Integrated paleohydrology reconstruction and Pliocene climate variability in Cyprus Island (eastern Mediterranean)

Efthymios Tsiolakis¹, Stella Tsaila-Monopoli², George Kontakiotis³, Assimina Antonarakou¹, Mario Sprovieri⁴, Maria Geraga², George Ferentinos², George Theodorou³, Andreas Zissimos¹

¹Cyprus Geological Survey Department, Lefkonos, 1, 1415, Nicosia, Cyprus
²Faculty of Geology, University of Patras, Panepistimioupoli Patron, Patra 265 04, Greece
³Faculty of Geology & Geoenvironment, Department of Historical Geology-Palaeontology, National & Kapodistrian University of Athens, Panepistimiopolis-Zografou, 15784, Greece
⁴Istituto per l’Ambiente Marino Costiero (IAMC-CNR), Italy

aantonar@geol.uoa.gr

Abstract. The present study describes the Pliocene paleoenvironmental evolution and the main paleoclimatic trends of Cyprus Island (southeastern Mediterranean) reconstructed using planktonic foraminifera. The Essovouyes-Exovouyes section, which is located on the boundary of Messaoria basin in the north and Larnaka basin in the south, corresponds to a continuous record from 5.21 to 1.8 Ma and therefore provides good data for the paleoclimatic reconstruction northeast of the Troodos mountain range. The sedimentary sequence of the studied section is about 90 meters thick and characterized of pinkish to brownish massive marls, rhythmic sedimentary cycles of yellow to light grey homogeneous marls and brownish organic-rich laminated layers, brown to light grey sandy marls, light yellow marly sands enriched in macrofossils, and yellow massive fine- to coarse-grained bioclastic calcarenites at the top. We particularly focused on its middle part (3.9-3.0 Ma time interval), which consists of well-preserved cyclic marine sediments, including organic-rich laminated brownish sapropelitic layers alternating with grey homogeneous marls. This part of the section was measured and sampled at 0.1 to 0.55 m intervals, which allowed us to perform a detailed biostratigraphic analysis. Seven astronomically dated planktonic foraminiferal bioevents were recognized and constrained the age model of the studied interval through the linear interpolation. Within this biostratigraphic framework, the first occurrence of *Globorotalia crassaformis* is highlighted in this study and confirms the presence of the Zanclean/Piacenzian boundary (3.6 Ma). Integrated micropaleontological, sedimentological, and geochemical (Total Organic Carbon; TOC, and stable oxygen and carbon isotope; $\delta^{18}$O, $\delta^{13}$C) analyses revealed the presence of numerous cycles that resulted in the sapropelitic/homogeneous marl alternations. The sapropelites developed around the Zanclean/Piacenzian boundary suggest a climate characterized by fluctuations of warm/temperate to humid conditions associated with a highly stratified water column at times of precession minima. Moreover, long term trends in oxygen isotopes are correlated with the sea surface temperature (SST) record derived from the planktonic foraminiferal assemblages (Planktonic Paleoclimatic Curve; PPC) and mostly reflect changes in global climatic conditions, with a more local or regional signal superimposed on this record. In particular, both the PPC and $\delta^{18}$O records indicate three distinct warm periods.
interrupted by two cooling events centred at 3.62 and 3.54-3.36 Ma respectively. Furthermore, the statistical analysis of the planktonic foraminifera revealed that the surface primary productivity and temperature show the highest explanatory power for their distribution and influence the hydrological regime of the studied area. Overall, this work confirms that multidisciplinary strategies and multiproxy study performed on Neogene sections can provide a powerful tool for monitoring the palaeoclimatic evolution of the eastern Mediterranean in relation to the global climatic system over the Pliocene.

1. Introduction

The Pliocene epoch (5.33-2.58 Ma) represents a time of exceptional interest for deciphering the impact of global climatic and paleoceanographic changes. Particularly, the early Pliocene [1-3] as well as the mid-Pliocene Warm Period (mPWP: 3.3-3.0 Ma) [4, 5] experienced an extremely warm climate compared to the average of the Quaternary, and therefore have become a highly valued geological target in which to explore climate processes in a warmer world. With respect to the pre-industrial era, early to middle Pliocene surface temperatures over land and oceans were elevated [6-8], and climate model estimates indicate that the global annual mean surface temperature was 2.70 to 4.05°C higher [9-11] with significant latitudinal differences [12, 13]. The hydrological cycle was enhanced [11, 14], ice sheets were smaller [15], sea-level was higher [16, 17], forest cover was expanded [18] and arid deserts were contracted [18]. Moreover, the similarity of the Pliocene palaeogeography to that of today, the occurrence of fossil assemblages similar to modern ones, and the well-preserved marine geological records [6, 19] indicate that a relatively good insight into the ocean conditions and biosphere during a warm global Pliocene climate can be assembled. Therefore, such key intervals provide documentation and a better understanding of a warmer-than-present world, and the predictive ability of climate models [15]. Given the benefits derived from this synergy, this timespan could be considered as a priority for both environmental reconstruction and climate modelling.

The Neogene marine stratigraphy in the eastern Mediterranean Sea has been of great interest to Earth scientists, with its sedimentary sequences exposed on land to reflect paleoceanographic and paleoclimatic conditions that have undergone considerable variations [20-25]. The cyclic sedimentary sequences of marls and marly limestones known as the Zanclean “Trubi Formation” [8, 26] and the high frequency alternations of marls and organic-rich sapropelitic layers [27] that intersect the Zanclean/Piacenzian (Z/P) boundary represent relevant examples of establishing their link with orbital precession forcing and monsoon-induced hydrological changes in the Mediterranean region [28-30]. Therefore, the sedimentary archive of the eastern sector of this marginal basin represents one of the best disposed areas for Pliocene reconstructions [26, 27, 31, 32]. Simultaneously, the dynamics of planktonic foraminiferal communities are of paramount significance in paleoenvironmental studies, because they quickly respond to oceanographic changes primarily involving temperature, salinity, primary production, and water column stratification and density variations [33-44]. Moreover, the calcareous planktonic foraminiferal biostratigraphy historically provides a first-order chronostratigraphic framework in many land-based sedimentary sequences.

The Mediterranean basin due to its latitudinal position in combination with its semi-enclosed, the configuration is very sensitive to climatic perturbations [33, 45], and therefore, its sediment consists of physical recorder of the paleoclimatic processes that took place in the past. Especially for the Cyprus Island, due to its location under high latitude obliquity and mid-low latitude precessional influence, it provides an ideal area for the interpretation of paleoceanographic records [46]. Here we present the first multidisciplinary high-resolution study of the stratigraphic interval encompassing the Z/P transition in Cyprus. The studied succession, the Essouyoues-Exouyoues section, belongs to one of the most impressive outcrops of the lower-middle Pliocene deposits in the entire eastern Mediterranean basin. We explicitly focus on the paleoceanographic and paleoclimatic conditions, shedding light on
the climate in the easternmost Mediterranean basin and on the nature of global teleconnections during the “warm Pliocene”.

2. Material and Methods

2.1. Geological setting and sedimentology

The Essovouyes-Exovouyes section consists of two tabular hills with Plio-Pleistocene sediments, which are located at the boundary of Central Mesaoria basin to the north and Larnaka basin to the south, at the northeastern margins of the Troodos Mountain Range in Cyprus island (Figure 1). The 90 meters thick sedimentary sequence of the Essovouyes-Exovouyes composite section is overlying with clear unconformity above grey laminated marls and white gypsiferous marls of the Messinian (Kalavasos Formation). From the bottom to the top consists of pinkish to brownish massive marls, rhythmic sedimentary cycles of yellow to light grey homogeneous marls and brownish organic-rich laminated layers, brown to light grey sandy marls, light yellow marly sands enriched in macrofossils, and yellow massive fine- to coarse-grained bioclastic calcarenites at the top (Figure 2). This work is focused on the 24 meters thick lower middle part of the Essovouyes-Exovouyes composite section, which consists of 35 rhythmic sedimentary cycles each one of which is comprised by a grey homogeneous marl layer alternating with one organic-rich brownish laminated sapropelic marly layer (Figures 1 and 2).

![Figure 1. Location map of the studied area](image)

2.2. Micropaleontological and geochemical analyses

The studied section was measured and sampled at 0.1 to 0.55 m intervals, and a total of 81 samples were processed for foraminifera using standard separation techniques. Quantitative and qualitative planktonic foraminiferal analyses were carried on the studied samples by counting at least 300 specimens per sample from splits of the 125 μm size fraction using an Otto micro-splitter. All planktonic foraminifera were identified and counted and the data were transformed into percentages over the total abundance of planktonic foraminifera. The planktonic paleoclimatic curve (PPC; Figure 3) was constructed using the equation \((w-c)/(w + c) \times 100\), where \(w\) represents warm-water and \(c\) cold-water indicators respectively [47, 48]. The sea surface productivity curve (SSP or E-index of [33]; Figure 3) was estimated using the sum of the eutrophic species versus the sum of the eutrophic plus
oligotrophic species. In order to decode the paleoenvironmental factors that affected the studied interval, we also carried out a Principal Component Analysis (PCA) on the planktonic foraminiferal assemblages using the PAST multivariate statistical software package. This method combines samples with similar species composition to simplify the data set into a small number of independent factors. Total organic carbon (Corg) concentrations (Figure 3) were carried out in 81 dried and homogenized samples using an ELTRA CS810 coal-sulfur analyzer, following the high temperature dry burning method, according to the ISO 10694: 1995 "Soil quality - Determination of organic and total carbon after dry combustion". All analyses were done in duplicate in the chemical laboratory of the Cyprus Geological Survey Department. Geochemical analysis (Figure 3) further consists of stable oxygen ($\delta^{18}$O) and carbon ($\delta^{13}$C) isotope analysis on 30 specimens of the planktonic foraminifer *Glogigerinoides ruber*. The isotopic analyses were carried out at the “Istituto per l’Ambiente Marino Costiero (IAMC-CNR)” in Italy.

3. Results and discussions

3.1. Chronostratigraphic framework of the section

From the qualitative and quantitative analyses, 34 planktonic foraminifera species were identified, which allowed us to recognize seven astronomically dated bioevents for the chronostratigraphic reconstruction of the studied section. In particular, were recognized the LCO *Globorotalia margaritae* (3.98 Ma), LO *Globorotalia margaritae* (3.81 Ma), FO of *Globorotalia crassaformis* (3.6 Ma), disappearance of *Globorotalia puncatulata* (3.57 Ma), reappearance of *Globorotalia crassaformis* (3.35 Ma), reappearance of *Globorotalia puncatulata/Globorotalia bononiensis* (3.31 Ma) and LO of *Sphaeroidinellopsis* (3.19 Ma) (Figure 2). The first occurrence of *G. crassaformis* is highlighted in this study and confirms the presence of the Z/P boundary (3.6 Ma). The studied section ranges from the upper part of MPL3: *G. margaritae-G. puncticulata* Concurrent Range Zone to the lower part of the MPL5a: *G. bononiensis* Interval Subzone [49]. The above astronomically dated planktonic foraminiferal bioevents were used to constrain the age model of the studied interval through linear interpolation, which spans from 3.98 to 3.0 Ma.

3.2. Paleoclimatic and paleoceanographic implications

Alternating oligotrophic and eutrophic planktonic foraminiferal assemblages were observed, reflecting changes in the marine environment during the deposition of the homogeneous and laminated marls respectively, in response to climatic variations. In particular, within grey homogeneous marls the species *G. falconensis*, *G. glutinata*, *G. decoraperta*, *G. ruber* and *N. acostaensis* are abundant. In laminated layers, the species *N. acostaensis*, *G. bulloides*, *G. falconensis*, *G. apertura*, *G. obliquus*, *G. trilobus* and *G. ruber* are dominated. The statistical analysis revealed three main factors PCA-1, PCA-2 and PCA-3, which represents 76.25% of the total variance. The PCA-1 factor, which represents 46.19% of the variance is expressed positively by loadings of the eutrophic species *N. acostaensis* and *G. bulloides*, and negatively by loadings of the oligotrophic species *G. ruber*, *G. apertura* and *G. obliquus* [29, 33, 48]. Therefore, PCA1 could be considered as the marine productivity factor. The PCA-2 factor, which represents 18.94% of the biodiversity, also exhibits a bipolar character. The positive loading taxa (*G. apertura* and *G. ruber*) thrive in warm waters, while the negative loading taxa (*G. falconensis*, *N. acostaensis*) prefer colder conditions [33, 47, 48]. Therefore, PCA2 could be considered as a temperature axis, with higher temperatures towards its positive side. The third varimax factor (PCA-3) explains 11.12% of the total variance and is also bipolar with the one pole to be expressed positively by species living in a highly stratified water column (e.g. *G. apertura* and *G. ruber*) and negatively by species typical of the weak development of these conditions (e.g. *T. quinqueloba*, *G. scitula*, *G. glutinata*) [33, 47, 48]. Henceforth, this is referred to as the stratification factor. In figure 3 is illustrated the strong correlation between the above factors with SST and SSP curves. Based on our results, mainly the primary productivity and secondly the sea surface temperature and water column stratification show the highest explanatory power for the planktonic foraminiferal distribution, and influence the hydrological regime of the studied area.
Figure 2. Chrono-stratigraphic column of the Essovouyes-Exovouyes section with relative frequencies of the most representative planktonic foraminifera, along with the recognized bioevents.

Figure 3. Correlation between PPC and SSP curves with PCA 1, PCA 2 and PCA 3.
From the bottom to the top of the studied interval, shortly before the first occurrence of *G. crassaformis* at 3.6 Ma, low-amplitude fluctuations of mainly negative $\delta^{18}O$ values are observed between -2.30‰ to 0.71‰, indicating the first long-term warm period in our record. The highest TOC values in sapropelic layers have been also recorded within this interval (Figure 4). Around 3.6 Ma, the first high positive $\delta^{18}O$ value of 1.91‰ has occurred, indicative of an abrupt cooling event. Upwards, for the time interval between 3.59 to 3.45 Ma, the second interval with relatively light $\delta^{18}O$ values ranging from -1.54 to 0.30‰ is documented, which corresponds to the second short-term warm period recorded at the studied sedimentary sequence. The heaviest $\delta^{18}O$ value (4.59‰) measured at ~3.36 Ma represents a strong cooling event at the early Piacenzian. Finally, between 3.20 to 2.99 Ma, a third warm period was recognized, as evidenced by the negative $\delta^{18}O$ values (up to -2.51‰).

![Figure 4](image)

**Figure 4.** Correlation between Total Organic Carbon (TOC), oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) stable isotopes, Sea Surface Productivity (SSP) based on Eutrophicated species, Planktonic Paleoclimatic Curve (PPC) with insolation, obliquity and eccentricity curves [50] during Zanclean-Early Piacenzian

Comparison between the PPC and the $\delta^{13}C$ record (Figure 4) shows an excellent similarity in long- and short-term trends, mostly reflecting changes of global climatic conditions, with a more local or regional signal superimposed on this record. Both records reveal three distinct warming periods at around 3.98 to 3.61 Ma, 3.59 to 3.45 Ma and 3.20 to 2.99 Ma, which are interrupted by two cooling events recorded at around 3.61 Ma and 3.36 Ma. This general trend is well comparable with other time equivalent Mediterranean records [30]. The third warm interval recognized coincides with the warm period that has been recorded in Pliocene sediments of the Atlantic Ocean between 3.3 and 3.0 Ma [4, 5]. Furthermore, variations in TOC and $\delta^{13}C$ records are negatively correlated with oxygen isotope data. Increased carbon isotope values correspond to warmer periods and are well correlated with the precession minima and summer insolation maxima (Figure 4). Such a configuration indicate that the presence of organic rich layers essentially triggered by changes in seawater stratification, due to high freshwater influxes in the eastern Mediterranean, which resulted to the productivity increase and pycnocline shoaling within the euphotic layer, and finally leading to the intensification of the Deep Chlorophyll Maximum (DCM) layer. These hydrographic conditions favoured the oxygen depletion of deep waters leading to dysoxic/anoxic conditions on the seafloor, and further allowed the
accumulation of organic matter and the formation of the sapropels mainly of the lower part of the section, where the relative high TOC values and elevated percentages of \( N. \text{acostaensis} \) were recorded. Overall, the sapropels developed around the Zanclean/Piacenzian boundary suggest a climate characterized by fluctuations of warm/temperate to humid conditions, associated with a highly stratified water column at times of precession minima.

4. Conclusions
Planktonic foraminiferal biostratigraphy in this study confirms the presence of the Zanclean/Piacenzian boundary of the early Pliocene marine succession in the Essovouyes-Exovouyes section. Integrated micropaleontological and geochemical analyses have led to the paleoclimatic and paleoenvironmental reconstruction of the southeastern Mediterranean, characterized by the presence of numerous sedimentary cycles composed of sapropelic/homogeneous marl alternations. The cyclically developed sapropelic layers around the Z/P boundary suggest a climate characterized by a period of warm temperate conditions and a highly stratified water column that occurred at times of precession minima. Additional multivariate statistical analysis revealed that sea surface productivity, temperature, and water column stratification controlled the faunal composition and the hydrographic regime of the eastern Mediterranean Sea during the Pliocene.

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