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Upper Paleocene paleoenvironmental reconstruction using *Coccolithus pelagicus* and $\delta^{13}C$ stratigraphy from the Al-Uwayliah Formation, northeastern Libya.

Hassan S. Hassan

University of Misurata, Faculty of Environmental Sciences and Natural Resources, Department of Geology, Misurata, Libya

Highlights

- **Cool to temperate ocean conditions near the southern edge of the Tethys helped dominance of Coccolithus pelagicus while strong water circulation and ample nutrients led to excellent fossil preservation.**
- **A spike in carbon isotope values during the late Paleocene marks a steady rise, after which levels slowly drop right up to the edge of the Eocene era. That key shift in methane levels gets cut short though - because a local gap in the rock record wipes out the core PETM drop.**
- **Late Paleocene chalks of the Al-Uwayliah Formation were deposited in open-marine outer to middle neritic in calm water setting with minimal terrigenous input and well-oxygenated waters.**

A R T I C L E I N F O

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A B S T R A C T

Marine chalk rocks in the north-east of Libya are an archive of sea conditions that evolved after the boundary between the Cretaceous and Paleogene periods in the southern part of Tethys. In the Al-Uwayliyah Formation of the Jabal Akhdar region, *Coccolithus pelagicus*, which reflects paleoenvironmental conditions, is found within the upper Paleocene chalky limestones. In a remarkably well preserved stratigraphic sequence, primarily Paleocene rocks are found, providing good opportunities for late Paleocene marine environments to be precisely reconstructed.
Paleoenvironmental interpretation integrates four data sources: mineral composition, microscopic texture, nannofossil assemblages, and carbon isotope ($\delta^{13}C$) ratios. Before the Paleocene-Eocene Thermal Maximum, conditions in surface waters and carbon cycling were assessed using this data. The main composition of the dominant chalk-wackestone facies is of pelagic carbonate ooze, rich in planktonic foraminifers and nannoplankton. From mid to outer shelf depths, sediments built up in quiet, wide areas of the seafloor - no strong currents involved. Because rivers did not reach far out, land-derived particles stayed scarce here. Calm conditions meant organisms mixed nutrients efficiently, leaving behind minimal biological waste. Freshwater runoff brought some silt now and then yet overall supply stayed low. Over time, gentle flows delivered tiny particles that settled slowly beneath the surface layer.
Out at the edge of the Paleogene, surface waters likely stayed chilly thanks to a swarm dominated by Coccolithus pelagicus. Nutrients seemed decent, circulation smooth, temperatures within range for cool zones. Near the close of the Paleocene, a slight bump in carbon isotope values appeared - then softened until just before the Eocene takeover. That rise, then fade, lines up well with earlier carbon trends during the PETM era, though one big detail is missing: any dip in isotopic signal.

1. Introduction

Following the extinction event at the end of the Cretaceous period, there were massive climate and environmental shifts on Earth during the Paleocene epoch. This led to a gradual recovery of marine ecosystems during the Paleocene (66–56 Ma) following the end-Cretaceous mass extinction. Following a substantial recovery of marine ecosystems, the period culminated in a significant expansion of marine productivity at PETM (McInerney and Wing, 2011). The recovery of the open ocean's ecosystem relied heavily on calcareous nannofossils. Rock samples provide a critical archive for reconstructing ancient environmental conditions. Coccolithus pelagicus is found in the oceans of the entire planet and lives in numerous marine settings. This species is found in areas of high productivity, such as the coastal waters off southern Australia and New Zealand, where it is typically found in the summer months at temperatures ranging from 4 to 15°C. This species first appears in the Paleocene (e.g., Dylmer, 2013) and is commonly found in chalk formations. This abundant presence in the chalk of the Paleocene time suggests that in the surface waters at the time, there was a cool, well mixed state, facilitating a constant food supply (Cachão, 2000).

In northeastern Libya, the mountain Jabal al Akhdar played a strategic role when the southern margin of the Tethys Ocean faced it during the Paleocene. The Al-Uwayliah Formation consists primarily of white, chalky foraminiferal wackestone. The late Paleocene age of the formation is supported by the calcareous nannofossil zone NP9 and the planktonic foraminiferal zone *Planorotalites pseudomenardii*. Such zones are useful for determining the age of marine sedimentary sequences (Carson, 1991; Premnath *et al*., 1993). The deposits overlie the upper Cretaceous shallow marine carbonates of the Wadi Dukhan Formation and are overlain by the lower Eocene nummulitic limestones of the Darnah and Apollonia formations. Research by El Hassi et al. (2021) and Tmalla (2007) found that the Paleocene-Eocene transition was accompanied by changes in tectonic activity, paleoenvironmental conditions, and sea level fluctuation.

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Research into the paleoecology and paleo-oceanography of Paleocene chalks in northeastern Libya was conducted by examining three types of information. This included detailed observations of the composition and microscopic texture of the Al Uwayliah Formation, examination of nannofossils of the species *Coccolithus pelagicus*, and measurements of the carbon-13 isotopic composition of the carbonate rocks. The study brings together SEM images of coccoliths with photographs taken at chalk outcrops in the field, using carbon-13 isotope measurements to track and interpret global climate patterns and changes in oceanic water conditions.

2. Geological and Stratigraphic Setting

Stretching from the northeast to the southwest, the Jabal al Akhdar anticlinal mountain is located in the Cyrenaica area, which faces the Mediterranean Sea to the south (Fig. 1). During the convergence of the African and Eurasian tectonic plates in the Late Cretaceous and Cenozoic eras, the region's inverted Mesozoic basin was uplifted. The region is characterized by a thick sedimentary succession spanning from the Jurassic to the Miocene and comprising both Mesozoic and Cenozoic strata. This succession is subdivided into two distinct geological formations. The first dates from the Upper Cretaceous and consists of marine carbonates, while the second, a Paleogene clastic and mainly carbonate formations. In northeastern Libya, the Wadi Dukhan Formation comprises Cretaceous sea-floor sediments. These are primarily limestones and dolostones that accumulated in very shallow water. They are overlain by an unconformity, above which lie the Paleocene carbonates of the Al-Uwayliah Formation. The complete Danian–Selandian sedimentary succession preserved adjacent to the unconformity has been used to constrain an approximately 11 Myr time gap at the Al-Uwayliah type locality and to identify a larger hiatus of about 21 Myr in areas where Paleocene sediments are absent.

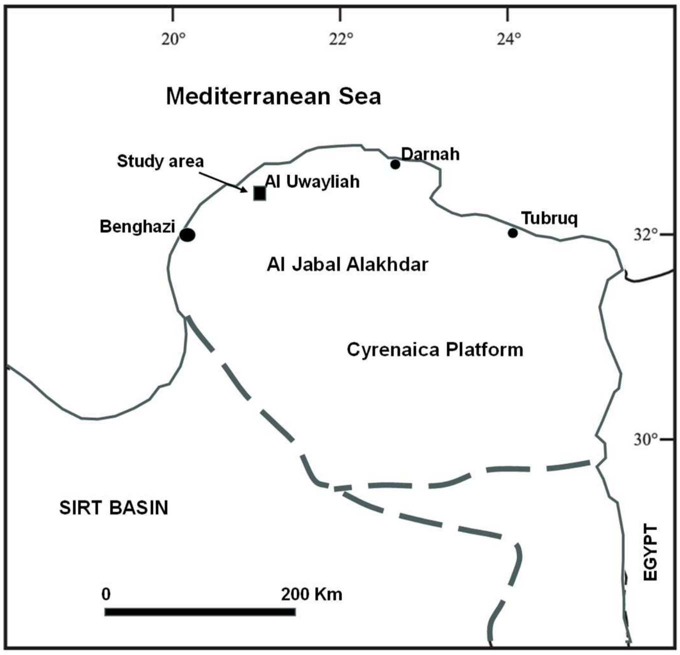

Fig. 1. Location map of the study area, Al-Uwayliah Formation outcrop in northeastern Libya.

2.1 Al-Uwayliah Formation

The northeast-southwest trending Jabal al Akhdar anticline traverses the Cyrenaica region, with its northern flank reaching the Mediterranean Sea. The area contains a thick sequence of rocks deposited between the Jurassic and Miocene periods. The area comprises two separate geological formations, namely the upper Cretaceous shallow marine carbonates, and the Paleogene carbonates and clastics, and the Neogene (El Hawat and Shelmani, 1993). The Upper Cretaceous Wadi Dukhan Formation in northeastern Libya consists of shallow-water limestones and dolostones and is overlain unconformably by the Paleocene carbonates of the Al-Uwayliah Formation, which are in turn overlain by the lower Eocene nummulitic limestones of the Darnah and Apollonia formations (Fig. 2). Geologists used the Danian-Selandian unconformity interval from this site to estimate a time gap of 11 million years at Al Uwaylah and a 21 million year gap in places where Paleocene units are missing (El Hassi *et al.*, 2021).

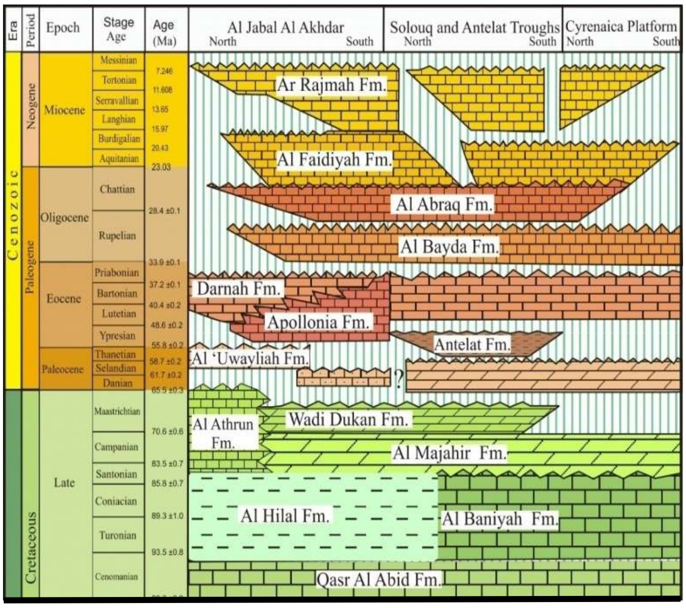

Fig. 2. Stratigraphic section of Upper Cretaceous-Tertiary rocks in northeastern Libya (Modified after Hassan and Kendall, 2014).

3. Materials and Methods

The chalky limestones of the Paleocene age originated from the measured sections of the Al Uwayliah Formation which are situated in north eastern Libya, as shown in Fig. 3. The field photographs show the chalk outcrops displaying bedding, colours and contacts with the underlying Wadi Dukhan Formation and the limestones above in Apollonia/Darneh. The team prepared a sample in order to have hand specimens for both a scanning electron microscope and for thin section petrography to study *Coccolithus pelagicus* and other nannofossils.

The study made use of a scanning electron microscope (SEM) in order to examine the specimens using qualitative and semiquantitative SEM analysis methods; these methods focused on the preservation and abundance of *C. pelagicus*. This analysis enabled the identification of the species and the reconstruction of past environmental conditions based on three SEM images that revealed various structural features.

The stable isotope ratios in the carbonate from micritic sections of the chalk were determined by the University of South Carolina laboratory team. They did this by analysing powders which had been obtained through the process of coring. The carbon isotope measurements made in this study have been correlated with the stratigraphic height of the geological samples analysed to create a $\delta^{13}C$ v. height profile for the Paleocene. This local curve correlates with the published $\delta^{13}C$ records from the Paleocene/Eocene boundary in Tethyan and other locations including the Egyptian Dababiya GSSP and the Italian Scaglia Rossa and associated sections (Dupuis *et al.*, 2003).

4. Results

4.1 Lithology and microfacies

These soft, pale grey to white fine-grained chalks are predominantly biomicrite. Layering is more distinct in hand samples than in outcrops, with both thick and thin beds preserved. This is due to the chalk changing from thick to thin layers, still retaining its pelagic origin through its fine grain composition. The rock is composed of various foraminifera and nannofossils that are distributed throughout the sample, forming its internal framework. The area in question contains wackestone units that are visually distinguishable from the adjacent marly sediments by their fainter colouration. Wackestones here owe their existence to processes that occurred locally, affecting both the distribution of micrite and the rates of calcium carbonate deposition.

Fig. 3. Field photograph of Paleocene chalk deposits of the Al-Uwayliah Formation exposed in northeastern Libya, showing massive to weakly bedded chalky limestone.

The rock has a texture of either microsparitic or micritic and consists of pelagic carbonate mud, as seen in petrographic analysis of a thin section. Despite some instances where they have microspar and early cement infills, the matrix contains numerous planktonic foraminifers, their structures preserved. These benthic foraminifera are occasionally found in a manner consistent with open ocean sediments, at depths below where wave action would normally be. A micritic matrix, which is characterised by fine grain sizes, contains small amounts of fine sand and very fine silt particles. Throughout the study area, the ocean debris, which includes the remains of ostracodes, sea urchin spines and other animal bones was discovered. These fragmented bioclasts are dispersed throughout the region at much lower concentrations than the micritic matrix. These pelagic mud-dominated chalk microfacies, of the Al-Uwayliah type section, are characterised by their low content of siliciclastic material and by their numerous planktonic foraminifera (Muftah *et al*., 2002).

The microfacies recognised in the studied samples match the type known from the Al-Uwayliyah Formation as chalky mudstone-wackestone. Tmalla in 2007 found that the formation is composed solely of upper Paleocene levels due to a significant stratigraphic break which has removed all Danian and early Selandian strata. In the fine grained pelagic carbonates which are accompanied by little quantities of siliciclastic material it is noticed that the region had been formed under tranquil open sea conditions located on a vast, shallow, shelving bank of carbonate sediments. This is consistent with the absence of indicators for shallow water, such as large benthic foraminifera and coarse skeletal debris.

The thin section reveals a variety of diagenetic properties which can be observed. The rock contains different kinds of alteration. The alterations made to the chalk did not remove its characteristic sedimentary layering since the original textures of the sediment remain intact. Coccolithus pelagicus SEM photographs show well preserved fossils when viewed at the microscopic level. The occurrence of wackestone and mudstone microfacies containing chert nodules, echinoid spines, ostracodes, planktonic foraminifera, microspar, and micritic mud indicates deposition in an open-marine pelagic environment.

4.2 Nannofossil assemblages and *Coccolithus pelagicus*

The planktonic foraminiferal and calcareous nannofossil fauna of the type and parastratotype sections indicate that the studied chalk section belongs to NP9 nannofossil zone and P. pseudomenardii planktonic foraminiferal zone as described by Tmalla (2007). The absence of Danian and early Selandian assemblages from the fossil record can be attributed to a major stratigraphic gap which is thought to have been triggered by a period of tectonic uplift experienced by the Jabal al Akhdar region. This uplift appears to have caused a combination of non-deposition and erosion during the early Paleocene.

The period in question comprises nannofossils, with *Coccolithus pelagicus* and other Paleocene era forms such as *Chiasmolithus, Toweius* and *Discoaster* species present. The good preservation of *Coccolithus pelagicus* with minimal recrystallization, indicates its continuous presence in this interval. This implies marine carbonate productivity in the open ocean continued steadily. Low terrigenous input suggests deposition occurred in an outer neritic setting characterized by sustained plankton productivity.

With a global distribution, *C. pelagicus* is found everywhere and research into its marine ecology has been recorded in both modern and past Quaternary times. Dominating its environment are the species, which inhabit well mixed waters and surface water systems with cool to temperate temperatures and rich in nutrients. The species is the most dominant coccolithophore in Paleocene deposits in Libya, where the chalk was formed. The southern margin of the Tethyan Ocean, during the late Paleocene era, had sea water temperatures that fell in between cool and temperate conditions. This is unlike tropical water and yet there were still sufficient nutrients available to allow for a high growth rate of coccolithophores (Cachão, 2000).

Photomicrographs by the scanning electron microscope in Fig. 4 show the elliptical to subcircular form of the shield of *Coccolithus pelagicus*, the distal shield being made up of imbricating calcite. The central part of the coccolith is either empty or weakly occupied, its features corresponding with previous research on this species. During this period, the calcareous nannoplankton *Cocolithus pelagicus* retained both its taxonomic and ecological status. The $\delta^{13}C$ isotope signature of the carbonates changed throughout the section. This change is due to variations in both global and local carbon cycle mechanisms.

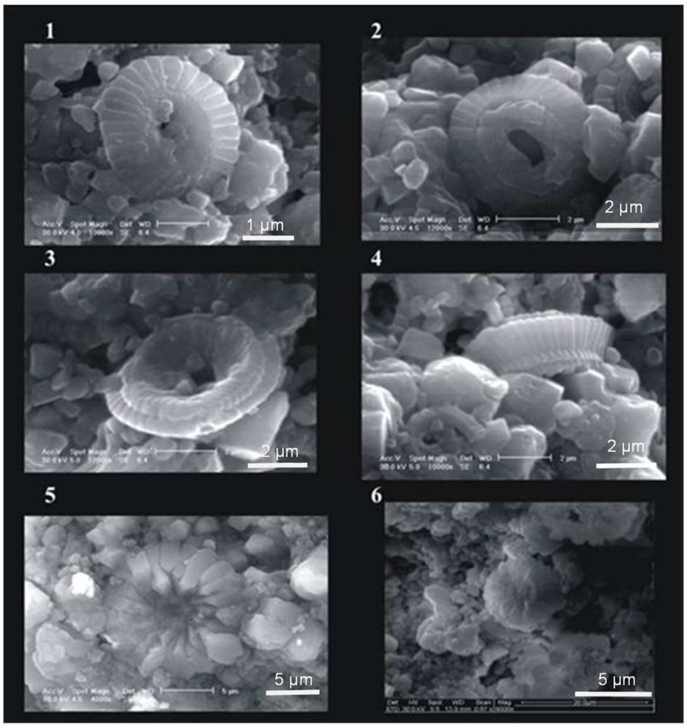

Fig. 4. Scanning electron microscope (SEM) images of *Coccolithus pelagicus* from Paleocene chalk of NE Libya.

4.3 Carbon-isotope (δ13C) record

The carbon isotope curve from the Paleocene chalk shows a plateau in the middle of the epoch that became gradually less positive toward the top. Our study's absolute values show patterns similar to those of published δ13C curves for the late Paleocene from the Tethyan localities at Dababiya, Egypt, and pelagic sections in central Italy (D'Onofrio et al., 1993). In the region of north-eastern Libya, biostratigraphic data of the Al-Uwayliah Formation indicate the presence of late Paleocene deposits (NP9, zone of Pseudomenardia pseudomenardii) up until the base of an unconformity which is succeeded by Eocene limestones. The $\delta^{13}C$ record indicates that the Al-Uwayliah section extends up to the onset of the Paleocene Eocene Thermal Maximum, but the main negative carbon-isotope excursion is truncated by the regional unconformity and is therefore not fully preserved.

Minor local fluctuations in δ13C of carbonate material were observed within the preserved period. This signifies that there were minor fluctuations in the activity of living organisms and in ocean water circulation patterns. There is no negative isotope shift of this magnitude in the PETM at this location, resembling the pattern observed in the CIE. Consequently, the PETM does not appear to be present here. The δ13C carb record from Libya provides a vital palaeoclimatic and palaeo-environmental history detailing how the CO2 levels changed before the PETM. This information gives an understanding of the climate and environmental conditions at the Tethyan Ocean's southern margin.

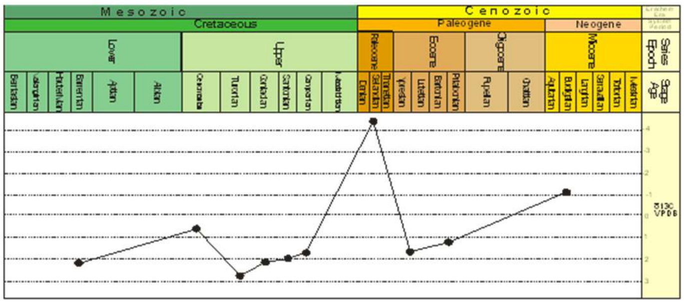

Fig. 5. Stratigraphic profile of carbonate δ13C values from northeastern Libya, showing trends through the Paleocene and into the Paleocene–Eocene boundary.

5. Discussion

During the Danian-Early Selandian hiatus, as Tmalla (2007) pointed out, there is no older paleocene fauna present. This suggests that the succession is a high-resolution but incomplete upper paleocene archive. The results from the Uwaylah well are consistent with the type of microfacies and the nannoplankton fossils found at Uwayliah locality (Muftah *et al.*, 1984)

5.1 Depositional environment and paleoecology

Carbonate sedimentation occurred on an outer to middle neritic ramp below wave base during periods of low energy conditions in the ancient environment. This was within the photic zone. This is indicated by the wackestone and mudstone microfacies which contain the foraminifers and nannoplanktons of a neritic zone but no terrigenous material. Deep waters, ranging from tens to hundreds of metres in depth, are implied by the presence of pelagic carbonate mud and the absence of shallow water indicators such as large benthic foraminifera and reefal facies. The lack of rich organic layers and foraminiferal assemblages suggests that the deep waters were oxygenated, indicating that it was a marine shelf in open water with circulation.

During this period, Coccolithus pelagicus, a species which thrives in present-day cool temperate and upwelling regions was extremely abundant (Saavedra-Pellitero *et al.*, 2010). The nannofossil fauna remained unchanged in this period with *Coccolithus pelagicus* continuing to dominate, suggesting steady sea conditions and continuous pelagic carbonate formation during the late Paleocene in the Al-Uwaylah Formation.

5.2 Integration of δ13C and nannofossil data

The δ13C curve of the carbonates in northeastern Libya provides valuable information on how the nannoplankton species relate to the ocean's climate conditions in the past. The high $\delta^{13}C$ values in the mid-Paleocene suggest enhanced burial of ^{12}C-enriched organic carbon (e.g., McInerney and Wing, 2011). This was at a time when Earth's climate was remaining steady; however a following δ13C drop had an effect on worldwide carbon cycle, and it had the Earth on a course towards conditions seen during the PETM.

During the PETM there was a 2-3 per mil negative shift in the carbon-13 isotope in marine calcium carbonates. The PETM is identified in Tethyan sections by a negative $\delta^{13}C$ excursion and a shift in the nannofossil fauna from cool, nutrient rich waters to warmer, less nutrient rich ones. These studies have shown the same pattern of findings (D'Onofrio *et al.*, 2006). The faunal composition at the Dababiya QPC in Egypt during the PETM shows a relatively small percentage of *C. pelagicus*. The area was largely dominated by species that thrive in warmer environments. Throughout the Italian Paleogene this species was present everywhere, but the population numbers fell when the climate reached its peak and distinct water layers appeared.

The Libyan sit e under investigation is from a geological sequence which dates to the end of the Paleocene period and is older than the PETM, but is not from the base of the Eocene. During the pre-PETM, the outer shelf waters of the southern Tethyan margin remained cool-temperate due to efficient water circulation. Despite this, a species called *Coccolithus pelagicus* remained unchanged. This situation was unaffected by extreme greenhouse effects. These isotopic values from a sample of calcium carbonate suggest several small-scale environmental disturbances and fluctuations in local plant life productivity.

5.3 Northeastern Libya in a southern Tethyan context

Given its paleogeographic position in north eastern Libya, this region was at the middle of the southern Tethyan seaway. This seaway connected the mid-Atlantic Ocean to the Tethys and the Indo-Pacific realms (Table 1).

Table 1. Summary of Coccolithus pelagicus abundance trends in relation to δ13C variations across Paleocene–Eocene records from Libya, Egypt (Dababiya), and Italy (Scaglia Rossa).

Location	δ13C Trend	Coccolithus pelagicus Abundance	Interpretation
Northeastern Libya	Mid-Paleocene δ13C high, decline near PETM	High, stable through Paleocene	Stable open-marine pelagic conditions prior to PETM; resilience of Coccolithus
Egypt (Dababiya GSSP)	Sharp negative excursion at PETM onset	Declines relative to Discoaster and Rhomboaster	Community restructuring; warming and oligotrophy reduce dominance
Italy (Scaglia Rossa)	Late Paleocene stable δ13C, drop at PETM	Reduced dominance at PETM, but persists	Similar resilience pattern; warming shifts community composition

These early Paleocene marine sediments at this site offer valuable evidence for scientists to study the dispersion of species from one region to another and the effects of the early Earth's greenhouse conditions on marine life. In southern Tethys, the conditions on the outer shelf during the late Paleocene were constant with the presence of moderate temperatures and a plentiful supply of nutrients, thus allowing *Coccolithus pelagicus* to thrive before this period of the PETM was interrupted by a period of warming and acidification of the oceans. These events are recorded in the fossil record as shifts in community composition. Research has been ongoing for more than 20 years on this particular aspect (Schulte *et al*., 2009; D'Onofrio *et al*., 2006; McInerney and Wing, 2011). The Libyan carbonate isotope curve of $\delta^{13}C$ has similarities to the worldwide trends of the Paleocene-Eocene Thermal Maximum, as shown in Fig. 6.

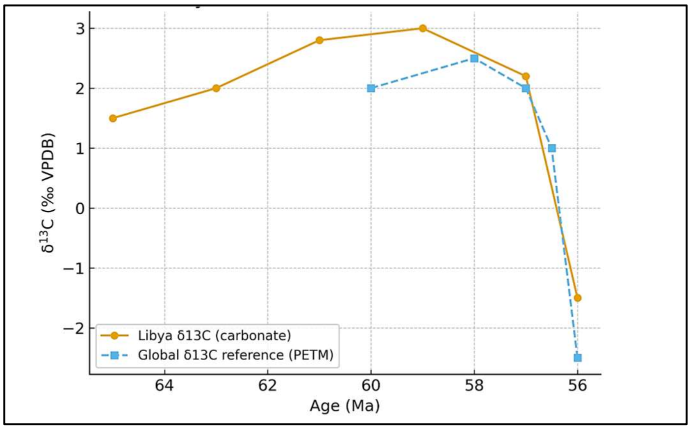

Fig. 6. Correlation of Libya $\delta^{13}C$ curve with global Paleocene–Eocene reference trend, highlighting the negative carbon isotope excursion (CIE) at the PETM.

Fig. 6 shows early stages of a negative $\delta^{13}C$ shift–this tie to the beginning of the Paleocene–Eocene Thermal Maximum. At the Al-Uwayliah site, the shift from one climate phase to another is captured. Yet because of an overlapping gap - the local Eocene base unconformity-the full depth of the $\delta^{13}C$ fluctuation disappears.

The combination of field photographs of outcrops of the chalk, with scanning electron microscope images of specimens of *C. pelagicus* and a curve of the isotopic composition of carbon in the chalk, helps in the paleoenvironmental reconstruction. Data from the outcrop and thin-section observations reveal that the sediment consists of fine-grained material deposited in the pelagic environment, which contains minimal terrigenous components. The SEM photographs show well-preserved *C. pelagicus* throughout the sample section, indicating continuous presence. Although a complete CIE for the PETM exists below the regional unconformity, which marks the base of the Eocene, the $\delta^{13}C$ profile indicates that a carbon-isotope signature in north-eastern Libya correlated with worldwide carbon cycle events.

6. Conclusions

The Al-Uwayliyah Formation is thought to have been deposited in open shelf carbonate ramp. This is shown in the minimal amounts of non-marine material within the formation and the presence of oxygen in the ancient water. There is also pelagic sedimentation within the formation. The chalky limestones in the study area are preserved and dated to the late Paleocene (late Selandian to Thanetian), which predates the Eocene. This interval falls within the late Selandian to Thanetian stages of the Paleocene. The combination of biostratigraphic and geological data supports the conclusion. The presence of calcareous nannofossil zone NP 9, and of the planktonic foraminifer zone Planorotalites pseudomenardii, confirms this age determination. The area of Jabal al Akhdar has undergone tectonic uplift, which brought about a regional break in the sequence, causing the loss of all Paleocene rock layers prior to the latter part of the Paleocene epoch. The nannofossil assemblages, rich in calcium carbonate, are dominated by Coccolithus pelagicus. This suggests that the late Paleocene surface waters were cool to temperate with a rich supply of nutrients and good mixing. A mid-Paleocene carbonate carbon-13 isotope positive anomaly exists. This anomaly declined slowly through the late Paleocene until it reached the Paleocene/Eocene boundary. It matches the worldwide pattern of the late Paleocene carbon cycle but lacks the negative shift in carbon-13 isotope seen in the rest of the world during the PETM. The geological record suggests the carbon isotope excursion at the PETM is truncated by an unconformity at the base of the overlying Eocene limestones. Integration of data from microfacies, nannofossils, scanning electron microscopy and stable carbon isotope analysis of the stratigraphy has provided Libyan scientists with the data they require to study the late Palaeocene environment around the southern margin of the Tethyan Sea. The location gives a useful insight into the environmental shift which occurred before the PETM in the nearby areas.

Acknowledgments

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