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Stable carbon and oxygen isotopes of benthic and planktonic foraminifera as palaeoenvironmental and palaeoclimatic proxies for the Bartonian–Priabonian in northwestern Saudi Arabia

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The Eocene epoch is known for its fluctuations in climate patterns and the dominance of global greenhouse climate. The Rashrashiyah Formation represents the middle to upper Eocene (biozones E13–E14) marine deposits of claystone to limestone in Saudi Arabia and contains well- to poorly-preserved planktonic and benthic foraminifera. Four different genera were selected for isotopic analysis (*Acarinina* spp., *Subbotina* spp., *Cibicidoides* spp., and *Uvigerina* spp.). Foraminiferal calcite was used to define the depth of habitat for each genus and mode of life. Four equations were used to infer palaeotemperatures from foraminiferal calcite; three equations are applicable for estimation of sea-surface temperatures (SST) from planktonic foraminifera data, while the fourth equation is applicable estimation of bottom-water temperatures using benthic foraminifera data. The mean SST derived from *Acarinina* spp. is ~38°C, while the mean bottom water temperature based on *Uvigerina* spp. is 26°C. Palaeotemperatures derived from this study are notably higher than those reported from this area in the existing literature. This discrepancy may be due to the unique palaeoclimatic and palaeogeographic conditions prevalent in the study area. The stable isotope curve is used to infer the transition between the Bartonian and Priabonian and the general cooling trend during this period.

Key words: stable isotopes, foraminifera, palaeoceanography, palaeotemperature, Eocene.

INTRODUCTION

The Eocene epoch, a significant period in the Cenozoic Era, was marked by a substantial warming trend that began at its onset. This warming event, which followed a prolonged global greenhouse climate, was a pivotal moment in Earth's climatic history (Zachos et al., 2008). The Eocene was characterized by frequent, short-lived (<200,000 years) fluctuations in temperature. However, a longer-term warming event, the Middle Eocene Climatic Optimum (MECO), also occurred during this period (Bohaty and Zachos, 2003). The MECO, lasting ~500 ky, was characterized by elevated atmospheric CO_2 levels (Bijl et al., 2010), a shallower carbonate compensation depth, and a significant warming of both surface and deep waters ~40 Ma, with temperatures increasing by 4–6°C (Bohaty and Zachos, 2003). Following the MECO, a long-term late Eocene cooling trend ensued, culminating in a period of maximum $\delta^{18}O$, used as a climate proxy. This event, occurring ~37.35 Ma, suggests significant global cooling and/or the growth of ice sheets. Microfossil palaeoecological evidence also supports the occurrence of cooling ~37 Ma (Villa et al., 2014). This event, known as the Priabonian Oxygen Isotope Maximum (PrOM) Event, lasted ~140 ky (Scher et al., 2014).

High-quality isotopic records and accurate data interpretation are crucial for understanding historical climate systems. Isotopic compositions of calcareous benthic and planktonic foraminifera are widely utilized to recreate surface and bottom water habitats, as well as to infer secular variations in tempera-

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ture, productivity, global ice volume, ocean circulation, and carbon oxidation rates (Zachos et al., 2001). Prior interpretations (Bohaty and Zachos, 2003; Cramer et al., 2009) of stable isotope data obtained from pelagic and benthic foraminifera suggest a multifaceted climatic history during the Paleocene. This history is characterized by an initial protracted cooling trend followed by a subsequent warming phase. Superimposed on this long-term trend are numerous rapid fluctuations and short-lived events. These climatic variations are primarily attributed to changes in atmospheric pCO_2, as inferred from carbon isotope data (Cramer et al., 2009). Alternative interpretations rely on SST estimations derived from samples exhibiting well-preserved distinctions between surface, deep-dwelling, and bottom-dwelling taxa (Pearson et al., 2001). Notably, these interpretations focus on time-ordered datasets where reasonable SST values, along with identifiable trends and correlatable events, are observed.

While global palaeoceanographic research has made substantial strides, our understanding of past ocean conditions in specific regions, particularly the Arabian Peninsula, remains incomplete. The stratigraphic sequences of the Turayf-Sirhan Basin in north-west Saudi Arabia represent a significant knowledge gap in the fields of stable isotope analysis and palaeoceanography for the western Tethys during the late Eocene. Although eastern Saudi Arabia possesses thick marine Paleogene sedimentary sequences, diagenetic processes have largely obscured the delicate features of microfossils in carbonates. This study aims to address this knowledge gap by investigating late Eocene foraminiferal assemblages from the Turayf-Sirhan Basin. By analysing the isotopic composition of four different foraminiferal genera, we aim to reconstruct local palaeotemperatures and contribute to a broader understanding of Eocene environmental conditions in this understudied region.

GEOLOGICAL SETTINGS AND STUDY AREA

The Turayf-Sirhan Basin, also known as the Azraq-Sirhan Basin, is a significant synclinal geological feature located in northern Arabia, extending through eastern Jordan and north-western Saudi Arabia. Bounded by two major transtensional faults, this NW–SE oriented basin is part of the Neo-Tethyan framework and the Syrian Arc System (Powers et al., 1966; Bahrawi and Elhag, 2019). Its origin dates back to the Late Cretaceous, influenced by marine transgression and faulting, which led to the deposition of a thick carbonate and mixed sediment belt. The basin continued to develop during the Early Paleogene, particularly influenced by the Al-Jawf rifting event, until the late Eocene to early Oligocene, marked by a decrease in sea level and tectonic activity between the Arabian and Eurasian plates. The basin contains over 6 km of Paleozoic to Neogene sediments, with Cretaceous, Paleogene, and Neogene strata primarily outcropping (Guiraud et al., 1999).

The Rashrashiyah Formation, part of this sedimentary sequence, is present in northwestern Saudi Arabia near the Al Qurayyat water well (Fig. 1A). It features a thickness of ~75 m, predominantly composed of greyish-white chalk, calcareous bituminous claystone, and crystalline limestone (Meissner et al., 1990). The formation exhibits a significant unconformity at its upper boundary with the Sirhan Formation (Fig. 1B). Field studies at Qurayyat village revealed a 52 metre outcrop (Fig. 1C), with the Rashrashiyah Formation measuring 50 m and the overlying Sirhan Formation consisting of 2 m of sandstone (Fig. 2). The studied section is a candidate for the Bartonian and Priabonian reference sections in Saudi Arabia, according to research by Korin et al. (2025) and Kaminski and Korin (2025) on the same outcrop. It represents two planktonic foraminifera biozones, E13 and E14 of Berggren and Pearson (2005). High-resolution sampling was conducted at 60 cm intervals for this study.

METHODS AND SAMPLE PREPARATION

A total of 50 samples, principally composed of marly limestone and indurated limestone, were collected from the studied outcrop. Each sample, weighing ~500 grams, was obtained from the fresh surface of the outcrop trench.

MICROPALAEONTOLOGY

Microfossils were extracted by crushing 100 grams of each sample and boiling it with washing powder for 45 minutes. The samples were then washed with fresh water using a 63 μm sieve and dried at 60°C for two hours. Another method was tried to clean the foraminifera tests using only fresh water, but the isotopic results were unreliable due to the intact clay particles that can't be removed using only water. Cisneros-Lazaro et al. (2022) used a similar method, as the samples were boiled at 90°C, giving a reliable result for interpretation. The samples were examined under a stereomicroscope (*Olympus SZX7*), and the desired genera for isotopic analysis were selected based on the taxonomies of Pearson et al. (2001) for planktonic foraminifera and Loeblich and Tappan (1987) for benthic foraminifera. Images of selected gold-coated planktonic and benthic foraminifera were captured using a Scanning Electron Microscope (*JEOL JCM-7000 Desktop SEM*).

STABLE CARBON AND OXYGEN ISOTOPES

While advanced palaeotemperature proxies like clumped isotopes and fluid inclusions require larger samples than available in this study, stable oxygen isotopes are used as the most suitable proxy. Carbon and oxygen isotope data were obtained from well-preserved foraminifera from four genera: *Subbotina* spp., *Acarinina* spp., *Cibicidoides* spp., and *Uvigerina* spp. Samples were carefully selected to avoid dissolution or secondary calcite. The largest specimens (>125 microns) were chosen to minimize size-related variations in $\delta^{18}O$ and $\delta^{13}C$, with average sample weights ranging from 40 to 250 μg of carbonate. Between one and 30 specimens were measured per sample, depending on preservation condition and genus size. A total of 168 samples were analysed, with 10% being blind duplicates for validation. Samples underwent acid digestion in a Kiel IV carbonate device with phosphoric acid (102–105%) at 70°C for 480 seconds to release CO_2, which was cryogenically purified and analysed using a *Thermo Finnigan MAT-253+* mass spectrometer, achieving precisions of 0.04‰ for $\delta^{13}C$ and 0.08‰ for $\delta^{18}O$. Isotope ratios are reported in δ notation relative to the VPDB standard, with standard conversions to the SMOW scale. Instrumental drift was monitored by using an internal lab working standard calibrated to VPDB via international reference materials (KIS; KFUPM Iceland Spar) (Herlambang et al., 2022).

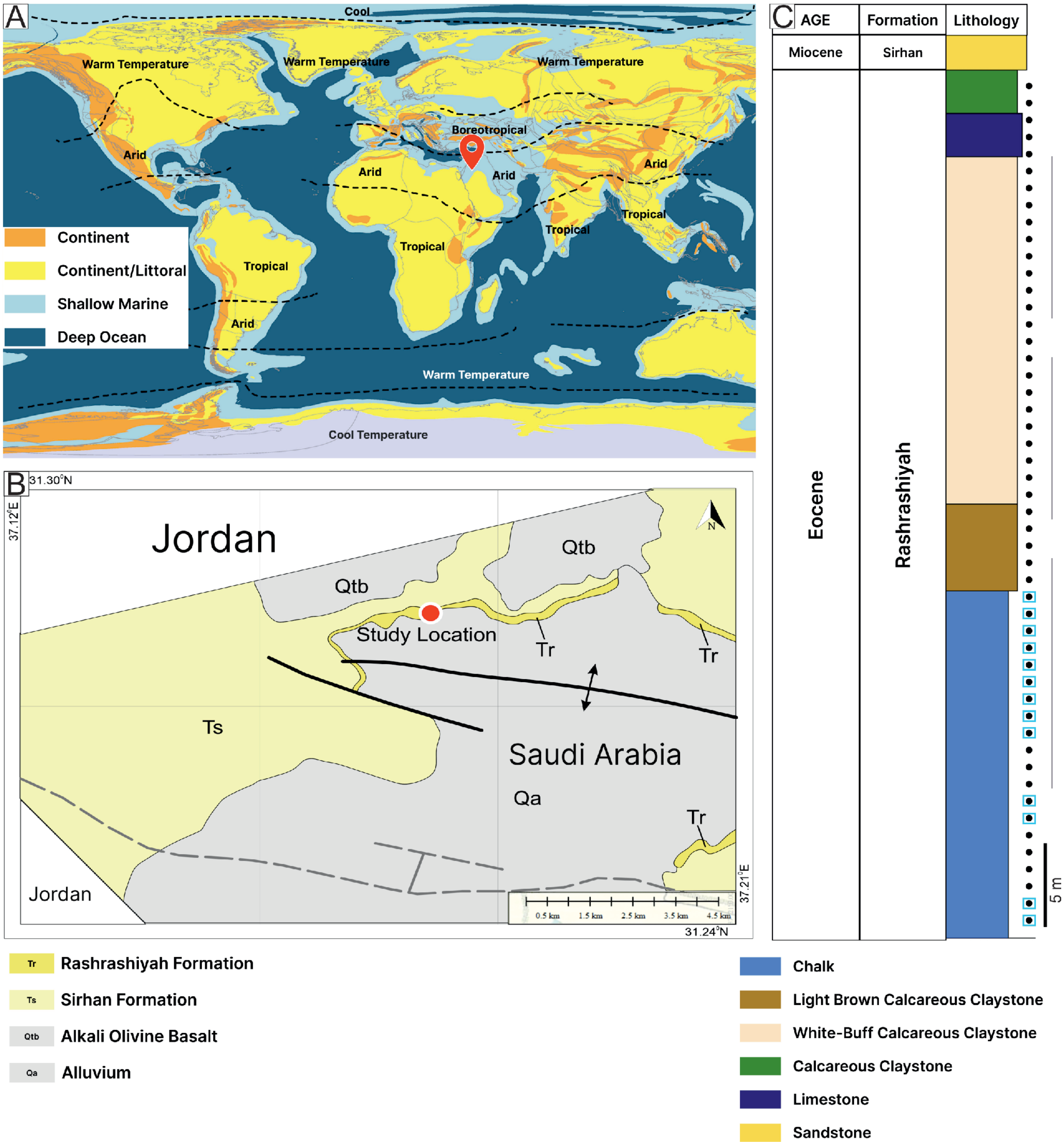

Fig. 1A – palaeogeographic map showing the study area during the late Eocene; the palaeoclimate zones are after Boucot et al. (2013); B – geological map of the study area showing the main studied outcrops, modified after An Nabk quadrangle map; C – lithological log of the study area; the black dots represent the sample locations, while the blue boxes indicate the pristine samples

PALAEOTEMPERATURE EQUATIONS

Palaeotemperature reconstruction in this study utilized oxygen isotope fractionation in foraminiferal tests, guided by frameworks from Pearson (2012). Four key palaeotemperature equations were employed, based on various foraminiferal taxa from different marine habitats:

1. Cultured *Globigerinoides sacculifer* (planktonic foraminifera) by Erez and Luz (1983): $T(°C) = 17–4.52 (\delta^{18}O_c – \delta^{18}O_{sw}) + 0.03(\delta^{18}O_c – \delta^{18}O_{sw})^2$.

2. Cultured *Orbulina universa* (high light) (planktonic foraminifera) by Bemis et al. (1998): $T(°C) = 14.9–4.80 (\delta^{18}O_c–\delta^{18}O_{sw})$.

3. *In situ Cibicidoides* and *Planulina* (benthic foraminifera) by Lynch-Stieglitz et al. (1999): $T(°C) = 16.1–4.76 (\delta^{18}O_c–\delta^{18}O_{sw})$.

4. Cultured *Globigerinoides sacculifer* (high light) (planktonic foraminifera) by Spero et al. (2003): $T(°C) = 12.0–5.57 (\delta^{18}O_c–\delta^{18}O_{sw})$, where $\delta^{18}O_c$ and $\delta^{18}O_{sw}$ are the isotopic values for the foraminiferal calcite and the sea water, respectively.

Fig. 2A – outcrop of the Rashrashiyah Formation and its lateral and vertical extension; B – contact between the Rashrashiyah and Sirhan formations

For the $\delta^{18}O$ value of palaeowater, this study adopted –1.27‰ VSMOW, consistent with Kim and O'Neil (1997), aligning with Shackleton's (1974) earlier estimates for an ice-free world.

PRESERVATION AND THE EFFECT OF DIAGENESIS

The studied samples are abundant in well-preserved foraminifera, both benthic and planktonic, characterized by pristine tests, indicating minimal cementation or infill (Fig. 3). Wade et al. (2021) described the exceptional microfossil preservation in our area as a Konservat-Lagerstätte, which is used to describe the exceptionally well-preserved microfossils in the fossil record. The good preservation is attributed to several factors:

– rapid burial and high sedimentation rates, reducing exposure to degrading bottom waters;
– low sediment permeability due to high clay content, limiting damaging fluid circulation;
– shallow burial depth, indicated by low thermal maturity of organic matter, which minimizes diagenetic alteration (van Dongen et al., 2006).

Diagenetic issues, such as calcite overgrowths, could lower apparent temperatures by 1–5°C (Pearson et al., 2001), but this does not fully account for the observed temperature discrepancies. The $\delta^{13}C$ signature of diagenetic calcite, typically around +3‰, suggests minimal alteration of the original isotopic signal (Pearson et al., 2001). Microscopic examinations revealed heterogeneity; while some samples were exceptionally preserved, which are collected from the claystone dominated interval, others showed significant diagenetic alteration, including calcite overgrowths and signs of dissolution, which are collected from the calcareous limestone intervals. SEM analysis confirmed that well-preserved specimens retained pristine features, while altered samples exhibited rhombohedral calcite crystals.

Our stable isotope analysis indicated that altered foraminifera displayed more negative $\delta^{13}C$ and $\delta^{18}O$ values compared to well-preserved specimens. We utilized SEM analysis to establish the threshold for pristine foraminifera (Fig. 3). Pristine $\delta^{13}C$ and $\delta^{18}O$ values were defined as ranging from –2 to +3‰ and –4 to 0‰, respectively (see Fig. 4). This supports İbilioğlu and Köroğlu's (2024) findings that planktonic foraminifera are more susceptible to diagenetic alteration than benthic species.

RESULTS

PRISTINE AND THE ALTERED ISOTOPIC VALUES

Our analysis encompassed four distinct foraminiferal genera. Two of these genera are planktonic, inhabiting different water column depths. The remaining two genera are benthic; one dwells on the seafloor (epifaunal), and the other lives within the sediment (infaunal).

The first foraminiferal genus we examined, *Acarinina* spp., inhabits the mixed-layer zone of the water column (Aze et al., 2011). A total number of 45 samples were analysed. This genus exhibited a range of $\delta^{13}C$ values from –5.9 to 2.4‰, with a mean value of –2.5‰. Similarly, the $\delta^{18}O$ values spanned a range of –9.5 to –2.3‰, with an average a mean value of –7.3‰. The next foraminiferal genus, *Subbotina* spp., occupies a deeper habitat within the water column, specifically the thermocline zone (Aze et al., 2011). There were 48 samples analysed in all. This genus displayed $\delta^{13}C$ values ranging from –6.7‰ to +1.7‰, with a mean value of –3.6‰. Likewise, its $\delta^{18}O$ values spanned a range of –9.7 to –2.0‰, with a mean value of –7.5‰.

Among the benthic foraminifera, we first focus on the epifaunal genus *Cibicidoides* spp. This genus dwells on the seafloor, often preferring an elevated habitat (Linke and Lutze, 1993). In total, 25 samples were analysed. *Cibicidoides* spp. exhibited $\delta^{13}C$ values ranging from –4.9 to +0.1‰, with a mean value of –2.1‰. Similarly, its $\delta^{18}O$ values spanned a range of –7.9 to –0.9‰, with a mean value of –4.5‰. The second benthic genus we analysed is the shallow infaunal *Uvigerina* spp., which dwells within the seafloor sediment. In total, 48 samples were examined. *Uvigerina* spp. showed $\delta^{13}C$ values ranging from –5.9 to 0‰, with a mean value of –2.7‰. Likewise, its $\delta^{18}O$ values spanned a range of –8.9 to –0.2‰, with a mean value of –4.9‰ (Fig. 4).

PRISTINE ISOTOPIC VALUES

Following the application of the established thresholds for unaltered isotopic values to the analysed samples, only 39 samples were identified as pristine. This implies that the remaining samples exhibited isotopic signatures indicative of diagenetic alteration (Fig. 4). Following the same pattern of describing the isotopic results, nine samples of *Acarinina* spp. were analysed: the $\delta^{13}C$ values range from 0 to +2.4‰ with a

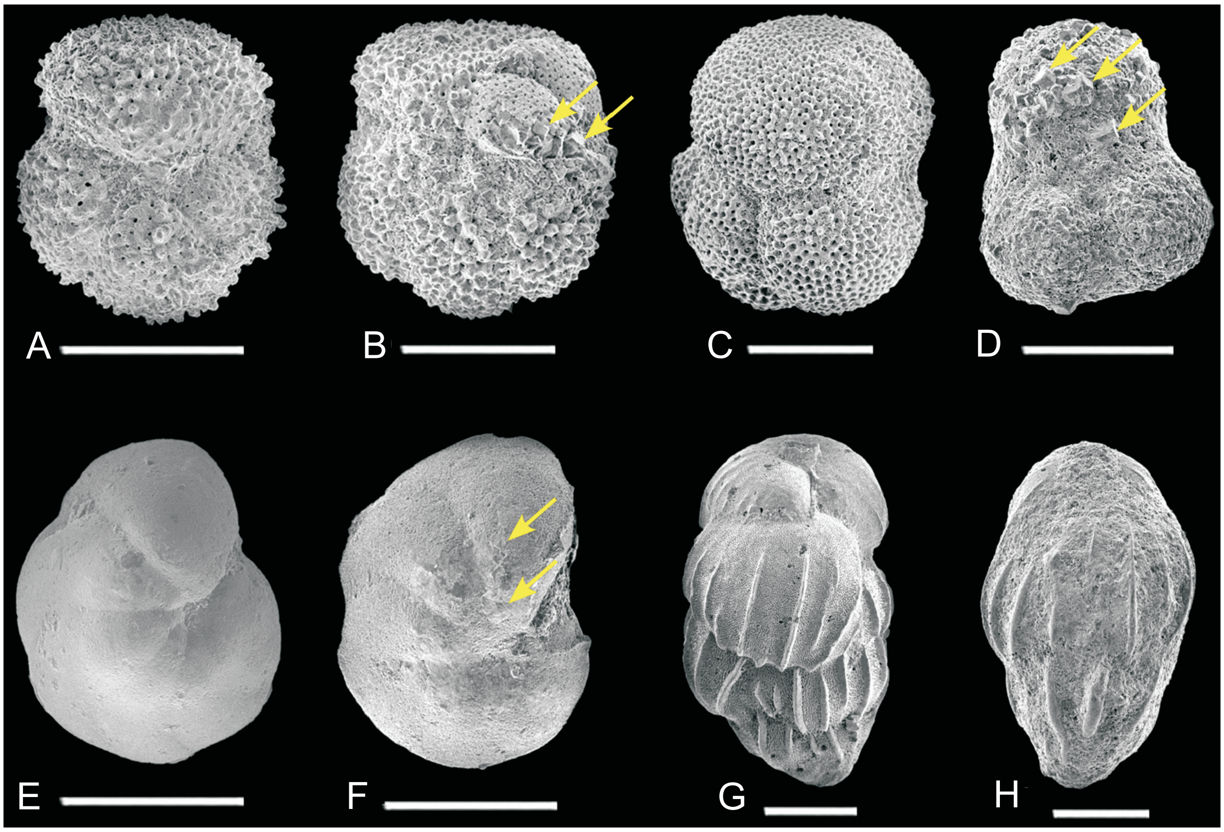

Fig. 3. SEM images showing an example of the pristine and altered specimen of each genus

A – pristine *Acarinina* sp. shows the muricate structure and the micropores; **B** – altered *Acarinina* sp. with secondary calcite crystal precipitated at the right side of the specimen; **C** – pristine *Subbotina* sp. shows the cancellate wall texture and the micropores; **D** – altered *Subbotina* sp. shows the rhombohedral crystals of the secondary calcite with no preservation of the cancellate wall texture; **E** – pristine *Cibicidoides* sp. showing the sutures with no evidence of secondary calcite precipitation; **F** – altered *Cibicidoides* sp. with few secondary calcite crystals in the middle of the specimen; **G** – pristine *Uvigerina* sp. showing the phialine neck and the wall ornamentation; **H** – altered *Uvigerina* sp. with dissolution features; the yellow arrows indicate the calcite crystals; scale bars = 100 μm

mean of +1.5‰. Likewise, $\delta^{18}O$ values range from –3.9 to –2.3‰ with a mean value of –3.1‰. For *Subbotina* spp., only eight samples were found to be pristine, with $\delta^{13}C$ isotopic values ranging from +0.1 to 1.7‰, with a mean value of +0.6‰. Similarly, the $\delta^{18}O$ values spanned a range of –3.3 to –2.0‰, with a mean value of –2.5‰. Nine samples of *Cibicidoides* spp. lie within the pristine range of isotopic values. This genus has $\delta^{13}C$ isotopic values ranging from –1.8 to +0.1‰, with a mean value of –0.7‰. Likewise, $\delta^{18}O$ values range from –2.9 to –0.9‰, with a mean value of –1.7‰. The most resilient genus to diagenesis is *Uvigerina* spp., with 13 diagenetically unaltered samples. The $\delta^{13}C$ isotopic values range from –0.6 to 0‰, with a mean value of –0.3‰. Similarly, the $\delta^{18}O$ values spanned a range of –1.6 to –0.2‰, with a mean value of –0.8‰ (Fig. 5).

PALAEOTEMPERATURE

The palaeotemperature equations were applied to the samples that show unaltered stable oxygen isotopic values. For estimating the SST, three out of four equations were applied to the surface-dwelling planktonic foraminifera, and the last equation was used for estimating the bottom-water temperature using the stable oxygen isotope values of benthic foraminifera. SST was reconstructed for isotopically unaltered *Acarinina* spp. specimens using three established palaeotemperature equations. The Erez and Luz (1983) equation yielded a temperature range of 33.7 to 41.5°C, with a mean SST of 37.5°C. This value is very similar to the summer SST measured in the Saudi sector of the Arabian Gulf today (Prayudi et al., 2024). Similarly, the Bemis et al. (1998) equation indicated an SST range of 32.3 to 40.1°C, with an average of 36.0°C. Finally, the Spero et al. (2003) equation produced an SST range of 32.1 to 41.2°C, with a mean value of 36.5°C. These results demonstrate some variation among the different equations, although they all suggest a similar range of SSTs. Mirroring the approach used for *Acarinina* spp., palaeotemperature equations were applied to isotopically unaltered *Subbotina* spp. specimens to reconstruct palaeotemperatures at their respective water depths. The Erez and Luz (1983) equation yielded a temperature range of 32.3 to 38.4°C, with an average of 34.3°C. Likewise, the Bemis et al. (1998) equation suggested a temperature range of 30.8 to 37.0°C, with a mean of 32.9°C. Finally, the Spero et al. (2003) equation produced a similar range of 30.4 to 37.6°C, with an average value of 32.8°C. The bottom water temperature equation of Lynch-Stieglitz et al. (1999) was applied for the epifaunal benthic genus *Cibicidoides* spp. The bottom water temperature indicated a range of 26.5 to 36°C, with an average of 30.2°C.

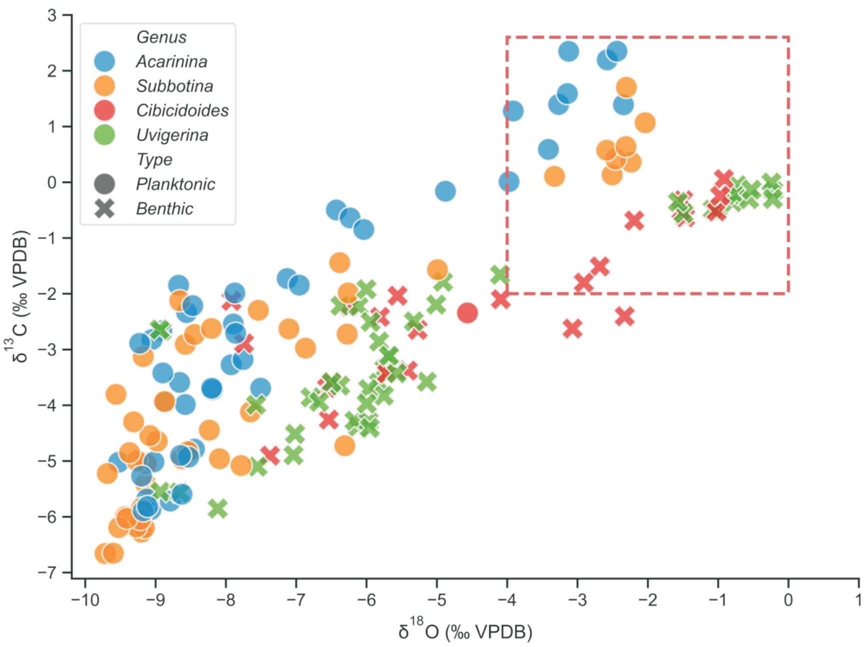

Fig. 4. Stable δ^{13}C and δ^{18}O data for the studied genera for both pristine and altered foraminifera

The dashed red box represents the pristine isotopic values based on the thresholds for δ^{13}C being –2‰ and δ^{18}O being –4‰

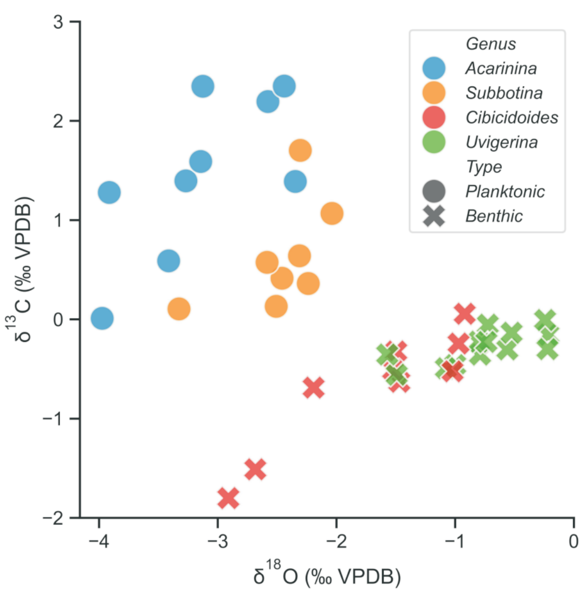

Fig. 5. Stable δ^{13}C and δ^{18}O data for the studied genera for pristine foraminifera

Consistent with the approach used for *Cibicidoides* spp., the Lynch-Stieglitz et al. (1999) palaeotemperature equation was applied to isotopically unaltered *Uvigerina* spp. specimens. This equation estimates the temperature of the porewater a few centimetres below the seafloor sediment. The analysis yielded a palaeotemperature range of 23.2 to 29.6°C, with an average temperature of 25.8°C, reflecting the infaunal habitat of this benthic genus (Table 1).

DISCUSSION

DEPTH ORDERING

Emiliani (1954) proposed that the depth distribution of foraminifera species could be inferred from their oxygen isotopic compositions, exploiting the general temperature decrease with ocean depth. This approach has demonstrated efficacy in

Table 1

The palaeotemperature summary statistics estimated for each genus using different equations

Genus		Erez and Luz (1983)	Bemis et al. (1998)	Lynch-Stieglitz et al. (1999)	Spero et al. (2003)
Acarinina	Min	33.7°C	32.3°C		32.1°C
	Max	41.5°C	40.1°C		41.2°C
	Mean	37.5°C	36.0°C		36.5°C
Subbotina	Min	32.3°C	30.8°C		30.4°C
	Max	38.4°C	37.0°C		37.6°C
	Mean	34.3°C	32.9°C		32.8°C
Cibicidoides	Min			26.5°C	
	Max			36.0°C	
	Mean			30.2°C	
Uvigerina	Min			23.2°C	
	Max			29.6°C	
	Mean			25.8°C	

modern species with known depth habitats (Shackleton, 1974; Fairbanks et al., 1982) and has been widely applied to extinct taxa (Berger et al., 1978; Douglas and Savin, 1978). Planktonic foraminifera exhibit restricted bathymetric distributions, occupying specific water depths such as the euphotic zone or thermocline, and demonstrate latitudinal variability, inhabiting tropical, temperate, or cool regions. Their ecological niches can be inferred through analysis of test morphology and $\delta^{18}O$ signatures (Boersma and Premoli Silva, 1987). Environmental proxies can be inferred from planktonic foraminiferal assemblages and population dynamics. Species inhabiting surface waters typically exhibit depleted $\delta^{18}O$ and enriched $\delta^{13}C$ values, contrasting with those dwelling in deeper thermocline or bathyal zones, which possess heavier $\delta^{18}O$ and depleted $\delta^{13}C$ signatures. Accordingly, *Acarinina* spp., characterized by enriched $\delta^{13}C$ and depleted $\delta^{18}O$ values, are interpreted as surface mixed layer dwellers. Conversely, *Subbotina* spp., with depleted $\delta^{13}C$ and enriched $\delta^{13}C$ values, are inferred to have inhabited thermocline or deeper depths (Aze et al., 2011).

Isotopic analysis in our study area indicates that *Acarinina* spp. of $\delta^{13}C$ and $\delta^{18}O$ mean values of +1.5 and –3.1‰, respectively, lived at mixed layer (shallow depth) depths, whereas *Subbotina* spp. of $\delta^{13}C$ and $\delta^{18}O$ mean values of +0.6‰ and –2.5‰, respectively, lived near or at the thermocline. The observed isotopic disparity between planktonic foraminifera inhabiting the mixed layer and thermocline can be attributed to the presence of photosymbionts. Notably, *Acarinina* sp. is recognized for its symbiotic association with minute organisms, such as dinoflagellates (Giorgioni et al., 2019).

While temperature exerts a minimal influence on $\delta^{13}C$ (Emrich et al., 1970), other factors predominate. The isotopic composition of dissolved inorganic carbon (ΣCO_2) in the local sea water, from which foraminiferal tests precipitate, is a critical determinant. Photosynthesis by symbiotic organisms preferentially utilizes the lighter carbon isotope, thereby enriching the residual sea water in the heavier isotope. Consequently, surface waters exhibit enriched $\delta^{13}C$ values due to this photosynthetic fractionation process. *Acarinina* spp. exhibits pronounced offsets in both $\delta^{13}C$ and $\delta^{18}O$, indicative of pronounced vertical migration within the water column on a seasonal basis. This phenomenon, often termed "seasonal variations" (Pearson et al., 1993), is likely driven by warming conditions, potentially following isotherms or nutrient gradients (nutriclines) (Giorgioni et al., 2019; Fig. 6). While *Subbotina* spp. also displays evidence of seasonal migration, *Acarinina* spp. vertical movement may be constrained to the euphotic zone due to its symbiotic relationship with photosynthetic organisms (Giorgioni et al., 2019).

Seasonal changes in temperature of ~4°C cause about a 1.0‰ change in the oxygen isotope values of foraminifera tests living at the surface of the ocean. However, the changes in carbon isotope values due to seasonal changes are much smaller (Deuser, 1987). Pearson et al. (1993) characterized seasonal variations in environmental conditions as "noise", which can obscure underlying stratigraphic and ecological patterns within foraminiferal assemblages. The observed variability in $\delta^{18}O$ and $\delta^{13}C$ values among *Subbotina* spp. throughout the study area might be attributed to ecological flexibility that allowed these organisms to inhabit a range of water depths. Despite the migration of vertical of *Subbotina* spp. is limited than the *Acarinina* spp. due to the lack of symbiotic relationships and preference for cooler thermocline habitats. Consequently, a migration to warmer, shallower waters seems unlikely for this species (Bralower et al., 1995).

Generally, benthic foraminifera exhibit a positive correlation between mean $\delta^{18}O$ values and average living depth, whereas a negative relationship exists between mean $\delta^{13}C$ values and depth. Studies of stained foraminifera specimens from undisturbed surface sediments have revealed that these organisms occupy distinct microhabitats within and above the sediment column, responding to specific food and oxygen availability conditions (Fontanier et al., 2002). Complementary to faunal studies, pronounced pore water $\delta^{13}C$ gradients, reaching magnitudes of up to –1.0‰ per centimetre, have been documented within the sediment-water interface (McCorkle and Emerson, 1988). Consequently, prevailing pore water geochemistry strongly influences the isotopic composition of benthic foraminiferal tests. Epifaunal taxa, such as *Cibicidoides* spp. of $\delta^{13}C$ mean value of –0.7‰, residing at the sediment-water interface, primarily reflect the isotopic composition of bottom water dissolved inorganic carbon. In contrast, infaunal taxa, including *Uvigerina* spp. of $\delta^{13}C$ mean value of –0.3‰, exhibit a pronounced isotopic signature derived from the underlying pore waters (Mackensen et al., 2000). It is noteworthy that the $\delta^{13}C$ signature of *Cibicidoides* spp. may exhibit depletion relative to the $\delta^{13}C$ of bottom water DIC in regions characterized by pronounced seasonal phytodetritus sedimentation. This observa-

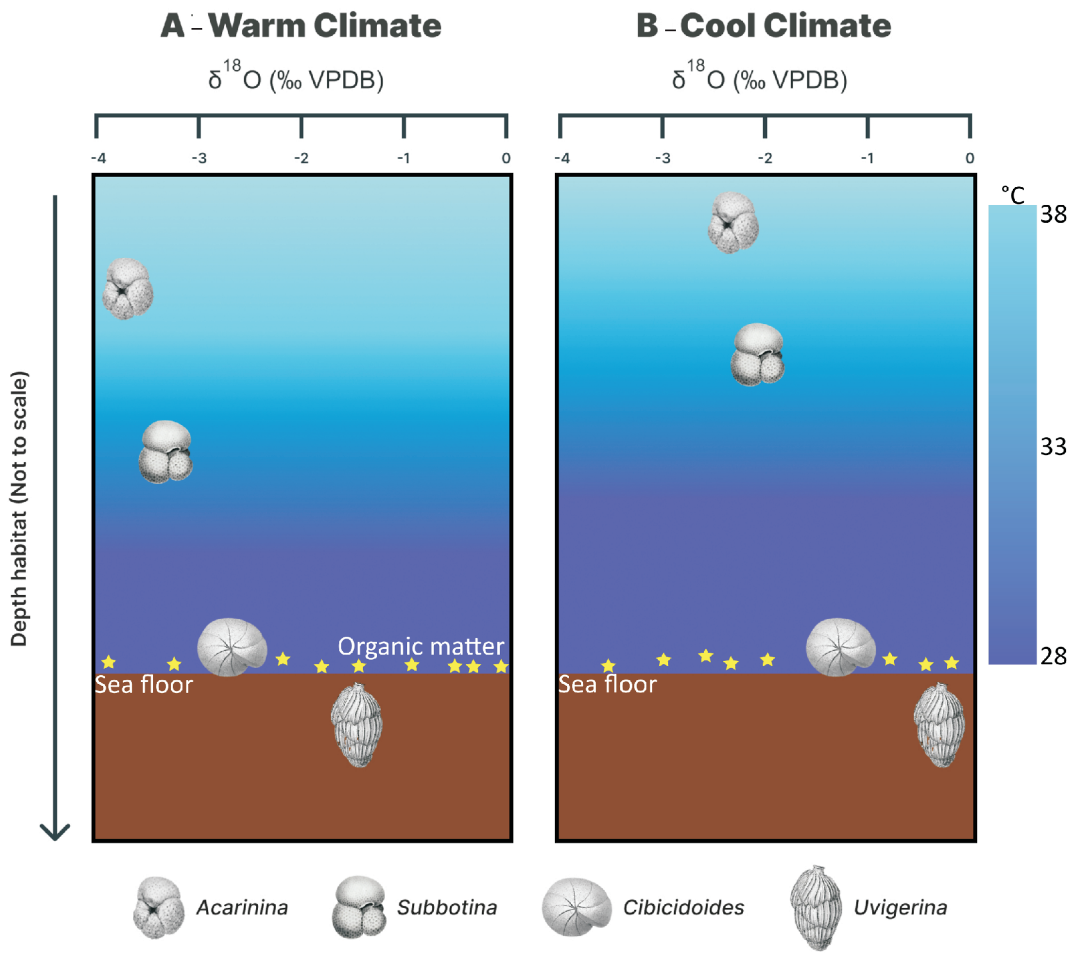

Fig. 6. Schematic model diagram showing the living depth habitat (not to scale) for each genus corresponding to the stable oxygen isotope values

A – a warm climate scenario where planktonic foraminifera dwell at deeper depths for adaptable temperatures; the small yellow stars on the sea floor represent the organic matter responsible for releasing CO_2; **B** – a cool climate scenario where the planktonic foraminifera changed their dwelling depths; temperature gradient based on mean values; the colour gradient represents the temperature, where the light blue is the warmest sea water and the dark blue is the coolest sea water

tion suggests the potential incorporation of CO_2 released during the decomposition of recently deposited organic matter at the sediment-water interface into the foraminiferal calcite (Mackensen et al., 1993).

PALAEOTEMPERATURE RECONSTRUCTION

Palaeotemperature reconstructions based on $\delta^{18}O$ analyses within the Turayf-Sirhan Basin indicate a consistently warmer climate during the middle-late Eocene compared to modern conditions. The maximum SST of 41.5°C with an average of 38.7°C derived from *Acarinina* spp. and the maximum bottom water temperature of 36°C with an average of 30.2°C derived from *Cibicidoides* spp. significantly exceed the palaeotemperature estimated for the late Eocene (Cramer et al., 2009; Fig. 5). Other palaeotemperature studies estimate that the SST during the Eocene exceeded 30°C at 55° South in tropical conditions (Zachos et al., 2006). Furthermore, revised calibrations for the TEX_{86} proxy (Kim et al., 2008) give SSTs ranging from 35 to 40°C within the equatorial Indian Ocean during the Eocene, as indicated by Pearson et al. (2007). Given the arid conditions prevailing over the Arabian Plate since the Paleocene (Fig. 1A; Boucot et al., 2013), we anticipate that our study area will reveal higher SSTs compared to other regions of the world. Indeed, our calculated temperatures are within the range of temperatures observed today in the shallow Saudi sector of the Arabian Gulf, where the SST may reach 39–40°C in summer (Prayudi et al., 2024). An additional explanation for the elevated SSTs observed in our study compared to their global counterparts is the meridional heat transport model proposed by Huber and Sloan (2001). This model shows that the Earth's equatorial region, receiving the most intense solar radiation, acts as a heat source for the planet. Consequently, regions situated between 10° and 40° East experience the greatest influx of meridionally transported heat, potentially contributing to the high SSTs recorded in our study area. A palaeotemperature offset of ~7–8°C is evident across all analysed genera except for the *Cibicidoides* spp., consistent with recent observation of ~8°C annual temperature variation in mid-latitude mid-ocean regions.

Unlike their planktonic counterparts, benthic genera exhibit a more restricted depth habitat, with minimal flexibility for vertical migration. While infaunal taxa such as *Uvigerina* sp. may exhibit limited depth penetration within the sediment column (Schmiedl et al., 2004), this depth range is insufficient to induce significant temperature variations, so the variation in temperature is a result of change in bottom-water temperature. While epifaunal *Cibicidoides* spp. and *Nuttallides* spp. have been extensively utilized for palaeotemperature reconstruction, as exemplified by the work of Zachos et al. (2001), their potential contamination by isotopically altered carbon and oxygen derived from decomposing organic matter may compromise their accuracy in reflecting true bottom water conditions. In contrast, infaunal *Uvigerina* spp., residing deeper within the sediment, are less susceptible to this influence. Our study corroborates this notion, as the palaeotemperature estimate derived from *Uvigerina* sp. (averaged 25.8°C) aligns more plausibly with expected bottom water conditions compared to the anomalously high temperature (averaged 30.2°C) calculated for *Cibicidoides* spp.

STABLE ISOTOPES AND THE GLOBAL TRENDS

The Bartonian/Priabonian boundary is still a subject of debate, as there is a lack of comprehensive outcrop candidates to precisely define it. Studies conducted in Italy have defined the boundary using micropalaeontological and geochemical analyses (Agnini et al., 2021). Despite extensive research, previous studies have relied on bulk $\delta^{13}C$ and $\delta^{18}O$ analyses, which were not able to capture the short-lived warming event at the Bartonian/Priabonian boundary documented by Bohaty and Zachos (2003) and Cramer et al. (2009). In our data, the measured $\delta^{13}C$ and $\delta^{18}O$ for the study area revealed that the lower part of the outcrop is showing pristine foraminiferal calcite (Fig. 7), which represents the Upper Bartonian and the Lower Priabonian defined by correlation with global isotopic curve by Cramer et al. (2009). In order to reveal the $\delta^{13}C$ and $\delta^{18}O$ trends, we removed the altered signatures (Fig. 8). Starting from the elevation of ~1 m, all genera exhibited an increase in $\delta^{18}O$ values, indicative of cooling temperatures, which coincided with an increase in $\delta^{13}C$ values. This cooling trend persisted at an elevation of ~5 m, as evidenced by *Acarinina* spp., with $\delta^{18}O$ values reaching –2.35‰, corresponding to SST of 33.7°C. At an elevation of ~6 m, a decrease in $\delta^{18}O$ values, recorded by *Uvigerina* spp., indicated a cooling of bottom water temperatures to 29.2°C. Due to the poor preservation of planktonic foraminifera, sea surface temperatures could not be determined. The bottom water temperatures showed a slight increase in temperature at an elevation of ~10 m, where the $\delta^{18}O$ for the *Cibicidoides* spp. and *Uvigerina* spp. reached –1.52 and –0.73‰, respectively. For the SST, the *Acarinina* spp. showed depletion in $\delta^{18}O$ and a decrease in temperature, which is unexpected and may be due to vital activity or movement through the water column. At an elevation of ~15 m, all genera indicated an increase in both SST and bottom water temperature. *Acarinina* spp. recorded an SST of 41.1°C, while *Cibicidoides* spp. indicated a bottom water temperature of 35.9°C. We hypothesize that this rapid decrease in both SST and bottom water temperature marks the onset of the short-lived warming event associated with the transition from the Bartonian to the Priabonian stages, as documented by Bohaty and Zachos (2003), Cramer et al. (2009), and Scher et al. (2014). From that elevation up to ~20 m, all genera recorded an increase in temperature for both SST and bottom water temperature. Scher et al. (2014) re-

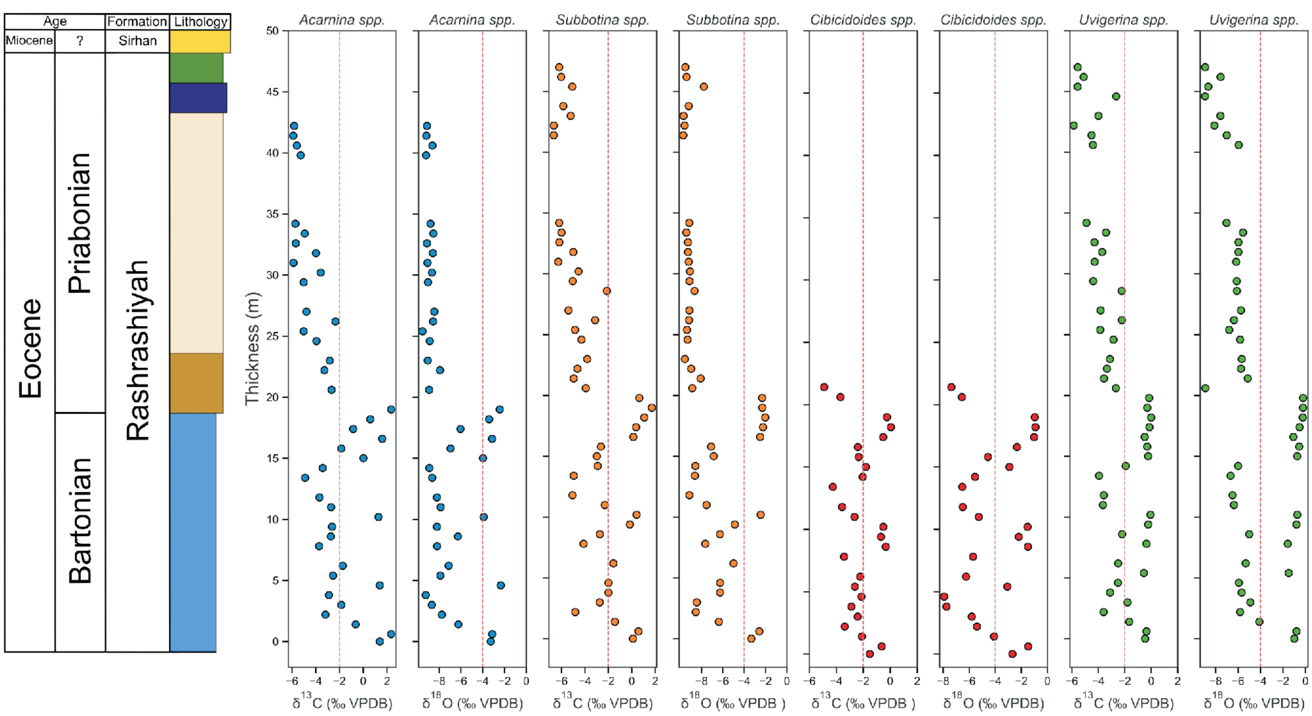

Fig. 7. Stable $\delta^{13}C$ and $\delta^{18}O$ data of the studied genera against unit thickness

The red dashed lines represent the threshold values between the pristine and altered values; symbols are in **Figure 1**

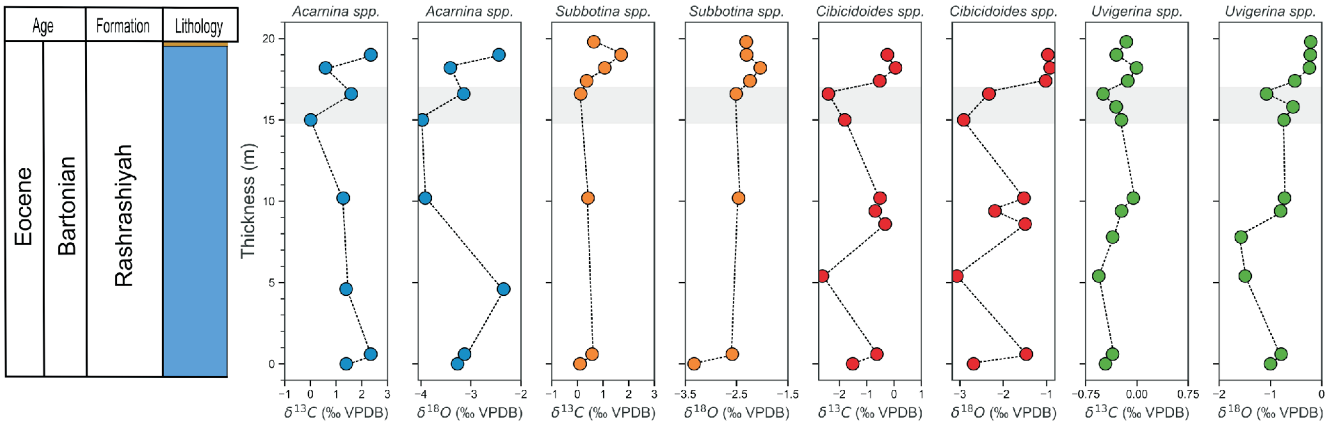

Fig. 8. Stable $\delta^{13}C$ and $\delta^{18}O$ data of the pristine foraminifera against unit thickness

The transition between the Bartonian/Priabonian is shaded with grey colour; symbols are in Figure 1

ported this cooling as the PrOM, which is a cooling event following the middle Eocene climatic optimum and the Bartonian/Priabonian transition event. In general, the isotopic curves in this study can capture the general cooling trend after the MECO (Scher et al., 2014).

CONCLUSIONS

This study investigates the palaeoclimatic conditions of the western Tethys within the Turayf-Sirhan Basin by analysing stable isotope compositions of four foraminiferal genera that lived during the latest stages of the Eocene epoch. Differentiating between diagenetically altered and pristine tests was crucial for accurate palaeotemperature reconstructions. Planktonic foraminifera, particularly *Acarinina* spp., displayed isotopic signatures indicative of a shallow, warm-water habitat, likely influenced by symbiotic relationships. In contrast, the benthic genus *Uvigerina* spp. provided more reliable palaeotemperature estimates due to its infaunal lifestyle and reduced susceptibility to diagenetic alteration. The obtained palaeotemperature values suggest a significantly warmer climate in the Turayf-Sirhan Basin compared to global averages during the late Eocene, a result that is similar to the temperatures observed in the modern-day Saudi sector of the Arabian Gulf. The general isotopic trends coincide with the global trend of general cooling followed the MECO and the warming interval that marks the onset of the Bartonian/Priabonian.

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Data availability statement. The original research findings of this study are presented in full in this article. For further details or inquiries, please contact the corresponding author(s).

Author contributions. SA: Writing – review and editing; Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. AK: Writing – review and editing, Methodology. AH: Writing – review and editing, Data curation, Methodology. JDH: Writing – review and editing, Data curation, Supervision. MIN: Writing – review and editing, Project planning. AAB: Writing – review and editing, Project planning. AMM: Writing – review and editing, Project planning. ISZ: Writing – review and editing, Project planning. MAK: Writing – review and editing, Data curation, Methodology, Funding, Supervision.

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