Original Research Article

Paleoenvironment of the early Miocene Akyar Formation: insights from stable isotope analysis of benthic foraminifera

ABSTRACT

We present new stable isotope data and discuss paleoenvironmental conditions of benthic foraminifera in the lower Miocene deposits (Akyar Formation) from the Yazıhan (N-NW Malatya) and Muşardağı (Baskil, SW Elazığ) areas located at the eastern part of the Taurus-Anatolian platform. The Akyar Formation is composed of limestone, mudstone, calcirudite, and calcarenite interlayers including rich foraminiferal assemblages. They show Aquitanian-Burdigalian in age. The foraminiferal assemblage, bivalve identified as *Hyotissa hyotis*, and the abundance of corals indicate a tropical to subtropical warm paleoenvironment from the inner shelf to the slope. $\delta^{18}O$ values of foraminifera species have quite negative values between -7.99 and -0.27‰, and $\delta^{13}C$ values are from -1.56 to +0.41‰. According to isotopic data and fossil content, paleosalinity is at the normal salinity levels. The obtained paleotemperature data from the $\delta^{18}O$ values show that, the early Miocene the sea water temperature was extremely high. It is assumed that high temperatures were possibly related to the Yamadağ volcanism, starting from the late Cretaceous to the middle-late Miocene in the northern part of the area.

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Keywords: Benthic foraminifera, Isotopic data, Paleoenvironment, Early Miocene, Malatya basin

1. INTRODUCTION

The study area is located northeast of the Malatya Basin and covers the eastern part of the Malatya-Ovacık Fault. The Malatya Basin, covering an area of about 1000 km² on the eastern Taurus-Anatolian platform, is a part of the southern branch of the Neotethys Sea, eastern Türkiye (Fig. 1). Geological studies in the Malatya Basin were started by Birand (1938). It was followed by several studies on stratigraphy, tectonics, paleontology, clay geology, sedimentology, isotope geochemistry and petroleum geology etc. (Asutay, 1988; Avşar, 1983; Ayan & Bulut, 1961; D'Onofrio et al., 2021; Gedik 2015; Giorgioni et al., 2019; Görmüş, 1992; Koral & Önal, 2007; Önal & Kaya, 2007; Örçen, 1986; Türkmen et al., 2007; Ural, 2013; Ural et al., 2015).

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Due to the differences in the sequences outcropping in the north and south of the Malatya basin, the basin was divided into two sub-basins, namely the Hekimhan and Gündüzbey sub-basins (Ayyıldız et al., 2015; Önal & Gözübol, 1992). Our study area is located in the Hekimhan sub-basin.

Foraminiferal shell oxygen and carbon isotope analyses began to be used in paleoceanography after Emiliani (1955) used deep-sea core isotope records to interpret temperature cycles in the Pleistocene climate. Oxygen and carbon stable isotopes have been shown to be reliable for understanding the growth history and climate records of modern and fossil marine invertebrates such as corals, bivalves, gastropods, and foraminifers (Jones & Allmon, 1995; Zachos et al., 1992).

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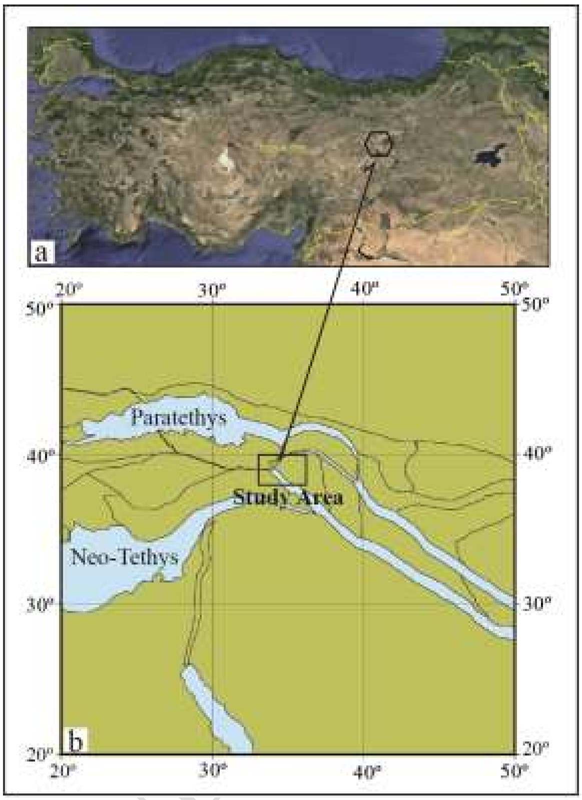

Fig. 1(a). Location map of the study area (satellite photo from Google Earth), (b) The paleogeographic location of the area under study is depicted on a paleogeographic map of the eastern Neo-Tethys at 18 Ma *http://www.odsn.de/odsn/services/paleomap/paleomap.html*

Stable isotope compositions of fossil taxa in the region had not been previously studied. Therefore, in this study, we attempted to acquire information on the deposition conditions of the early Miocene foraminiferal shells based on stable isotope analysis ($\delta^{18}O$ and $\delta^{13}C$).

2. MATERIALS AND METHODS

The materials of the present study consist of 50 systematic samples collected from the Yazıhan (Malatya) and Muşardağı (Baskil-Elazığ) measured stratigraphic sections with a total thickness of 217 meters (Fig. 2). The Muşardağı section is on the K40 c2 and c3 sheets in the northwest of the Baskil district of Elazığ province, and the Yazıhan section is on the K40 d1 sheet in the northwest of Malatya province. Muşardağı section coordinates are as follows:

The section's beginning and ending coordinates are K40 c2 E 463750, N 748750, and K40 c3 E 462500, N 767500. The Yazıhan section has the following coordinates: E14 0000, N82 7000 begin and end at E14 6500, N84 5000 (Fig. 2a). Samples collected from sections included benthic and planktonic foraminifera, a bivalvia *Hyotissa hyotis*, bryozoa, ostracoda and corallinae. Soft rock samples were washed through a 63-μm sieve using a 17% hydrogen peroxide solution for 24 hours. The remaining fraction was oven-dried and dry-sieved at 63 μm, 125 μm, and 250 μm. At the end of micropaleontological examinations, benthic and planktonic species were described. Some representatives of each investigated species were examined with a scanning electron microscope (SEM).

$\delta^{18}O$ and $\delta^{13}C$ analyses for 20 samples of benthic foraminifera and 12 samples of planktonic foraminifera from the stratigraphic sections measured in the Akyar Formation were performed in the Iso-Analytical Laboratory (UK). Before being dried for 24 hours in a drying oven to eliminate moisture, samples were first weighed into clean Exetainer TM tubes (then crushed in situ). Septum caps were affixed to the tubes containing the samples. After being in an acidic environment for one night, the samples were heated at 60°C for two hours to make sure that all of the carbonate was turned into CO_2. The tubes were subsequently purged with 99.995% helium. Continuous Flow-Isotope Ratio Mass Spectrometry (CF-IRMS) was subsequently employed to assess the CO_2 gas emitted from the samples. A magnetic field separates various gas species based on their mass. They are then measured simultaneously using a collection array called a Faraday cup to determine the isotopomers of CO_2 at m/z 44, 45, and 46. The carbon dioxide (CO_2) was isolated using gas chromatography utilizing a packed column. The chromatographic peaks were then ionized and accelerated using the Europa Scientific 20-20 Isotope Ratio Mass Spectrometer (IRMS). Coplen et al. (1983) used phosphoric acid to digest samples for isotopic analysis and injected it through the septum into the vials.

The samples' isotope temperatures were determined using the following equation (Shackleton, 1974):

$$T\ (°C) = 16.9 - 4.38\ (\delta^{18}O_c - \delta^{18}O_w) + 0.1\ (\delta^{18}O_c - \delta^{18}O_w)\ 2. \qquad (1)$$

The water where the organism lives has a stable isotope ratio of $\delta^{18}O_w$, where "T" is the temperature (°C).

Craig and Gordon (1965) discovered a salinity-water isotope relationship because $\delta^{18}O_w$ varies with salinity.

$$\delta^{18}O_w = 0.66\ S - 23.5. \qquad (2)$$

The stable isotope ratio of the water the organism lived in is represented by $\delta^{18}O_w$, while the salinity level is represented by S. After this important study, many new ways and formulas have been developed to calculate paleosalinity (S) from the $\delta^{18}O_w$ value, such as those established by Railsback and Anderson (1989). In this study, salinity values were calculated by taking into account these studies and formulas and fossils.

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After the micropaleontological studies, species of benthic and planktonic organisms were named using the Ellis and Messina Catalogue of Micropaleontology (1940–present) and different foraminifera-focused studies (e.g.; Boersma, 1977; Bolli et al., 1994; Cahuzac & Poignant, 1997; Douglas, 1973; Hayward & Buzas, 1979; Iaccarino et al., 2007; Kender et al., 2008; Loeblich & Tappan, 1988; Miller et al., 1985; Nomura, 1986; Székely et al., 2017; Van Morkhoven et al., 1986; Woodruff, 1985).

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3. GEOLOGICAL SETTING AND STRATIGRAPHY

The Malatya basin is located on the Eastern Taurus Platform and covers an area of approximately 1000 km^2. It is a part of the southern branch of the Neo-Tethys Sea and is divided into two sub-basins, the Hekimhan and Gündüzbey basins, based on their sedimentological differences. The basement rocks in the study area consist of Paleozoic-Mesozoic metamorphics of the Malatya massif, as shown in “Figures 2 and 3”. The Hekimhan Formation lies unconformably over the basement rocks and comprises red-green conglomerate, sandstone, and claystone. Following it are limestone, sandstone, and marl interbeds containing rudist and other macrofossils. Sediments and Deveci Volcanics of the Campanian-Maastrichtian age are widely exposed in the Hekimhan and its surrounding area (Görmüş, 1992; Sarı et al., 2016). The Eocene Yıldıztepe Formation rests on the Hekimhan Formation with an angular unconformity. The formation starts with basal conglomerates and continues to the top with sandstone and mudstone interlayers. It consists of thick to very thick bedded claystone with macro- and microfossils. The Suludere, Yıldıztepe, and Gedik Formations are of Eocene age. The Oligocene Dumanlar Formation lies unconformably over the Eocene units and comprises conglomerate, sandstone, and mudstone. The lower Miocene Akyar Formation consists of conglomerate, sandstone, claystone, and reefal limestone. The middle-upper Miocene Karaca Formation lies unconformably over the Akyar Formation and consists of conglomerate, sandstone, shale, and lignite beds. The Karaca Formation is unconformably overlain by the Pliocene-aged Sultansuyu Formation, which consists of conglomerates, as shown in “Figures 2a and 3”.

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3.1. Akyar Formation

In this study, we used the name Akyar as suggested by Önal (1988), because Akyar Formation is well exposed in the Akyar Valley to the northeast of Yazıhan (Fig. 2a). The Akyar Formation begins with light brown, medium-thick bedded sandstones. Towards the top, it passes into green, medium-thick bedded mudstones, marls and thick-bedded and massive limestones. The thickness of the formation is 250-500 meters in the north of the basin and 12-60 meters in the south and east, and is rich in foraminifera, *Hyotissa hyotis*, bryozoa, ostracoda and corallinae (Fig. 3 and 4). The Akyar Formation unconformably sets above the Dumanlar Formation and is overlain by the Karaca Formation with a disconformity. Yamadağ Volcanics, which are middle-upper Miocene in age and form a part of the Miocene volcanism widely distributed in Eastern Anatolia, overly the Akyar Formation (Bozkaya & Yalçın, 1991).

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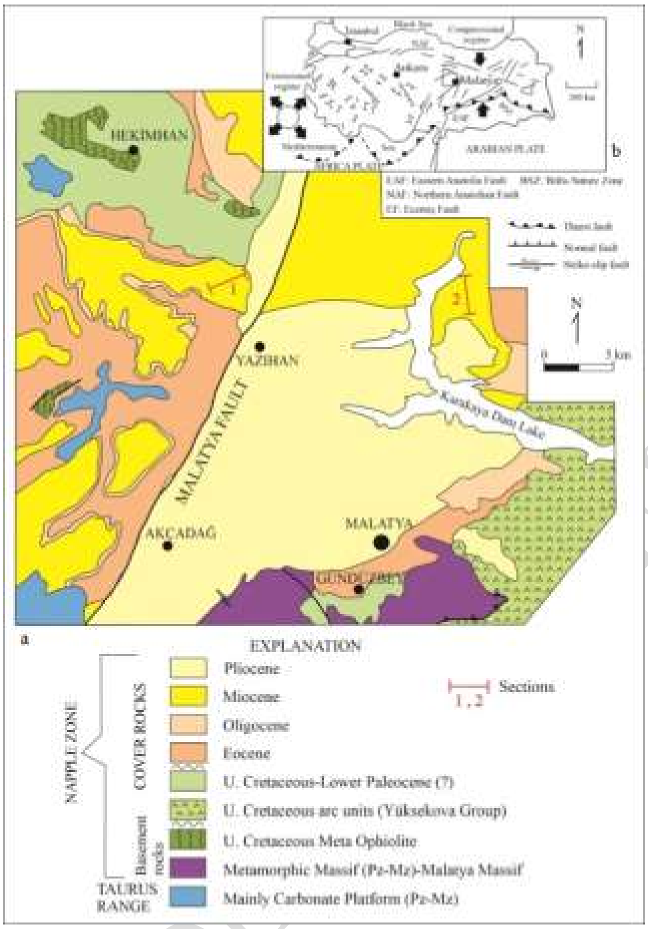

Fig. 2(a). Geological map of the study area (after Önal, 2009), (b) Tectonic settings of Türkiye (modified from Şengör & Yılmaz, 1983)

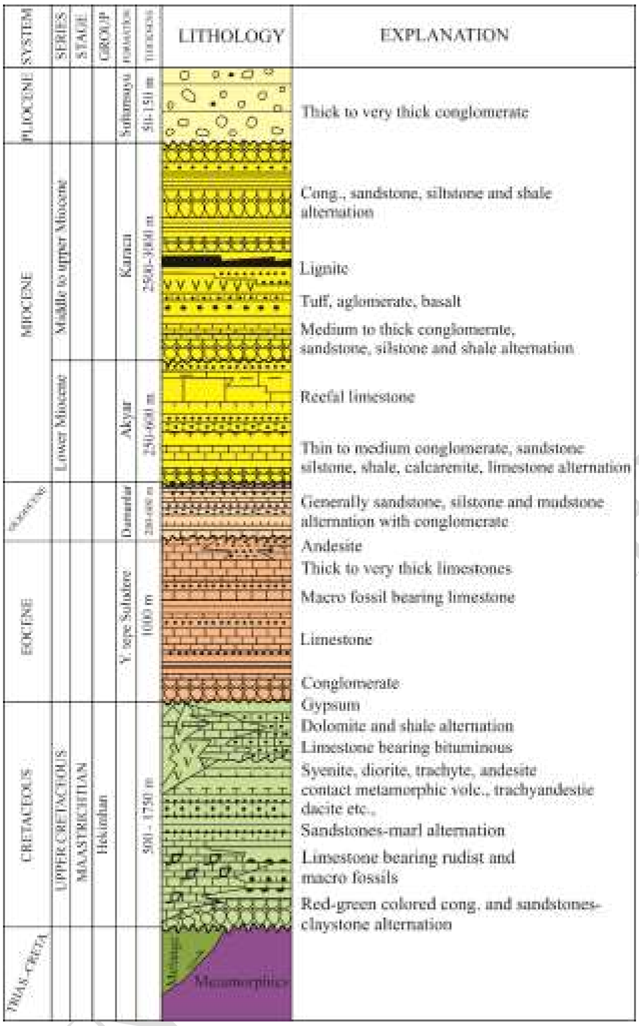

Fig. 3. Stratigraphic columnar section of the Hekimhan sub-basin of the Malatya basin (modified from Önal, 1988)

Fig. 4. *Hyotissa hyotis* view and its location, Akyar Formation near Yazıhan

The benthic foraminiferal assemblages of the Akyar Formation consist of 33 species belonging to 25 genera. These genera include *Anomalinoides*, *Astacolus, Cibicides, Cibicidoides, Dentalina, Elphidium*, *Globobulimina, Gypsina, Lagena, Lenticulina, Marginulina, Marginulinopsis*, *Miogypsina, Nodosaria, Osangularia*, *Planulina, Robulus, Saracenaria*, *Semivulvulina, Siphonina, Siphonodosaria*, *Spiroplectinella, Textularia, Uvigerina,* and *Vulvulina*. The benthic foraminiferal assemblages are categorized into SBZ 24 and SBZ 25 Zones (Figs. 5 and 6).

Planktonic foraminiferal genera belonging to the family Globigerinidae have also been identified: *Dentoglobigerina* spp.*, Globigerina* spp.*, Globoturborotalita* spp. and *Trilobatus* spp. (Determined by Deniz İBİLİOĞLU).

Foraminiferal assemblages suggest that the Akyar Formation was deposited during the early Miocene. In addition, the fossil records of *Hyotissa hyotis* in Western America date back from the early Miocene to the present (Cristín & Perriliat, 2013; Glenn, 1904).

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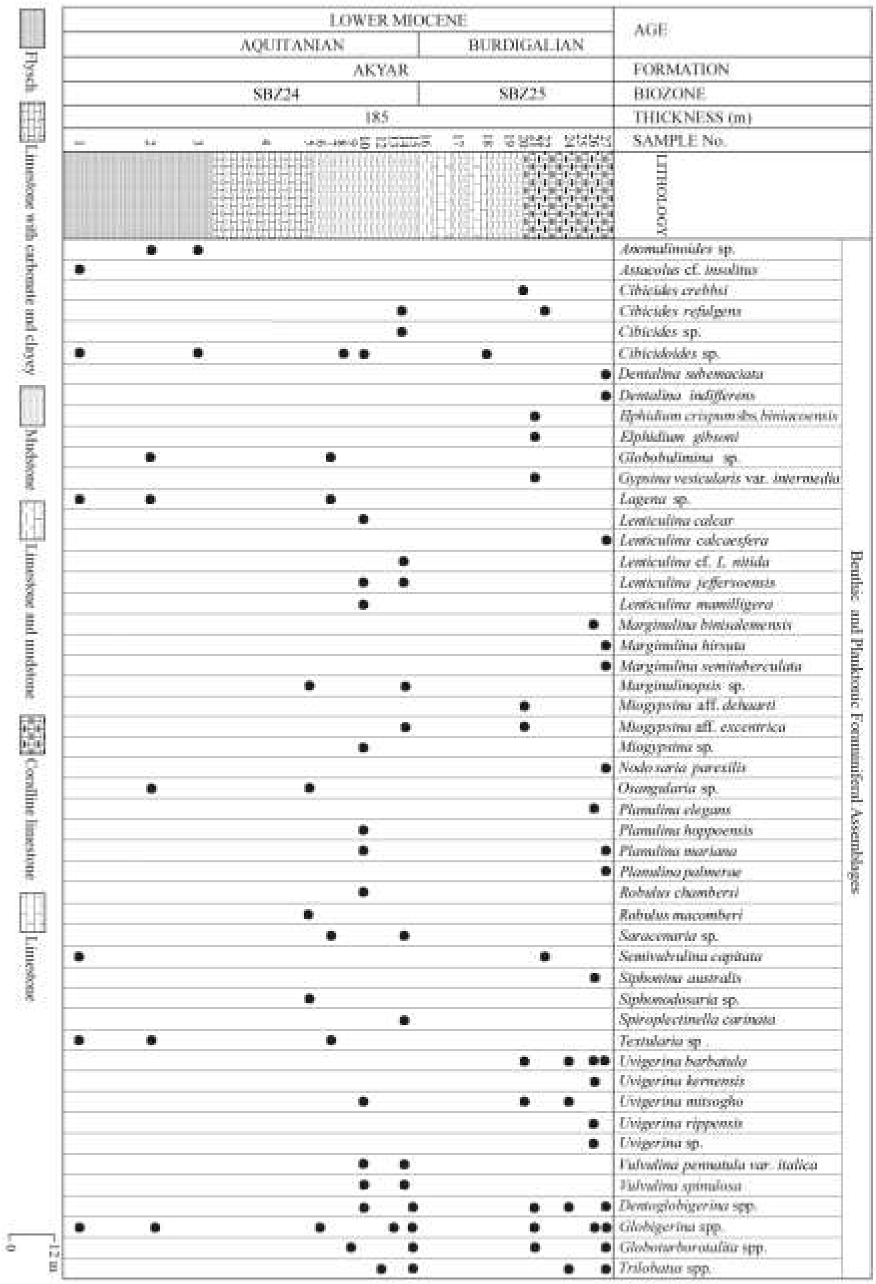

Fig. 5. Benthic and planktonic foraminiferal assemblages of the Yazıhan Section

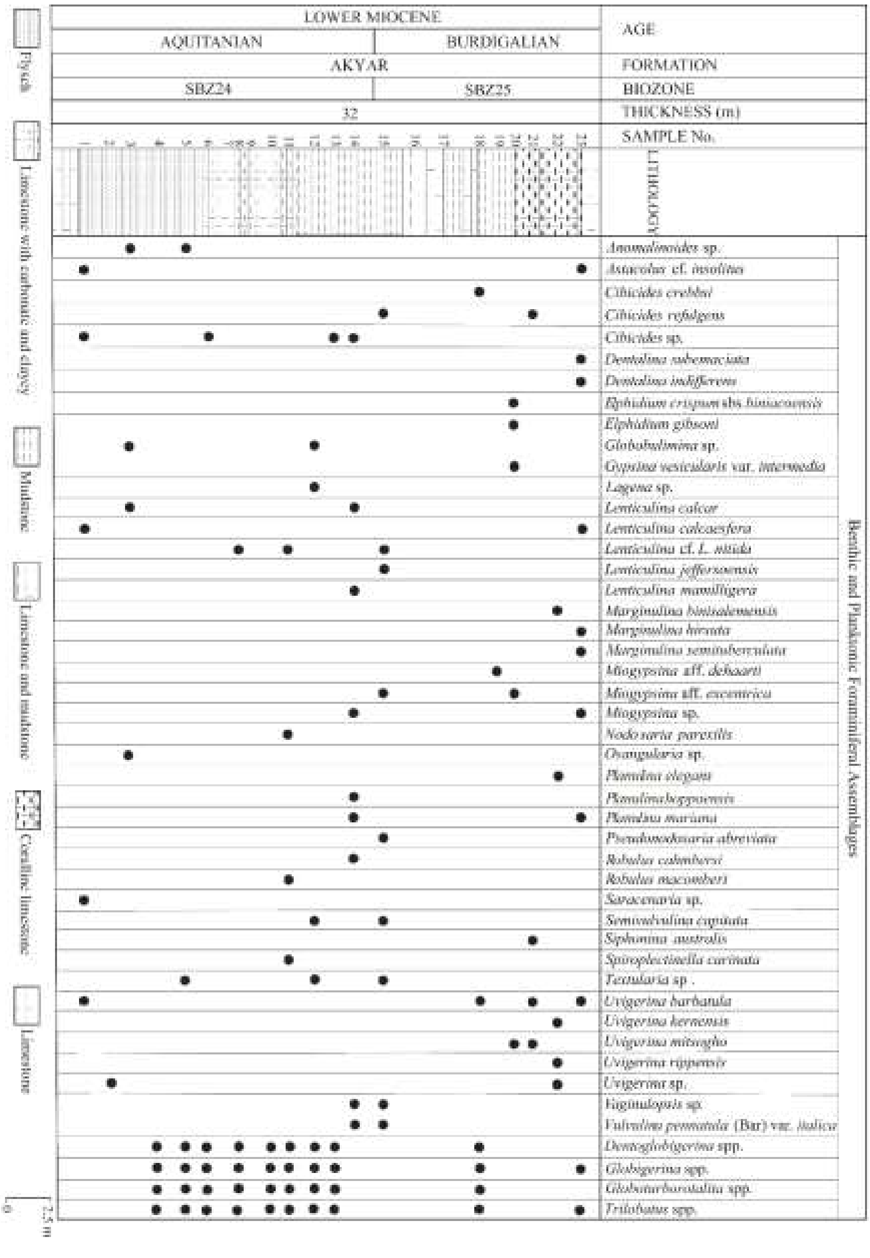

Fig. 6. Benthic and planktonic foraminiferal assemblages of the Muşardağı Section

4. RESULTS AND DİSCUSSİON

We examined the δ¹⁸O and δ¹³C isotopic records of foraminiferal shells from the Akyar Formation in the Hekimhan sub-basin of the Eastern Tethys region to ascertain the characteristics of the environment during the early Miocene. The foraminiferal assemblages found in the strata of the Akyar Formation are well-preserved, exhibit a high level of diversity, and are easily identifiable. The detailed stratigraphic temporal control of the analyzed sections, as well as the high sampling density, enabled us to reveal the paleoenvironmental conditions for the first time (Figs. 7 and 10-11).

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4.1. Foraminifera and other fossils

Paleoenvironmental interpretations rely on a direct comparison between fossil foraminifera and their ecological environments, particularly because benthic foraminifera provide excellent paleoenvironmental indicators (e.g., Nebelsick et al., 2013). Benthic foraminifera are used in many studies about past climate and ocean changes because they are easy to find, very common, and quickly show how the environment has changed.

The benthic foraminiferal assemblages in the deposits of the Akyar Formation are well preserved. Hence, foraminifera considered autochthonous provide an excellent basis for thoughts about the paleoenvironment. Water temperature and other factors control the distribution patterns of shallow-water benthic foraminifera. It is known that many taxa prefer cold, temperate, or warm bottom water. The bottom water temperature is closely related to the water depth, and if the depth exceeds approximately 100 meters, temperate bottom waters are formed even in tropical regions (Murray, 2006). *Elphidium* assemblages typically favor cold temperate to tropical inner shelf environments, whereas *Lenticulina* prefers cold bottom waters and current marine assemblages. *Lenticulina* likes to live in outer shelf-bathyal areas at a depth of 20 meters, while *Uvigerina* spp. prefers deeper habitats between 100 and over 4500 meters and usually does not live shallower than 100 meters. However, the preferred depth range of Miocene *Lenticulina* species shifted toward the inner shelf area (Rögl & Spezzaferri, 2002). Furthermore, *Lenticulina calcar* is an upper bathyal form (Van Morkhoven et al., 1986). A foraminiferal assemblage dominated by *Elphidium* and *Cibicidoides* in the Miocene strata is characteristic of shallow marine environments with low water depths close to the coast. *Elphidium* assemblages live at a depth of 0-50 m, typically in cold-temperate and tropical inner shelf environments, whereas *Miogypsina* lives in shallow waters (up to 50-80 m), while *Siphonina australis* is usually found in mid-bathyal depth (~100 m water depth) (Drooger, 1993; Miller et al., 2008).

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Globigerina and *Globoturborotalita* are surface dwellers, with the latter species also found in the Pacific and Indian Oceans, ranging from temperate to mid-latitudes. In contrast, *Trilobatus* is a deep-dwelling species that prefers depths greater than 50 meters (Spezzaferri et al., 2018).

The presence of shallow water forms (e.g., *Elphidium*) at various levels in both stratigraphic sections, along with the occurrence of *Hyotissa hyotis* and corals in the upper parts of the sections, indicates a shallow inner shelf (neritic) environment, especially given the scarcity or absence of deep-sea representatives. Additionally, the abundance of infaunal and planktonic taxa at certain levels suggests a middle-outer shelf environment, typically at depths of 50 to 100 meters.

The Akyar formation, as evidenced by the identified epifaunal and infaunal benthic foraminifers and planktonic foraminifers in the examined Yazıhan and Musardağı sections, was deposited from the inner shelf to the outer shelf (Fig. 7).

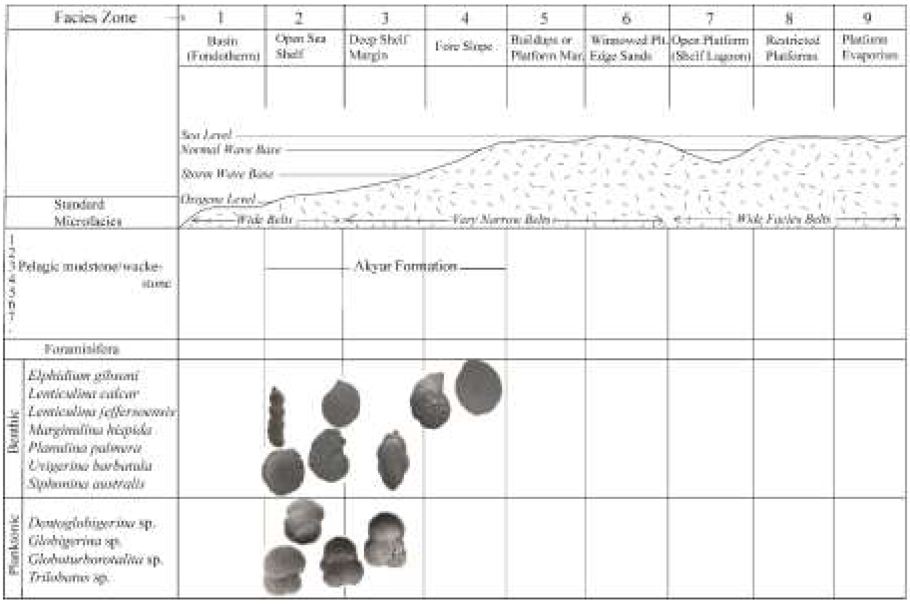

Fig. 7. Depositional environments and facies of the Akyar Formation (arranged from Flugel, 2004; in accordance with Wilson, 1975)

The *Hyotissa hyotis* species, detected in the uppermost levels of the Yazıhan and Muşardağı sections, has a maximum length of 14 cm, a width of 10 cm, and a height of 7.5 cm (Determination: İzzet HOŞGÖR). This oyster is found in tropical and subtropical waters and has spread from the Indo-Pacific to the eastern Pacific regions. Reports indicate that *Hyotissa hyotis* inhabits depths ranging from 0 to 50 meters, with a typical range of 0 to 5 meters in tropical environments. Recently, researchers discovered this species approximately 30 meters deep in Florida and on Jeju Island in Korea. These oysters thrive in water temperatures between 14.8 °C and 22.9 °C, with seawater salinity levels ranging from 24.7 to 31.2 PSU (Bieler et al., 2004). In the Yazıhan and Muşardağı sections, benthic foraminifera such as *Cibicidoides, Lenticulina,* and *Planulina* have been found in association with *Hyotissa hyotis*. Additionally, bryozoa, ostracoda, and corals were identified at these levels. The observed foraminiferal diversity indicates that salinity is within the normal range. It is widely accepted that the highest foraminiferal diversity occurs under standard sea conditions, with salinity rates ranging from 32 to 37 (Murray, 2006).

4.2. Stable isotope

The results of stable isotope compositions of samples collected from 20 benthic foraminifera and 12 planktonic foraminifera of the Yazıhan and Muşardağı sections indicate that $\delta^{18}O$ has dramatically high negative values ranging from -7.99 to -0.27, and $\delta^{13}C$ values range from -1.56 to +0.41 (Tables 1 and 2).

Table 1. Stable isotope values and seawater temperatures of foraminifera in the Yazıhan section

Foraminifera	**$^{13}C_{V\text{-}PDB}$**	**$^{18}O_{V\text{-}PDB}$**	**T(ºC)**
Cibicidoides sp.	-0.02	-4.06	31.2
Lenticulina calcaesfera	-1.31	-3.44	28.2
Cibicidoides sp.	-0.19	-5.11	36.6
Cibicidoides sp.	-1.55	-6.44	43.7
Lenticulina mamilligera	-1.21	-3.25	27.3
Miogypsina aff. *exentrica*	-1.38	-6.69	45.1
Elphidium gibsoni	-1.27	-3.67	29.3
Uvigerina barbatula	-0.53	-0.80	16.0

Table 2. Stable isotope values and seawater temperatures of foraminifera in the Muşardağı Section

Foraminifera	**$^{13}C_{V\text{-}PDB}$**	**$^{18}O_{V\text{-}PDB}$**	**T(ºC)**
Uvigerina sp.	-0.79	-3.90	30.4
Lenticulina calcar	0.22	-2.40	23.4
Textularia sp.	-1.56	-4.54	33.7
Cibicides sp.	-0.21	-4.27	32.3
Lenticulina cf. *L. nitida*	-0.10	-0.98	16.9
Cibicides crebbsi	0.17	-2.04	21.6
Vaginulopsis sp.	0.07	-0.30	13.9
Lenticulina cf. *L. nitida*	-0.58	-0.27	13.8
Pseudonodosaria abbreviata	-0.69	-6.11	41.9
Uvigerina barbatula	-0.62	-5.13	36.7
Uvigerina sp.	0.41	-2.70	24.6
Astacolus cf. *insolitus*	-1.32	-7.99	52.4

In these sections, δ^{18}O and δ^{13}C values exhibit a slight positive correlation (R^2 = 0.1088 and 0.4035) but are not strong enough to be considered significant ($p > 0.05$) (Figs. 8 and 9). Although this relationship implies a potential link between the two isotopic measurements, analyzing additional samples could further enhance our understanding of the early Miocene environment in the studied areas.

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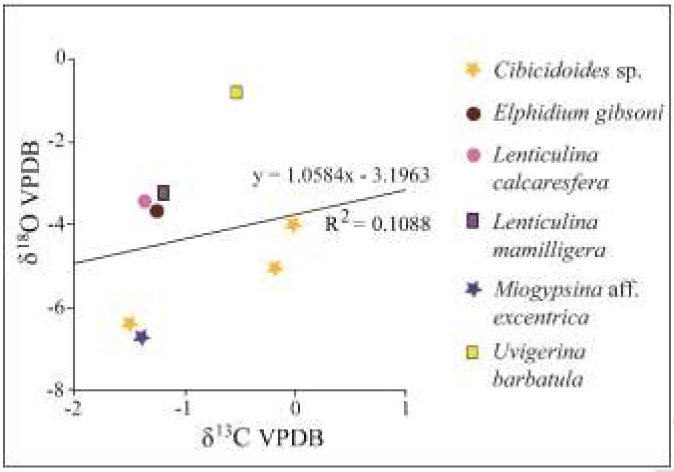

Fig. 8. Cross plots and histograms of the covariance between δ ^{18}O and δ ^{13}C measured for foraminifera in the Yazıhan Section

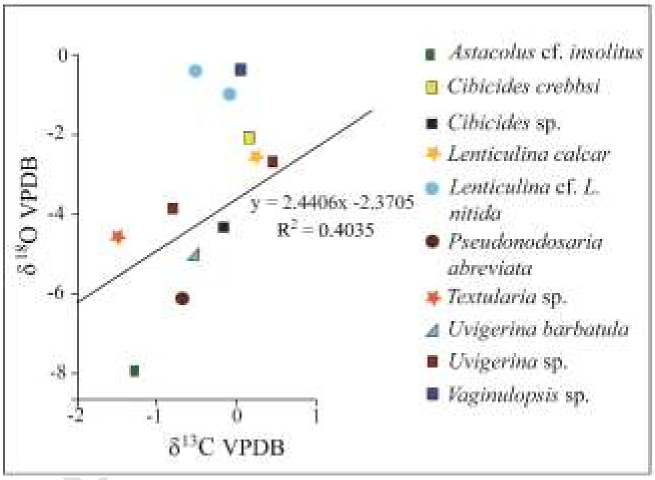

Fig. 9. Covariance between δ^{18}O$_w$ and δ^{13}C for the foraminifera in the Muşardağı Section, represented by cross plots and histograms

Some of the isotopic deviations observed in the δ^{18}O and δ^{13}C curves in the Yazıhan and Musardağı sections are due to the degree of local climatic changes. However, these sections show a significant increase in seawater temperature at certain levels. Two warming phases were observed in the Yazıhan

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section, while one warming phases were observed in the Musardağı section during the early Miocene. Temperature estimates based on oxygen isotopes of foraminifera at these levels indicated a wide range of seawater temperatures between 13.8 °C and 52.4 °C. The temperature of 52.4 °C is also significantly high for species living in a tropical region (Tables 1 and 2, Figures 10 and 11).

Carbon isotope data from early Miocene samples show the degree of seawater level fluctuation. In addition, the carbon isotope curves indicate changes in ocean productivity and the loss of oxygen (Núñez-Useche et al., 2020). Furthermore, sea level is associated with $\delta^{18}O$ values, and as $\delta^{18}O$ values become negative, sea level rises (Miller et al., 2008) (Figures 10 and 11).

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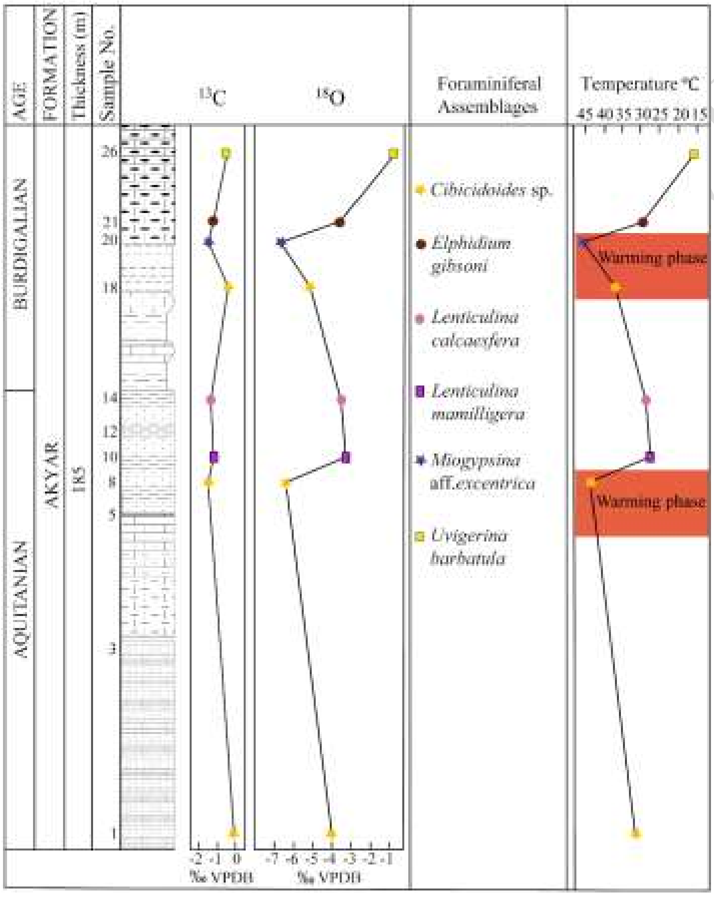

Fig. 10. Paleotemperature (°C) and $\delta^{18}O_w$ (PDB) oscillations in the Yazıhan Section during the early Miocene

The signals from the most stable isotopes were analyzed and interpreted in terms of air temperature. However, Craig and Gordon (1965) established a salinity-water isotope relationship regarding paleosalinity. In the subsequent years, several other methods were developed to determine paleosalinity using $\delta^{18}O_{sw}$ (e.g.; Malaizé & Caley, 2009; Railsback & Anderson, 1989; Wolff et al., 1999). The application of these methods yielded paleosalinity values indicating that the paleosalinity was within the normal levels.

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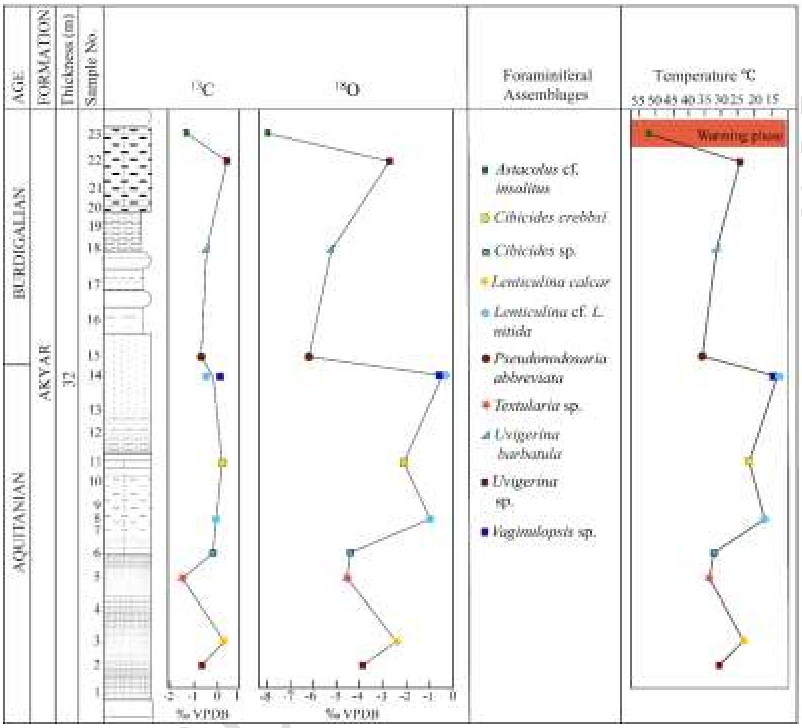

Fig. 11. Paleotemperature (°C) and $\delta^{18}O_w$ (PDB) oscillations in the Muşardağı Section during the early Miocene

4.3. Discussion

Allan and Matthews (1982) proposed that $\delta^{18}O$ readings in foraminifera typically range from -2 to +2‰. Our investigation indicates that the measured $\delta^{18}O$ levels are markedly more negative. Contrary to the potential 1‰ variance in $\delta^{18}O$ readings of *Lenticulina* species documented by Grossman (1987) and Dubicka et al. (2021), a discrepancy of -2.13‰ is observed in the Musardağı section.

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Kennett (1977) argued that the sea surface temperatures of the Subantarctic and Antarctica were significantly warmer than they are today during the early Miocene. Savin et al. (1981) and Miller et al. (1987) suggested that $\delta^{18}O$ values exhibited an increasing trend toward the end of the early Miocene. Anthonissen (2012) also noted that warming during the early Miocene occurred in the northeastern North

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Atlantic. Conversely, Shackleton and Kennett (1975) and Shackleton (1977) found that the warmest period in the early Miocene reached 10°C. They also reported that the $\delta^{18}O$ values for the genus *Uvigerina* were positive, ranging from 0.71 to 4.11, while the $\delta^{13}C$ values ranged from -0.46 to +1.27.

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In our study, the $\delta^{18}O$ values for the genus *Uvigerina* ranged from -3.90 to -0.80‰, indicating negative values, while the $\delta^{13}C$ values varied from -0.79 to +0.59‰. Based on the $\delta^{18}O$ values for the foraminifera in the Yazıhan section, the lowest and highest seawater temperatures were 16ºC and 45.1ºC, respectively (Table 1 and Fig. 10). The estimated seawater temperature for the Muşardağı section ranged from 13.8ºC to 52.4ºC (Table 2 and Fig. 11). This notable increase in temperature cannot be solely attributed to seasonal variations. Large-scale polar ice sheet formation, volcanic activity, and significant evaporation can all contribute to changes in the water isotope ratio (Hudson & Anderson, 1989). The studied area has documented considerable volcanic activity (Bozkaya & Yalçın, 1991; Ercan & Asutay, 1993; Gürer, 1992). Therefore, the shift in the water isotope ratio resulted in abnormal increases in seawater temperature.

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Haq et al. (1988) and Zachos et al. (2001) indicated in their research that sea levels experienced a relative decline during the late Aquitanian. The results from the studied sections also suggest that the sea level decreased at the end of the Aquitanian.

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Even though the $\delta^{18}O$ values of the foraminiferal fauna found in this study are much more negative than those from similar studies in different regions of the world during the early Miocene, the $\delta^{13}C$ values match those findings.

5. CONCLUSION

Based on the species of the benthic foraminiferal genera, SBZ24 and SBZ25 were zones determined in the early Miocene sediments from the Hekimhan sub-basin, eastern Türkiye. Foraminiferal assemblages and "*Hyotissa hyotis*" indicate the age of the Akyar Formation in the early Miocene (Aquitanian-Burdigalian).

The $\delta^{18}O$ and $\delta^{13}C$ analysis results of early Miocene foraminiferal species indicate short-term temperature decreases and overheating phases. In the early Miocene, $\delta^{18}O$ values are between -7.99 and -0.27‰, and paleotemperatures range from 13.8ºC to 52.4ºC. We believe that the short-term, extreme increase in temperature likely originated from the Yamadağ Volcanism, located north of the study area, which dates from the late Cretaceous to the middle-late Miocene.

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$\delta^{13}C$ values varying between -1.56 and +0.41‰ provide information on the sea-level changes. The stable isotope analysis results and fossil content indicate the sea-level changes during the early Miocene. According to the fossil coverage and results of calculations based on $\delta^{18}O$ values, paleosalinity was at the normal level.

The biotic assemblages of the shallow marine part of the Akyar Formation demonstrate that deposition took place in a shallow marine environment in the warm waters of tropical and subtropical regions; a significant increase in the abundance of infaunal and planktonic taxa is an indicator of transition to a low-energy, middle-outer shelf environment.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The author(s) hereby declare that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) or text-to-image generators were used in the creation or editing of this manuscript.

COMPETING INTERESTS

The authors have stated that no competing interests exist.

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