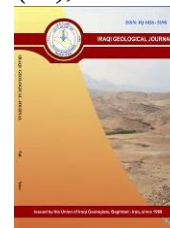




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## Sedimentary Facies and Stable Isotope Evidence of the Middle Miocene Fatha Formation of the Zagros Foreland Basin, Kurdistan Region, NE-Iraq: Insights into the Icehouse-Warmer Transition

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### Abstract

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Integrated sedimentary facies, stable carbon, and oxygen isotope analyses were conducted on the Fatha Formation in the Kurdistan Region, Northeastern Iraq, in order to investigate the depositional environments and paleoclimate during an icehouse-to- greenhouse transition. The analysis of stable  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopes was applied for the first time to reconstruct the paleoclimate. The formation mainly consists of alternations between claystone, marl and carbonate rocks with some gypsum lens intercalations. Thirteen microfacies were identified within the carbonate lithofacies, which are stacked into three facies associations: representing peritidal (FA1), characterized by supratidal sabkha to intertidal settings under saline conditions; lagoonal (FA2), representing sedimentation in restricted, low- to moderate-energy saline lagoons; and open lagoonal environments (FA3) which comprise marl lithofacies and show variations from lagoon to open marine based on fauna content. Claystone was influenced by climate-controlled oxidation and siliciclastic input, shaped by tectonics during the Zagros orogeny. Nodules and laminated gypsum within the claystone indicate a sabkha environment. Additionally, the occurrence of sandstone near the top of the formation suggests a continental, fluvial setting. The  $\delta^{13}\text{C}$  data are positive, and the  $\delta^{18}\text{O}$  data are negative, indicating that the paleoclimate during deposition was warm. Variability in  $\delta^{13}\text{C}$  values reflects fluctuating organic carbon inputs, and marine ecosystems had more nutrients available, which possibly led to the growth of marine organisms. The oxygen isotope signatures reflect episodic increases in evaporation rates, causing  $\delta^{18}\text{O}$  depletion, and are aligned with the global Middle Miocene Climatic Optimum warming trends. The deposition occurred across various environments, ranging from shallow marine to continental, and was influenced by sea-level fluctuations and a warmer climate during the Middle Miocene Climate Optimum.

**Keywords:** Fatha Formation; Middle Miocene; Stable isotope; Foreland basin; Miocene climate optimum; Northern Iraq

### 1. Introduction

The Fatha Formation (Lower Fars) is a significant depositional unit in the Middle East, and serves as a caprock for several oil reservoirs in Iraq (Bellen et al., 1959; Tucker, 1999; Sharland et al., 2004; Jassim and Buday, 2006). It was deposited within a wide, shallow foreland basin along the Zagros–Taurides collision zone, encompassing a range of environments from open marine to supratidal and continental settings (Al-Juboury and McCann, 2008). The formation is composed of 10–40 cycles, each cycle represents a progression from low-energy calcareous mudstones to higher-energy carbonates or

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lagoonal carbonates, topped by evaporites and sometimes capped with red siliciclastic deposits (Abdullah et al., 2021). The depositional environments of the Fatha Formation include marl, limestone, and evaporite units, which were interpreted to have been deposited in a range of shallow marine settings, including subtidal, intertidal, and supratidal environments (Shawkat and Tucker, 1978; Shawkat, 1979; Tucker, 1999). Abdullah (2016) established the age of the Fatha Formation through strontium stable isotope dating of carbonate and evaporite samples, finding that the formation was deposited during the late Burdigalian to early Langhian period, approximately 15.45 - 18 million years ago.

The greatest greenhouse phase occurred between 59 and 50 million years ago during the Middle Paleocene to Early Eocene (Zachos et al., 2001; Zhao et al., 2001). A rapid cooling phase during the Early Oligocene led to formation of polar ice caps. These climate changes are inferred from stable oxygen isotope ( $\delta^{18}\text{O}$ ) data from benthic foraminifera worldwide, where lower  $\delta^{18}\text{O}$  values indicate warmer climates and higher values reflect cooler conditions (Zachos et al., 2001; Zhao et al., 2001). After the Early Oligocene,  $\delta^{18}\text{O}$  values decreased during the Middle Miocene Climatic Optimum (MMCO) (from 17 to 14 Ma), a period of warmer conditions with two brief cooling events between 17.2 and 16.8 Ma and 16.2 and 15.8 Ma (Zhao et al., 2001). During the Miocene, the Zagros foreland basin was part of the eastern Neo-Tethys, constituting a seaway that connected the Indian Ocean to the Proto-Mediterranean Sea (Rögl, 1999; Harzhauser et al., 2007). The expansion of the E-Antarctic ice sheet led to significant climate changes, shifting from the warmest condition of the MMCO to colder conditions. This relatively long-term climate transition was marked by a series of shorter-term climate variations, including high-amplitude sea-level fluctuations (Flower and Kennett, 1994; De Boer et al., 2010). The Fatha Formation (Middle Miocene) was deposited in the foreland basin; this formation is composed of mixed carbonate, siliciclastic, and evaporite bodies.

The climate during the Middle Miocene was predominantly arid and warm, as evidenced by the thick evaporite layers of the Fatha Formation, which were possibly deposited during the Miocene Climatic Optimum from 17 to 14 Ma. These evaporite deposits are restricted to the basin centers, with surrounding carbonate and mudstone sequences reflecting the broader depositional environment and paleogeography (Jassim and Goff, 2006; Zachos et al., 2001; Zhao et al., 2001). However, no previous work has examined  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotope records for the carbonate lithofacies of the Fatha Formation. The aim of this research is to conduct a comprehensive sedimentary facies analysis by integrating field investigations and thin-section studies with high-resolution  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotope records for carbonate cycles. This approach aims to enhance understanding of the transition from icehouse conditions to warmer climates during the Middle Miocene Climatic Optimum and to elucidate the mechanisms behind short-term paleoclimate fluctuations and associated paleoenvironments.

## 2. Materials and Methods

The study area, situated on the northeastern margin of the Arabian Plate, is in northern Iraq (Kurdistan Region). Field data were collected from two outcrop sections, documenting lithology, grain size, macrofossil types, sedimentary structures, and contacts. Thin sections were prepared from limestone and marly limestone samples from the Fatha Formation. A total of 70 thin sections were prepared at the workshop GeoErbil, Erbil, Kurdistan Region, Iraq. The thin sections were stained with Alizarin Red solution to distinguish calcite from dolomite minerals, following the procedures outlined by Friedman (1959). Each thin section was examined under a microscope to identify the petrographic components. The classification of the carbonate rocks follows Dunham (1962) and Embry and Klovan (1971). Fifteen samples were processed to extract microfossils using extraction technique. Initially, the samples were treated with a mixture of hydrogen peroxide and water to decompose disaggregated materials. Following this, they were boiled with sodium carbonate for about six hours, rinsed with

distilled water, desiccated, and passed through a series of sieves with mesh sizes of 20, 40, 80, 120, and 200.

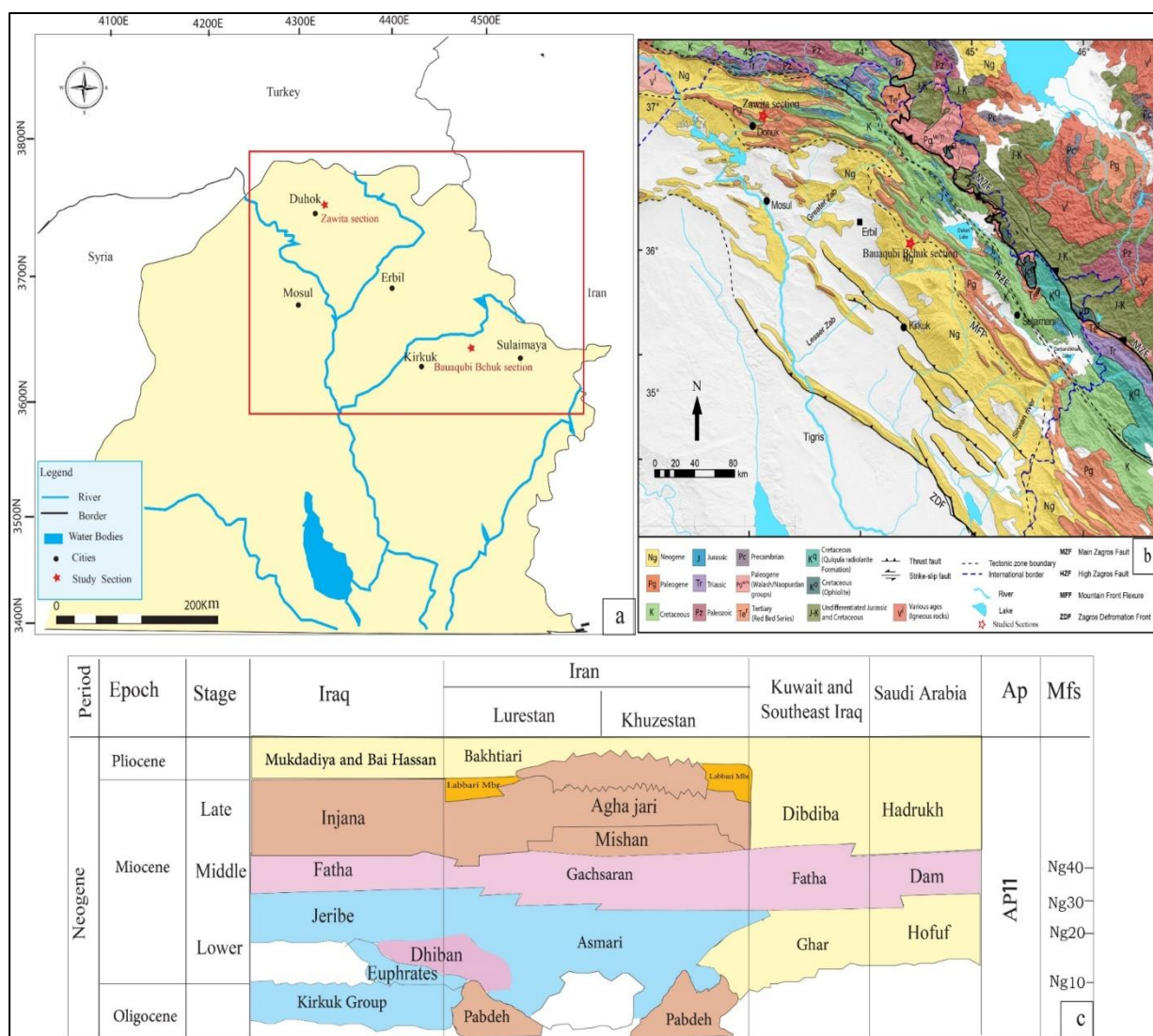
A total of 17 samples were collected from surface exposures in both sections. These samples were prepared for stable carbon and oxygen isotope investigations by breaking them into small fragments and creating approximately 50 mg of powder for laboratory analysis. The powdered samples were reacted with 100%  $\text{H}_3\text{PO}_4$  at 25 °C for 24 hours to release  $\text{CO}_2$ , and then processed at the Cornell Isotope Laboratory. Two sections of the Fatha Formation were studied: the Bauaqubi Bchuk section, from which a total of 53 samples were collected. This section has a thickness of 230 m and is situated in the Low Folded Zone. It consists of cyclic sedimentary rocks, gray marl, carbonate, evaporite (gypsum), sandy limestone, and clastic units. It rests conformably above the Injana Formation and below the Jeribe Formation. The second section, Zawita, from which a total of 24 samples were collected, is located in the High Folded Zone. It is 79 m thick and consists of cycles of bluish-grey marl, marly limestone, limestone, sandy limestone, and clastic units; notably, it lacks gypsum beds and has conformable contacts with the Injana Formation but is unconformable with the Euphrates Formation.

### 3. Geologic and Stratigraphic Setting

The Fatha Formation was deposited within the Zagros Foreland Basin, which is oriented northwest–southeast and extends from Syria to Iraq and Iran. The formation includes thick evaporitic horizons in northern Iraq, whereas in the central and northern parts, the Fatha Formation is dominated by sandstones, mudstones, and red claystone (Le Garzic et al., 2019). The depositional basin of the formation extends for roughly 1,800 km in length and reaches a width of 250–300 km (Bahroudi and Koyi, 2004; Beydoun et al., 1992). The Kurdistan Region is located in northern Iraq, on the northeastern margin of the Arabian Plate. Tectonically, the formation is more extensively exposed in the Low Folded Zone than in the High Folded Zone (Sissakian and Mohammed, 2007).

In the northwestern Zagros belt, the thickness of the Fatha Formation increases from 300 m at the basin margin to about 600 m in the depocenter (Dunnington, 1958; Koshnaw et al., 2020). Lithofacies range from mixed siliciclastic–carbonate and evaporite cycles, typically, each cycle includes, marl, carbonates, evaporites, and siliciclastic deposits in upward succession (Tucker, 1999). The nature of the lower contact of the Fatha Formation changes significantly from one locality to another. In some localities, the Fatha Formation rests conformably on the Jeribe Formation (Sissakian et al., 2016). It also unconformably overlies the Euphrates Formation when the Jeribe Formation is missing. In northern Iraq, within the High Folded Zone, the lower part of the Fatha Formation consists of the Basal Fars Conglomerate, which occurs above the Pila Spi (Middle Eocene)–Euphrates (Lower Miocene) formations, forming an unconformity (Bellen et al., 1959). The upper boundary with the Injana Formation (Upper Miocene) is gradational, marked by a transition into clastic-dominated successions (Al-Juboury, 1994; Jassim and Goff, 2006).

The Bauaqubi Bchuk section (36°08'06"N, 44°26'30"E), situated within the Bina Bawa anticline structure, is characterized by its tectonic position within the Low Folded Zone. In contrast, the Zawita section (36°55'25"N, 43°09'02"E), located at the Bekhair anticline structure, tectonic position within the High Folded Zone (Fig. 1a, b). In Iran, the Gachsaran Formation is equivalent to the Fatha Formation, while in Saudi Arabia and Qatar it is equivalent to the Dam Formation. The Agha Jari Formation is equivalent to the Injana Formation (Upper Fars) (James and Wynd, 1965; Sharland et al., 2004; Jassim and Goff, 2006) (Fig. 1c).



**Fig. 1.** a) Location map of the studied area; b) A geological map illustrating the major rock units in the NW Zagros belt, including the Fatha Formation within the Neogene Zagros foreland basin after Koshnaw et al. (2020); c) The regional correlation of the Neogene formations in Iraq, Iran, Kuwait, and Saudi Arabia (James and Wynd, 1965)

## 4. Results

### Facies analysis

Based on field observations of outcrops, the current research identified four lithofacies: carbonate, marl, claystone, and sandstone.

#### 4.1. Carbonate Lithofacies

Carbonate lithofacies comprise approximately 25% of the total thickness in the Bauaqubi Bchuk section and 19% in the Zawita section. They consist of limestones and dolomitic limestones, with thicknesses ranging between 0.2 to 6 m. These facies exhibit a gradual decrease in bed thickness upwards, resting on marl and marly limestone layers and capped by red claystone interspersed with local gypsum. Three carbonate facies associations (FA1, FA2, FA3) were identified through detailed litho-microfacies analyses, as summarized in Table 1.

**Table 1.** The identified microfacies and related deposition environment

| Microfacies                                                        | Main components                                                                                                            | Environment                                                 |
|--------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|
| Thrombolite Bindstone (FA1, a)                                     | Clotted calcite with evaporite pseudomorphs, micritic dolomitic groundmass                                                 | Supratidal(sabkha)                                          |
| Dolomitized lime Mudstone (FA1, b)                                 | Characterized by fine-crystalline dolomite                                                                                 | Supratidal(sabkha)                                          |
| Bioclastic Sandy Wackestone (FA1, c)                               | Ostracods, echinoids, and bivalves, associated with siliciclastic grains such as fine quartz and opaque minerals           | High-energy, nearshore intertidal environments              |
| Barnacles-Oyster Sandy Wackestone (FA1, d)                         | Ostracods, echinoids, and benthic foraminifera along with quartz grains and opaque minerals                                | high-energy intertidal environment                          |
| Peloidal Grainstone (FA1, e)                                       | Spherical and cylindrical shapes, Peloidal                                                                                 | Shallow, intertidal, high-energy environments               |
| Miliolid Wackestone (FA2, a)                                       | Contains miliolids and ostracods, with gypsum pseudomorphs                                                                 | Restricted lagoon, hypersaline, low-energy, arid conditions |
| Miliolids Mollusca Wackestone-Packstone (FA2, b)                   | <i>Quinqueloculina</i> , <i>Triloculina</i> , with scattered bivalve shells.                                               | Restricted lagoon                                           |
| Miliolids-Rotaliids Packstone- Grainstone (FA2, c)                 | <i>Ammonia</i> , <i>Elphidium crispum</i> , <i>Nonion</i> sp, <i>Quinqueloculina</i> sp and <i>Triloculina</i>             | shallow restricted lagoon.                                  |
| <i>Peneroplis</i> -Mollusca Packstone Grainstone. (FA3, d)         | <i>Dendritina rangi</i> , <i>Peneroplis</i> , ostracods, bivalves and Peloid                                               | Restricted lagoon                                           |
| Bivalve Peloidal Wackestone-Packstone (FA2, e)                     | Content bivalves and peloids with gypsum pseudomorphs                                                                      | Restricted, hypersaline lagoon environments                 |
| Fecal pellets -Peloid Grainstone (FA2, f)                          | dark, rounded to elongate shapes peloid, and lath-shaped and lozenge forms, pseudomorphs of evaporite minerals             | Lagoon, semi-arid, low-energy conditions                    |
| Echinoids-Bryozoan Wackestone- Packstone (FA3, a)                  | bryozoans, echinoids, echinoid spines, and <i>Triloculina</i> , <i>Elphidium</i> , <i>Ammonia</i> , and <i>Textularina</i> | Open lagoon                                                 |
| Bioclastic Sandy Mollusca -Miliolid- Wackestone-Packstone (FA3, b) | Abundance of bioclasts, mollusk fragments, miliolids. echinoid spines, peloids                                             | Open lagoon                                                 |

#### 4.1.1. Peritidal facies association (FA1)

- Thrombolite Bindstone (FA1, a).

This microfacies was observed in the lower part of the formation in both sections. These beds have a thickness measuring between 0.3 to 0.5 m, lack sedimentary structures, and contain no recorded fossils. Microscopic studies have revealed dolomitic thrombolite bindstone consisting of clotted fabrics of dolomitized limestone with pseudomorphs of gypsum (Fig. 2a).

Interpretation: Gypsum-rich thrombolites occur in evaporitic, hyposaline, and restricted lagoonal lithofacies, as recorded in Los Roques, Venezuela (Petrash et al., 2012). Evaporite pseudomorphs typically develop in arid to semi-arid, shallow-marine settings such as sabkhas (Zamannejad et al.,

2013). It has been proposed that these facies represent a supratidal sabkha environment by Wilson (1975) and Flügel (2010), particularly within facies zone FZ 9A, which correlates with SMF 25N.

- Dolomitized lime Mudstone (FA1, b).

This microfacies is commonly found in the lower part of the Fatha Formation in the Bauaqubi Bchuk section. It is characterized by the absence of sedimentary and biogenic structures and has a thickness of about 20 cm. Microscopic studies show that the dolomudstone is dominated by fine-crystalline dolomite (penecontemporaneous) crystals (Fig. 2b).

Interpretation: The Dolomitized Lime Mudstone, the association of fine-grained sediments or gypsum in recent supratidal settings is well recognized, particularly along the Trucial Coast of the Arabian Gulf (Yechieli and Wood, 2002; Alsharhan and Kendall, 2003; Bontognali et al., 2010; Flügel, 2010; Sadooni et al., 2010). These facies, characterized by the absence of biota or by rare miliolids, occur mostly in supratidal environments during short periods of sea-level fall (Tucker and Wright, 1990). The fine-crystalline dolomite, together with gypsum or its pseudomorphs and desiccation structures, suggests deposition within an evaporitic carbonate tidal flat in a sabkha environment under arid conditions (Saeed, 2017). This microfacies corresponds to depositional settings associated with the SMF 25 and FZ 9 microfacies zones, as described by Wilson (1975) and Flügel (2010), and has been interpreted as a supratidal sabkha environment.

- Bioclastic Sandy Wackestone (FA1, c).

This microfacies is generally found in the upper part of the Fatha Formation at both studied sections. The rock thickness ranges between 0.1 to 0.2 m and exhibits laminated to cross-bedded structures composed of mixed carbonate and siliciclastic lithologies (Fig. 3c). Microscopic studies display a mixture of carbonate grains, primarily calcite shell fragments from ostracods, echinoids, and bivalves, conjunction with siliciclastic grains including fine quartz size between 0.1 to 0.2 mm and opaque minerals (Fig. 3d).

Interpretation: This facies type was deposited in a high-energy, near-coastal intertidal to inner-shelf environment (Flügel, 2010). The occurrence of mixed carbonate and siliciclastic lithologies in the shelf setting commonly reflects lateral facies transitions driven by fluctuations in sea level and variations in sediment supply. The presence of physical lamination indicates dynamic conditions influenced by tides or waves. Overall, these facies represent shallow-marine shelf deposits formed under variable sedimentary and energy conditions typical of nearshore coastal intertidal environments. These facies correspond to zone FZ 8 of Wilson (1975) and SMF 19 of Flügel (2010), suggesting restricted lagoonal setting.

- Barnacles - Oyster -Sandy Wackestone (FA1, d).

The barnacle–oyster– sandy wackestone is observed in the lower part of the Zawita section, with a thickness ranging between 0.1 to 0.2 m. Field observations of the carbonate rock demonstrate indistinct laminations (Fig. 2e). Microscopic analysis found that the wackestone contains a diverse biogenic assemblage, including barnacles, oysters, ostracods, echinoids, and benthic foraminifera along with quartz grains size between 0.2–0.3 mm and opaque minerals (Fig. 2f).

Interpretation: According to Flügel (2010), barnacles are highly resistant to abrasion and are commonly associated with intertidal zones and nearshore settings. Coletti et al. (2024) found that barnacle diversity is greatest in shallow and nearshore waters and decrease moving offshore. Additionally, the occurrence of barnacles with oysters suggests deposition in intertidal to sublittoral waters (Schmitt, 1957). The laminated sedimentary structure, dominated by quartz, chert, and feldspar with scattered shell fragments, implies a high-energy intertidal environment subject to sea-level fluctuations.

- Peloidal Grainstone (FA1, e).

This microfacies is observed in the lower and upper parts of the Bauaqubi Bchuk section. The thickness of the bed varies between 0.2 to 0.3 m. Fractures and lamination are common sedimentary structures, and no fossils were recorded. Microscopic studies show that the spherical and cylindrical shapes of peloidal grains. However, interstitial spaces are infilled by calcite spar, and some of the pore spaces between the peloids are locally infilled by gypsum cement (Fig. 2g).

Interpretation: The peloidal grainstone is characterized by micritized grains that show evidence of microbial activity, along with aggregates of fine carbonate mud. Notably, the paucity of micrite matrix between the peloids suggests that the original fine-grained material has been significantly washed out, indicating a high-energy depositional setting. The peloids are predominantly homogeneous and well-rounded, implying active reworking by energetic processes. Their micritization indicates microbial involvement in cementation, which is common in shallow-marine environments. Thus, this depositional setting is consistent with depositional settings associated with the SMF 16 and FZ 8 microfacies zones, as described by Wilson (1975) and Flügel (2010), which indicate intertidal environments.

#### 4.1.2. Lagoon facies association (FA2)

- Miliolid Wackestone (FA2, a)

This microfacies is observed in the lower part of the Fatha Formation in both sections. The thickness of the bed varies between 0.2 and 0.4 m. Microscopic studies reveal an ostracod wackestone that contains a few miliolid foraminifera, quartz grains, and calcite pseudomorphs after gypsum (Fig. 2h).

Interpretation: Miliolid foraminifera are very common in inner-shelf lagoonal environment (Flügel, 2010; Dill et al., 2012). Additionally, the presence of quartz and gypsum pseudomorphs indicates hot, arid conditions. The gypsum has undergone diagenetic and sedimentary modification (pseudomorphism), including dissolution and replacement of gypsum minerals by calcite. These facies have been interpreted as a restricted lagoon environment. They are consistent with facies zone FZ 8 of Wilson (1975), involving restricted lagoonal settings.

- Miliolids Mollusca Wackestone- Packstone (FA2, b)

This microfacies was observed in the lower part of the formation in both sections. The thickness of the bed varies between 0.2 to 0.3 m and show no sedimentary structures (Fig. 2i). Microscopic studies show the co-occurrence of larger benthic foraminifera, including *Quinqueloculina* sp., and *Triloculina* sp., with some scattered bivalve shells. The miliolids are selectively subjected to micritization. Intergranular spaces are infilled by sparite, and secondary gypsum, which appears as a light pink color, is also present (Fig. 2j).

Interpretation: benthic foraminifera (Miliolid) are common in these facies and mostly suggest an inner-shelf lagoonal environment (Flügel, 2010; Dill et al., 2012). This depositional setting is consistent with depositional settings associated with the SMF 18 and FZ 8 microfacies zones, as described by Wilson (1975) and Flügel (2010), and is interpreted as deposition in a lagoon.

- Miliolids- Rotaliids Packstone- Grainstone (FA2, c)

This microfacies has been found in the lower part of the formation at both sections. The thickness of the bed varies between 0.1 to 0.3 m and lack sedimentary structures (Fig. 2k). Microscopic studies display a grain-supported fabric mainly composed of miliolid foraminifera, such as *Ammonia beccarii*, *Elphidium crispum*, *Nonion* sp., *Quinqueloculina* sp., and *Triloculina* sp. Microspar cement includes a few peloidal grains, probably formed through micritization of miliolids and rotaliids foraminifera. The brownish to tan coloration of the grains indicates the presence of micritized or partially recrystallized carbonate. The matrix consists of fine- to medium-crystalline carbonate cement, light brown in color. Several dark-colored, elongated voids likely represent organic residue or dark mineral inclusions; these dark patches may indicate minor diagenetic alteration or minor organic content (Fig. 2m).

Interpretation: Large populations of miliolids such as *Quinqueloculina* sp., and *Triloculina* sp., with rotaliids (*Ammonia*) characterize normal-marine to lagoonal environments with salinities ranging from 32 to 65‰ (Reinhardt et al., 1994). *Ammonia* is a common genus found in shallow, and brackish-lagoonal environments (Martin, 1950; Murray, 1991). The presence of benthic foraminifera, including miliolids and rotaliids, suggests deposition in a hypersaline lagoon (Debenay et al., 2001). Grainstone texture indicates the winnowing of fine-grained sediment by tidal currents within shallow, and restricted to semi-restricted environments. This depositional setting corresponds to depositional settings associated with the SMF18 and FZ 8 microfacies zones, as described by Wilson (1975) and Flügel (2010), and indicates a shallow restricted lagoon.

- *Peneroplis* -Mollusca Packstone Grainstone. (FA3, d)

This microfacies has been found in both the lower and upper parts of the Fatha Formation at both sections. The thickness of the bed varies between 0.1 to 0.3 m and show no sedimentary structures (Fig. 3n). Microscopic study shows the co-occurrence of larger benthic foraminifera such as *Dendritina rangi*, *Peneroplis farsensis*, ostracods, and bivalves. Peloids are rounded to sub rounded and occur in scattered distribution, appearing as microcrystalline grains that may have originated from foraminifera and mollusca without internal structures (Fig. 3o).

Interpretation: *Peneroplis* foraminifera are present in very shallow-marine or lagoonal settings. Modern peneropliids inhabit shallow, quiet-water environments (Hottinger, 1997). *Peneroplis*, *Quinqueloculina* sp., *Triloculina* sp., *Elphidium* sp., and *Ammonia* sp. are commonly found in lagoonal environments of the Arabian Gulf (Murray, 1991; Amao et al., 2016). According to Geel (2000), the existence of miliolina foraminifera implies restricted lagoonal and hypersaline environments. This depositional setting is consistent to depositional settings associated with the SMF18 and FZ 8 microfacies zones, as described by Wilson (1975) and Flügel (2010), and is interpreted as deposition in a restricted lagoon.

- Bivalve Peloidal Wackestone- Packstone (FA2, e)

This microfacies is observed in the lower and upper parts of the Fatha Formation at the Bauaqubi Bchuk section and in the lower part of the Zawita section. These beds have a thickness of 0.2 m. Microscopic studies found that this microfacies is dominated by bivalves and peloids. The bivalve shells exhibit clear evidence of micritization, followed by subsequent infilling by blocky cement. Additionally, a significant proportion of small, lath-shaped, dark-brown evaporite pseudomorphs (0.1 to 0.2 mm in size) is observed (Fig. 3p).

Interpretation: Bivalves are found in a variety of aquatic environments, while peloids are typically deposited in shallow, warm environments, particularly in tropical to subtropical settings (Flügel, 2010). The presence of peloids suggests active biological activity, and their association with packstone textures reflects moderate to low-energy conditions. Furthermore, the occurrence of lath-shaped gypsum crystals within these facies generally indicates deposition in restricted, hypersaline lagoon environments. This depositional setting is consistent with SMF 16 and FZ 8 microfacies zones, as defined by Wilson (1975) and Flügel (2010), and is characteristic of restricted, hypersaline lagoon environments.

- Fecal pellets -Peloidal Grainstone (FA2, f)

This microfacies is found in the lower part of the formation at the Bauaqubi Bchuk section. The thickness of the bed varies between 0.1 to 0.2 m with no observable sedimentary or biogenic structures (Fig. 2q). Microscopic observations indicate that fecal pellets are characterized by dark, rounded to elongate shapes, and consist of medium- to well-sorted, rounded grains. Sub-rounded evaporite pseudomorphs, displaying characteristic lath-shaped and lozenge forms, range from 0.1 to 0.2 mm in size. The spaces between fecal pellets and peloids are filled with calcite cement. Rare *Quinqueloculina* are also observed (Fig. 2q).

Interpretation: Pellets are the dominant form in subtidal and lower intertidal coastal settings within low-energy zones characterized by reduced sedimentation rates (Flügel, 2010). Gypsum pseudomorphs indicate formation during a semi-arid climate at low palaeolatitudes (Li and Powell, 2001). A considerable proportion of small, lath-shaped calcite pseudomorphs of evaporite has been observed. This depositional setting is consistent with depositional settings associated with the SMF16N and FZ 8 microfacies zones, as described by Wilson (1975) and Flügel (2010) is interpreted as a restricted lagoon setting.

#### 4.1.3. Open lagoon facies association (FA3)

- Echinoids- Bryozoan Wackestone Packstone (FA3, a)

This microfacies is found in the upper part of the Fatha Formation at the Bauaqubi Bchuk section. These beds have a thickness ranging from 0.2 m to 0.3 m and show no observable sedimentary or biogenic structures (Fig. 2r). Petrographic study show that it is characterized by high-diversity fossils, including fragmented mollusks, bryozoans, echinoids, echinoid spines, and abundant porcelaneous forms such as *Triloculina*, as well as hyaline forms of *Elphidium*, *Ammonia*, and *Textularina*. It has a mud-supported groundmass with occasional spar-filled voids, and many *Triloculina* are affected by micritization (Fig. 2s).

Interpretation: Echinoderms are commonly found in both shallow and deep-marine environments and can thrive in both warm- and cold-water conditions (Flügel, 2010; Scholle and Ulmer-Scholle, 2003). This microfacies shows a diverse assemblage of species and dominant open-marine biota such as echinoids, bryozoans, and echinoid spines. The presence of benthic foraminifera, including miliolids and rotaliids, indicates deposition in a lagoonal environment within a micritic to microsparitic groundmass, and is defined as an open lagoon with connection to open-marine conditions. Thus, this microfacies was deposited in a low- to moderate-energy environment at normal marine salinity within an open lagoon. It is comparable to SMF18 and FZ7 of Wilson (1975) and Flügel (2010), indicating an open-lagoon settings.

- Bioclastic Sandy Mollusca -Miliolid- Wackestone to Packstone (FA3, b)

This microfacies is found in the lower and upper parts of the Fatha Formation at the Bauaqubi Bchuk section. These beds thickness ranging from 0.1 to 0.2 m, lack sedimentary and biogenic structures (Fig. 2t). Petrographic analysis shows a notable abundance of bioclasts, mainly mollusca fragments, along with peloids and small foraminifera, including miliolids, within a micritic matrix and echinoid spines is also observed. Some grains are subjected to micritization and display relicts of the original miliolids (Fig. 2u).

Interpretation: The presence of diverse biota, including peloids and bioclasts within a micritic matrix, indicates low to moderate-energy conditions and suggests a shallow subtidal lagoonal environment (Wilson, 1975; Flügel, 2010). Echinoid spines indicate normal marine salinity for the depositional setting (Strasser et al., 1995). This microfacies corresponds to FZ7 and SMF10 of Wilson (1975) and Flügel (2010). Therefore, the evidence suggests that this microfacies was deposited in an open lagoon.

#### 4.2. Marl Lithofacies

These lithofacies are present in both studied sections; they were deposited at the base of the carbonate cycle and are considered part of the limestone units. The thickness ranges between 0.4 to 35 m. They usually represent the initial stage of shallowing-upward cycles, and this unit constitutes about 19% of the total formation thickness in the Bauaqubi Bchuk section and about 47% in the Zawita section (Fig. 6). The benthic foraminifera include miliolina (*Borelis melo*, *Quinqueloculina* sp., *Triloculina* trigonula, *Pyrgo*, *Peneroplis* sp.) and rotaliina (*Nonion*, *Ammonia beccarii*, *Ammonia tepida*,



**Fig. 2.** a) Photomicrographs display thrombolite bindstone; b) Photomicrographs display Dolomitized lime Mudstone with penecontemporaneous dolomite absence of fossils; c) A field photograph depicting a stratigraphic sequence consisting of a lower marl layer, followed by cross-bedded sandy limestone, and topped by an upper red clay layer; d) photomicrographs showing a mixture of carbonate grains, quartz, and opaque minerals; e) Field photograph showing the rock is light brown, with sedimentary structures and lamination; f) photomicrographs showing the barnacles -oyster- sandy with wackestone; g) photomicrographs showing micritization, peloidal- grain with very fine quartz within matrix; h) photomicrographs display, the Miliolid Wackestone; i) field photograph depicting, medium bedded light gray in color, lack of sedimentary structures; j) Photomicrographs displaying the co-occurrences *Quinqueloculina*, *Triloculina*, and bivalve are affected by micritization; k) field photograph showing light brown, thin-bedded fossiliferous limestone; m) photomicrographs showing, the mainly miliolid foraminifera other peloidal may be affected by micritization; n) Field photograph depicting show, medium thick, light gray, fossiliferous limestone; o) Photomicrographs include a larger benthic such as foraminifera *Dendritina rangi*, *Peneroplis* with a few peloids; p) Photomicrograph show bivalve, peloidal. The space between them is filled with micrite, small, lath-shaped, which has been observed; q) Photomicrograph shows fecal pellets are dark, rounded to elongate, well-sorted, lath-shaped gypsum. Rare *Quinqueloculina* are observed; r) Field photograph shows the cycle began with a lower marl layer, followed by limestone, and topped by marl and fossiliferous limestone; s) photomicrographs showing, fragmented mollusks bryozoan, echinoid, *Ammonia* and *Textularina* with occasional very thin quartz; t) Field photograph show, light gray, fossiliferous limestone lacks any sedimentary structures and biogenic; u) Photomicrographs showing. This microfacies includes *Triloculina* *Elphidium*, *Ammonia*, and is present in mud-supported groundmass.

*Elphidium crispum*), with rare planktonic foraminifera (*Globorotalia*) and textulariids (*Textularina*) present only in the lower unit; associated other fauna include gastropods, bivalves, echinoids, bryozoans, and ostracods.

Interpretation: The gray-green marl, abundant in benthic foraminifera, signifies lagoon environment with low energy. The fossil assemblage also includes gastropods, bivalves, echinoids, bryozoans, and ostracods, suggesting deposition in open-lagoon waters. Rare planktonic foraminifera together with *Textularina*, present only in the lower part of the formation, are associated with dominant benthic foraminifera and indicate deposition in open-marine conditions. This lithofacies, based on its faunal content, was deposited in environments ranging from lagoon to open-marine settings, same marl may locally lack identifiable fossils, suggesting deposition under supratidal conditions.



**Plate 1.** (a) *Borelis melo*; (b) *Ammonia beccarii*; (c) *Ammonia tepida*; (d) *Elphidium crispum*; (e) *Ammonia*; (f) *Elphidium*; (g) *Quinqueloculina*; (h) *Triloculina trigonula*; (i) *Pyrgo*; (j) *Peneroplis*; (k) *Cibicides*; (l) *Nonion*; (m) *Globorotalia*; (n) *Globorotalia*; (o) *Globigerina*; (p) *Textularina*; (q) *Ostracoda*; (r) *Gastropod*; (s) *Massive bryozoan* (t) *branching bryozoan*

#### 4.3. Reddish-brown Claystone Lithofacies

Medium- to thick-bedded claystone forms a common and significant lithologic component of the formation, with individual bed thicknesses ranging between 0.1 to 25 m. This lithofacies locally includes thin siltstone interbeds, which are frequently recorded toward the upper part of the formation. The proportion of claystone relative to carbonate rocks displays a clear westward decrease, constituting about 52% of the total formation thickness in the Bauaqubi Bchuk section and approximately 35% in the Zawita section (Fig. 6). The claystone occurs in repeated cycles with carbonate units, and its thickness generally increases upward through the stratigraphic succession. In many intervals, the claystone also includes isolated nodular gypsum bodies (Fig. 3a and c).

Interpretation: The repeated shallowing-upward cycles of the Fatha Formation, comprising basal marine marl, overlying lagoonal carbonates rich in benthic foraminifera, and capping red claystone and

evaporites, are best understood within the tectonically active Zagros foreland basin. Al-Juboury and McCann (2008) interpreted these marl, carbonate and evaporite cycles as the product of short-term relative sea-level fluctuations superimposed on long-term flexural subsidence related to thrust loading, with tectonics controlling accommodation, basin geometry, and restriction, and eustatic changes governing cyclicity. A similar tectono-stratigraphic framework was proposed in Geology of Iraq, where the Fatha Formation was placed in a foredeep to wedge-top setting, and progressive shallowing, sub-basin isolation, and late regressive evaporite and red-bed accumulation was linked to forebulge migration and episodic uplift. In contrast, Abdullah et al. (2021) emphasized oxidizing conditions under semi-arid climates and increased fine siliciclastic influx during regression as the immediate controls on red claystone formation, while Koshnaw et al. (2024) highlighted Middle Miocene uplift and deformation along the Zagros fold-thrust belt as drivers of enhanced hinterland erosion, increased sediment supply, and accelerated basin shallowing. Taken together, these views indicate that red claystone in the Fatha Formation is polygenetic, reflecting the combined influence of climate-controlled oxidation and siliciclastic input, but fundamentally organized and amplified by foreland-basin tectonics during continued Zagros convergence. The presence of nodules and laminated gypsum suggests evaporitic conditions typical of arid climates. This is interpreted to represent a sabkha depositional environment, characterized by periodic flooding followed by exposure. During flooding, the sabkha becomes submerged, promoting the precipitation of laminated gypsum within desiccation cracks as evaporite mineralization.

#### 4.4. Sandstone Lithofacies

Sandstone lithofacies were observed in the upper part of the Fatha Formation within the studied sections. The sandstone beds are characterized by thin to medium-bedded thickness between 0.3–0.5m and display ripple marks, lamination, and cross-bedded sedimentary structures (Fig. 3b and c). They constitute about 1% of the total formation thickness in two sections (Fig. 6). Microscopic studies show, notable clasts, including fine-grained chert, rock fragments mainly composed of carbonate material, and heavy minerals such as opaque minerals, including magnetite and hematite (Fig. 3f).



**Fig. 3.** a) Field photograph showing thin-bedded gypsum within red clay; b) Field photograph showing thin bedded laminated gypsum within red clay; c) Field photograph showing nodules of gypsum; d) Field photograph showing ripple mark sandstone; e) Laminated sandstone embedded within red clay; f) Photomicrographs sandstone, content quartz, chert, rock fragments, carbonate grain opaque minerals (magnetite, hematite) XPL view

**Interpretation:** Sandstone exhibits lamination and ripple lamination, indicating transport and deposition by currents and waves. The occurrence of sandstone within red clay, which was deposited under fluvial environment during flooding condition, indicating that these sandstones originated from

the adjacent hinterlands (Aqrabi, 1993), based on detrital zircon U-Pb ages. Provenance studies suggest Paleozoic rocks in the north and Paleogene rocks in the northeast (Koshnaw et al., 2019).

## 5. Stable Isotopes

The stable isotope analyses of carbonate samples from the Fatha Formation, as presented in Tables 2 and 3, indicate that the  $\delta^{18}\text{O}$  values are predominantly negative. In contrast, the  $\delta^{13}\text{C}$  values exhibit a range that includes both negative and positive deviations in the two studied sections. In the Bauaqubi Bchuk section, the majority of carbonate samples have positive values; only two samples 42 and 46 show negative values. The positive  $\delta^{13}\text{C}$  values may reflect the widespread deposition of organic-rich marine sediments (Dromart et al., 2003; Balaky et al., 2020). The negative  $\delta^{13}\text{C}$  value of sample 42 occurs because minerals were dissolved by fluids; this process can increase porosity, which was later filled with gypsum minerals. In evaporitic environments, particularly gypsum-forming settings  $\delta^{13}\text{C}$  values are relatively low (negative indicating organic or microbial influence (Jehlička et al., 2024). Similarly, the negative value in sample 46 is attributed to its highly porous content. When water interacts with carbonate rocks, minerals such as calcite and dolomite dissolve, releasing inorganic carbon into the water. This process results in a decrease in the mineral content of the rocks and a corresponding increase in dissolved carbon in the marine system, reflecting the original carbonate minerals involved. Variations in carbonate sources and carbon-cycling processes within the depositional environment are indicated by  $\delta^{13}\text{C}$  values range between -0.04 to +3.94%. Conversely, samples such as 43, with higher  $\delta^{13}\text{C}$  values +3.94%, represent more carbonate-rich settings, potentially influenced by marine or biogenic carbon sources.

Oxygen isotopes ( $\delta^{18}\text{O}$ ) in the Bauaqubi Bchuk section show negative values. The results of  $\delta^{13}\text{C}$  values show in Table 2 and Fig. 4 indicate that the majority of carbonate samples of the Fatha Formation range between -7.53 to -1.42‰, with all samples displaying negative values. A number of variables, including water temperature, salinity, and mineral origin, affect variations in oxygen isotopic composition (Balaky, 2012). Since  $\delta^{18}\text{O}$  concentrations tend to rise in cooler climates and fall in warmer ones, the observed decline in  $\delta^{18}\text{O}$  values during the Miocene reflects climatic warming. Furthermore, lighter isotopes are preferentially removed by evaporation in the Fatha Formation, enriching the remaining seawater with heavier isotopes and thereby raising salinity and  $\delta^{18}\text{O}$  values (Hudson, 1977; Veizer, 1983). Temperature and salinity are parameters that govern carbon-oxygen isotopic behavior in seawater; thus, climatic and environmental changes are reflected in oxygen isotopic behavior, while carbon isotopic behavior is associated with environmental conditions during cement precipitation.

Stable carbon isotope in the Zawita section show only negative values. The results of  $\delta^{13}\text{C}$  values in Table 3 and Fig. 5 indicate that the majority of carbonate samples of the Fatha Formation have positive values, except for samples 12 and 18, which also contain voids between grains caused by solution processes during diagenesis, this diagenetic process affected  $\delta^{13}\text{C}$  values. When water interacts with carbonate rocks, it dissolves inorganic carbon into solution. The carbon in the solution reflects the composition of the original carbonate minerals, leading to a decrease in  $\delta^{13}\text{C}$ . This suggests a low rate of organic matter accumulation during the formation of the carbonate beds of the Fatha Formation. Conversely, sample 13 shows an elevated  $\delta^{13}\text{C}$  value +1.38‰, reflecting more carbonate-rich condition potentially influenced by marine or biogenic carbon sources (Dromart et al., 2003) and suggesting that brief flooding occurred during the development of this unit.

The  $\delta^{18}\text{O}$  isotopic values range between -3.26 to -5.49‰, indicating variations in oxygen isotopic composition. All samples display negative values, which can be influenced by factors such as water temperature, salinity, and mineral composition. The  $\delta^{18}\text{O}$  values, especially the more negative ones (e.g., sample 12), indicate evaporative conditions that lead to isotopic enrichment or depletion depending on

temperature and water chemistry. The observed decline in  $\delta^{18}\text{O}$  to negative values during the Middle Miocene indicates a period of climatic warming

For the Middle Miocene limestone samples of the Fatha Formation in the two studied sections, the best discrimination of marine limestones as shown in Table 2, is provided by the following equation (Keith and Weber, 1964):

$$Z = 2.048(\delta^{13}\text{C} + 50) + 0.498(\delta^{18}\text{O} + 50)$$

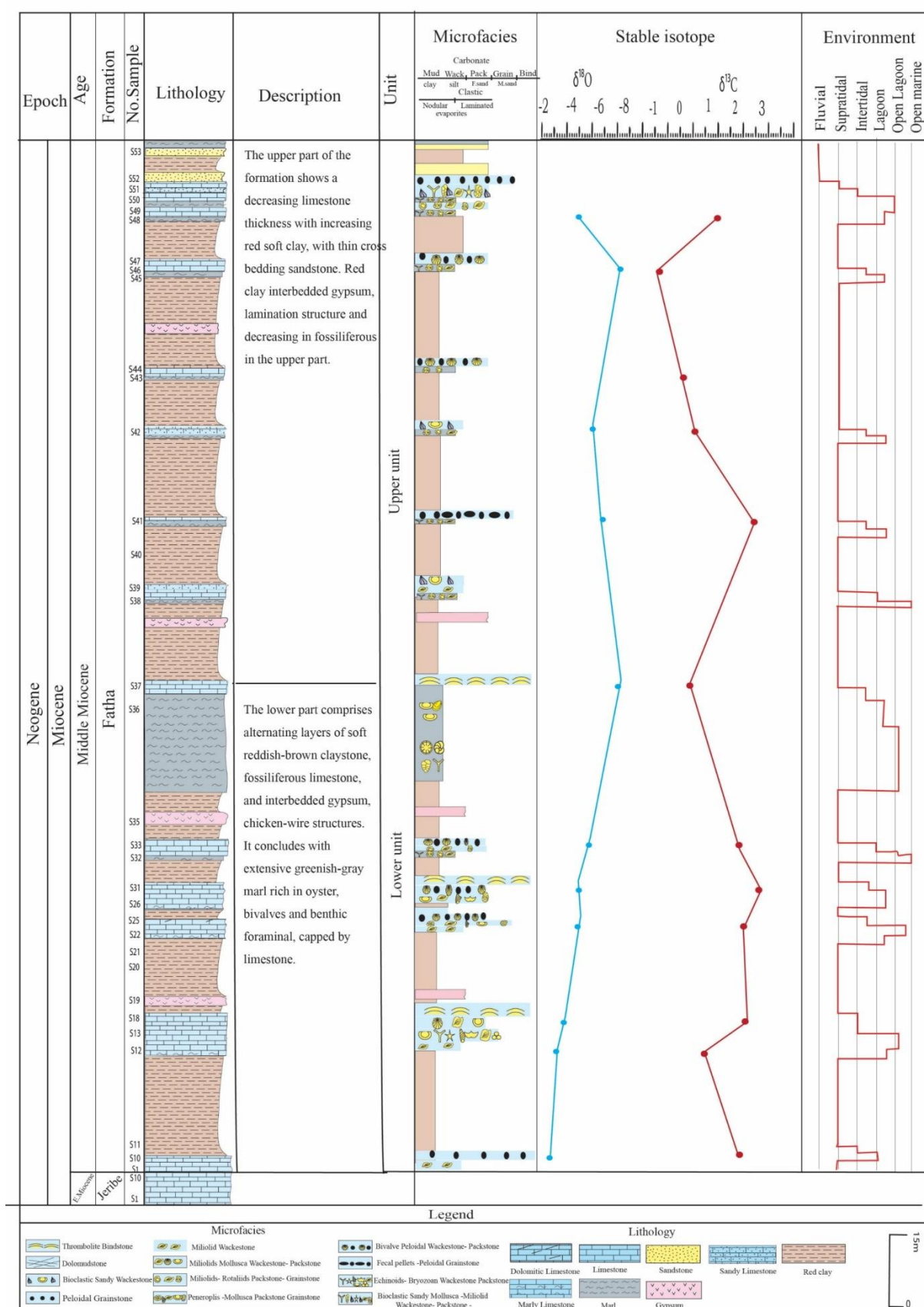
When both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  are expressed in ‰ PDB, carbonate samples exhibiting a Z-value greater than 120 are indicative of marine origins, whereas samples with a Z-value below 120 are distinguishing of freshwater environments.

**Table 2.** Carbon and Oxygen isotope compositions for the constituent facies and the calculated Z parameter of the Carbonates of the Fatha Formation, Bauaqubi Bchuk section (VPDB = Vienna Pee Dee Belemnite)

| Section                | Sample. No | Microfacies         | $\delta^{18}\text{O}$ VPDB | $\delta^{13}\text{C}$ VPDB | Z      | Type of Limestone |
|------------------------|------------|---------------------|----------------------------|----------------------------|--------|-------------------|
| Bauaqubi Bchuk section | S8         | Mudstone-Wackesto   | -2.73                      | 2.75                       | 131.65 | Marine            |
|                        | S12        | Mudstone            | -2.98                      | 0.83                       | 127.58 | Marine            |
|                        | S16        | Packstone-Grainston | -3.22                      | 2.40                       | 130.77 | Marine            |
|                        | S24        | Packstone           | -4.40                      | 2.42                       | 130.18 | Marine            |
|                        | S28        | Packstone           | -4.35                      | 3.08                       | 131.48 | Marine            |
|                        | S33        | Packstone-Grainston | -5.06                      | 2.23                       | 129.39 | Marine            |
|                        | S37        | Bindstone           | -6.96                      | 0.14                       | 124    | Marine            |
|                        | S41        | Grainstone          | -5.93                      | 2.08                       | 128.60 | Marine            |
|                        | S42        | Mudstone-Wackesto   | -5.61                      | -0.04                      | 124.45 | Marine            |
|                        | S43        | Packstone-Grainston | -1.42                      | 3.94                       | 134.65 | Marine            |
|                        | S46        | Wackestone-Packsto  | -7.53                      | -1.01                      | 121.65 | Marine            |
|                        | S48        | Packstone           | -3.61                      | 1.77                       | 129.24 | Marine            |

**Table 3.** Carbon and Oxygen isotope compositions for the constituent facies and the calculated Z parameter of the Carbonates of the Fatha Formation, Zawita section. (VPDB = Vienna Pee Dee Belemnite)

| Section | Sample. No | Microfacies           | $\delta^{18}\text{O}$ VPDB | $\delta^{13}\text{C}$ VPDB | Z      | Type of Limestone |
|---------|------------|-----------------------|----------------------------|----------------------------|--------|-------------------|
| Zawita  | S2         | Wackestone- Packstone | -3.26                      | 0.51                       | 126.87 | Marine            |
|         | S7         | Wackestone- Packstone | -3.69                      | 0.82                       | 127.16 | Marine            |
|         | S12        | Packstone             | -5.49                      | -0.86                      | 122.95 | Marine            |
|         | S13        | Packstone-Grainstone  | -4.57                      | 1.38                       | 127.99 | Marine            |
|         | S18        | Wackestone            | -4.55                      | -1.14                      | 122.73 | Marine            |



**Fig. 4.** Stratigraphic column and stable isotope of the Fatha Formation, Bauaqubi Bchuk section

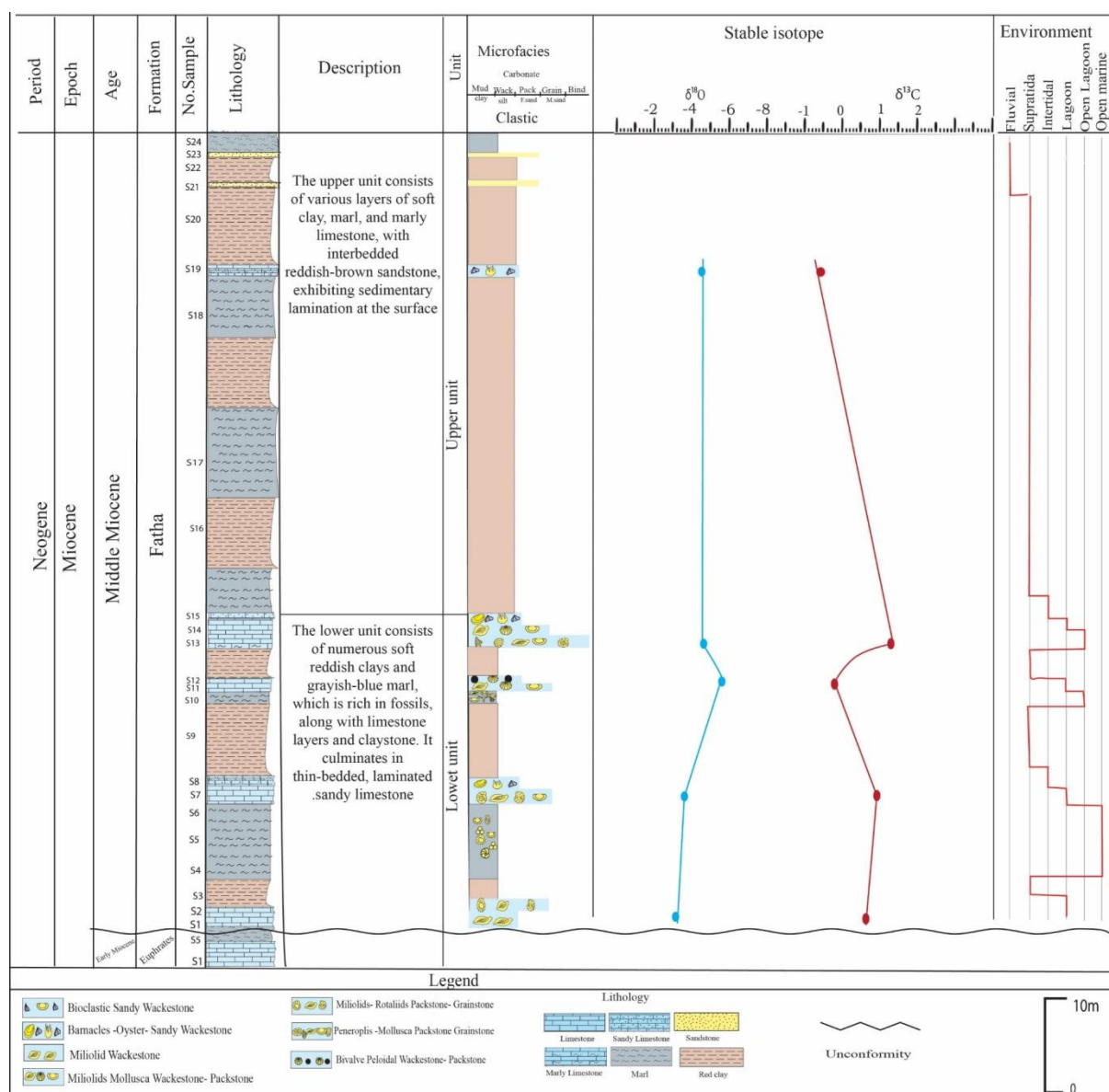


Fig. 5. Stratigraphic column and stable isotope of the Fatha Formation, Zawita section

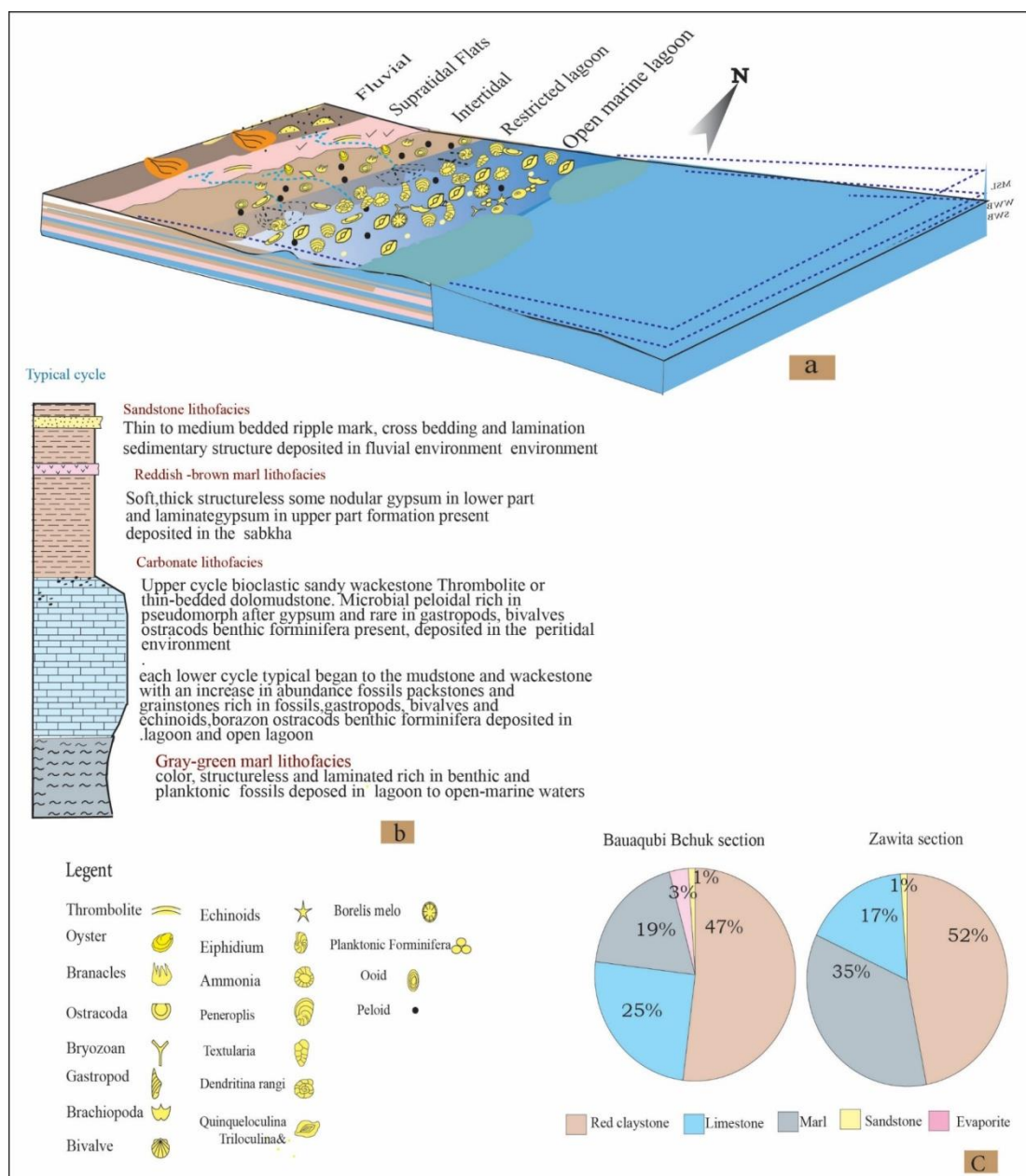
## 6. Depositional Model of Fatha Formation

The Fatha Formation, composed of mixed siliciclastic-carbonate and evaporite systems, is represented by the co-occurrence of three essentially different mechanisms of shelf development. The formation consists of numerous shallowing-upward cycles, each cycle beginning with gray-green marls, indicating deposition in hypersaline lagoons to open lagoons. However, the same gray marl bed that lacks fossils may indicate deposition in the supratidal zone. The overlying carbonate lithofacies show a progression from mudstone and wackestone to packstone and grainstone, reflecting lagoonal and open-lagoon environments. The upper section includes bioclastic sandy wackestone and features indicative of intertidal settings.

Based on these results, as well as microfacies analysis and isotopic ratios, it can be inferred that the carbonate lithofacies were deposited in a shallow-marine environment characterized by a warm, hypersaline, arid climate during the MMCO. During this period, increased nutrient availability in marine ecosystems likely facilitated the growth and preservation of marine fossils, particularly those in the suborder Foraminifera, such as *Miliolina* (*Quinqueloculina*, *Peneroplis*, *Triloculina*) and *Rotaliina*

(*Elphidium* sp., *Ammonia*), which prefer high temperatures and salinity, aligning with warmer environmental conditions as indicated by stable isotope analyses.

Carbonate lithofacies culminating in red claystone exhibit polygenetic features, resulting from climate-controlled oxidation and siliciclastic input, significantly shaped by foreland-basin tectonics amidst ongoing Zagros convergence. The presence of nodules and laminated gypsum indicates evaporitic conditions typical of arid climates, suggesting a supratidal depositional environment characterized by periodic flooding and subsequent exposure. During flooding, the sabkha remained submerged, allowing laminated gypsum to precipitate within desiccation cracks as evaporite mineralization. Sandstone lithofacies present in the upper part near the top of the contact, with ripple marks and cross-bedding, were deposited in a fluvial environment (Fig. 6a).



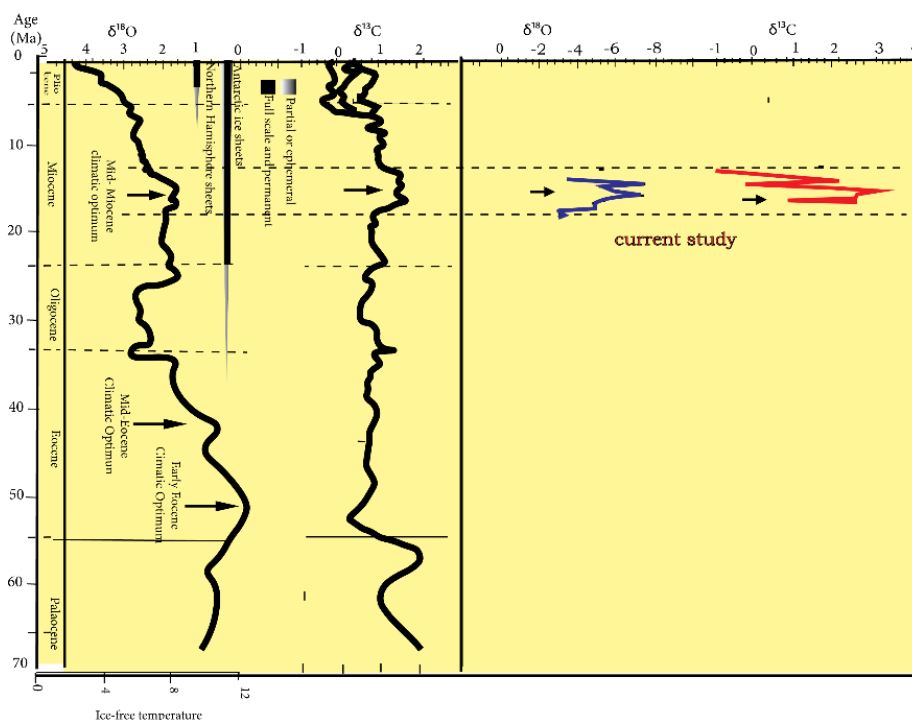
**Fig. 6.** a) Schematic depositional model of the Fatha Formation, Middle Miocene; b) A typical one-cycle features a shallowing-upward in the formation; c) Presents the dimensional pie diagrams illustrating the percentages of lithofacies for both studied sections

## 7. Discussion

The siliciclastic–carbonate successions of the Fatha Formation exhibit variations in depositional settings and comprise marl, carbonate–claystone, and evaporite cycles. A typical cycle generally begins with a basal marl deposited in lagoonal to open-marine settings. These strata are overlain by carbonate lithofacies, which are in turn capped by red beds with local gypsum bodies. Overall, the succession displays a shallowing-upward trend, although such features can also be observed within individual carbonate beds. The carbonate lithofacies comprise thirteen microfacies, representing a broad spectrum of depositional environments. The uppermost part of the sections is characterized by bioclastic sandy wackestone and features indicative of intertidal settings. The red claystone, displaying polygenetic traits influenced by climate-driven oxidation and siliciclastic input, was significantly affected by foreland-basin tectonics during ongoing Zagros convergence. The presence of nodules and laminated gypsum within the red claystone suggests evaporitic conditions typical of arid climates, interpreted as sabkha depositional environments. Additionally, sandstones near the top of the formation indicate a continental, fluvial setting. The sandstone-dominated upper succession reflects a transition to continental fluvial environments, coinciding with a Miocene climatic shift toward wetter conditions. This shift led to increased fluvial discharge and reduced hypersalinity. Prograding siliciclastics derived from the Zagros region increasingly dominated carbonate production, resulting in fewer marine intervals and the cessation of evaporite formation, indicative of foreland-basin evolution during the final stages of convergence.

The Middle Miocene Climatic Optimum was a period of globally elevated temperatures, marked by warmer conditions than both preceding and subsequent intervals. Lower to Middle Miocene units of the Fatha Formation were deposited under warm, arid climates, as evidenced by thick evaporite sequences, which may correlate with the Miocene Climatic Optimum (17–14 Ma; Zachos et al., 2001). The evaporites correspond to this warm interval, and  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopic ratios provide insights into paleoclimate by reflecting environmental parameters such as temperature, salinity, and climate variability. Carbonates precipitated from evaporated seawater show some enrichment in  $\delta^{18}\text{O}$  (McKenzie, 1981). All  $\delta^{18}\text{O}$  data from both sections are negative, indicating warmer global temperatures and a decline in global ice volume. Negative  $\delta^{18}\text{O}$  values range between -7.53 to -2.73‰ in the Zawita section and between -7.53 to -1.42‰ in the Bauaquubi Bchuk section. These isotopic ratios suggest that deposition occurred under arid to semi-arid conditions with episodic fluctuations in temperature and salinity, controlled by climate and sea-level changes during the Middle Miocene. Variations in  $\delta^{13}\text{C}$  reflect changes in biological productivity, organic matter decay, and the influx of isotopically lighter carbon, indicating fluctuating contributions of organic carbon and restricted marine conditions, both sensitive to climatic factors influencing biological activity.

The negative  $\delta^{18}\text{O}$  values, combined with both positive and negative  $\delta^{13}\text{C}$  values, support periods of increased evaporation,  $\delta^{18}\text{O}$  depletion, and warm conditions with evaporative isotopic enrichment. According to Miller (2005) and Haq et al. (1988), global sea-level elevation ranged between 25 and 175 m during the Middle Miocene. These positive sea-level stands correspond with the stable isotope results of the present study, suggesting warmer climatic conditions during this period. The abundance of fossils during the Middle Miocene indicates that carbonates and marl of the Fatha Formation were deposited under warm, high-salinity conditions, supported by positive  $\delta^{13}\text{C}$  values and negative  $\delta^{18}\text{O}$  values. The analysis of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  stable isotopes shows that negative  $\delta^{18}\text{O}$  and near-zero to slightly positive  $\delta^{13}\text{C}$  values align with global warming trends during the Miocene Climatic Optimum. The isotopic ratios observed in this study correspond closely to global warming trends (Fig. 7).



**Fig. 7.** Oxygen-Carbon isotope showing the Middle Miocene Climatic Optimum (MMCO) (Zachos et al., 2001) and illustrates the isotopic ratios,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  in the current study, which correspond to the chart of global warming trends

## 8. Conclusions

The mixed siliciclastic-carbonate system of the Middle Miocene Fatha Formation was investigated using stable isotope analyses ( $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ) in tandem with detailed petrographic and microfacies studies to reconstruct paleoenvironmental conditions and depositional dynamics. Two sections were examined: the Bauaqubi Bchuk section, located in the Low Folded Zone, comprising cycles of gray marl, carbonate, red clay, sandstone, and evaporite. At this section, the formation shows conformable contacts with both the overlying Injana Formation and the underlying Jeribe Formation. In contrast, the Zawita section, situated in the High Folded Zone, displays lithologies comparable to those of the Bauaqubi Bchuk section, but without gypsum intercalations. The upper contact with the Injana Formation is conformable, whereas the lower contact with the Euphrates Formation is unconformable.

The investigations revealed four sedimentary lithofacies: carbonate, marl, red clay, and sandstone. The marl lithofacies intervals were deposited under relatively normal marine conditions at high sea level, when the basin was connected to the open ocean and maintained a positive water balance. The carbonate lithofacies were deposited in peritidal environments, including supratidal, intertidal, and restricted settings, with occasional open-lagoon phases. Fossil abundance and diversity clearly decrease upward within the carbonate lithofacies, implying shallowing-upward cycles. The abundance of benthic foraminifera, gastropods, bivalves, echinoids, bryozoans, and ostracods indicates a biologically productive environment, consistent with positive  $\delta^{13}\text{C}$  values that reflect significant contributions from marine carbonates. Negative  $\delta^{18}\text{O}$  values suggest relatively warm conditions, consistent with deposition in a warm marine environment. Global sea level elevation during the Middle Miocene aligns with the stable isotope results, indicating warmer climatic conditions during that period. Red claystone in the formation reflects climate-controlled oxidation and siliciclastic input. Nodules and laminated gypsum lenses within the red beds indicate arid, evaporitic conditions in sabkha environments, marked by cycles

of flooding and exposure. Thin- to medium-bedded sandstones present in the upper parts of the sections indicate continental fluvial settings, marking a transition from marine to continental deposition.

#### **Author Contributions: CRediT**

Avin Hameed: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. Sardar Balaky: Writing – review & editing. Azad Saeed: Writing – review & editing.

#### **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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#### **Data Availability**

Data will be made available on request

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