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## Marine Micropaleontology

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# Calcareous Nannofossil variability controlled by Milankovitch and sub-Milankovitch periodicity in the Monte San Nicola section (Gelasian GSSP / MIS 100–104)

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## ARTICLE INFO

## Keywords:

Gelasian  
Pliocene/Pleistocene boundary  
Nutricline depth variation  
Mediterranean

## ABSTRACT

The Quaternary marks the beginning of the ice ages, with the establishment of a stable Northern Hemisphere ice sheet. The Monte San Nicola section, southern Sicily (Italy) is the Global Boundary Stratotype Section and Point of the Gelasian Stage of the Lower Quaternary Subseries and is attracting new attention for providing valuable information on paleoclimate evolution.

Here we present a paleoenvironmental reconstruction based on new data from calcareous nannoplankton, the phytoplankton organisms that are sensitive to sea surface changes and water column dynamics. We adopt statistical and signal analysis to support our paleoenvironmental model. The most evident paleoenvironmental signal throughout the investigated interval is the contrast between the abundance patterns of placoliths and *Florisphaera profunda*, the former pointing to surface productivity (water column mixing, shallow nutricline), the latter to the establishment of a deep nutricline. The observed nutricline depth shift occurred with a regular precessional pace, following Northern Hemisphere summer insolation and, likely, North African monsoon activity. A significant periodicity of 8 kyr, in tune with late Quaternary Heinrich events, is also observed in nannoplankton taxa, supporting previous findings on the existence of suborbital climatic variability even at the Pliocene-Pleistocene transition.

## 1. Introduction

In Monte San Nicola section, the top of A5 sapropel (“Nicola bed”) is the Global Boundary Stratotype Section and Point (GSSP) of the Gelasian Stage, between Pliocene and Pleistocene Series and Neogene and Quaternary Systems (Cita et al., 2012; Rio et al., 1998). It is a boundary of

great interest in Stratigraphy because it corresponds to an interval of global paleoclimate evolution that marks the switch from “Cool-house” to “Icehouse” climate states (Westerhold et al., 2020), a key event in the climatic evolution of the Cenozoic. This interest is expressed by the recent effort of different research groups, that are revisiting the GSSP with modern analysis techniques (Stable isotope, Alkenon, X-ray

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<https://doi.org/10.1016/j.marmicro.2024.102397>

Received 28 June 2024; Received in revised form 11 September 2024; Accepted 13 September 2024

Available online 14 September 2024

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computed tomography) and approaches (high-resolution sampling) (Addante et al., 2024; Capraro et al., 2022; Radmacher et al., 2023; Zanola et al., 2024). This study deals with the new data on the calcareous nannofossil assemblages observed in the sediments from the Monte San Nicola area. It is aimed to assess and delineate the paleoenvironmental changes in the photic zone during the Pliocene-Pleistocene transition. In this way we intend to improve knowledge of the underlying mechanisms and regional responses to the intensification of the Northern Hemisphere Glaciation, which initiated from the glacial Marine Isotopic Stage (MIS) 100 and culminated with the definitive establishment of large Northern Hemisphere Ice Sheets and the periodic deposition of ice-rafted detritus (IRD) in the North Atlantic (Jakob et al., 2020; Rohling et al., 2014).

Calcareous nannoplankton/nannofossils are employed both in biostratigraphic and paleoenvironmental/paleoclimatic studies. They provide the highest biostratigraphic resolution in the Mediterranean zonations, e.g. an average resolution of 0.25 Ma in the late Gelasian-Calabrian interval (Di Stefano et al., 2023). They quickly respond to orbital and suborbital climate changes, at least since the Middle Pleistocene, especially in the Mediterranean area where these phenomena are significantly amplified (Di Stefano et al., 2015; Incarbona et al., 2022; Incarbona et al., 2008, 2009, 2013; Serrano, 2020). Calcareous nannoplankton also provide useful information for paleoenvironmental changes during the deposition of sapropel layers that represent a paleoceanographic extreme in terms of water mass physical-chemical properties (low salinity) and thermohaline circulation (Castradori, 1993; Incarbona et al., 2022; Incarbona et al., 2011; Negri et al., 1999).

Here we show high temporally resolved calcareous nannofossil data from the Monte San Nicola 'Mandorlo' section (Capraro et al., 2022). We planned the study of this section to complement a similar investigation on the historical type-section in which the Gelasian GSSP was defined (Rio et al., 1998), that gave poor results. From our preliminary unpublished analysis the nannofossil assemblages in the type-section appeared strongly affected by reworking of Neogene taxa, mostly *Discoaster* species, which obscured the biostratigraphic signal and hampered reliable palaeoenvironmental reconstructions. Furthermore, faulting and poor exposure conditions, observed a few meters above the Piacenzian/Gelasian boundary, compromised the type-section suggesting that the local stratigraphy was not continuous (see details in Capraro et al., 2022). By contrast, distribution patterns of taxa and groups in the 'Mandorlo' section and their statistical and signal analysis provide a sound new proof of concept for the reconstruction of the sea surface environment and water column dynamics across the Gelasian GSSP.

## 2. Material and Methods

### 2.1. Sediment samples and Chronology

The study area is located in the western sector of Monte San Nicola badlands, ca. 10 km North of Gela, southern Sicily (Italy; Fig. 1A). The local stratigraphy consists of a stack of deep-marine, cyclically organized muds that contain four sapropel clusters (O, A, B, C; Verhallen, 1987; Zijderveld et al., 1991). We focused our investigation on samples collected in the lower part of the "Mandorlo" section, in the interval between -300 cm (= top of sapropel A4; estimated age of 2.63 Ma) and + 700 cm (above the dark clayey layer associated to i-cycle 242; estimated age of 2.5 Ma) (Fig. 1B-C) (Capraro et al., 2022; Zanola et al., 2024). This interval includes the Sapropel layer MPRS A5 ("Nicola bed"), that is the lithological marker of the Gelasian GSSP (Rio et al., 1998). We constructed the age model through linear interpolation among 9 tie-points, identified in the distinctive peaks within the  $\delta^{18}\text{O}$  stratigraphy (MIS 99, 100, 102 and 104; ages from Lisiecki and Raymo, 2005) and in the sapropel layers (A5, A4/5, A4, A3 and A2; ages from Emeis et al., 2000; Lourens et al., 1996), following Zanola et al. (2024). The average sedimentation rate is 7.1 cm/kyr.

### 2.2. Calcareous Nannofossils

Calcareous nannofossil assemblages were studied from 101 samples picked every 10 cm (average resolution 1.34 kyr), prepared as standard smear slides (Bown and Young, 1998) and analysed with a polarized light microscope at x1000 magnification. We evaluated the relative abundance of in situ taxa by counting at least 500 specimens, and the abundance of reworked taxa by counting the number of reworked specimens versus in situ nannofossils. All abundances are expressed as percentage values. Taxa were identified following the taxonomic concepts used by Di Stefano et al. (2023) (and references therein), and by Young et al. (2003) and Jordan et al. (2004) for the extant species. All taxa, except for *Florisphaera profunda*, were organized in different groups: the "Placoliths", the Upper Photic Zone (UPZ) group, the *Discoaster* group, and the Miscellaneous (MS) group (Di Stefano and Incarbona, 2004; Incarbona et al., 2022; Incarbona et al., 2010b, 2013).

*Florisphaera profunda*, typical taxon of the lower photic zone, has been widely used to monitor past changes in nutricline depths (Beaufort, 1997; Incarbona et al., 2022; Incarbona et al., 2010a). It increases with respect to other coccolithophores when the nutricline is in the deep photic zone, in response to stratified and oligotrophic surface water at low- and middle-latitude (Baumann et al., 2005; Beaufort et al., 1997; HernándezAlmeida et al., 2019; Malinverno et al., 2009; McIntyre and Molino, 1996; Molino and McIntyre, 1990a, 1990b). However, during sapropel layers deposition in the eastern Mediterranean Sea, *F. profunda* benefits from the establishment of a distinct Deep Chlorophyll Maximum (DCM) (e.g., Cascella et al., 2021; Castradori, 1993; Incarbona et al., 2022; Kemp et al., 2000).

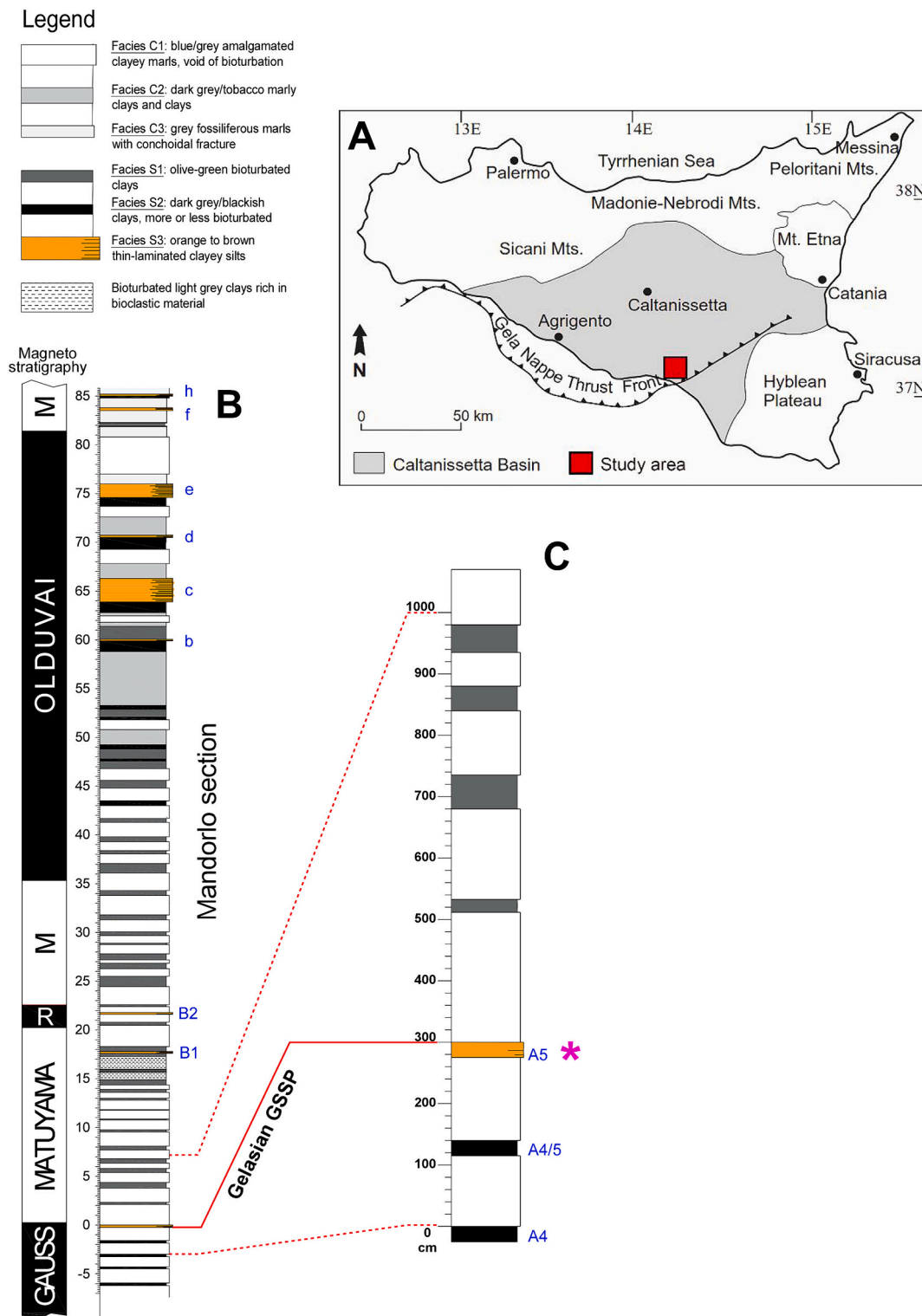
The Placoliths group includes small to medium-sized placoliths, such as *Pseudoemiliania lacunosa*, *Reticulofenestra* spp., and small *Gephyrocapsa*. Placoliths are r-strategist taxa, able to quickly respond to nutrient availability (e.g., Balestra et al., 2008; Broerse et al., 2000; Dimiza et al., 2008b, 2008a; Haidar and Thierstein, 2001).

The UPZ group includes *Umbellosphaera* spp., *Discosphaera tubifera*, *Rhabdosphaera* spp. and *Holococcoliths*. The UPZ species are considered K-strategist taxa, typical of warm and oligotrophic surface waters (Bonomo et al., 2012; Dimiza et al., 2008a; Oviedo et al., 2015; Young, 1994). The *Holococcoliths*, though belonging to different species, in living assemblages show an increasing abundance gradient from western to eastern Mediterranean Sea and a similar K-strategy (Bonomo et al., 2021; Dimiza et al., 2008b; Knappertsbusch, 1993; Oviedo et al., 2015). In studying Holocene fossil records, such as in the Sapropel S1, some authors attribute fluctuations in holococcoliths abundance to preservation effects and seafloor reventilation (e.g., Cascella et al., 2021; Incarbona et al., 2019). In older stratigraphic intervals, such as in the Pliocene and Pleistocene, holococcoliths preservation is also influenced by diagenetic processes. Consequently, we have chosen to include in the UPZ group the very rare holococcoliths observed, based on their ecological preferences.

The ecological preference of *Discoaster* taxa is still poorly-known (e.g., Aubry, 1998; Schueth and Bralower, 2015). However, there is a general agreement on their preference for warm and oligotrophic water, following their abundance at middle- and low-latitudes (Aubry, 1998; Bralower, 2002; ChepstowLusty et al., 1992; ChepstowLusty et al., 1989; Minoletti et al., 2001; Schueth and Bralower, 2015). According to Minoletti et al. (2001) discoasterids are shallow dwelling taxa, in contrast with other authors' suggestion as taxa with a deep photic layer preference (e.g., Aubry, 1998; Bralower, 2002; Schueth and Bralower, 2015).

The MS group includes *Helicosphaera* spp., *Pontosphaera* spp., *Umbilicosphaera* spp., *Calciosolenia* spp., and *Syracosphaera* spp. and all the other taxa which are very rarely found. MS group taxa thrive without a certain (or known) depth preference and have a wide range of ecological preferences (Incarbona et al., 2013; Young, 1994).

A final group (RN group) includes the observed reworked nannofossils from different stratigraphic intervals (Mesozoic, early Cenozoic)



**Fig. 1.** A) Position of the Monte San Nicola area (red box) within the Caltanissetta sedimentary Basin (Sicily). B) Essential stratigraphic information for the Mandorlo section. Left: magnetostratigraphy of the section. R: Reunion; M: Matuyama. Right: lithological log; legend is reported above. Individual sapropel layers are labelled in blue. C) Blowup of the stratigraphic interval of relevance for this study. Left: chronostratigraphic, lithological, and magnetostratigraphic logs (same as above). The red line marks the Piacenzian/Gelasian boundary. The dashed red line indicates studied interval. Purple asterisk indicate the “Nicola bed” (sapropel A5), physical reference for the Piacenzian/Gelasian boundary. (Modified from [Capraro et al., 2022](#)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the Cenozoic long-ranging taxa that show poor preservation (etching and/or overgrowth). Evaluation of reworked nannofossil abundance can provide useful information about land-ocean dynamics and sediment transport (Bonomo et al., 2014; Ferreira et al., 2008; Ferreira and Cachão, 2005), and permits to account for the continental terrigenous fluxes, that are useful for either paleoclimatic studies and reconstruction of large scale river runoff oscillation (Incarbona et al., 2009; Sprovieri et al., 2006).

The calcareous nannofossils percentage data are shown in supplementary material.

### 2.3. Signal analysis

The analysis of non-stationary (frequency changes with time) and non-linear signals was performed by applying the Ensemble Empirical Mode Decomposition algorithm (EEMD) by Wu and Huang (2009). The EEMD is an adaptive noise-assisted data analysis method that improves the ordinary Empirical Mode Decomposition (EMD) by Huang et al. (1998). Decomposition provides a powerful method to investigate the different processes behind a given time series data and separates in  $n$  IMFs short time-scale events from a general trend, highlighting sub-Milankovitch periodicities that are typically obscured by the more dominant Milankovitch periodicity (e.g., obliquity or precession). This technique assumes that any complicated signal can be decomposed into a finite, often small, number of components defined as “Intrinsic Mode Functions” (IMFs) (Huang et al., 1998). Each IMF represents an embedded characteristic simple oscillation on a separated timescale. IMF components were analysed with “REDFIT” and Cross Wavelet transform (XWT). All data were detrended prior to running the spectral analysis. All analyses were carried out with R (version 4.1.3) using the Rlibeemd (Luukko et al., 2016), dplr (Bunn, 2010), and Biwavelet (Liu et al., 2007) packages.

### 2.4. Statistical analysis

To compare nannoplankton compositional changes and abundance fluctuations with Marine Isotopic Stages (MIS), identified by Zanola et al. (2024) in the benthic foraminifera *U. peregrina*  $\delta^{18}\text{O}$  record, a stratigraphic constrained cluster analysis (clusters constrained by sample order) was performed with the software R (R - version 3.6.2) using the “rioja” package (Juggins, 2015 - version 0.9–26). The distance matrix was generated considering the relative abundance of five taxa/groups (placoliths, UPZ, *F. profunda*, *Discoaster*, MS). Data were first normalized, by subtracting the mean and dividing by the standard deviation (Wu et al., 2007).

## 3. Results

### 3.1. Calcareous Nanofossils

In the studied interval of Monte San Nicola ‘Mandorlo’ section, nannofossils are generally abundant and moderately or wellpreserved. In Fig. 2, the distribution patterns of nannofossil groups (Fig. 2 F, G, H, I) are shown in comparison with astronomical parameters (Laskar et al., 2004) (Fig. 2 C, D), *U. peregrina*  $\delta^{18}\text{O}$  record (Zanola et al., 2024) (Fig. 2 E) and sealevel reconstructions (Hayashi et al., 2020; Jakob et al., 2020) (Fig. 2 L, M).

Placoliths dominate the assemblage, with an average abundance of ~78 %, and show four main abundance minima. The first and more pronounced minimum coincides with the “Nicola Bed”, between 2.597 and 2.587 Ma, and is followed by other three episodes at 2.552–2.545 Ma, 2.525–2.520 Ma and 2.5 Ma (Fig. 2 H).

*Florispheera profunda* shows wide abundance fluctuations throughout the record, with an average abundance of ~10 % (min. ~2 % – max. ~26 %) (Fig. 2 F). Specifically we recognized five abundance peaks, the first two peaks in coincidence with the A4/5 (2.612–2.609 MA) and A5

(“Nicola Bed”; 2.593–2.588 Ma) sapropel layers, the other three within the olivegreen bioturbated clays intervals at 2.552–2.542 Ma (“ghost sapropel” interval of Becker et al., 2005), 2.525–2.520 Ma and 2.5 Ma (Fig. 2 F).

The MS group, that mainly consists of *Helicosphaera* spp. and *Umbilicosphaera* spp. specimens, is subordinated compared to placoliths and *F. profunda* throughout the studied interval, and shows a limited variability (usually between ~7 % and ~12 %) except for a high-abundance interval (mean value of ~22 %) between earliest MIS 104 (2.605 Ma) and “Nicola Bed” (2.580 Ma), that is comparable to the *H. carteri* and *H. sellii* increase reported by Addante et al. (2024), and for three distinctive peaks within MIS 100 (Fig. 2 G).

UPZ and *Discoaster* groups are largely subordinated to other groups/taxon, with percentages ranging between 0 and ~5 % and between 0 and ~2 % respectively (see supplementary material for percentage data).

Reworked nannofossils are present in all samples with an average abundance of ~37 % (min. ~20 % max. ~60 %) (Fig. 2 I). We identified three increasing trends, all of them characterized by a sharp abundance decrease in MIS 103 (2.588 Ma) just above the “Nicola Bed”, MIS 101 (2.557 Ma) and MIS 99 (2.505 Ma) (Fig. 2 I).

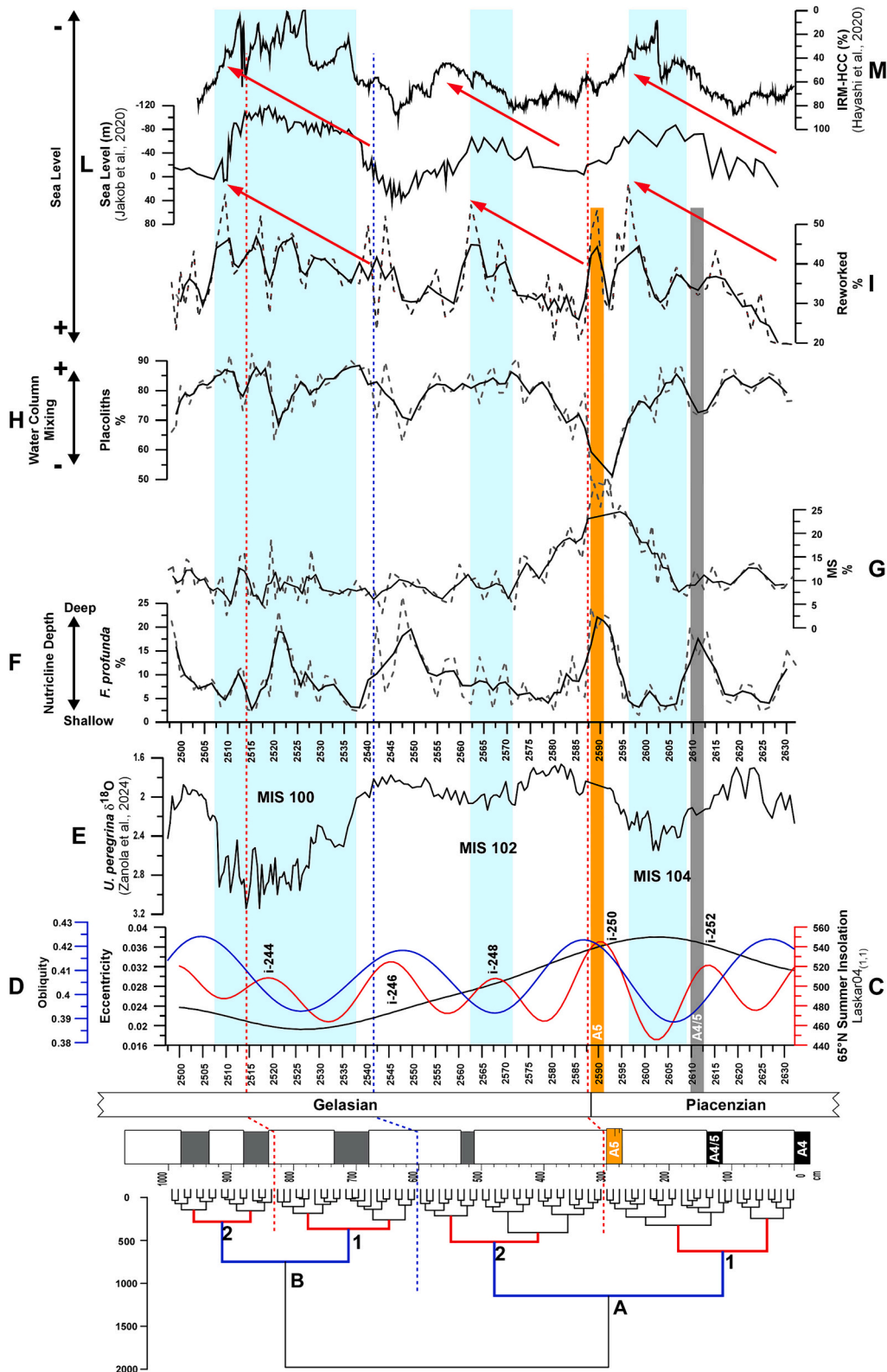
### 3.2. Statistical and signal analysis

The cluster analysis (Fig. 2 bottom side) allows the definition of two main groups of calcareous nannofossil assemblages, that characterize the intervals from the base of the section up to 2.542 Ma (cluster A) and from 2.542 Ma up to the top (cluster B). Both A and B clusters are further subdivided in subclusters as follows:

- the Piacenzian interval, that includes MIS G1, MIS104 and the onset of MIS103, characterized from the base of the section to 2.588 Ma by a sharp abundance decrease of placoliths group, increase in abundance of MS group, and two high abundance peaks of *F. profunda*, the youngest of which is coincident with the “Nicola Bed” (Subcluster A1);
- the earliest Gelasian, that includes MIS103, MIS102 and MIS101, characterized from 2.588 to 2.542 Ma by a sharp abundance increase of placoliths group, decrease in abundance of MS, UPZ and *Discoaster* groups and a gradually increase of *F. profunda* (Subcluster A2);
- the lower part of MIS100, characterized from 2.542 to 2.514 Ma by a slight abundance increase of MS group and an abundance peak of *F. profunda*, coincident with an abundance decrease of the Placoliths group (Subcluster B1);
- the upper part of MIS100 and MIS99, characterized from 2.514 Ma to the top of the section by an abundance increase of *F. profunda* and by an abundance decrease of placoliths group (Subcluster B2).

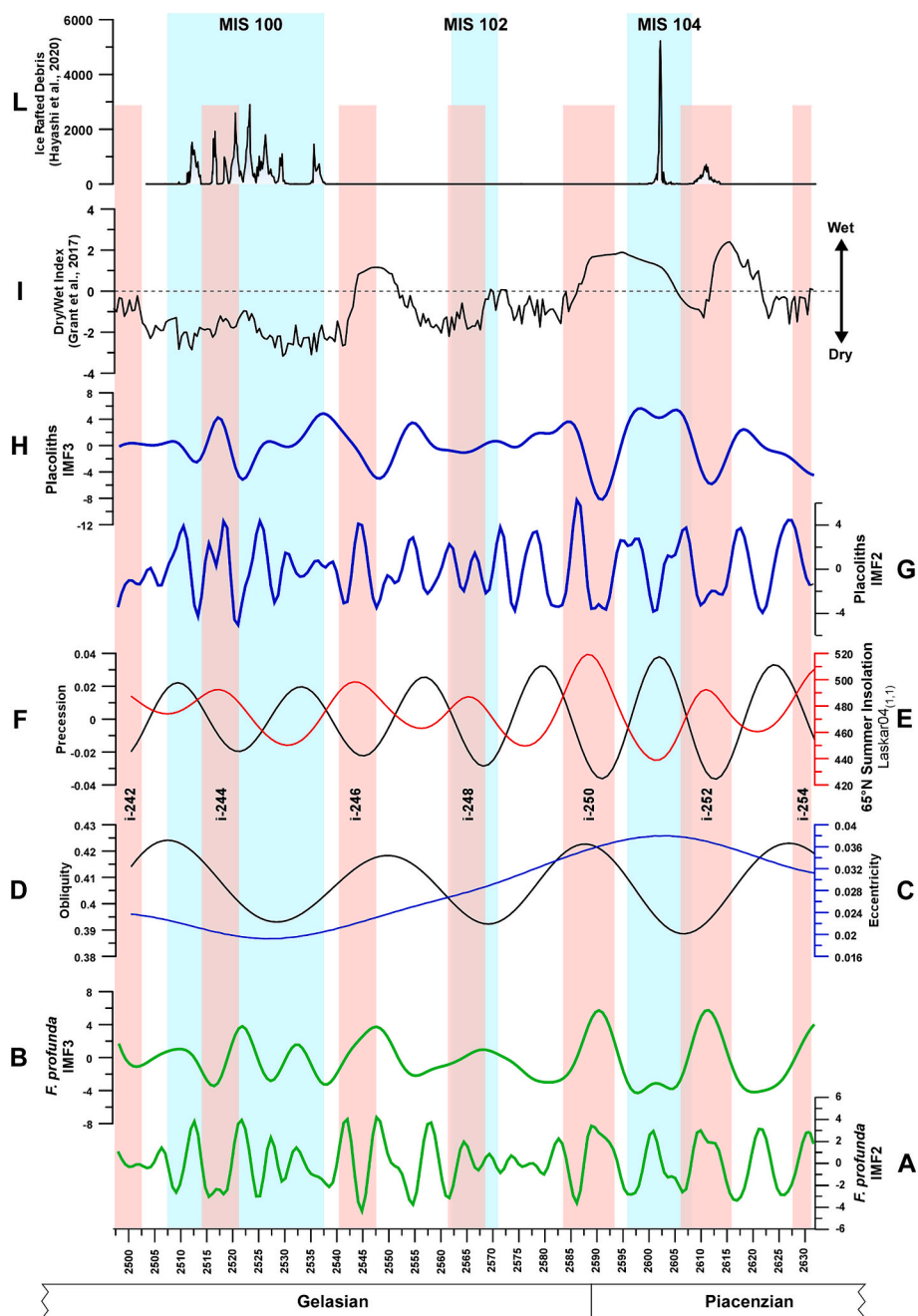
The EEMD analysis reveals five intrinsic mode functions (IMFs) plus the trends (IMFs 6) for *F. profunda* and placoliths signals. A first visual analysis of all IMFs shows that IMF2 and IMF3 recorded potentially significant subMilankovitch and Milankovitch periodicities respectively. Instead, all IMF1 and IMFs 4 to 6 recorded predominantly noise or trends. Thus, they were ruled out from the successive analysis. To get analytical results of periodicities, we applied REDFIT and CrossWavelet transform (XWT) on a total of 4 IMFs and the spectra. In Fig. 3 (A, B, and G, H), the IMF2s and IMF3s of *F. profunda* and placoliths are shown. Periodicities above 95 % of confidence interval (CI) are reported in Table 1.

The result highlights that the IMFs 3 component has a main peak at ~21 kyr, above the 95 % CI and, in the XWT analysis, a continuous anticorrelation between placoliths and *F. profunda* (Fig. 4 B). The visual correlation between summer insolation and all IMF3 suggests constant synchronicity between positive (negative) *F. profunda* (placoliths) peaks.



**Fig. 2.** – Line plots (dashed line = raw data; continuous line = 3 points running average) in time domain of selected calcareous nanofossils ([F] *F. profunda*, [G] MS group, [H] Placoliths group, [I] Reworked coccoliths) for the studied time interval, compared with [E] *U. peregrina*  $\delta^{18}O$  (Zanola et al., 2024), [L] relative Sea Level curve for the North Atlantic (Jakob et al., 2020), [M] IRMHC highcoercitivity component of isothermal remanent magnetization (Hayashi et al., 2020), [D] obliquity (blue line) eccentricity (black line) and [C] 65°N Summer insolation (red line) of the Laskar04<sub>(1,1)</sub> astronomical solution (insolation cycle numbers are reported). Orang and dark grey bands represents the A5 and A4/5 sapropels respectively. Light blue bands indicate glacial intervals (MIS104, 102, and 100 are reported). Red arrows represent sea level drop intervals.

In the bottom side: Stratigraphic constrained cluster analysis (continuous and dashed blue lines mark clusters A and B; continuous and dashed red lines mark subclusters A1, A2, B1, B2), chronostratigraphic, and lithological logs are reported. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 3.** –Line plots in time domain of IMF 2 and 3 of the [AB] *F. profunda* (green line) and [GH] Placoliths group (blue line) compared to [DC] obliquity, eccentricity, [FE] precession, and summer insolation (June) at 65°N according to the La04<sub>(1,1)</sub> orbital solution of Laskar et al. (2004) (insolation cycle numbers are reported), [I] dry/wet index of Grant et al., 2017, and [L] Ice Rafted Debris of Hayashi et al., 2020. Light blue and red bands indicate glacial intervals and insolation maxima respectively (MIS104, 102, and 100 are reported). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**  
Periodicity above 95 % CI, extracted from the IMF2 and IMF3 of the *F. profunda* and Placoliths group.

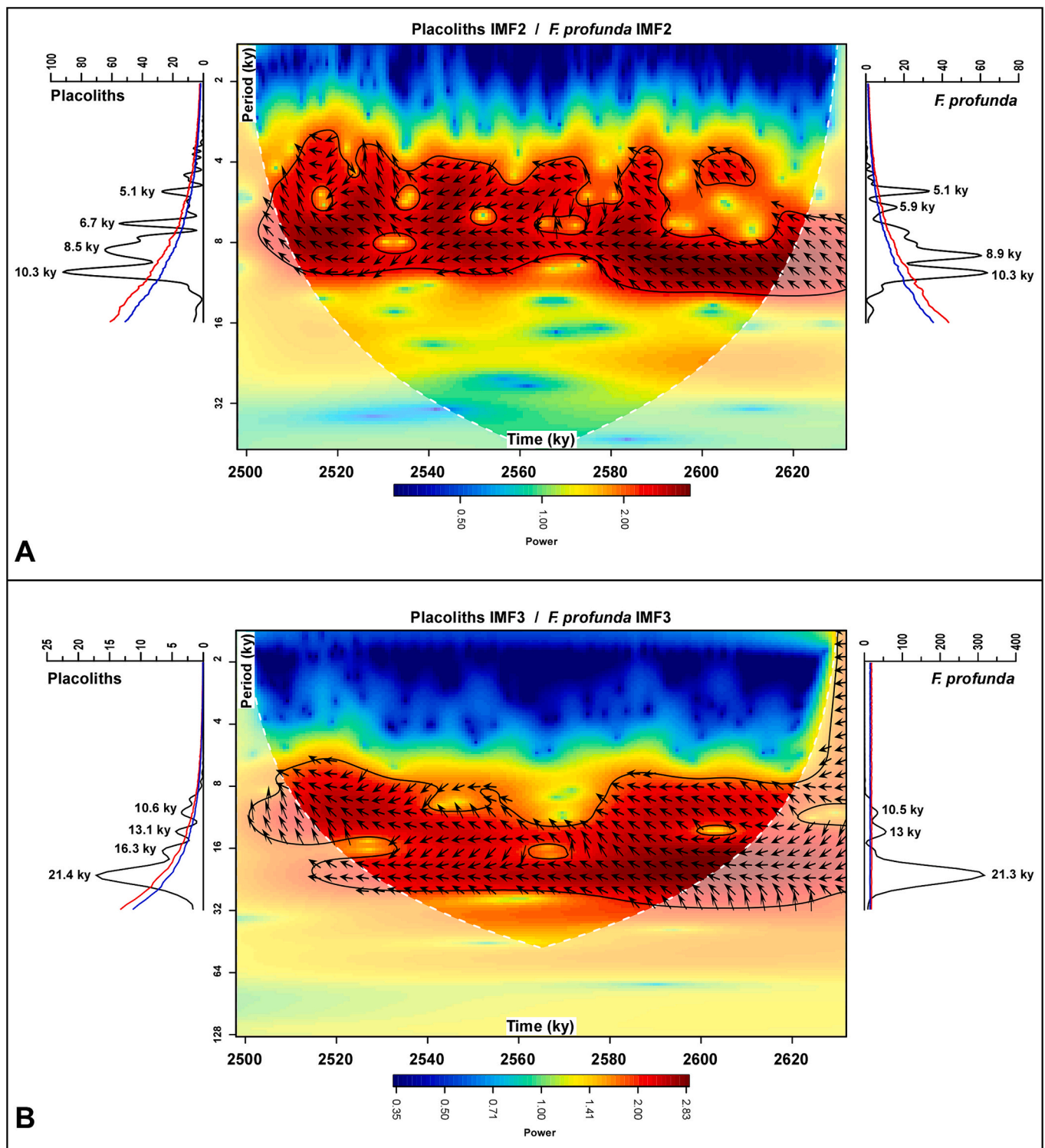
	IMF2	IMF3
<i>F. profunda</i>	10.32 kyr	21.35 kyr
	8.96 kyr	13.05 kyr
	5.91 kyr	10.58 kyr
	5.12 kyr	
	10.39 kyr	21.48 kyr
Placoliths	8.52 kyr	16.38 kyr
	6.78 kyr	13.10 kyr
	5.15 kyr	10.67 kyr

The IMFs 2 component shows high frequency periodicities, mainly at ~6 kyr and ~8 kyr. In the IMFs2 XWT analyses only the ~8 kyr periodicity show a continuous anticorrelation between placoliths and *F. profunda* (Fig. 4 A).

#### 4. Discussion

##### 4.1. Paleoenvironmental reconstruction

The Mediterranean area was particularly sensitive to Late Pliocene/ Early Pleistocene climatic changes, both in marine and continental settings (e.g., Bertini, 2010; CombourieuNebout et al., 2015; Fusco, 2010).



**Fig. 4.** Spectral analysis (line plots) of the [A] IMF2 and [B] IMF3 components for the Placoliths group and *Florisphaera profunda* unravelling the presence of orbital (precession) and suborbital periodicity in the 21 kyr and 6–8 kyr time domain respectively. Periodicities above 90 % (blue line) and 95 % (red line) of C.I. are reported. Cross wavelet analysis of IMFs (contour plots) confirming their pervasive occurrence throughout the studied interval. The white dashed lines and the white shaded area indicate the cone of influence boundary, Black line indicates 95 % C.I., black arrows indicate correlation (right arrows) and anticorrelation (left arrows) between Placoliths group and *F. profunda*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The most evident paleoenvironmental signal throughout the investigated interval is the contrasting abundance patterns of Placoliths and *F. profunda*, that countercorrelate and point to surface productivity (water column mixing, shallow nutricline) and the establishment of a deep nutricline, respectively (Beaufort et al., 1997; Incarbona et al.,

2008). These repeated water column dynamics, and the absence of a relevant amount of other nannofossil groups, are similar to the signals recorded in the eastern Mediterranean Sea during the Middle Pleistocene (Incarbona et al., 2022), including the strict link between *F. profunda* abundance peaks and Northern Hemisphere summer

insolation (insolation cycles i252/i242, see Fig. 2 C). In analogy with the most recent sapropel layers (Castradori, 1993; Kemp et al., 1999; Rohling and Gieskes, 1989), for sapropels A5 (“Nicola bed”) and A4/5 the nutricline uplift into the photic zone and the development of a distinct DCM can be inferred (Fig. 2 F), as possibly due to enhanced East African monsoon rainfall and the subsequent freshwater discharge into the eastern Mediterranean (Amies et al., 2019; Grant et al., 2022; Rohling et al., 2002). However, this phenomenon has occurred beyond sapropel layers deposition, at the top of MIS 101, in the early MIS 99 and within MIS 100 (Fig. 2 F, H; Fig. 3 – A, B, G, H). Comparison with the humidity/aridity index may explain part of the *F. profunda* IMF3 signal (Fig. 3 I), but also reveals some discrepancies, because rainfall in North Africa does not necessarily imply a sufficient northward monsoon penetration and the subsequent river runoff into the Mediterranean Sea (Grant et al., 2022; Incarbona et al., 2022). Particularly interesting is the development of a deep nutricline within the glacial MIS 100, around 2.520 Ma, that supports the hypothesis of a nutricline shoaling within the lower photic zone, occurring during drastic eustatic sealevel drops when water mass transport at Gibraltar and Sicily Straits was reduced (Incarbona et al., 2022; Myers and Haines, 1998; Rohling and Hilgen, 1991).

From the point of view of Milankovitch periodicities, the calcareous nannofossil fluctuations was modulated following the 21 kyr precession pace, as evidenced by comparison with the Northern Hemisphere summer insolation (Fig. 2 C), Placolith and *F. profunda* IMF3 (Fig. 3 B, H), and power spectra (Fig. 4 B) records. This 21 kyr precession pace of nannofossil fluctuations is in line with what was inferred by Addante et al. (2024).

Obliquity-driven paleoenvironmental changes are not visible from the signal analysis of single nannofossil groups or taxon. However, they have influenced the overall coccoliths assemblage, namely the clusters and subclusters in Fig. 2 (bottom side). In fact, clusters A and B reflect the intensification of Northern Hemisphere Glaciation that began since MIS 100, traditionally recognized as the marker of the “beginning of the ice ages” (Shackleton et al., 1984). The subclusters A1, A2, and B1, which enclose three obliquity minima, mirror the MIS104, 102, and 100 glacial intervals (Fig. 2 D). The effect of glacial/interglacial cycles is even more evident in the signal provided by reworked nannofossil, as a response of eustatic sealevel changes (Fig. 2 – I, L, M) and land erosion, that is by far effective during dry phases (Incarbona et al., 2010a; Incarbona et al., 2009).

Nannofossil signal analysis supports the response of planktonic assemblages also to suborbital climate variability, as already identified in the Monte San Nicola section by Becker et al. (2005) (based on planktonic and benthic foraminiferal  $\delta^{18}\text{O}$ ) and Zanola et al. (2024) (based on planktonic and benthic foraminiferal  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ), and it is particularly expressed in MIS 100. High-frequency variability, as recorded in *F. profunda* and MS abundance within MIS 100, suggests the rapid response by phytoplankton to suborbital climate changes (Fig. 2 – F, G; Fig. 3 A). Signal analysis confirms the occurrence of significant (> 95 % CI) suborbital periodicities in Placoliths and *F. profunda*, with only the periodicity around 8 kyr continuously recorded throughout the section (Fig. 3 – A, G; Fig. 4 A) and compatible with last glacial Heinrich events (Bond et al., 1992; Heinrich, 1988). The response of nannoplankton assemblages to Heinrich events depends on the hydrological setting. In the Iberian Margin and in the Gulf of Cadiz, *F. profunda* increases during Heinrich events, possibly because icebergs melting triggers a deep photic zone stratification (Colmenero-Hidalgo et al., 2004; Incarbona et al., 2010a). In contrast, in the central-western Mediterranean Sea, *F. profunda* increases in the lower part of interstadials (Incarbona et al., 2013). In the Mandorlo section, *F. profunda* abundance peaks are mainly aligned with the *U. peregrina*  $\delta^{18}\text{O}$  lighter values (Zanola et al., 2024), thus suggesting a similarity with the last glacial Mediterranean Sea (Incarbona et al., 2013). A higher-resolved analysis and the study of different planktonic organisms could further improve the understanding of these phenomena during the earliest Pleistocene.

## 5. Conclusion

We performed a high-resolution study of calcareous nannofossils on samples from the Gelasian GSSP outcrop (Italy, Southern Sicily), with the aim to assess and delineate the paleoenvironmental changes in the photic zone during the Pliocene-Pleistocene transition.

We identified the most evident paleoenvironmental signal throughout the investigated interval is the contrasting abundance patterns of Placoliths vs. *F. profunda*, that point to a surface productivity (water column mixing, shallow nutricline) and to the establishment of a deep nutricline, respectively. The nutricline depth variability follows the 21kyr pace of precession and Northern Hemisphere summer insolation, suggesting the principal role of salinity (related to North African monsoon) for water column dynamics.

The nannofossil clusters/subclusters and reworked specimen abundance respond to glacial and interglacial cycles, and to the establishment of the Northern Hemisphere ice sheet (MIS100). The signal analysis further highlights a significant periodicity of nannofossil taxa for 8 kyr, suggesting the quick response of phytoplankton even to suborbital climate changes.

Finally, we fully agree with Capraro et al. (2022) that suggest the “Mandorlo” section as the most suitable section for the Piacenzian-Gelasian and Pliocene-Pleistocene boundary and appropriate for hosting the Astronomical Unit Stratotype of the Gelasian Stage.

## Author Statement

All authors have approved the manuscript and agree with its submission to Marine Micropaleontology.

This manuscript has not been published nor is under consideration by another journal.

## CRediT authorship contribution statement

**Sergio Bonomo:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Elena Zanola:** Writing – review & editing, Data curation, Conceptualization. **Alessandro Incarbona:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Agata Di Stefano:** Writing – review & editing, Conceptualization. **Salvatore Distefano:** Writing – review & editing, Conceptualization. **Viviana Barbagallo:** Writing – review & editing, Data curation, Conceptualization. **Eliana Fornaciari:** Writing – review & editing, Conceptualization. **Patrizia Macri:** Writing – review & editing, Conceptualization. **Isabella Raffi:** Writing – review & editing, Conceptualization. **Nadia Sabatino:** Writing – review & editing. **Fabio Speranza:** Writing – review & editing, Conceptualization. **Mario Sprovieri:** Writing – review & editing. **Enrico Di Stefano:** Writing – review & editing, Supervision, Conceptualization. **Rodolfo Sprovieri:** Writing – review & editing, Supervision, Conceptualization. **Domenico Rio:** Writing – review & editing, Supervision, Conceptualization. **Luca Capraro:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare no competing financial and nonfinancial interests, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

## Data availability

Data in supplementary material

## Acknowledgments

AI acknowledges the support received from the NBFC, funded by the

Italian Ministry of University and Research, PNRR, Missione 4 Componente 2, project CN00000033, and the project PRIN 2022 - CUPES3D23004280006 - TIMPLEMED.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marmicro.2024.102397>.

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