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Research Article

MICROFACIES, SYSTEMATIC DESCRIPTION, TAXONOMY AND DEPOSITIONAL ENVIRONMENTS OF THE AZKAND FORMATION (LATE OLIGOCENE - EARLY MIOCENE) IN THE KIRKUK AREA OF THE ZAGROS BASIN, NORTHEASTERN IRAQ

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Abstract

Backgrounds: The Azkand Formation represents an important carbonate succession whose age, depositional environments, and platform evolution remain critical for regional paleogeographic reconstruction. This study provides a systematic micropaleontological and sedimentological investigation to refine its stratigraphic framework and environmental interpretation.

Methods: The Azkand Formation was systematically described and taxonomically classified at two key reference sections: the Khabaz Well-3 subsurface section and the Qara Chaugh Dagh surface outcrop. A total of fifty subsurface samples from Khabaz Well-3 and twenty-six surface samples from Qara Chaugh Dagh were analyzed using micropaleontological identification and detailed microfacies analysis to establish a robust depositional and chronological framework.

Results: The formation is characterized by high diversity and abundance of larger benthic foraminifera, including *Lepidocyclina*, *Amphistegina*, *Pararotalia*, *Neorotalia*, *Nummulitidae*, *Miogypsina*, *Miogypsinoides*, *Valvulina*, *Textularia*, *Operculina*, *Rotalia*, *Nephrolepidina*, and various encrusting forms. These assemblages constrain the age of the Azkand Formation to the Late Oligocene–Early Miocene interval. Microfacies analysis identified four distinct facies types: (1) fine bioclastic packstone dominated by small benthic foraminifera; (2) fine to very coarse bioclastic packstone rich in larger benthic foraminifera; (3) very fine to coarse larger foraminiferal packstone to grainstone; and (4) fine to very coarse bioclastic packstone to boundstone with coral and encrusting organisms. These facies indicate deposition within an isolated carbonate platform and slope system, ranging from deeper slope-toe environments to shallow sublittoral settings. Vertical and lateral facies variations reflect persistent open-marine conditions, moderate energy regimes, and episodic bioclastic reworking.

Conclusions: Integrated micropaleontological and sedimentological data demonstrate that the Azkand Formation represents a well-developed Oligo–Miocene carbonate platform system. The stratigraphic record provides valuable insights into regional

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paleogeographic evolution and improves understanding of carbonate platform .

Keywords : Azkand Formation, Oligocene-Miocene, Benthic foraminifera, Microfacies, Paleoenvironments, Iraq

Introduction

The study area is situated within the Kirkuk Governorate in the central northern region of Iraq, bounded by latitudes 36º 19' 12" and 36º 18' 30" and longitudes 45º 10' 15" and 45º 09' 44" (Fig. 1) (Buday, 1980).

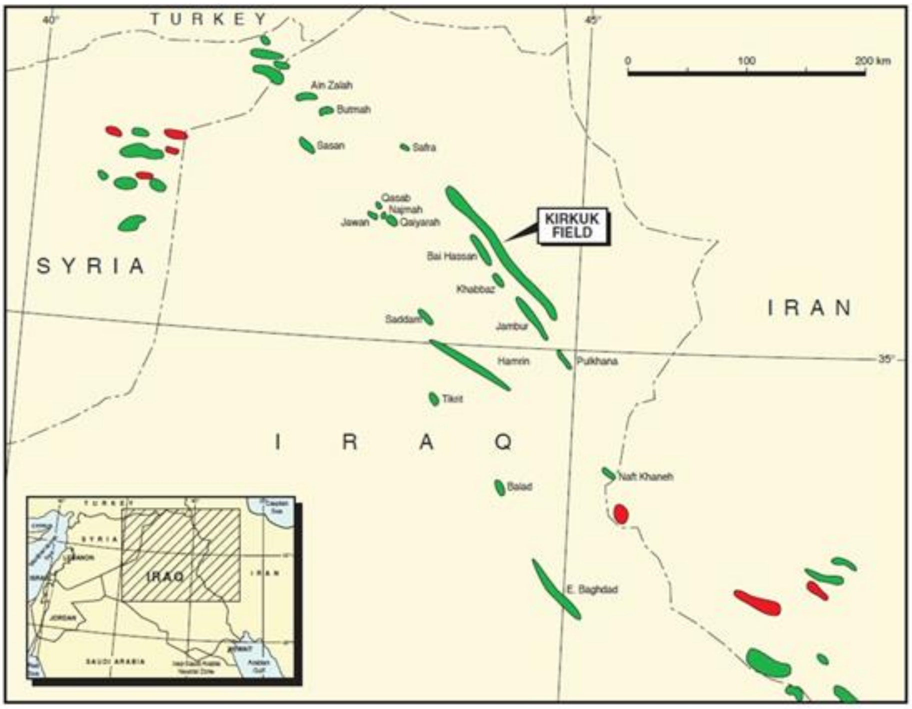

Fig. 1. Location map of the study area, Kirkuk Oil Fields, northern Iraq (after Buday, 1980)

Iraq's principal hydrocarbon reserves are predominantly hosted within the Oligocene carbonate successions, represented by the Kirkuk Group. Oil accumulation occurs within a long, narrow, steeply dipping anticline measuring approximately 95 km in length and 4 km in width, with three main culminations: Khurmala, Avanah, and Baba. The primary reservoir, known as the 'Main Limestone', is of Eocene–Oligocene age and comprises three depositional cycles of carbonate shelf-edge banks and bioherms situated along the margin of an intra-shelf basin.

Surface thrust faulting and dislocation of younger Tertiary strata have rendered subsurface structural interpretation challenging. Nevertheless, development drilling has confirmed the presence of a northwest-trending anticline with the aforementioned culminations. In addition to the Main Limestone, smaller oil accumulations have been identified in the Upper Cretaceous Shiranish and Middle Cretaceous Qamchuqa limestone formations since 1953. Production from the Main Limestone reservoir commenced in 1934.

The distribution of Oligocene sediments in Iraq is relatively limited in both areal extent and thickness (Van Bellen, 1956). The Azkand Formation was first defined by Van Bellen (1956) based on the "Main Limestone" of the Kirkuk, Bai Hassan, and Qarah Chauq Dagh structures in northern Iraq. The type locality is situated on the northeastern face of the Azkand Cirque, approximately three miles N-65°-E of the village of Azkand, on the southern dome of Qarah Chauq Dagh (Fig. 2). Lithologically, the formation is characterized by massive, dolomitic, and recrystallized limestone, typically exhibiting high porosity (Bellen

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et al., 1959). Fossils identified within the formation include *Heterostegina cf. assilinoides*, *Miogypsinoides complanata*, and *Rotalia viennoti*. The formation is likely of "Upper" Oligocene age, although this does not strictly correlate with the Upper Oligocene of Europe.

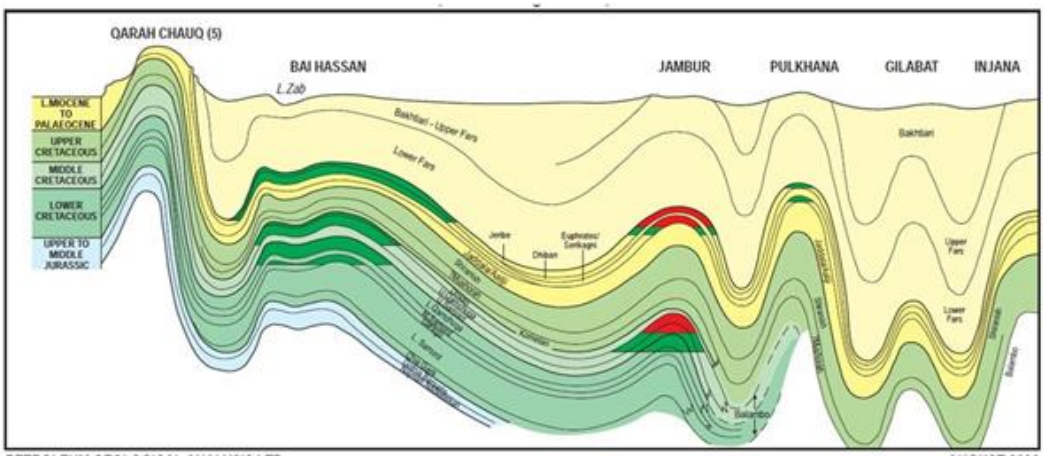

Fig. 2. Stratigraphic and structural features of the Azkand Formation in the Qara Chaugh Dagh to Injana area

The Azkand Formation unconformably overlies the Baba Limestone, a contact marked by a regional regression discussed by Van Bellen (1956). It is conformably overlain by the Anah Limestone Formation, which represents the reefal and lagoonal facies equivalent of the Azkand Formation and was deposited in fore-reef environments along both the northeastern and southeastern margins of the Oligocene Basin (Ditmar et al., 1971). The Baba Formation is considered representative of the northeastern region, while its extension to the southeastern shore area, particularly around Anah, has been confirmed by Ctyroky and Karim (1971), with the formation attaining even greater thickness there than in the northeast.

In the type locality, Bellen et al. (1959) documented the occurrence of larger foraminifera, including *Lepidocyclina s.l.* spp., *Nummulites fichteli*, *Operculina* sp., *Rotalia viennoti*, and *Heterostegina cf. assilinoides*, further supporting an Oligocene age assignment. In central Iraq, the Azkand Formation is widespread across numerous oil wells located southwest of the Lesser Zab River within the Kirkuk structure. It is also present on the northeastern flank of the Bai Hassan structure and crops out on the northern dome of Qarah Chauq Dagh, extending both northeastward and southwestward along the former Oligocene shorelines. Surface exposures occur in Qarah Chauq Dagh along the northeastern shoreline and along the Euphrates Valley, west of Anah, in the southwestern region.

In subsurface sections, the formation is encountered between the Ain Zala and Bai Hassan fields. In the southwestern region, the Oligocene formations exhibit unconformable boundaries with both underlying and overlying units (Buday, 1980). Within the Azkand and Baba formations, larger foraminifera are typically associated with shallow marine carbonate sediments, and facies exhibit continuous lateral variation within this environment (Ghafor, 2022a; Ghafor, Najaflou, 2022; Ghafor et al., 2025). Isopach and lithofacies maps of the Baba and Azkand shoal margins are provided in Figures 3 and 4.

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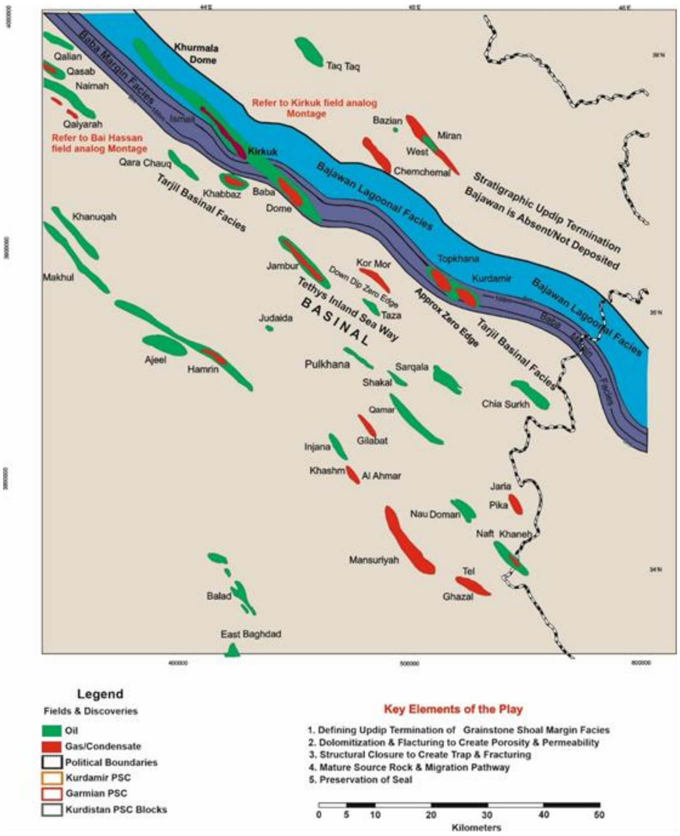

Fig. 3. Qara Chaugh Dagh to Injana schematic cross section (after Dunnington, 2005; 1974)

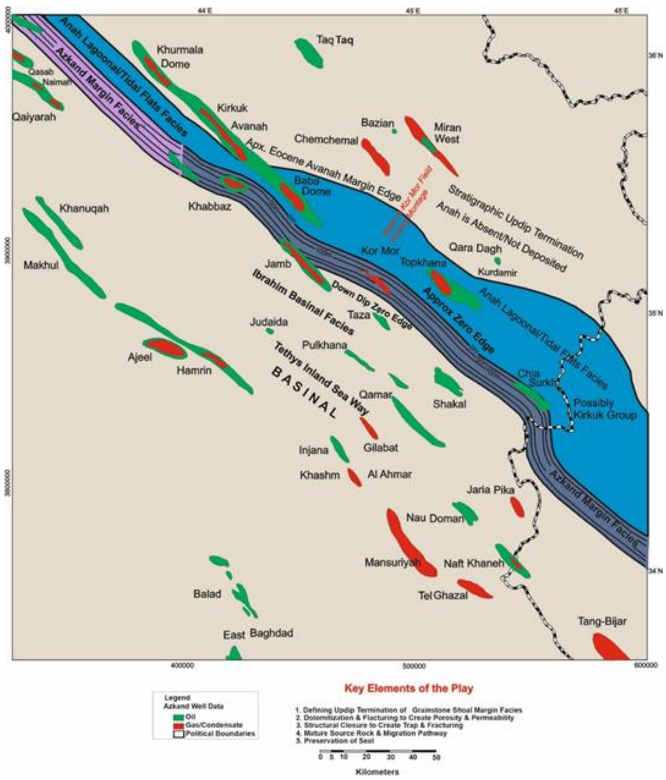

Fig. 4. Baba Formation shoal margin isopach and lithofacies map

Numerous studies have reported the occurrence of the Miocene Azkand Formation directly overlying the Oligocene Baba Formation within the same stratigraphic succession (Table 1).

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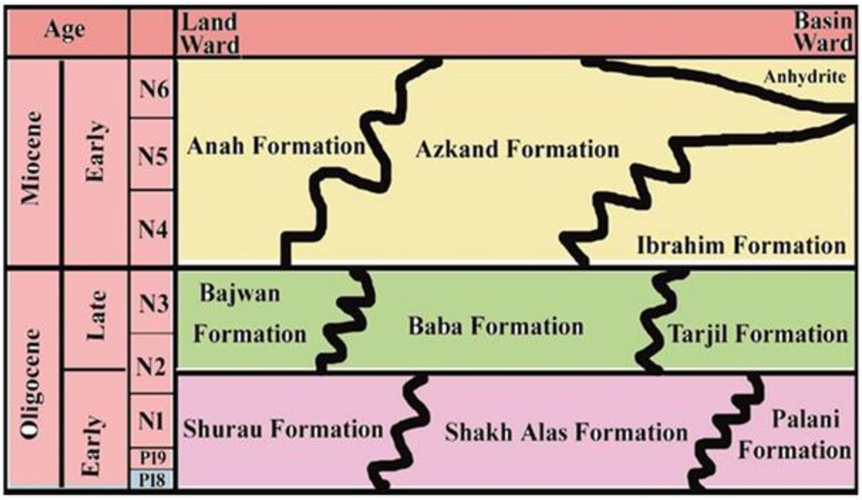

Table 1. Age relationships of Oligocene–Early Miocene formations in northern Iraq (after El-Eisa, 1992)

The present study focuses specifically on the Azkand Formation, which is stratigraphically overlain by the Bajwan Formation and underlain by the Shurau Formation (Ghafor, 2022b). The investigated area encompasses the Khabaz Well-3 and the Qara Chaugh Dagh sections, located within the Himreen–Makhul Subzone of the Foothill Zone on the unstable shelf (Buday, Jassim, 1987). According to Al-Kadhimi et al. (1996), the area lies within the Himreen Subzone of the Foothill Zone in the northeastern region of Iraq, approximately 10.2 km southwest to northeast of Kirkuk city.

While the Baba Formation has been extensively studied both sedimentologically and paleontologically across numerous oil fields in Iraq, its Late Oligocene age has been established based primarily on its faunal assemblages (Mohammed, 1983; El-Eisa, 1992; Bakkal, Al-Ghreri, 1993; Abid, 1997; Al-Guburi, El-Eisa, 2002; Ghafor, 2004, 2011, 2015; Ghafor, Muhammed, 2005, 2007, 2011; Muhammed, Ghafor, 2008). Recent global paleontological studies on the Late Oligocene include significant contributions by Ghafor, Ahmad (2019, 2021) and Ghafor, Muhammad (2006).

A stratigraphic correlation chart illustrating the positions of the Baba and Azkand formations across southern, western, and northern Iraq is presented in Fig. 5 (Harland et al., 1990; El Diasty et al., 2016). Numerous authors have studied the stratigraphy of Cretaceous units in the region, including Kassab (1976, 1978, 1979), Ghafor (1988, 1993a), Ghafor et al. (2023, 2024), Bakkal et al. (1993), Ghafor et al. (1993, 2012), Ghafor, Mohialdeen (2016, 2018), and Ghafor and Kareem (1999), as well as Ghafor and Baziany (2009) and Ghafor et al. (2025).

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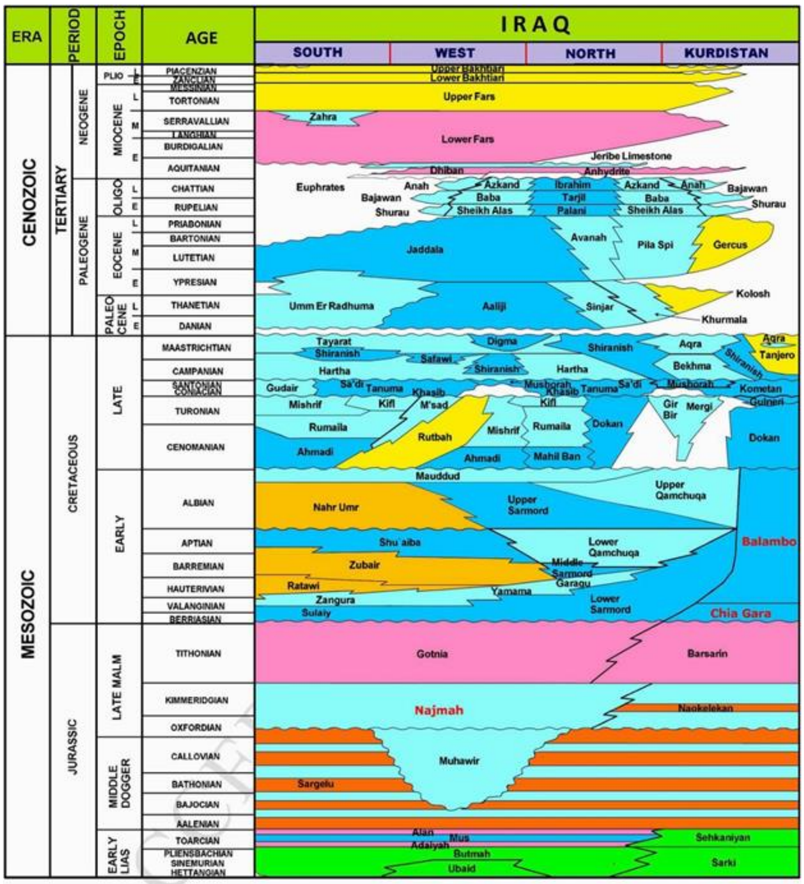

Fig. 5. Stratigraphic correlation chart showing the position of the Baba and Azkand formations in southern, western, and northern Iraq (Kurdistan Region) within the geological column of Iraq (after Harland et al., 1990; El Diasty et al., 2016). The representation of the Iraqi Kurdistan region has been modified

Paleogene units have also received considerable attention, with studies conducted by Al-Fattah et al. (2017, 2018, 2020a, 2020b), Al-Taee et al. (2024a, 2024b, 2024c), Al-Qayim et al. (2014), Ghafor and Al-Qayim (2021a), Al-Qayim and Ghafor (2022), and Ghafor and Muhammad (2022, 2023a, 2023b, 2025), Ghafor and Muhammad (2022, 2023a, b, 2025) and Al-Juboury et al. (2025).

The transitional K/Pg boundary units have also been investigated in detail through indifferent area of Iraq and the Kurdistan Region. These have been discussed and studied by Kassab et al. (1986), Ghafor (1988, 2000, 2020), Al-Shaibani et al. (1993), Sharbazheri et al. (2009a, and b, 2011), Al-Nuaimy et al. (2020) and Ghafor et al. (2024).

Studies focusing on Neogene formations include those by Ghafor (2004, 2010, 2014, 2022a, 2022b), Ghafor and Muhammad (2005 and 2006), Muhammad and Ghafor (2008), Ghafor and Najaflou (2022), as well as Ghafor et al. (2025) and Ghafor et al. (2025).

Oligocene/Miocene sequences are considered to be equivalent to the Asmari Formation in Iran, as identified by (Rashidi et al., 2022, 2023a, b, 2024; Rajabi and Ghafor, 2024, Ghafor et al., 2025; Ghafor et al., 2025a, b).

The Oligocene sediments in Iraq exhibit limited areal distribution and reduced thickness compared to older stratigraphic units (Bellen et al., 1959). These deposits are considerably less extensive than those of the Eocene, primarily restricted to the Mesopotamian Basin and largely absent in other regions (Ghafor,

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Ahmad, 2019). The Oligocene formations are typically bounded by unconformities separating them from both the underlying and overlying strata. A notable feature of the Oligocene is the absence of molasse-type deposits in the foredeep, coupled with its narrow depositional footprint.

Despite this limited extent, the Oligocene – together with the upper Eocene – records the development of a new sedimentary basin, primarily occupying areas that were formerly part of the emergent Khleisia Uplift and the stable shelf region north of the Euphrates River (Buday, 1980). Evidence for continuous sedimentation from the upper Eocene into the lower Oligocene, particularly in pelagic facies, remains inconclusive. Several biostratigraphic zones indicative of the early Oligocene – such as the *Cassigerinella chipolensis–Pseudohastigerina micra* Zone (Caribbean region, P19) and the *Globigerina tapuriensis* and *Globigerina selli–Globanomalina pseudobadoensis* Zones (Syria) – have not been identified within the Iraqi stratigraphic record (Blow, 1969; Jassim, Karim, 1984).

However, the occurrence of *Globanomalina micra*, a species believed to characterize Oligocene carbonate sequences, allows for regional correlation with equivalent formations in adjacent countries. In this context, the Jahrum Formation is considered representative of the Lower Oligocene, while the Asmari Formation corresponds to the Upper Oligocene (Bolli, Krasheninnikov, 1977; Ghafor et al., 2023c; Rashidi et al., 2023; Rashidi et al., 2024; Rajabi and Ghafor, 2024, 2025 (Rajabi and Ghafor 2025, Under publication), Ghafor et al., 2025), as illustrated in Fig. 6.

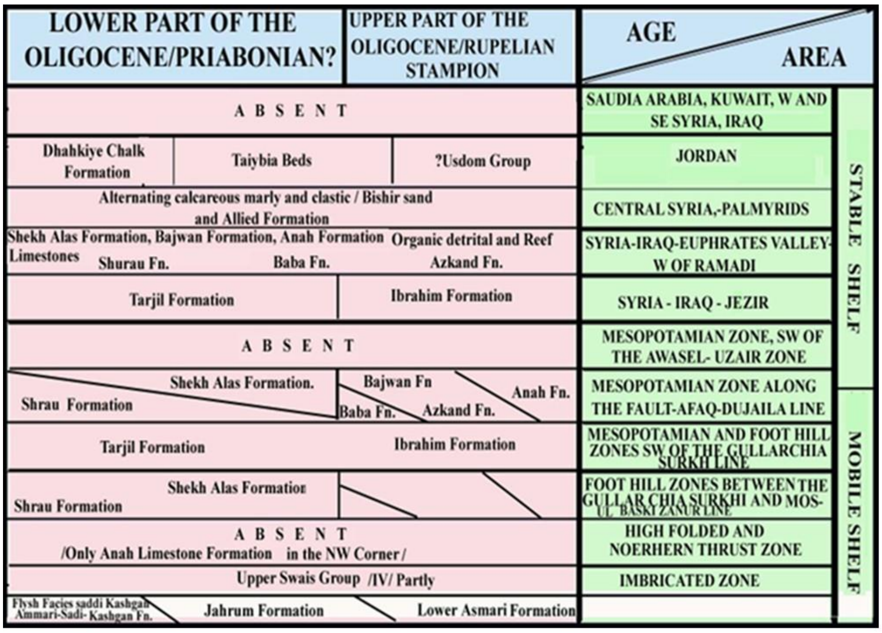

Fig. 6. Stratigraphic correlation of Oligocene sediments in Iraq with surrounding countries (after Buday, 1980

Oligocene Reservoir Facies

The Oligocene forms a significant reservoir horizon in the Kurdistan region of northern Iraq, most notably as the principal reservoir unit in the supergiant Kirkuk oilfield. This reservoir system is traditionally divided into nine formations within the Kirkuk Group (van Bellen et al., 1959). However, the depositional limits of the Oligocene are not well constrained, complicating precise interpretations of sediment distribution.

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Facies Distribution

Oligocene sediment thickness varies significantly, ranging from less than 10 meters to more than 300 meters. Dip measurements are largely unavailable from well data. Internal unconformities and conglomeratic layers are observed within the sequence. Deposition occurred mainly to the north of the Mountain Front Fold Zone, particularly near Bazian and Qara Dagh. The presence of Oligocene sediments northeast of the Anah–Qalat Dizeh Fault Zone is considered unlikely, although it cannot be definitively excluded. If present, the sediments in this area are expected to be thin and discontinuous.

Much of the Mosul High tectonic block lacks Oligocene sediments, likely due to erosion or non-deposition. In contrast, thicker sediment accumulations are observed in the Kirkuk tectonic block and extend into the Sirwan Trough and Sinjar areas. While the Kirkuk Group has traditionally been subdivided into fore-reef, back-reef, and open marine facies, evidence for true skeletal reef-building organisms is limited. Instead, reefal facies are better interpreted as biohermal buildups (Majid, Veizer, 1986). These accumulations likely represent early-stage, drowned reefs composed mainly of skeletal lime sands embedded in a muddy matrix. A basal conglomerate bed commonly marks the onset of upper Oligocene deposition, as observed at the Aj Dagh Anticline.

Reservoir Quality

The reservoir potential of the Oligocene formations is variable. The highest reservoir quality is typically associated with slope deposits – formerly referred to as "fore-reef" facies – of the Azkand, Baba, and Sheikh Alas formations. Southward and westward facies transitions into deeper basinal environments are characterized by increasingly condensed sequences and reduced porosity. Shelfal facies of the Kirkuk Group display diagenetic features such as dissolution, recrystallization, and cementation.

Prolonged subaerial exposure in the northwestern sector of the Kirkuk field has allowed for sustained meteoric water infiltration, resulting in significant dolomitization. This diagenetic process has enhanced porosity and facilitated hydrocarbon migration.

Hydrocarbon Shows and Production

The Oligocene carbonates of northern Iraq have proven to be prolific hydrocarbon reservoirs. The Kirkuk supergiant oilfield, producing primarily from Oligocene formations, has yielded oil since 1927, with early production rates reaching up to 100,000 barrels of oil per day (BOPD). By 2004, cumulative production reached approximately 15.5 billion barrels of oil and 5 trillion cubic feet (TCF) of gas, with an estimated 10.8 billion barrels of oil and 8.2 TCF of gas remaining (Verma et al., 2004).

Oil has also been produced from the Oligocene supersequence in other fields such as Kurdamir-1 (including a 1 TCF gas cap), Bai Hassan, and Jampur, all of which demonstrate the continued significance of the Oligocene as a reservoir unit. The stratigraphic relationships of the producing Cenozoic reservoirs are shown in Fig. 7. The fractured reservoir of Oligocene carbonates is shown in Fig. 8.

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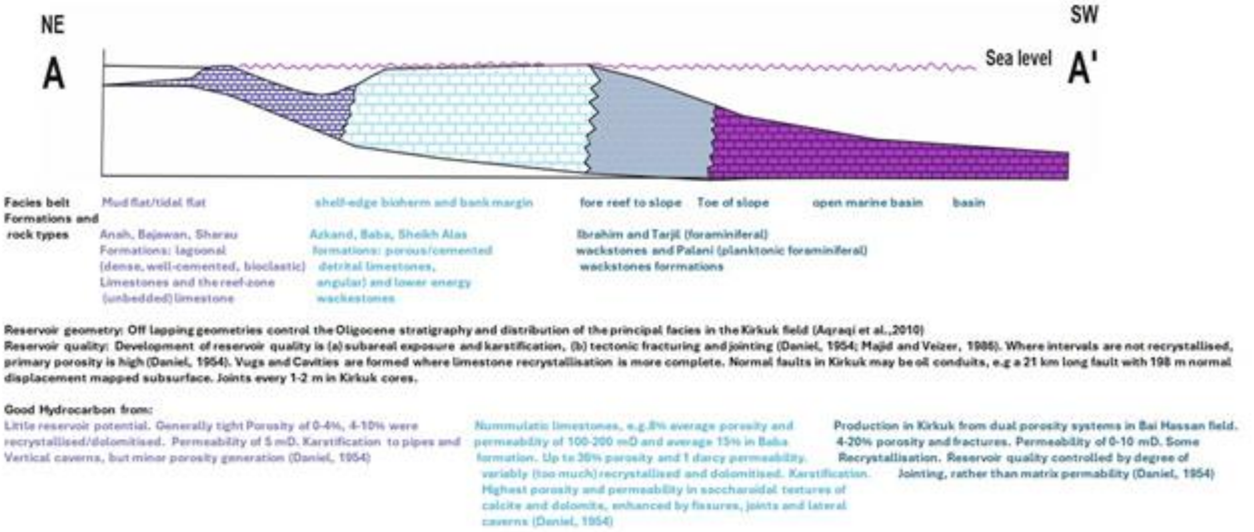

Fig. 7. Schematic section through the Oligocene carbonate ramp sequence

Fig. 8. Fractured reservoirs of Oligocene carbonates (example from the Kurdamir field)

The Kirkuk Field is situated along a series of northwest-trending anticlines within the folded belt of northern Iraq. Two distinct basement blocks – the Kirkuk and Mosul blocks – have been identified beneath this belt, based on variations in sediment thickness and structural orientations (Ameen, 1992). Internal faulting within these blocks influenced differential subsidence throughout the Mesozoic, and subsequent fault reactivation during Zagros orogenic compression likely inverted earlier grabens, resulting in the formation of prominent fold structures, including the Kirkuk Anticline.

The Kirkuk structure is a narrow, elongate anticline measuring approximately 95 km in length and up to 4 km in width, covering an area of roughly 300 km². The anticline is segmented into three major culminations – Khurmala, Avanah, and Baba – by two structural saddles**.** The Baba Dome plunges gently to the southeast, while the Khurmala Dome dips northwestward, collectively forming a four-way dip-closed

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structure. The fold is characteristically flat-topped and concentric, with steep limbs dipping at angles up to 50° (Fig. 9).

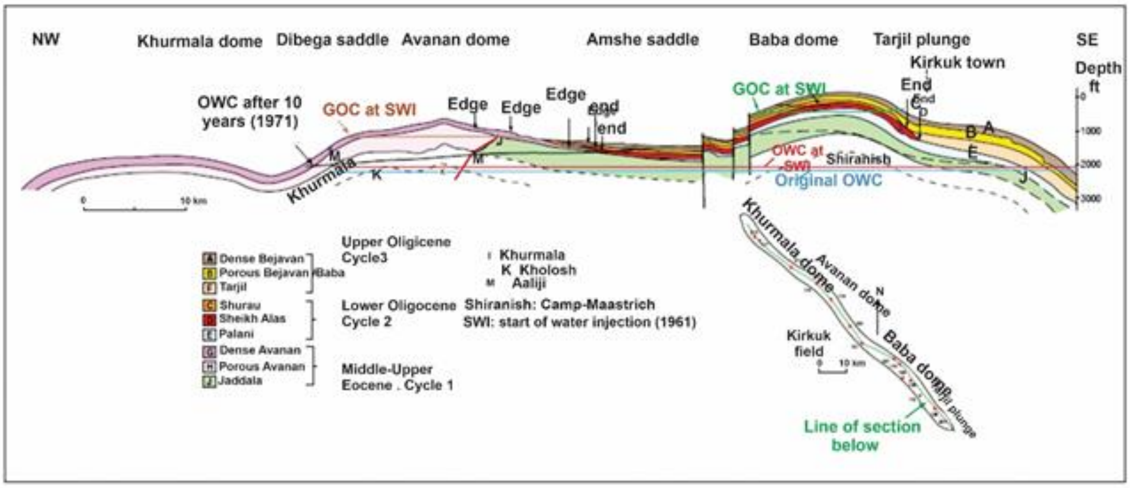

Fig. 9. NW–SE structural cross-section of the Kirkuk Field, illustrating reservoir geometry and fluid contacts (Alamir, 1972). The main reservoir over the Khurmala and Avanah domes does not extend into the Baba dome, while younger units in the Baba Dome and Amshe Saddle thin rapidly towards Avanah. See Fig. 10 for lithostratigraphy and depositional facies

While recent structural maps are not publicly available, versions from the 1960s depict several northwest- to north-trending faults intersecting the Main Limestone in the southern portion of the field, with throws reaching up to 650 feet. Reservoirs within the field are intensely fractured, particularly in crestal areas, with fracture density decreasing towards the flanks. The fracture systems predominantly originated from folding, though some are associated with fault zones (Daniel, 1954). Fracturing is most intense at the fold crest and at lateral bends in the fold axis.

The Upper Fars and Bakhtiari formations are detached at the base of the Lower Fars evaporites and exhibit discordant folding and thrust faulting above the Kirkuk structure. The Baba Dome has the shallowest crest, located at 75 ft ASL at the Main Limestone level, whereas the Avanah crest lies at 650 ft TVDSS (1446 ft). The Main Limestone is sealed by Middle Miocene Lower Fars evaporites. Although conglomerates, shales, and limestones of the intervening Lower Fars are generally non-reservoir, fractures linking these to underlying thin limestones have facilitated oil migration, integrating them into the Main Limestone reservoir system (Daniel, 1954). Surface seeps of gas and oil indicate minor seal breaches; however, the seal remains effective despite the long oil column and localized thin overburden (as little as 900 ft in certain areas). Structural trapping began in the Late Miocene.

In addition to the main limestone, smaller hydrocarbon accumulations occur in the fractured carbonates of the Middle and Late Cretaceous, which are sealed by shale units (Fig. 10). The reservoir properties of facies in the Kirkuk field, are shown in the table below (Table 2).

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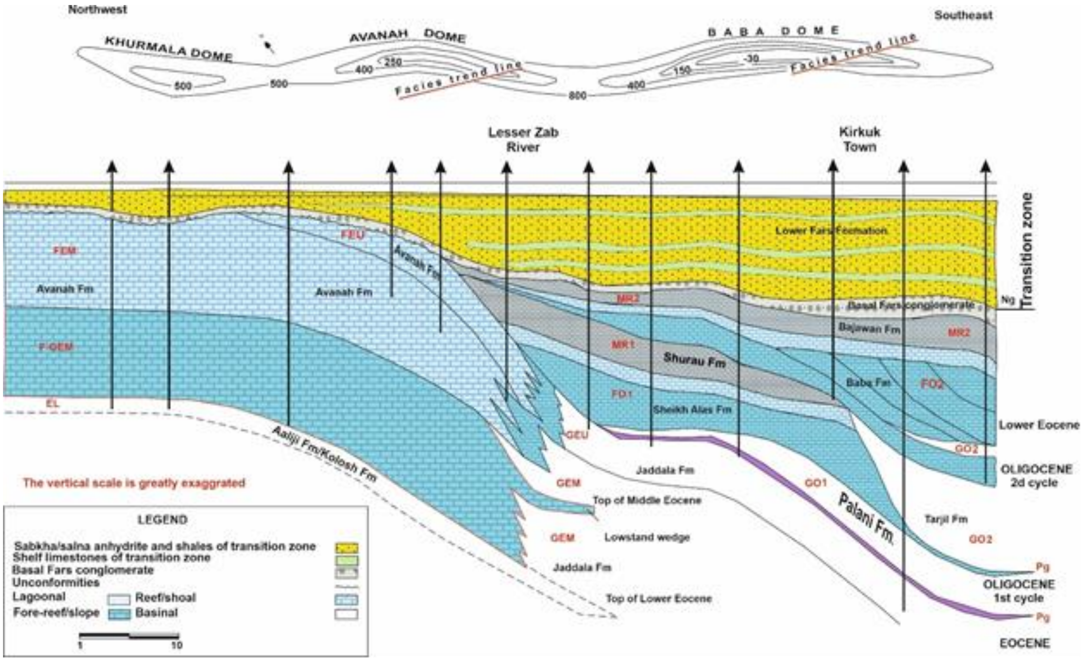

Fig. 10. Schematic cross-section through the Kirkuk Field showing stratigraphic relationships of producing Cenozoic reservoirs (Aqrawi et al., 2010). Note the distinctive flapping geometries

Table 2 Reservoir properties of facies in the Kirkuk Field

Facies (from Daniel, 1954)	porosity(%) measured	Permeability (mD) (estimated)
Transition zone Limestines	0-30 (av. 5%)	about 100
Porcellanous reef/back –reef facies	0-4	0-5
Diagenetically altered reef/back –reef	4-10	not available
Partly recrystallised fore-reef facies	18-36	50-1000
Globigerinal micrites	8-18	0-10
Globigerinal micrites with turbidites	4-20	not available

Materials and Methods

The Oligocene–Miocene subsurface succession within the Low Folded Zone is being investigated for its paleontological and paleoenvironmental characteristics. The study focuses on two sections: Khabaz Well-3 and the Qara Chaugh Dagh surface section. A total of 76 fossiliferous limestone samples have been collected – 50 from Khabaz Well-3 and 26 from Qara Chaugh Dagh. Both sections exhibit nearly identical lithology. Microfossil identification follows established taxonomic frameworks, particularly those of Rajabi and Ghafor (2025) (Under publication) and Serra-Kiel et al. (2016).

Review of the Azkand Formation

The Azkand Formation was initially described by Van Bellen in 1956 from surface exposures in the Azkand Cirque of the Qara Chaugh Dagh structures. It comprises massive dolomite and recrystallized limestone with varying porosity (Bellen et al., 1959). Similar lithology is observed across various regions, showing notable resemblance to the Baba Limestone Formation. The typical thickness of the Azkand Formation is approximately 100 meters.

Representing a fore-reef depositional environment, the formation is fossiliferous and includes taxa such as *Heterostegina cf. assilinoides*, *Miogypsinoides complanata*, and *Lepidocyclina* spp. (Bellen et al., 1969). The presence of *Miogypsinoides complanata* in the basal portion indicates a Late Oligocene age. The

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lower contact with the Baba Limestone is conformable, marked by an 8-meter dolomitized limestone transition, while the upper boundary is gradational, typically leading into the Anah Limestone Formation.

The Azkand Formation is also reported from subsurface wells in western Iraq, such as Mileh Tharthar No. 1 and from limited occurrences in the eastern regions, including the Qaiyarah structure (e.g., Gusair No. 1, Ibrahim No. 1) (Bellen et al., 1969). Surface exposures occur along the Euphrates River valley, although some outcrops previously attributed to the Azkand may now be reassigned to the Baba Formation. The formation has been identified in both southwestern and northeastern margins of the Oligocene basin (Buday, 1980).

Al-Hashimi and Amer (1985) studied the Azkand Formation in Wadi El-Kheshka (Anah–Al Qaim area) and Ibrahim Well No. 1, identifying microfossils such as *Miogypsinoides complanata*, *Miogypsinoides deharti*, *Rotalia viennoti*, *Lepidocyclina (Nephrolepidina)*, *Heterostegina antillensis*, *Nummulites vascus*, various miliolids, and calcareous algae – collectively supporting an upper Oligocene age.

Subsequent investigations across northern and northwestern Iraq confirm the formation's Late Oligocene–Early Miocene age (e.g., Abid, 1997; Al-Guburi, El-Eissa, 2002; Ghafor and co-authors, 2004-2025). Regionally, the Azkand Formation is considered equivalent to Iran's Asmari Formation (Rashidi and Ghafor, 2022; Rashidi et al., 2023, 2024; Rajabi and Ghafor, 2024, 2025).

Together, the Baba and Azkand formations serve as important lithostratigraphic units for reconstructing the region's geological evolution and provide valuable data for petroleum exploration. These formations have been extensively studied (e.g., Ghafor, 2004, 2011, 2015, Ghafor, Muhammed, 2005-2011; Ghafor, Ahmad, 2019, 2021; Roozpeykar, Moghaddam, 2016; Ghafor et al., 2023a, 2023b, 2025; Ghafor, Lawa, Karim, 2003; Ghafor, Karim, Sissakian, 2014).

Results and Discussion

Microfacies and Subdivision of Larger Foraminifera

The larger foraminiferal assemblages identified within the Azkand Formation comprise four principal generic groups: *Lepidocyclina*, *Miogypsina*, *Miogypsinoides*, and *Amphistegina*. Additional associated taxa include *Austrotrillina*, *Pararotalia*, members of the family *Nummulitidae*, alveolinids, coralline algae, and various encrusting foraminifera. A quantitative analysis of thin sections revealed distinct spatial and stratigraphic variations in the abundance and distribution of these taxa.

In the Khabaz Well-3 section, *Lepidocyclina* and encrusting foraminifera are most frequent in the lower stratigraphic units, while *Nummulitidae* become increasingly dominant in the upper units. In contrast, the Qara Chaugh Dagh section displays a more uniform vertical distribution of *Lepidocyclina* and *Amphistegina*, although localized peaks in encrusting foraminifera are evident in Unit IV.

Microfacies Subdivision of the Azkand Formation

Based on lithological and paleontological characteristics observed in petrographic thin sections, the Azkand Formation has been subdivided into four distinct microfacies (Figs 11, 12 and 13).

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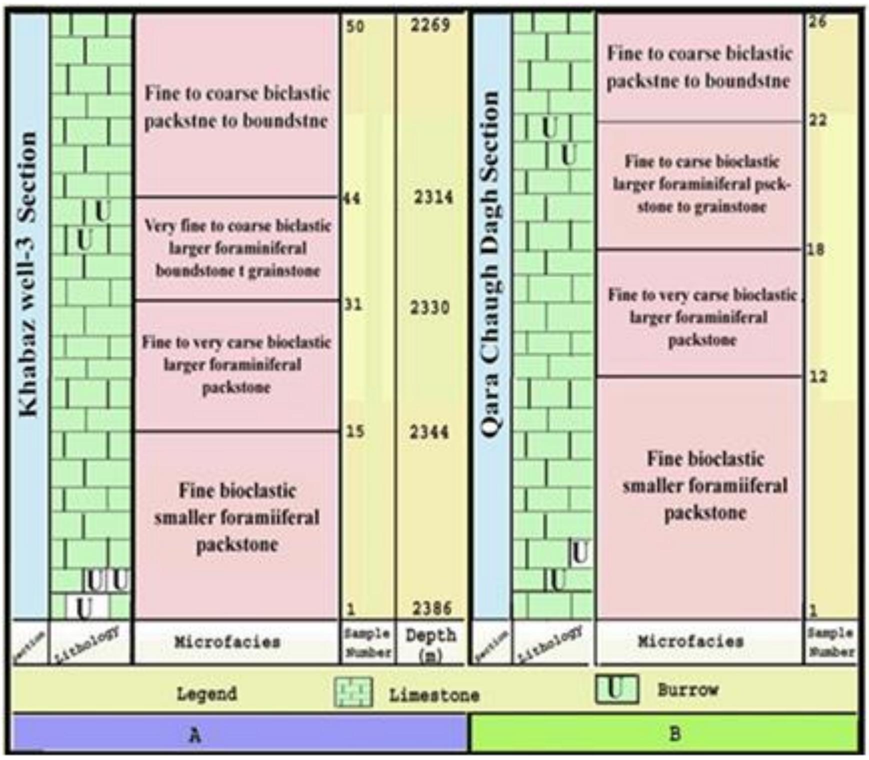

Fig. 11. A – Lithostratigraphic section of the Azkand Formation in the Khabaz well-3 section. B – Lithostratigraphic section of the Azkand Formation in the Qara Chaugh Dagh section

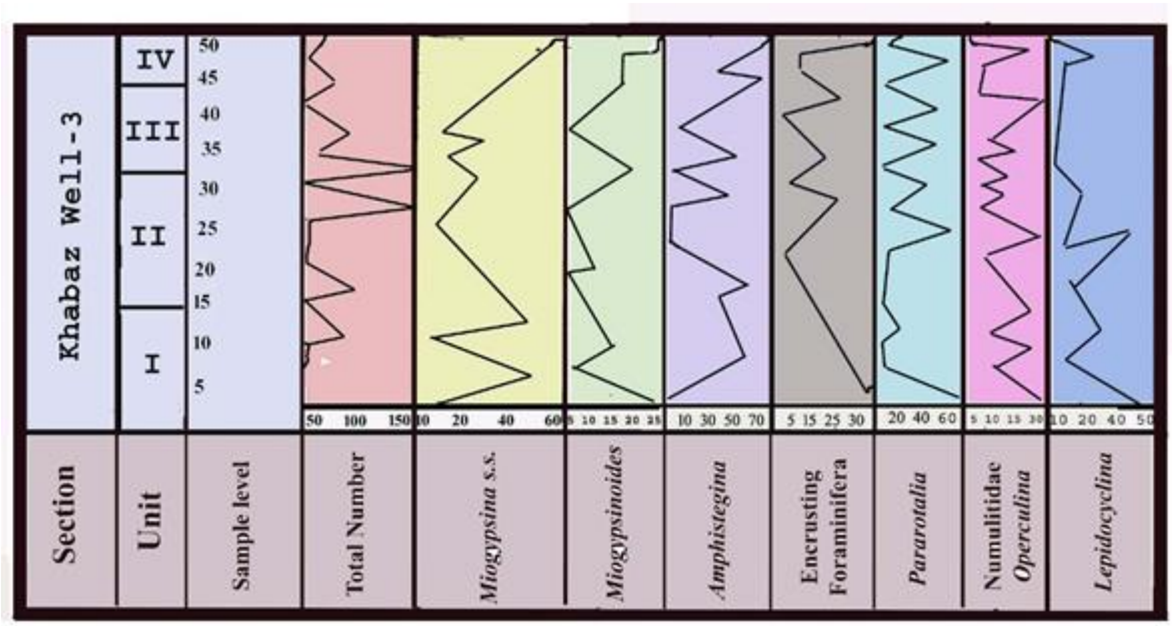

Fig. 12. A – The total numbers and relative frequency of larger foraminifera in thin sections of units (**I, II, III**, and **IV**) in the Azkand Formation at the Khabaz Well-3 section. **B –** The total numbers and relative frequency of larger foraminifera in thin sections of units (**I, II, III**, and **IV**) in the Azkand Formation at the Qara Chaugh Dagh section

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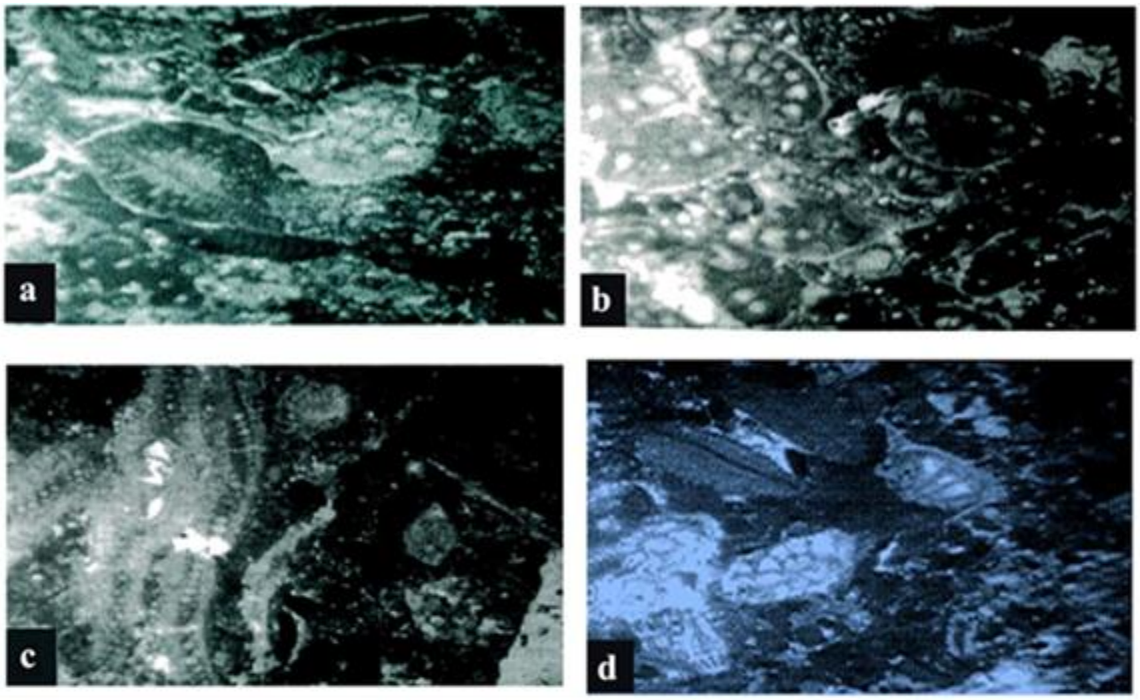

Fig. 13. a – Unit I: Coarse foraminiferal packstone, sample 7, Khabaz well-3 section, Azkand Formation. (15X). **b** – Unit II: Foraminiferal packstone to grainstone, sample 22, Khabaz well-3 section, Azkand Formation. (15X), **c** – Unit III: Coarse grainstone into packstone, with Amphistegina, L(N.), sample 18, Qara Chaugh Dagh section, Azkand Formation, (15X). **d** – Unit IV: Smaller foraminiferal packstone, sample 26, Qara Chaugh Dagh section, Azkand Formation. (15X).

Each microfacies reflects specific depositional conditions and faunal assemblages. The following is a detailed description of **Unit I**:

Unit I: Fine Bioclastic Smaller Foraminiferal Packstone

This basal microfacies is approximately 36 meters thick in the Khabaz Well-3 section and 24 meters thick in the Qara Chaugh Dagh section. It is characterized by bedded, fine- to medium-grained packstone with a generally porous texture. Larger bioclasts are rare within this unit. Individual beds range in thickness from 35 centimeters to 1 meter.

Bioturbation is frequent and evident across various scales, with both small- and large-diameter burrows observed. The lower 10 meters of Unit I in the Khabaz section are distinguished by a fining-downward grain-size trend. Above this interval, the trend reverses, transitioning from fine to medium-fine, and eventually to coarser packstone in the upper portion of the unit.

Planktic foraminifera are relatively abundant in the lower part of the unit, especially in the Khabaz Well-3 section. Bioclasts exceeding one millimeter in size are generally infrequent; however, the basal portion contains occasional large bioclasts, leading to a local grading into floatstone, particularly evident in the Qara Chaugh Dagh section. These larger components include coral fragments, echinoid remains, and larger benthic foraminifera, often associated with encrusting foraminiferal species.

Larger Foraminifera Assemblages

The relative frequency of *Lepidocyclina* within the studied sections is generally low, ranging from 5% to 25%. Specimens often exhibit large diameters of up to 1 cm. Taxa such as *Miogypsina*, *Miogypsinoides*,

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Amphistegina, and members of the *Nummulitidae* family (notably *Heterostegina* and *Operculina*) persist throughout the lower portion of Unit I.

Interpretation of Unit I

The scarcity of coarse bioclasts – typically indicative of shallow marine conditions – suggests a progressive deepening of the depositional environment during the formation of the lower part of Unit I. In contrast, the presence of dolomitic limestone, particularly in the Qara Chaugh Dagh section, points to a shallowing trend during the deposition of the upper portion of this unit. The basal unit in Khabaz Well-3 measures approximately 13 meters in thickness, while in the Qara Chaugh Dagh section it is around 10 meters thick.

Unit II: Bedded Fine to Very Coarse Foraminiferal Packstone

This unit, found directly above the basal interval, comprises bedded fine to very coarse packstone, with individual bed thicknesses ranging from 0.5 to 2 meters. The coarse fraction is dominated by subrounded bioclasts derived from larger foraminifera and algae. The coarsest carbonate grains are generally smaller than 5 mm, except for a thin zone near the base where grains exceed this size.

Thin section analysis reveals that trochospiral and planispiral forms of smaller benthic foraminifera are significantly more abundant than serial forms. This distribution suggests moderate energy conditions.

Larger Foraminifera in Unit II

Preservation of larger foraminifera varies from poor to moderate. The number of specimens per thin section ranges from 16 to 250. *Miogypsinoides* dominates the lower part of the unit, reaching relative frequencies exceeding 30%. *Pararotalia* constitutes approximately 40% of the assemblage in the lowermost portion of Unit II in the Qara Chaugh Dagh section. *Amphistegina* is also a significant component, comprising 5% to 15% of the assemblage. *Nummulitids* (e.g., *Heterostegina*, *Spiroclypeus*, *Operculina*) are present throughout, with the latter occurring more frequently in the upper part. Although *Lepidocyclina (Eulepidina)* and *Lepidocyclina (Nephrolepidina)* rarely exceed 1%, they are locally abundant (up to 30%) at the unit's base.

Interpretation of Unit II

The composition and texture of bioclasts suggest deposition within a shallow, open marine slope or platform setting. A fining-upward trend is evident and may reflect a gradual deepening of the depositional environment.

Unit III: Very Fine to Coarse Bioclastic Packstone to Grainstone

Unit III is composed of fine to very coarse packstone beds that often grade into grainstone. Individual beds range in thickness from 40 cm to 1 meter. In the Qara Chaugh Dagh section, large burrows (2-3 cm in diameter) are frequent. The lower portion is dominated by coarse calcarenite, which transitions into medium to fine calcarenite in the upper layers.

The thickness of Unit III is approximately 15 meters in Khabaz Well-3 and 12 meters in Qara Chaugh Dagh. Coarse fractions in the lower beds commonly exceed 2 mm in diameter, with grains being well-rounded. These coarse components consist primarily of larger foraminiferal tests, echinoid fragments, and algal debris (*Melobesioideae*). Encrusting forms, including *Lithoporella melobesioides* (Foslie, 1909), are also common.

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Larger Foraminifera in Unit III

This unit contains abundant larger foraminifera, with total specimen counts reaching up to 500 per thin section. Assemblages are dominated in the upper part by *Miogypsina s.s.*, which reaches 50%-60% relative abundance. *Amphistegina* occurs in association with *Miogypsina*, though with considerable variability in frequency. *Miogypsinoides s.s.* increases in abundance in intervals where *Miogypsina s.s.* frequencies are lower. In the lower part of the unit, *Lepidocyclina (Nephrolepidina)* is prominent, comprising up to 60% of the assemblage. Encrusting foraminifera and *Heterostegina* are also common.

Interpretation of Unit III

The dominance of coarse-grained carbonate components and an upward coarsening trend suggest sustained shallow, high-energy depositional conditions, likely in a sublittoral open marine environment. The transition between microfacies indicates prolonged shallowing.

Unit IV: Fine to Very Coarse Bioclastic Packstone to Boundstone

Unit IV is 34 meters thick in the Khabaz Well-3 section and 15 meters in the Qara Chaugh Dagh section. It is characterized by loosely bedded fine to medium packstone at the base, grading into coarse packstone and locally boundstone at the top. Larger bioclasts are generally rare in this unit. The coarse fraction includes *Lepidocyclina (Nephrolepidina)*, *Miogypsina s.s.*, *Pararotalia*, encrusting foraminifera, and coral fragments – many of which give the sediment a floatstone-like texture.

Larger Foraminifera in Unit IV

Lepidocyclina (Nephrolepidina) occurs in low to moderate frequencies (5%-16%). *Miogypsinoides s.s.* remains present, particularly in the upper portion. Coral fragments are abundant and include reef-building taxa, providing further evidence for shallow marine conditions.

Interpretation of Unit IV

The presence of a diverse assemblage of larger foraminifera (*Lepidocyclina*, *Amphistegina*, *Heterostegina*, *Pararotalia*, *Miogypsina s.s.*, *Miogypsinoides s.s.*), combined with abundant coral material, indicates a shallowing upward trend, characteristic of a shallow marine platform or reef-associated environment during the deposition of this unit.

Oligocene Facies Distribution in the Kirkuk Field

The Early to Middle Oligocene facies observed in the Kirkuk Field are illustrated in Fig. 14.

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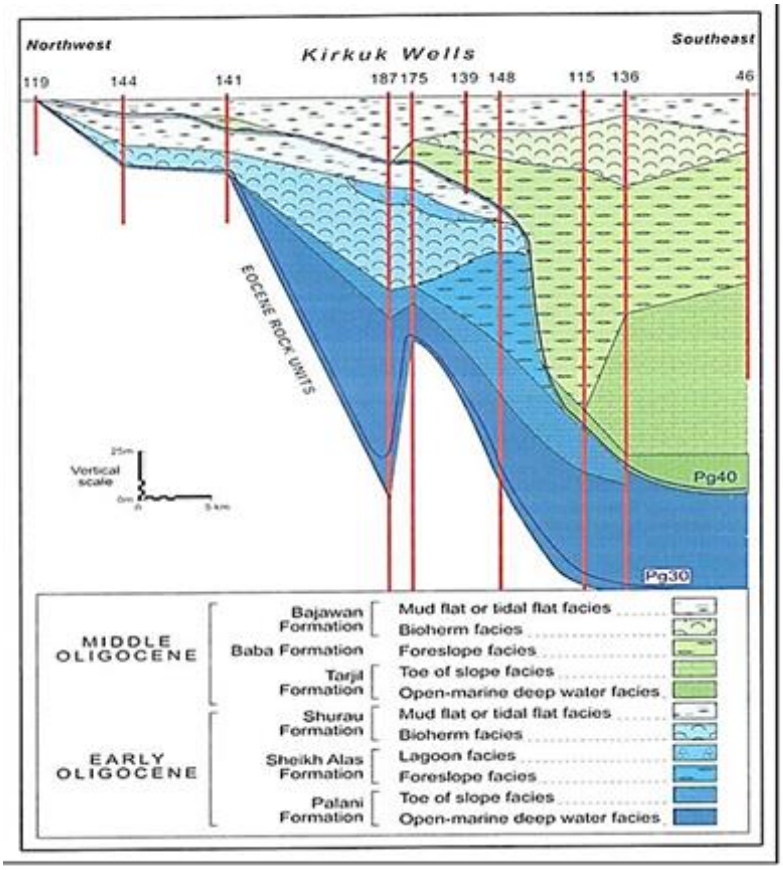

Fig. 14. Early to Middle Oligocene facies in the Kirkuk Field (after Aqrawi et al., 2010; modified from Majid, Veizer, 1986)

Identified and assigned to specific formations. These facies represent a range of depositional environments, from deep marine to shallow lagoonal and tidal flat settings:

Palani Formation – Characterized by toe-of-slope facies and open marine deep-water deposits.

Sheikh Alas Formation – Represents lagoonal and fore-slope facies, indicative of a transitional marine environment.

Shaurau Formation – Includes mudflat or tidal flat facies and localized biohermal buildups.

Tarjil Formation – Similar to the Palani Formation, this unit comprises toe-of-slope and deep open marine facies.

Baba Formation – Interpreted as fore-slope deposits, typically associated with slope-margin carbonate settings.

Bajwan Formation – Composed predominantly of tidal flat and mudflat facies, often associated with restricted marine conditions.

Systematic Description and Taxonomy of Larger Benthic Foraminifera

Larger Benthic Foraminifera (LBF) are among the most significant fossil groups in the Oligocene–Early Miocene carbonate successions of the studied region (Figs 15-18).

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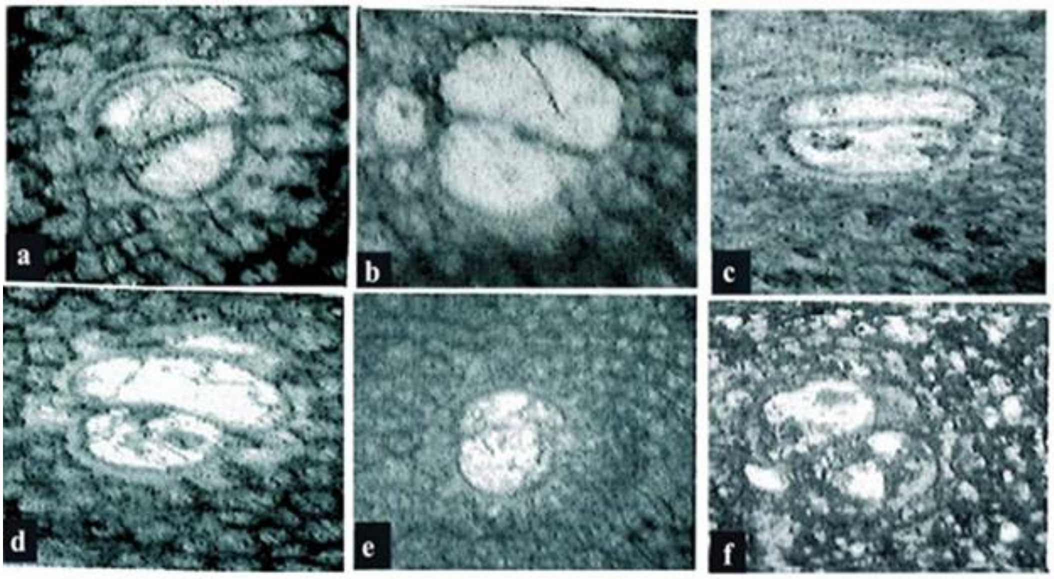

Fig. 15. a-e: *Lepidocyclina (Nephrolepidina)* from Units I–III, various samples (e.g., 3, 7, 16, 18, 20) in Khabaz Well-3 and Qara Chaugh Dagh sections, Azkand Formation. All oriented thin sections under magnifications 30×–40×

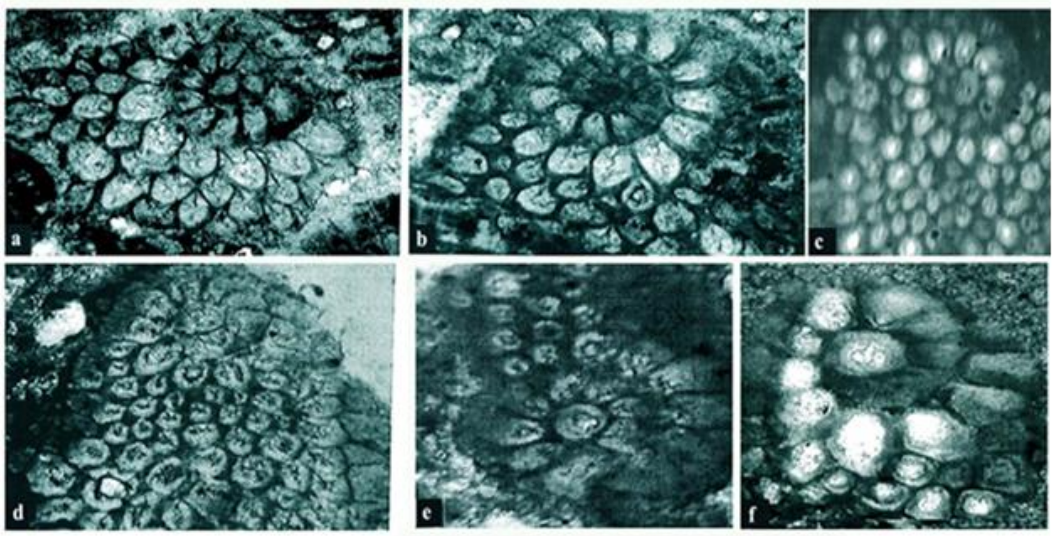

Fig. 16. a-f: Oriented thin sections showing various larger foraminifera

a–b: *Miogypsinoides complanata*, Unit I
c: *Lepidocyclina (Nephrolepidina)*, Unit I
d: *Miogypsinoides formosensis*, Unit II
e: *Miogypsinoides bantamensis*, Unit III
f: *Miogypsina gunteri*, Unit III

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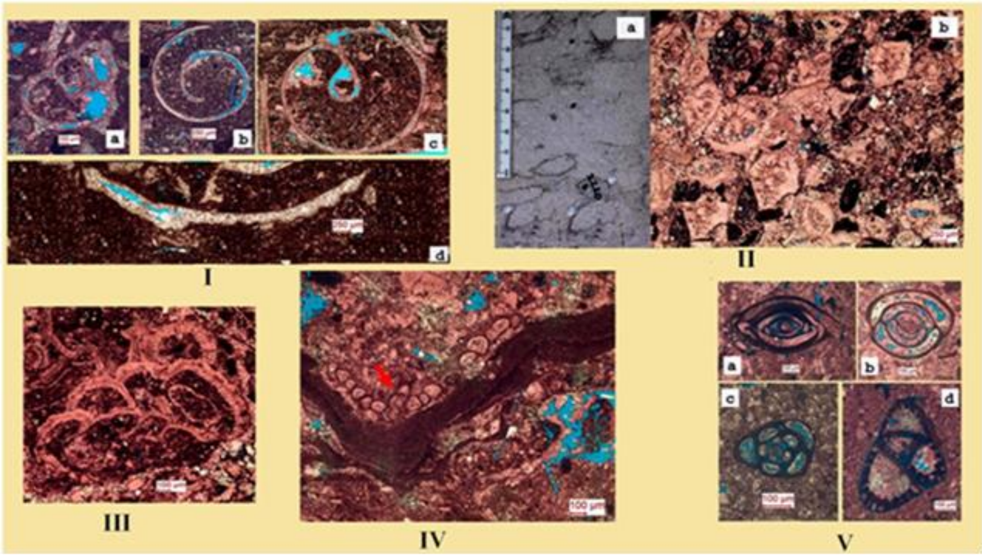

Fig. 17. I: Molluscan bioclasts (gastropods, bivalves) with neomorphic spar and biomoldic porosity. **II:** Core photograph and thin section showing *Ophiomorpha*-burrowed packstone with abundant *Nummulitidae* and miliolids. **III–V:** Foraminiferal assemblages including larger encrusting hyaline forms and small miliolids (*Austrotrillina*), showing microenvironments on coral and algal substrates

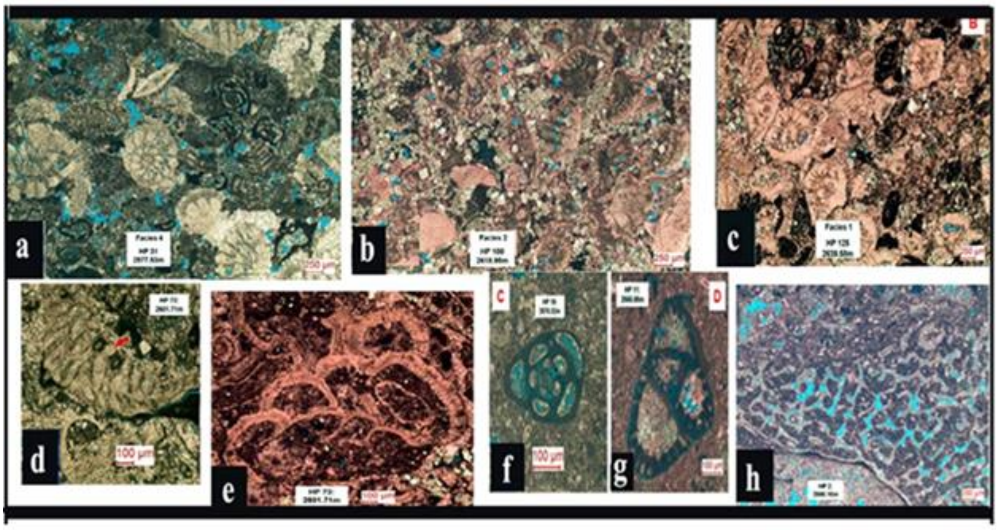

Fig. 18. Selected larger foraminifera and associated fossils from the Azkand Formation: a-c: *Nummulitidae* and echinoidsd, h: Encrusting coralse: Encrusting foraminifera, f-g: *Austrotrillina howchini*

The taxonomic study was based on a set of 76 rock samples collected from one surface outcrop (Qara Chaugh Dagh section) and one subsurface section (Khabaz Well-3). Thin sections were randomly selected from these samples to ensure a representative assemblage.

The identification and classification of LBF species follow standard taxonomic frameworks established in the literature. The systematic taxonomy is based on the works of the following key references:

Lamarck (1804)
d'Orbigny (1826)
Joly & Leymerie (1848)
Gumbel (1870)

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Blanckenhorn (1890)
Greig (1935)
Ellis & Messina (Catalogue of Foraminifera, 1940–2015)
Henson (1936, 1950)
Bolli (1957)
Smout & Eames (1958)
Adams (1968)
Blow (1969)
Loeblich & Tappan (1988)
Cahuzac & Poignant (1997)
Sirel (2003, 2013)
Serra-Kiel et al. (2016)
Habibi (2017)
Boudagher-Fadel (2018)
Olsson et al. (2018)
Wade et al. (2018a, 2018b)
Basso et al. (2019)
Roozpeykar et al. (2019)
World Foraminifera Database (accessed 2024)

This taxonomic framework supports the reliable identification and biostratigraphic interpretation of the foraminiferal assemblages, enabling detailed facies correlation and paleoenvironmental reconstruction within the studied formations.

Systematic Description and Taxonomy of Larger Benthic Foraminifera

The following taxonomic descriptions are based on thin-section analysis of 76 carbonate samples from both surface (Qara Chaugh Dagh) and subsurface (Khabaz Well-3) sections. Classification follows internationally recognized taxonomic frameworks and key literature references as cited below.

Order: *Foraminiferida* Eichwald, 1830

Suborder: *Rotaliina* Delage & Hérouard, 1896

Family: *Nummulitidae* de Blainville, 1827

Genus: *Heterostegina* d'Orbigny, 1826

Species: *Heterostegina assilinoides* Blanckenhorn, 1890

References:

Habibi, 2016a: pl. 1, fig. 14

Habibi, 2017: pl. 1, figs. 7, 8, 11

Parente & Less, 2019: figs. 6E–L

Description:Megalospheric specimens with a circular planispiral test; identified in axial section by thick to medium walls and clearly defined chamberlets.

Remarks: Illustrated specimens are derived from samples 4 and 10.

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Stratigraphic Distribution: Reported from the early Chattian (SBZ 22) of southwestern Turkey (Özcan et al., 2009) and from the late Rupelian–early Chattian (SBZ 21-22) in eastern Turkey (Gedik, 2014). Its range extends into SBZ 22B-23 (Cahuzac & Poignant, 1997; Parente & Less, 2019). In this study, it occurs from the Rupelian to the Chattian.

Family: *Austrotrillinidae* Loeblich & Tappan, 1987

Genus: *Austrotrillina* Parr, 1942

Species: *Austrotrillina asmariensis* Adams, 1968

References:
Boudagher-Fadel & Lokier, 2005: pl. 1, fig. 3 (as *A. howchini*)
Gedik, 2015: pl. 1, figs. 12-16, 24, 29
Fernandez-Canadell et al., 2017: figs. 3A, 4A-G

Description:Characterized by straight, narrow, and closely packed alveoles that do not bifurcate.
Species: *Austrotrillina howchini* (Schlumberger, 1893)

References:
Gedik, 2014: pl. 3, figs. 17, 23, 24

Description:Test wall is porcelaneous with an alveolar inner layer. Alveoles vary from fine to coarse and may be simple or exhibit bifurcating/trifurcating patterns.
Family: *Rotaliidae* Ehrenberg, 1839
Subfamily: *Rotaliinae* Ehrenberg, 1839
Genus: *Neorotalia* Bermúdez, 1952
Species: *Neorotalia viennoti* (Greig, 1935)
References:
Hottinger et al., 1991: p. 27, figs. 8/1, 2
Bassi et al., 2007: pl. 3, figs. 1-7
Habibi, 2016a: pl. 1, figs. 6-7
Description:Characterized by a trochospiral test with a strongly asymmetrical outline.
Genus: *Rotalia* Lamarck, 1804
Species: *Rotalia viennoti* Greig, 1935
References:
Greig, 1935: p. 524, pl. 58, figs. 1-4
Adams & Bourgeois, 1967: p. 26, pl. 4, fig. 1
Description:Test is trochospirally coiled with 2-2.5 whorls and a central V-shaped plug. The wall is calcareous and hyaline; test diameter ranges from 0.5-0.7 mm.
Remarks: Specimens are from samples 1 and 19.
Family: *Lepidocyclinidae* Scheffen, 1932
Subfamily: *Lepidocyclininae* Scheffen, 1932
Genus: *Lepidocyclina* Gümbel, 1870
Species: *Lepidocyclina* sp.
Description:Characterized by a thin-walled, multilocular embryonal stage enclosed by a thickened wall. Equatorial chambers are hexagonal, with numerous well-differentiated lateral chambers.
Remarks: Observed in samples 2 and 23.

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Genus: *Eulepidina* Douville, 1908
Species: *Eulepidina dilatata* (Michelotti, 1841)
References: Habibi, 2017: pl. 2, fig. 2; pl. 4, fig. 4
Parente & Less, 2019: fig. 15J-O
Description: Embryo is subcircular with a thick wall. The test is long, thin, and discoidal, measuring ~1 cm in diameter and 1-2 mm in thickness.
Species: *Eulepidina* sp.
Description:Test is discoidal and biconvex; megalospheric form has a small, well-developed protoconch.
Remarks:Illustrated specimens are from samples 13 and 14.
Subfamily: *Helicolepidinae* Tan, 1936
Genus: *Nephrolepidina* Douville, 1911
Species: *Nephrolepidina marginata* (Michelotti, 1841)
References:Matsumaru, 1992: fig. 2, figs. 1-4
Description:Megalospheric test is small to moderate, biconvex with large conical pustules.
Species: *Nephrolepidina praemarginata* (Douville, 1924)
References: Poignant, 1967: pp. 197-211, pl. 5
Sirel, 2003: p. 302, pl. 4
Description:Small, biconvex test with central thickening; equatorial chambers rhombic in outline.
Species: *Nephrolepidina* sp.
Description:Megalospheric test is biconvex with a reniform deuteroconch.
Remarks: Observed in samples 13 and 14.
Stratigraphic Distribution: Occurs from the Rupelian to Early Chattian in the studied sections.
Genus: *Miogypsinoides* Yabe & Hanzawa, 1928.
Species: *Miogypsinoides formosensis* (Yabe & Hanzawa, 1928)
References:Amirshahkarami, 2008: pl. 2, figs. 1–9
Description: Irregular test with planispiral whorls. Recognized in horizontal thin sections by the arrangement and number of spiral chambers.
Species: *Miogypsinoides* sp.
Description:Megalospheric test with an irregular, planispiral configuration.
Remarks:Identified in sample 14.
Superfamily: *Textulariacea* Ehrenberg, 1838

Family: *Textulariidae* Ehrenberg, 1838
Subfamily: *Textulariinae* Ehrenberg, 1838
Genus: *Textularia* Defrance, 1824
Species: *Textularia* sp.

Description: This taxon is characterized by an agglutinated test with biserial chamber arrangement. The size of the chambers increases gradually toward the apertural end.

Superfamily: *Ataxophragmiacea* Schwager, 1877

Family: *Valvulinidae* Berthelin, 1880
Subfamily: *Valvulininae* Berthelin, 1880

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Genus: *Valvulina* d'Orbigny, 1826
Species: *Valvulina* sp.

Description: The test is agglutinated and approximately spherical. It is distinguished by its high spire and relatively large size.

Palaeoecological Constraints

The Azkand Formation records a complex depositional history ranging from high-energy slope settings to low-energy protected lagoonal and supratidal environments. Unit I reflects a transgressive system in which fine-grained packstone replaced coarser facies, indicating environmental deepening. The increased frequency of small foraminifera in the lower part of this unit supports this interpretation, while the return of large *Lepidocyclina* and coral debris in the upper part suggests renewed shallowing.

In Unit II, the dominance of coarse-grained bioclastic floatstone with *Lepidocyclina*, *Heterostegina*, and *Spiroclypeus* indicates deposition in a shallow photic zone. The presence of large burrows and photic-zone organisms suggests lateral transport and reworking in a high-energy setting.

Unit III contains a more diverse assemblage, with a clear deepening trend supported by increasing *Amphistegina* and *Miogypsina* frequencies. The peak occurrence of *Lepidocyclina (Nephrolepidina)* in its lower part indicates deposition in a shallow sublittoral open marine setting.

Finally, Unit IV marks the terminal phase of shallowing, with evidence of boundstone development, encrusting foraminifera, crustose coralline algae, and possible hardground surfaces. These points to brief interruptions in sedimentation or condensation episodes near the top of the Azkand Formation sequence.

Conclusions

The Azkand Formation in Khabaz Well-3 and the Qara Chaugh Dagh section is characterized by a high abundance and diversity of larger benthic foraminifera.

The taxonomic assemblages suggest a Late Oligocene to Early Miocene age for the formation.

Four distinct microfacies were recognized across the two studied sections:

Fine bioclastic packstone dominated by small foraminifera;

Fine to very coarse bioclastic packstone with larger foraminifera;

Very fine to coarse larger foraminiferal packstone transitioning to grainstone;

Fine to very coarse bioclastic packstone to boundstone with coral and encrusting forms.

The environmental interpretation suggests deposition in an isolated slope or carbonate platform system, ranging from deeper slope toe facies to shallow sublittoral environments.

Persistent marine conditions, moderate energy regimes, and occasional bioclastic reworking shaped the observed vertical and lateral facies variations throughout the Azkand Formation.

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Authors' contributions

Conceptualization: I.G.; Methodology: I.G. and R.R.; Software: A.J.; Validation: I.G.; Formal analysis: I.G and A.J; Investigation: I.G. and A.J.; Visualization: R.R.; Writing—original draft preparation: I.G.; Writing—review and editing: A.J.; Supervision: I.G.; Fund.; Project administration: I.G. and A.J; Resources: R.R.; Data curation: R.R.

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All authors read and approved the final manuscript.

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Data availability
No datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate
Non applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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