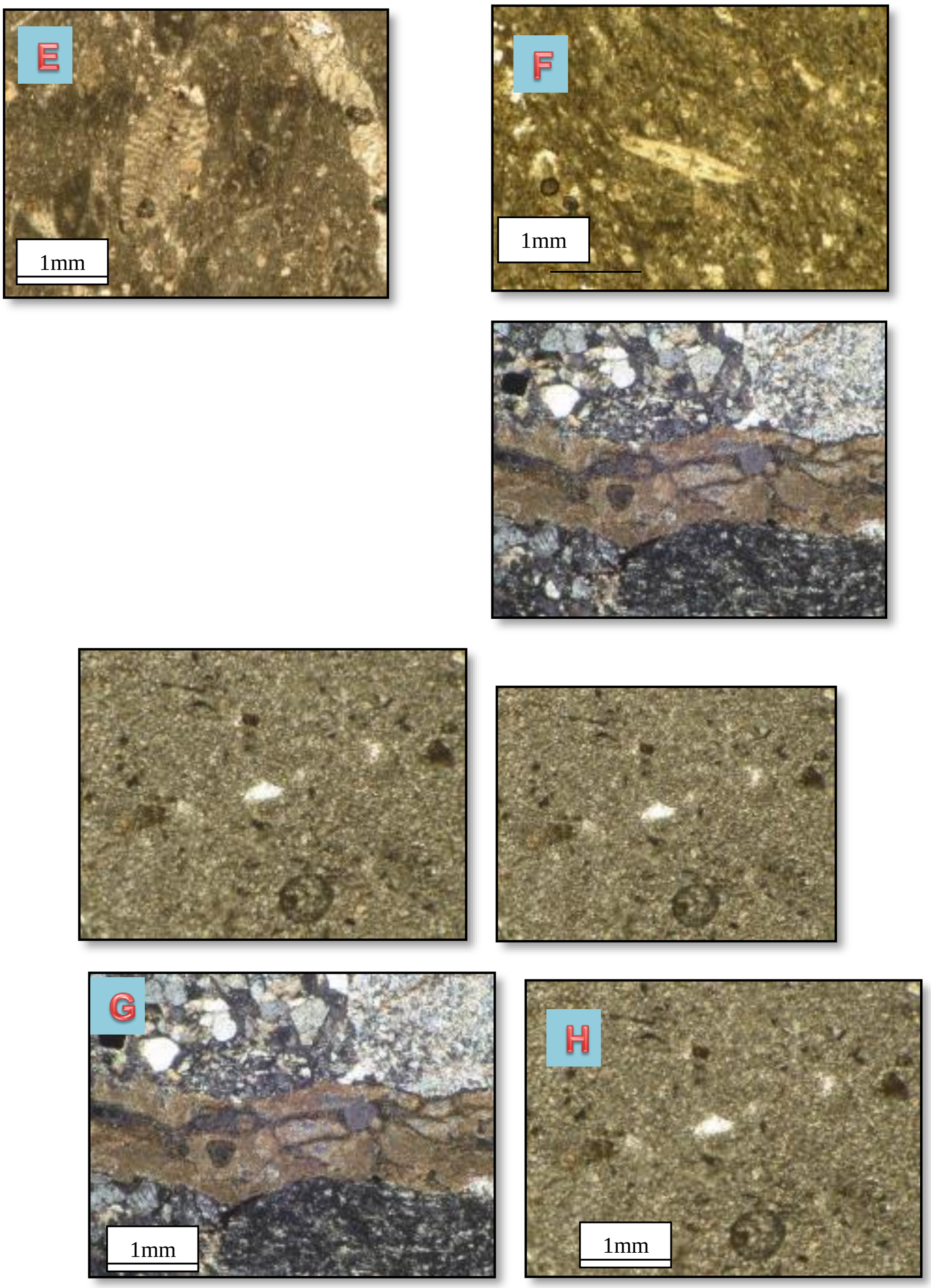


Figure 8. A: Miliolids in the packstone-grainstone facies (XPL); B: Bryozoa in packstone (XPL); C: Alveolina in a background of micrite (XPL); D: Nummulites in the wackestone-packstone facies (XPL); E: Discocyclina in the wackestone-packstone facies (XPL); F: Operculina in a background of micrite (XPL); G: Fractures in carbonate rocks (XPL); H: Fenestral fabric (XPL).

- Lagoon

Field observations show layers of fossil-rich argillaceous limestone and thin-bedded limestone, corresponding to a lagoonal section. Micrite content increases in these facies, with the matrix composed of cement and micrite. Due to the small size of outer lagoon shoals, there is free water exchange with the open sea. This zone lies within the influence of normal wave activity and the photic zone [14].

The thick shells of *Nummulites* indicate relatively turbulent and shallow conditions [16]. Facies in the inner lagoon are micrite-rich, with skeletal components of benthic foraminifera possessing porcellaneous and agglutinated shells, characteristic of calm, shallow environments with limited water circulation [7, 16].

The uniform and small size, good sorting, and color of the peloids suggest a fecal origin in a marine environment with normal salinity and muddy substrates. The presence of fecal pellets generally indicates warm, supersaturated carbonate seas with low energy and restricted water circulation [9, 17].

The identified lagoon zone reveals that the sedimentary environment is highly favorable for carbonate formation. With sufficient light, salinity, and turbulence, it supports the life of benthic foraminifera with agglutinated shells, ranging from restricted lagoonal environments to shallow open seas. For benthic foraminifera with calcareous shells, this extends from the outer lagoon to shallow open seas (Flügel, 2010) (Table 1, Figure 9).

Table 1. Facies and sedimentary environments identified in the study area.

Sedimentary Environment	Subfacies	Facies	Facial Groups
Internal ramp	Lagoon	Nummulites/orbitolites bioclast packstone	Benthic foraminiferal bioclast packstone (A)
		Benthic foraminiferal bioclast packstone grainstone	
Inner to middle ramp	Nummulite stacks	Nummulites packstone to wackestone	Nummulites wackestone to packstone (B)
		Nummulites packstone	
		Nummulites bioclast peloidal packstone	
Internal ramp	Open sea	Nummulites/Discocyclina wackestone to packstone	Planktonic foraminiferal *Discocyclina*/*Nummulites*/*Operculina* wackestone to packstone (C)
		Nummulites/*Assilina* packstone	
		Operculina/*Nummulites* packstone	

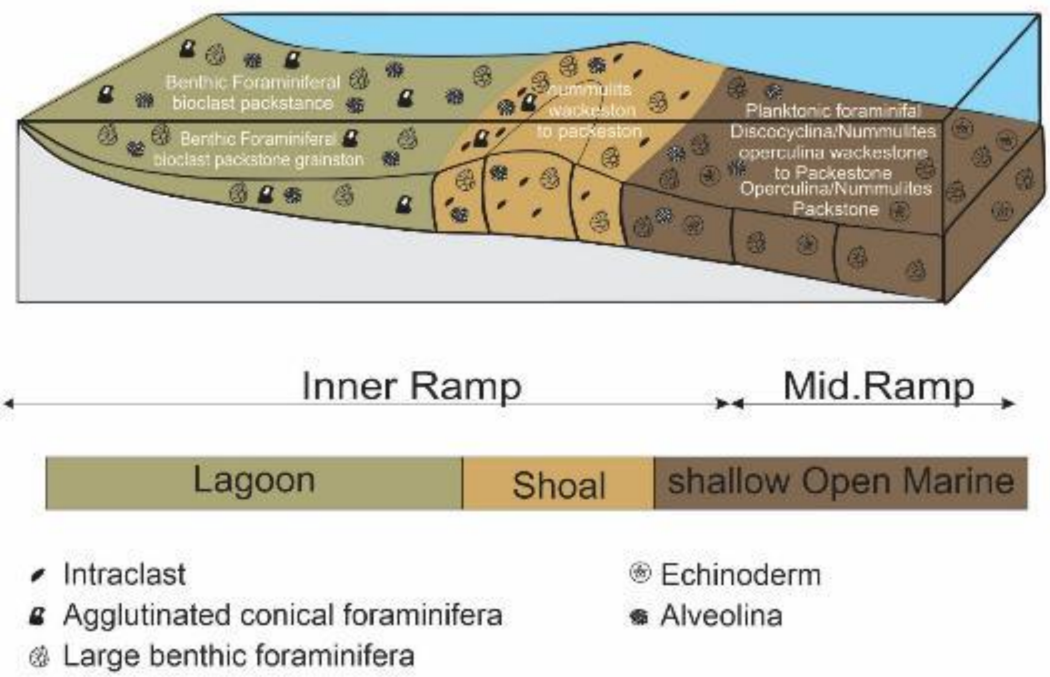


Figure 9. The sedimentary model of the Eocene deposit facies in the study area.

4.3. Diagenetic Processes in the Study Area

In the study area, diagenesis of clastic rocks includes cementation, compaction, pressure dissolution, and pore filling, while diagenesis of carbonate rocks involves micritization, cementation, neomorphism, compaction, fracturing, dolomitization, dissolution, and organic activities.

4.3.1. Diagenesis in Clastic Rocks

Cementation

- **Siliceous Cement:** Siliceous cement is observed as a pore and fracture filler or as overgrowth cement in some microfacies. The silica may originate from pressure dissolution, clay mineral transformations, feldspar alteration to clay minerals, or dissolution of siliceous particles and silicates (Friedman, 1997). Alkaline waters in restricted environments with high silica concentrations may also supply siliceous cement. Secondary sources of silica include groundwater in intergranular spaces of sandstones, leading to overgrowth cementation in quartz sandstones.
- **Carbonate Cement:** Calcite is one of the most common cements in sandstones. Poikilotopic and blocky fabrics are observed in microfacies (Figure 10B).
- **Dolomitic Cement:** This cement is observed as euhedral to anhedral forms, with varying sizes and iron contents. Grains may float within the cement matrix, or voids are completely filled with dolomitic cement.
- **Clay Cement:** Clay cements form during burial diagenesis [18]. In the studied sandstones, they fill pores and fractures and form coatings around framework grains, excluding their contact points. These cements are monomineralic due to their restricted formation conditions, whereas detrital clays are polymictic, originating from diverse sources.

Compaction and Pressure Dissolution

Compaction refers to any process that reduces the overall volume of a rock. It is observed in two forms: mechanical and chemical. Mechanical compaction involves deformation (Figure 10A), grain rearrangement, and the development of various types of grain contacts.

4.4. Diagenesis in Carbonate Rocks

Micritization

Micritization occurs during the early stages of marine diagenesis at the interface between seawater and sediment [19]. Processes such as microbial activity and sediment fragmentation contribute to micritization. Generally, micritized grains associated with endolithic microbial colonies are observed in low-energy, shallow marine environments.

In many cases, living organisms bore into grains during early sediment deposition, initiating micritization. This process may eventually produce completely micritized grains [12]. After the dissolution of internal grain portions, micritic envelopes can preserve the original grain shape. Ooids and intraclasts are often entirely micritized. The primary mineralogical composition of ooids is a key factor in their complete micritization (Figure 10D).

Cementation

The types of cement fabrics observed in carbonate rocks of the study area are as follows:

- **Isopachous Rim Cement:** This cement typically forms as needle-like or fibrous coatings around grains and void spaces. Isopachous rim cement suggests formation in early marine diagenetic environments. It requires seawater supersaturation with respect to calcium carbonate and calm conditions, forming uniform coatings around grains. In the study area, this cement is prominent in ooidal and bioclastic grainstone facies of barrier environments, often replaced by dolomite.
- **Syntaxial Overgrowth Cement:** Syntaxial overgrowth cement is commonly associated with freshwater but also forms in marine and burial conditions. This cement is widespread in facies near the barrier and open sea, particularly in ooidal grainstones.
- **Equant Mosaic Cement:** This type of cement forms in burial diagenetic and freshwater environments. Equant crystals indicate slow growth rates, low fluid flow, low temperatures, low CO^{3}_{2-} and high PCO^{2} [12, 13]. Typically forming after lithification and sediment compaction, it represents secondary cement generation [14]. In the study area, equant mosaic cement is observed in void spaces of grainstone and packstone facies.
- **Granular Cement:** Granular cement consists of small, uniform crystals and primarily forms in

freshwater and burial environments, representing secondary cement generation [12, 13]. In the study area, granular cement appears sparingly in grainstone and packstone facies, forming fine, nearly uniform crystals in void spaces after primary cementation (Figure 10C).

- **Blocky Cement:** Blocky cement forms as large crystals with well-defined edges, filling intergranular spaces. This type of cement forms in freshwater and burial environments [12, 13]. Its occurrence indicates low Mg/Ca ratios in the forming fluids. Occasionally, blocky cement fills fractures, suggesting formation during freshwater diagenesis post-uplift.

Neomorphism

Neomorphism includes processes such as the recrystallization of aragonitic bioclasts into calcite or the transformation of fine-grained calcite into coarser crystals [14]. In many cases, neomorphic bioclasts exhibit selective fabrics where cement crystals form only within the fossil shell, leaving the surrounding matrix unchanged (Figure 10F).

Compaction

Compaction encompasses processes that reduce the volume of rock masses (Flügel, 2004). Both physical and chemical compaction evidence is observed in the study area.

- **Physical Compaction:** This is observed mainly in packstones with high grain density, indicating mechanical compaction. Evidence includes fractured and crushed skeletal grains, broken peloids, and deformed ooids. The presence of clay minerals delays cementation, enhancing compaction and reducing porosity. Siliceous components, as grains or cement, also intensify pressure dissolution processes.
- **Chemical Compaction:** Chemical compaction or pressure dissolution occurs after physical compaction, potentially reducing limestone layer thickness by 20–35%. This process provides material for burial cement formation. Features include concave-convex (Figure 10E) and sutured grain contacts, stylolites, and dissolution seams. Stylolites form at moderate to high depths, serving as evidence of burial diagenesis [12, 13].

Fracturing

Fractures of varying dimensions, from small veins a few millimeters wide to extensive features, are common. Fractures may be open or filled with calcite or dolomite cement.

Dolomitization

Dolomitization is one of the most significant diagenetic processes in carbonate rocks. Based on crystal size, shape, and boundaries, dolomites are categorized as follows (Figure 10H):

- **Dolomicrite:** These fine crystals, ranging from 5–16 microns, are uniform in size with indistinct crystal boundaries. Quartz grains and peloids are often associated with them.
- **Dolomicrospar:** Crystals range from 16–100 microns, are semi-euhedral to anhedral, and have straight intercrystalline boundaries. Intercrystalline porosity is often abundant, partially filled with calcite.
- **Dolospar:** These medium-sized crystals (70–260 microns) form dense, relatively coarse mosaics with cloudy centers and flat, semi-euhedral to anhedral edges. Dolospars occasionally fill void spaces and fractures, sometimes disrupting the primary sedimentary fabric.

Dissolution

The passage of undersaturated carbonate fluids through carbonate rocks causes the dissolution of unstable minerals. This process typically occurs in near-surface diagenetic environments but may also occur on the seafloor or during deep burial. In the study area, dissolution forms irregular or moldic pores in certain microfacies. Extensive moldic and vuggy dissolution is observed in grainstone facies, partially filled later by silica and dolomite.

Organic Activities

Organisms play a significant role during diagenesis, contributing to features such as bioturbation, micritization, and the formation of fossil traces (Figure 10G).

4.5. Paragenetic Sequence

The paragenetic sequence outlines the relative timing of various events, essentially depicting their order of occurrence. The timing of diagenetic processes in a rock system depends on factors such as sediment texture, composition, pore fluid characteristics, and climate [12-14].

Based on evidence from the studied samples, post-depositional events and diagenetic alterations can be interpreted in three stages: marine diagenesis, meteoric diagenesis, and burial diagenesis (Table 2).

Marine diagenesis occurs at the surface, on the seafloor, in shallow and deep waters, as well as in the intertidal to supratidal zones [12, 13]. In the studied samples, this diagenesis is evidenced by processes such as complete or partial micritization of some allochems, the presence of syntaxial and isopachous cements, and bioturbation.

Meteoric diagenesis occurs when sediments are exposed above the water surface. Key processes in this environment include dissolution, cementation, and neomorphism. Under these conditions, sediments are influenced by undersaturated carbonate fluids [13]. In the studied samples, selective dissolution resulted in the removal of allochems, creating secondary porosity. Second-generation cements, including mosaic, isopachous, and blocky cements, formed at this stage. Neomorphism manifested as the transformation of micrite to microspar and the recrystallization of dolomites in some samples.

Burial diagenesis encompasses a series of alterations occurring below the near-surface diagenetic zone and above the low-grade metamorphic environment in sediments and rocks [14]. Processes such as compaction, the formation of cements (e.g., blocky and drusy), dolomitization, thermal stabilization of minerals, alteration, and organic matter maturation occur during this stage. A significant portion of the lifespan of carbonate sediments is spent in this environment. Only erosion or uplift can re-expose these sediments or rocks to surface conditions. In the studied samples, increased grain packing, fractured shells of some allochems, sutured grain contacts, and the presence of stylolites provide evidence of burial diagenesis.

Table 2. Paragenetic sequence of studied rock facies.

Diagenetic Environment / **Diagenetic processes**		**marine**	**Shallow Burial**	**Medium Burial**	**Meteoric**
Micritization					
Cementation	Equant isopachous Rim cement				
	Equant sparry mosaic cement				
	Drusy mosaic cement				
	Syntaxial overgrowth calcite cement				
Physical compaction					
Chemical compaction (pressure dissolution)					
Fracturing					
Dissolution pits and					

vugs	

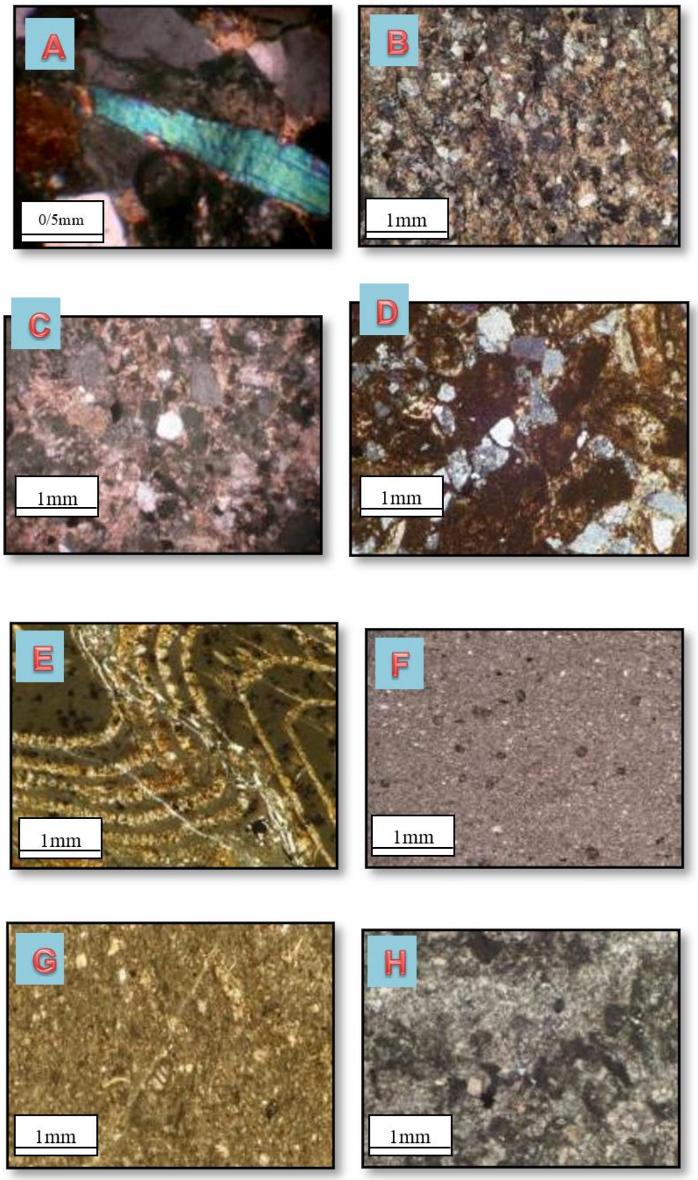


Figure 10. A: Bending of mica minerals in sandstone (PPL); B: Carbonate cement in sandstone (PPL); C: Presence of granular calcite cement (PPL); D: Micritized skeletal grain in carbonate rock (PPL); E: Convex-concave contact between Alveolina fossil grains (PPL); F: Neomorphism (PPL); G: Biogenic features in carbonate rocks (PPL); H: Dolomitization in carbonate rocks; crystals exhibit shaped to amorphous fabric (XPL)

5. Conclusion

The study of Eocene sedimentary deposits in Saravan identified two main facies groups: clastic and carbonate. Based on the identified facies, sedimentary environments were determined. Evidence in the Eocene sandstone-shale sequences of Saravan strongly suggests turbiditic sequences. This evidence includes:

a) Thick sequences of well-bedded sandstone-shale layers with planar, extensive bedding.

b) Sharp basal contacts in sandstones, transitioning gradually to shale upward.

c) Bouma sequences with sedimentary structures such as graded bedding, flow and groove casts, horizontal lamination, cross lamination, linear parting, and ripple marks.

d) Fossil evidence indicating a deep depositional basin.

e) Absence of features such as mud cracks, rain prints, root horizons, paleosols, vertebrate footprints, in-situ biotic assemblages, or large-scale cross bedding, which would indicate shallow water deposition.

In carbonate facies, key fossils include benthic foraminifera, particularly Nummulitids, Alveolinids, and other identified fossils, suggesting an Eocene to middle Eocene age for the region. Facies analysis indicates deposition occurred in middle and inner ramp environments. Facies containing benthic foraminifera, such as Assilina and Discocyclina, and carbonate mud indicate calm, offshore conditions in the middle ramp. Facies with abundant skeletal fragments and grainstones containing benthic foraminifera suggest deposition in relatively high-energy environments such as shoals. Facies rich in echinoderm fragments, porcellaneous benthic foraminifera, and agglutinated foraminifera were deposited in semi-restricted to restricted, shallow, and low-energy lagoonal environments. Autochthonous carbonate facies with wackestone to packstone textures and planktonic foraminifera are associated with basin environments. Fossil evidence is extensively utilized for sedimentological and depositional environment interpretations.

Diagenetic alterations in limestones began with micritization resulting from microbial activity. This was followed by the formation of isopachous calcite cement during early diagenesis. Partial dissolution removed some isopachous cement and carbonate mud. Mosaic calcite cementation and recrystallization of micrite to microspar likely occurred with increasing burial depth. Further burial diagenesis resulted in grain orientation, compact fabrics, skeletal shell deformation, and the development of pressure dissolution seams. Coarse calcite cements formed in fractures post-pressure dissolution.

The impact of global warming at the Paleocene–Eocene boundary, with associated marine transgression and increasing depth on the carbonate platform, is evident in the study area. Rising sea levels created favorable environments for benthic foraminifera proliferation in the Eocene deposits of the study area. Accumulations of Alveolina and miliolids indicate semi-enclosed zones with relatively high salinity and moderate nutrient levels. In contrast, the abundance of large hyaline-shelled benthic foraminifera such as Nummulites, Assilina, and Discocyclina suggests shallow open marine areas with normal salinity and low nutrient availability.

Light and turbulence effects are evident in thickened shells of foraminifera in shallow carbonate platform areas and thinner shells in deeper zones. Substrate type impacts are observed as larger shells in sandy substrates and smaller shells in muddy substrates. The high diversity and abundance of benthic foraminifera in the study area suggest deposition in warm tropical to subtropical waters.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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