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Past Analogues of Deoxygenation Events in the Mediterranean Sea: A Tool to Constrain Future Impacts

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Abstract: Human-induced carbon emissions are altering the modern climate, with severe repercussions on ecosystems. Among others, anthropogenic pressure is causing deoxygenation of the bottom water, with the widespread establishment of hypoxic zones in several Mediterranean areas. The geological archives allow investigating past deoxygenation dynamics (sapropel events) and their impact on marine ecosystems. Here, we compare the causes and the evolution of deoxygenation dynamics which occurred during two different time periods (Messinian and Holocene) in different paleoceanographic settings based on their micropaleontological content. The Messinian sapropel events are the result of increased export productivity during a relatively cold and arid context, triggering bottom anoxic conditions. The Holocene sapropel formed in response to weakening/stopping of the thermohaline circulation due to increasing temperature and freshwater input. Our results suggest that the deoxygenation dynamics in the Mediterranean in the near future will not follow the trend characteristic of the Holocene deep-sea sapropel because of the predicted drying trend. Differently, the paleoceanographic setting triggering the Messinian shallow-sea sapropels is comparable with the modern situation in different Mediterranean areas, where human-induced eutrophication is promoting deoxygenation. Based on these results, we suggest that the patchy deoxygenation trend in the Mediterranean Sea caused by climate warming may lead to a drastic change in the ecosystem services which would likely impact human activities.

Keywords: sapropel; anoxia; calcareous nannofossils; foraminifers; climate change; marine productivity; thermohaline circulation



Citation: Mancini, A.M.; Bocci, G.; Morigi, C.; Gennari, R.; Lozar, F.; Negri, A. Past Analogues of Deoxygenation Events in the Mediterranean Sea: A Tool to Constrain Future Impacts. *J. Mar. Sci. Eng.* **2023**, *11*, 562. <https://doi.org/10.3390/jmse11030562>

Academic Editor: Weidong Zhai

Received: 7 February 2023

Revised: 2 March 2023

Accepted: 3 March 2023

Published: 6 March 2023



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1. Introduction

During post-industrial times, human activities have severely impacted the biogeochemical cycles and ecosystems through exceptional emissions of CO₂ into the atmosphere, which has ultimately affected modern climate evolution [1]. Among other environmental factors (i.e., ocean fertilisation), the current warming trend is expected to lead the global ocean to an overall oxygen deficiency [2]; similarly, the semi-enclosed Mediterranean Sea is expected to face this issue [3]. This is due to the effect of warmer temperatures, which cause a decrease in the oxygen solubility of seawater, a weakening of the thermohaline circulation strength [2], and an increase in the oxygen consumption by prokaryotic metabolism [4,5]. During the last 50 years, the global oxygen inventory in the open ocean has been reduced by ~2% [6] and the coastal water of more than 500 sites reported oxygen concentration <2 mg L⁻¹ [7], which is the threshold often used to define hypoxia. Globally, the oxygen minimum zone (OMZ) in the period 1990–2008 has expanded by an area comparable to the size of the European Union (4.5 million km²) [8]. The expansion of the OMZ is a recurrent feature associated with warming in the geological record, such as those which occurred during the Paleocene–Eocene thermal maximum (~55.5 Ma), with severe consequence

for marine biota [9,10]. The condition of increasing oxygen starvation is negatively impacting benthic biocenosis [11], and zooplankton and fish production [12]. Furthermore, the combined effect of warming and deoxygenation have a synergic negative effect on marine biocenosis, called “oxythermic stress” [13]. A negative synergic effect was also hypothesized for the combined impact of ocean acidification and deoxygenation in some molluscs and fish taxa [14]. Therefore, understanding the main variables involved in the current climate change is crucial to better constrain, and possibly predict, future impact scenarios. In this regard, the study of the past is a precious resource to understand long-term environmental dynamics for deoxygenation trends and depict future impact scenarios. The Mediterranean Sea is a key area to investigate this issue because in the geological past it experienced widespread deoxygenation events recorded by distinct dark layers called sapropels. According to [15], sapropels are discrete layers > 1 cm thick deposited in open marine pelagic realms and containing more than 2% organic carbon. The sapropel events can be seen as perturbations of the carbon and oxygen cycles; indeed, these events record an increase in organic carbon burial in response to anoxic conditions. Sapropels are cyclically deposited in the Mediterranean Sea in response to specific climate, oceanic circulation, and biogeochemical cycling [16,17] controlled by variation in the Earth’s orbital parameters [18]. Although [19] proposed a single mechanism explaining the sapropel occurrence in the Mediterranean throughout the Neogene and Quaternary, the authors of [20] propose different paleoceanographic settings for the Messinian sapropel deposition in the shelf setting of the Sorbas Basin, located in the western Mediterranean (Figure 1). Differently from the coeval deep-sea sapropel deposited in the eastern Mediterranean, the anoxic condition for sapropel deposition in the western Mediterranean was triggered by natural variation in primary productivity and export regimes favoured by restricted condition and paced by the precession index [20]. The bottom anoxic condition was a response of the ecosystem to eutrophication, similar to that currently occurring in different Mediterranean shelves and enclosed areas caused by human activity [21–25].

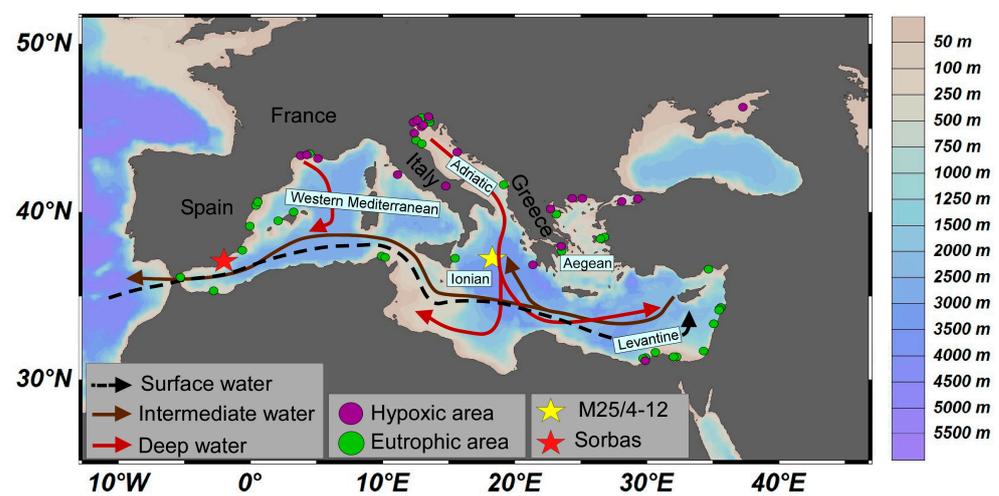


Figure 1. Map of the studied area. Yellow star indicates the M25/4-12 core location; red star indicates the Sorbas Basin location. Arrows indicate the major currents and their depth in the water column. Purple and green circles identify the location of hypoxic and eutrophic areas recorded from 1960 to 2010 in the coastal zones of the Mediterranean Sea (modified from UNEP-MAP [22,24]). Map obtained using the Ocean Data View software [26], (<https://odv.awi.de>, accessed on 2 December 2022).

The aim of this paper is therefore to compare sapropels deposited in different times and oceanographic settings (Messinian shallow western Mediterranean Sea vs. Holocene deep eastern Mediterranean Sea) to find the best past analogue of the current deoxygenation dynamic in the Mediterranean Sea, allowing to obtain clues for possible future impacts.

2. Oceanographic and Climatic Framework

The Mediterranean is a semi-enclosed sea characterised by a specific hydrographic regime. The Strait of Sicily virtually separates the Mediterranean Sea into two sub-basins, the eastern and western Mediterranean with different processes and characteristics of the water masses [17]. The eastern sub-basin is characterised by three distinct water masses: the Atlantic Modified Water (AMW; 0 to ~200 m), the Levantine Intermediate Water (LIW, 200–500 m), and the eastern Mediterranean Deep Water (EMDW; <500 m). The AMW flows eastward from the Strait of Sicily progressively gaining salinity as a result of the warm and dry weather in this part of the basin; near the Turkish coast, during winter, the cooling causes buoyancy loss to the AMW which sinks, forming the LIW which moves west towards the Adriatic Sea and the western Mediterranean through the Strait of Sicily. The LIW is underlying the EMDW, which moves west through the Strait of Sicily and a part is mixed with the cold water originating in the Adriatic shelf, forming the Adriatic Deep Water (ADW). The Western Mediterranean Deep Water (WMDP) forms during winter in the Gulf of Lyon and is coupled with an effective Bernoulli aspiration through the Gibraltar Strait [17]. Due to these thermohaline processes, the eastern Mediterranean is more sensitive to oxygen deficiency at the sea bottom compared to the western Mediterranean.

Future projections [27–29] indicate a scenario characterized by a progressively weaker thermohaline circulation, due to intense stratification driven by warming of the Mediterranean water. In addition, the freshening of the Atlantic Ocean due to Arctic ice melting could potentially increase the basin stratification by decreasing the AMW density. The main impact of this circulation change is on the oxygen content of the water column with possible negative impacts on marine ecosystems. In addition, the weakening of thermohaline circulation is coupled with eutrophication in several coastal and enclosed areas [22,23], increasing the production and export of biomass and consequently the consumption of the dissolved oxygen.

Sapropel and Deep-Sea Anoxia

Major climate oscillations, such as the alternation of ice ages and interglacials, are induced by seasonal and latitudinal changes in the amount of insolation; the latter is caused by variations in the movement of the Earth's rotational axis (precession and obliquity) modulated by eccentricity [30]. At the same time scale, in the Mediterranean Sea, anoxic events caused the periodic deposition of sapropel during the past 15 Ma [17,31]. Sapropels have been recovered in sediment cores throughout the Mediterranean Basin and in onshore marine successions around the basin, showing a pattern related to the precession cyclicity (~21,000 years) [17]. They were discovered during the Swedish Deep Sea Expedition (1948) and their deposition is related to glacial–interglacial cycles [32]: the combination of warm, low-density superficial water resulted in the stratification of the water column and in the stagnation of bottom waters. Later, it was pointed out that sapropels are linked to reduced oxygen supply triggered by limited deep-water circulation and/or increased oxygen demand due to enhanced primary productivity, or a variable combination of the two [17]. Sapropels represent some of the best-documented marine anoxia-driven carbon burial events, well developed in times of maximum eccentricity (high seasonality), and often missing during times of minimum eccentricity (low seasonality) [17].

Literature on the Quaternary sapropels shows that the weakening/shutdown of the LIW exerted first-order control on their formation [17,33]. Today, the LIW supplies enough salt to the Adriatic and Aegean Sea for the formation of the EMDW in winter [34]. This water mass is critical for the Mediterranean thermohaline circulation, supplying oxygen to the deep basin during events of dense water formation. At the times of the most recent sapropels' formation, the African monsoon shifted in response to orbital cycles and increased the Nile discharge, which drastically decreased the LIW formation (i.e., freshening of the Levantine basin), and in turn, decreased the EMDW formation [17]. Therefore, the deterioration of the thermohaline circulation is thought to play a primary role in the

sapropel deposition during the Plio-Quaternary, through variation in the freshwater influx and nutrient supply to the basin.

As for the Messinian sapropels, they represent the sedimentary response to restricted condition and, as in the case of the Plio-Quaternary sapropels, their sedimentation followed precession-induced climatic fluctuations [35], allowing the tuning of the sapropel (stratigraphic) midpoint with precession minima—insolation maxima [36,37]. Indeed, the progressive basin restriction of the Mediterranean Basin was the result of tectonic processes that reduced the water exchange between the Mediterranean and the Atlantic through the paleo Gibraltar Strait [38]. The restriction of the Mediterranean Basin proceeded by steps, which were dated at 7.19, 6.7, 6.4, 6.1, and 5.99 Ma [20,39,40]. Each of these steps marked a deterioration of the bottom water circulation, which increased the bottom water residence time leading to oxygen deficiency at the seafloor [39–41]. The eastern Mediterranean was already subjected to sapropel deposition since the Langhian, but their formation was typical of the eccentricity maxima [31,42]. Starting from 7.19 Ma, the restriction allowed their formation also during eccentricity minima, when oscillations of the insolation were less extreme [19,41,43]. Indeed, during the late Miocene, the eastern Mediterranean was more affected by runoff (from the north African rivers) compared to the western part (Figure 2) and to the modern situation [44]. In addition, freshwater spill from the Paratethys [45] further enhanced the water column stratification in the eastern part of the basin (Figure 2). The second restriction step (6.7 Ma) marked the onset of cyclical sapropel deposition also in the western Mediterranean (Figure 2) [46]. In a small peripheral basin of the western Mediterranean (Sorbas Basin, 37°05'49'' N–2°03'19'' W; Figures 1, 2 and 3A–C), the cyclical sapropel deposition occurred on the shelf and was triggered by enhanced organic carbon export to the seafloor in response to high productivity in the water column [20], suggesting a different mechanism for the sapropel formation in the different Mediterranean sub-basins.

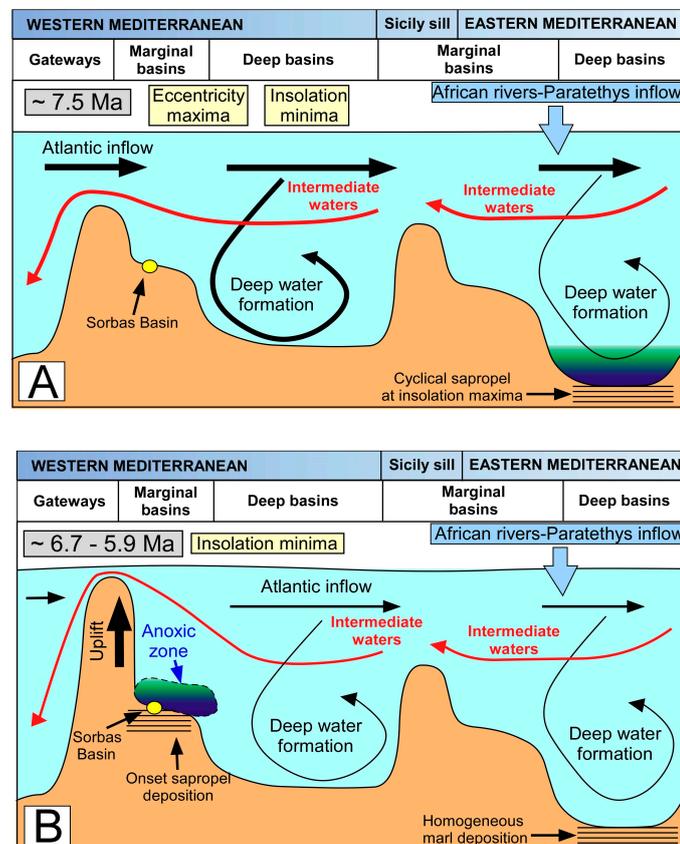


Figure 2. Cont.

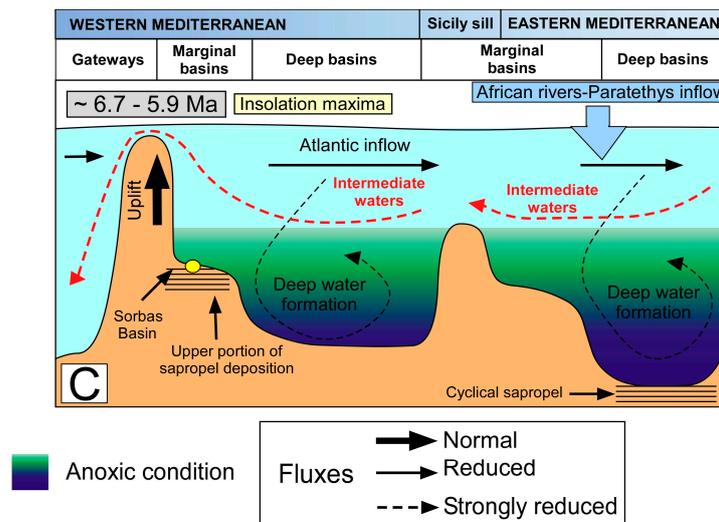


Figure 2. Sketch showing the Late Miocene thermohaline circulation in the Mediterranean in relation with the deposition of sapropel. (A): Thermohaline circulation and sapropel deposition (constrained from present circulation pattern and on the basis of the Messinian sedimentary succession) [34,39,41, 43,44,47,48], when open marine condition and vigorous thermohaline circulation prevailed. (B,C): Thermohaline circulation after the restriction step dated at ~6.7 Ma [41,43,44,47–51] during insolation minima (B) and insolation maxima (C) periods. Sketch modified after [41].

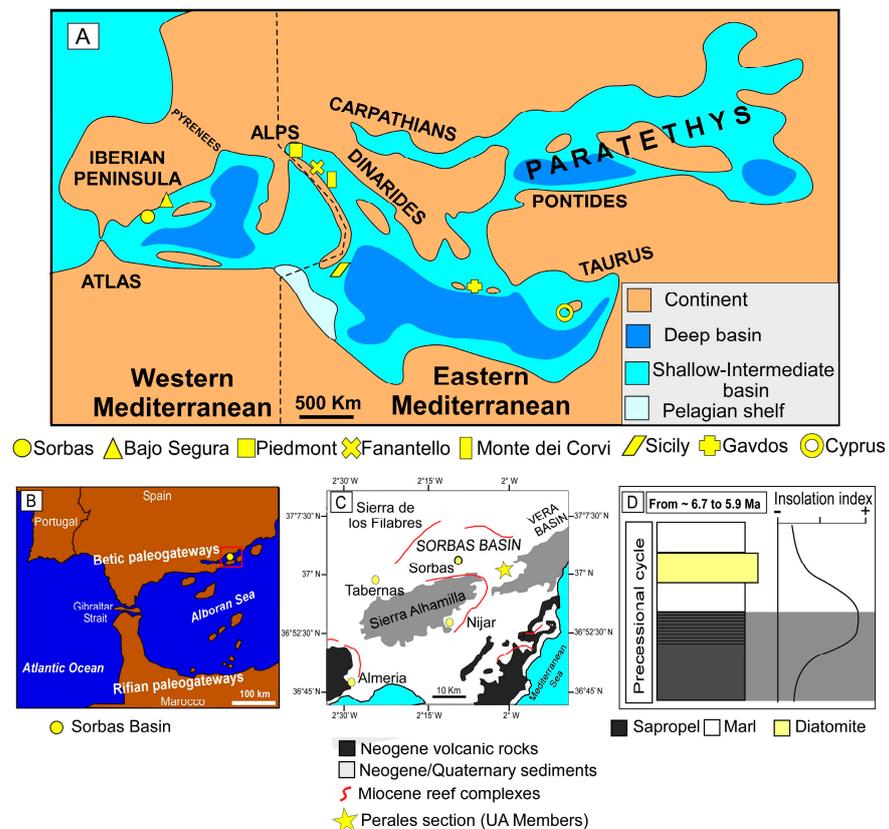


Figure 3. (A): Messinian paleogeography of the Mediterranean with the principal localities in which sapropels were recorded. Modified after [52]. Data from [19,40,47–49,51,53–55]. (B): Sorbas Basin paleogeographic location from ~6.7 to 5.9 Ma, modified after [56,57]. (C): Geological map of south-east Spain showing the location of the studied interval. (D): Basic sedimentary cycle of the Sorbas Basin recording precessional footprint and its relationship with insolation index [58].

3. Material and Methods

3.1. The Sapropels of the Sorbas Basin

The Sorbas Basin forms part of the Betic Corridor, which was one of the northern Atlantic–Mediterranean connections during the late Miocene (Figure 3B). The basin is elongated and bounded by the Sierra de Filabres and by the Sierra Alhamilla to the north and to the south, respectively (Figure 3C). The Messinian is represented by the Abad Member, which was deposited in the basin depocenter and consists of hemipelagic sediment [59]. Based on the different lithologies, the Abad Member can be divided into two units: the Lower Abad (LA), with the base at approximately the Tortonian/Messinian boundary (~7.2 Ma) and the Upper Abad (UA), starting at 6.7 Ma [59]. Both units record the precessional signal through different pattern of the lithological expression and of the micropaleontological content. The LA is characterized by an alternation of massive whitish marls and massive grey marls [59]; the UA deposits are characterized by a quadripartite cycle (sapropel—marl—diatomite—marl). A total of 34 cycles are present in the UA [49].

The sedimentary cyclicity of the Sorbas Basin from 6.7 to 5.9 Ma (UA Member) was studied in detail by means of micropaleontological (foraminifera and calcareous nannofossil) and isotopic analyses [20,49,60–62] to reconstruct the main paleoenvironmental change related with precessional fluctuations. The age model relied on magnetostratigraphy, biostratigraphy, and cyclostratigraphy [49,59]. We used the depositional model proposed in [20], which compiled all the available datasets presented in the literature regarding the UA [20,49,60,61]. The depositional model was based on high resolution (less than 0.4 Ka resolution) studies conducted on four precession-driven lithological cycles (6.62–6.54 Ma) [60,61]; and with lower resolution studies (3.3–2.0 Ka resolution) [20,49]. The temperature index was calculated [46,49,60] considering the fluctuation of the planktic foraminifera which proliferate in warm-oligotrophic water (*Globigerinoides obliquus*, *G. sacculifer*, *Orbulina universa*, and *Globoturborotalita apertura*) over the taxa proliferating in cold-eutrophic water (*Globigerina bulloides* and *Turborotalita quinquerloba* and *T. multiloba*) [63,64]. As the benthic foraminiferal association is entirely composed of taxa characteristic of low oxygen and high organic carbon flux to the seafloor, such as the genera *Uvigerina*, *Bolivina*, and *Bulimina* [49,65–67], the variation in the absolute abundance of benthic foraminifera (number of specimens/gram of dried sediment) reflects organic carbon and oxygen availability at the seafloor [20,68,69]. Therefore, the benthic foraminiferal absolute abundance is used as an index of bottom oxygenation to the seafloor. Finally, a DCM index was provided considering the fluctuation in relative abundance of the calcareous nannofossil taxa *Sphenolithus abies*, since this taxon is reported to have similar ecological requirements to the living *Florisphaera profunda*, which proliferates in the lower part of the photic zone [20,70].

3.2. The Sapropel S1 in the M25/4-12 Core

The studied sapropel S1 was described by [71] in the core M25/4-12 (37°58' N 18°11' E), collected at 2467 m depth in the Ionian Sea (Figure 1), during the R/V *Meteor* cruise 25/4 (August 1993). In 2013, the sampling was further refined at higher resolution (1 cm pacing). The new data presented here focus on Section 1 of the core (Supplementary Materials S1, Section S2.1, Table S1), where 10 AMS ¹⁴C datings were provided by the Radiocarbon laboratory at ANU (Australian National University) and calibrated with Marine stage 20 [72].

A total of 35 samples were prepared for micropaleontological investigation, with an overall sample resolution of 1 cm across the S1 and every 5 cm in the remaining part of the section. Standard smear-slides were prepared for the calcareous nannofossil analysis and successively observed at 1250× by polarized light microscopy. For the foraminiferal analysis, we wet-sieved the dried sample, previously weighted, to obtain two size fractions: >150 μm and 150–63 μm. The calcareous nannofossils and foraminiferal relative and absolute (foraminifera only) abundance were calculated following taxonomic identification.

3.3. Micropaleontological-Based Indexes as a Proxy of Deoxygenation Event

We calculated several micropaleontological indexes to compare with previously applied methods for constraining the dynamics of Messinian deoxygenation. These indexes are based on the assumption that the distribution pattern of some taxa is mainly related to selected environmental parameters, such as sea surface temperature and productivity. To this end, a foraminifera-based temperature index was calculated with the formula:

$$W/C_{\text{forams}} = \%W / (\%W + \%C)$$

where C are the cold foraminiferal taxa (*Globorotalia inflata*, *Globorotalia scitula*, *Globorotalia truncatulinoides*, *G. bulloides*, *Neogloboquadrina dutertrei* and *N. incompta*) and W the warm foraminiferal taxa (*Orbulina universa*, *Globigerinoides ruber*, *G. trilobus* and *Globoturborotalita rubescens*), according to [73].

A foraminifera-based productivity index was calculated through the % sum of eutrophic and opportunistic specimens (*G. bulloides*, *Turborotalita quinqueloba* and *Globigerinita glutinata*) according to [73].

A coccolith-based Deep Chlorophyll Maximum (DCM) was calculated based on the abundance fluctuation of *F. profunda*, this taxon being a deep photic zone dweller which shows high abundance when the nutrients are preferentially located in the lower photic zone [71,74]. We calculated the DCM index using the formula (modified after [75]):

$$DCM_{\text{cocco}} = \%F / [\%F + \%UPZ]$$

where F is the *F. profunda* abundance and UPZ are the upper photic zone dweller specimens (in our case, we consider *Emiliania huxleyi*). This index shows how much of the productivity was concentrated in the deep part of the photic zone.

Finally, the benthic foraminiferal absolute abundance is used to track the change in the bottom oxygenation, since their abundance and spatial occurrence is mostly controlled by nutrient and oxygen availability to the seafloor [67].

4. Results

4.1. Micropaleontological Signature of the Sorbas Basin Sapropel

Micropaleontological analyses performed in the Sorbas Basin spanning 6.7–5.9 Ma (UA Member) [46,49,60–62] were recently summarized in [20] (Figure 4), integrating all the available data regarding the sapropel deposited in the UA Member to build a general depositional model explaining the environmental changes associated with the deposition of the different lithologies (Figure 4). The micropaleontological analyses revealed different planktic and benthic assemblages at the sapropel base and in the middle-upper part of the sapropel (Figure 4). At the sapropel base, the prevalence (up to 100% of the assemblage [47]) of cold-eutrophic planktic foraminifera and high benthic foraminiferal abundance (in some cases exceeding 200 specimens g^{-1}) is observed [49,60,61]; conversely, warm-oligotrophic foraminifera and DCM dwellers dominate the middle-upper part of the sapropel Figure 4 [20,49,60,61]. This portion of the sapropel is also laminated and shows scarce or even absent benthic foraminifera. In the upper part of the sapropels, the high abundance (up to 100% of the total assemblage [47]) of warm-lover taxa indicates maximum values of the insolation index.

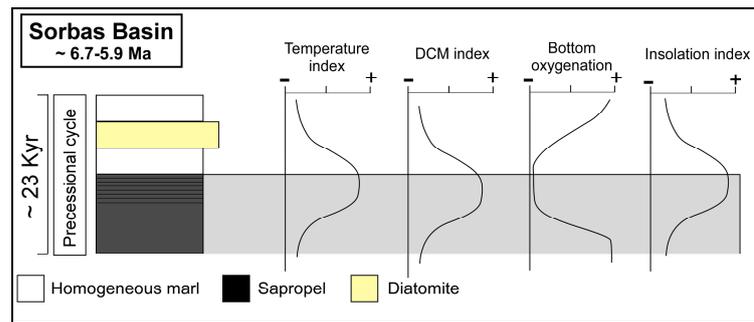


Figure 4. Sketch showing the micropaleontological feature characterising the cyclical sapropel deposition during the Messinian (from 6.7 to 5.9 Ma) in the Sorbas Basin. Data from [46,49,60,61], summarized by [20]. More details in the Section 4.1.

4.2. Micropaleontological Signature of Sapropel S1

Based on the radiometric ages (Figure 5), the studied interval spans from 27.3. BP to the Z1 tephra, corresponding to the Vesuvius eruption (79 A.D.), that is used as an additional data point for the age model. Based on the age model, a greyish interval that we identify as “protosapropel” occurs between 41 cm and 36.5 cm (11.7–10.4 Ka cal. BP) and from 36.5 to 24.5 cm (7.3 Ka cal. BP), the dark colour typical of the sapropel is evident. From 24.5 cm to 20 cm (5.6 Ka cal. BP), the colour turns to light brown/red (Supplementary Materials S1, Section S2.1, Figure S1), which corresponds to the oxidized sapropel [76]. Above this interval, between 20 cm and 7 cm the sediment colour is the typical pink characterizing bioturbated hemipelagic sediment, and at the top of the core the Z1 tephra (7–0 cm) [77] occurs. Our stratigraphic log was then correlated with insolation curve at 65° N [58].

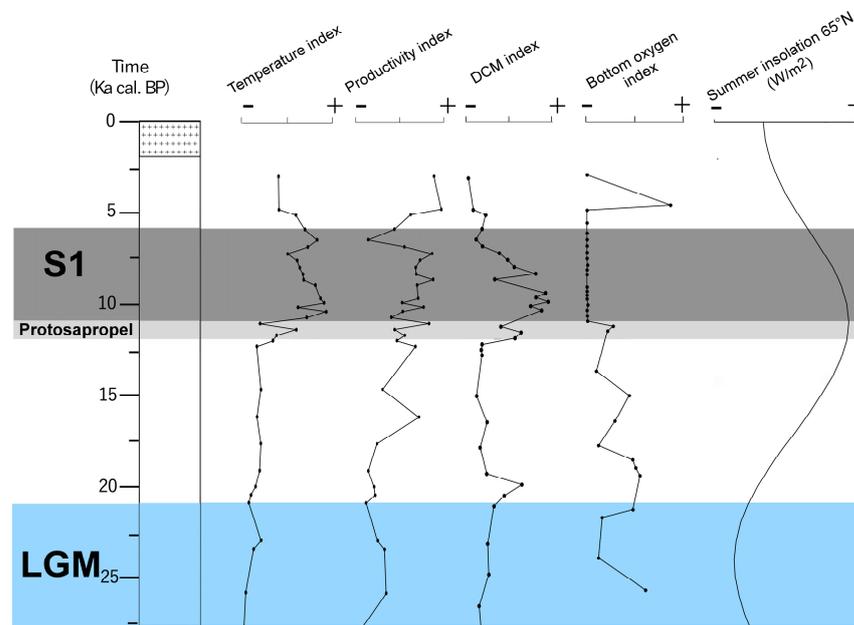


Figure 5. Micropaleontological—based and insolation indexes [58].

Raw micropaleontological results of the studied interval are reported in the (Supplementary Materials S1, Sections S2.2 and S2.3, Figures S2 and S3). Figure 6 summarizes the main fluctuations observed in the calculated indices: the foraminifera-based temperature index shows low values in the lower portion of the studied interval, where the assemblage was composed of cold-eutrophic taxa (*G. scitula*, *N. incompta* and *G. bulloides*) [73]. This suggests that the Last Glacial Maximum (LGM) falls between 27.6–20.9 Ka cal BP (Figure 5). This index increased below the protosapropel (11.7 Ka cal BP), and in the visible sapro-

pel interval showed higher temperatures than in the overlying and underlying sediment (Figure 5). The foraminifera-based productivity index, although fluctuating, recorded an upward gradually increasing trend, punctuated by a short drop at the top of the visible sapropel. The coccoliths-based DCM proxy recorded a short peak just above the LGM and higher values within the S1 (Figure 5). Finally, the oxygenation index was null in the sapropel and highly fluctuated (from 0 up to 104 specimens g^{-1} , Supplementary Materials S1, Section S2.3) below and above it (Figure 5).

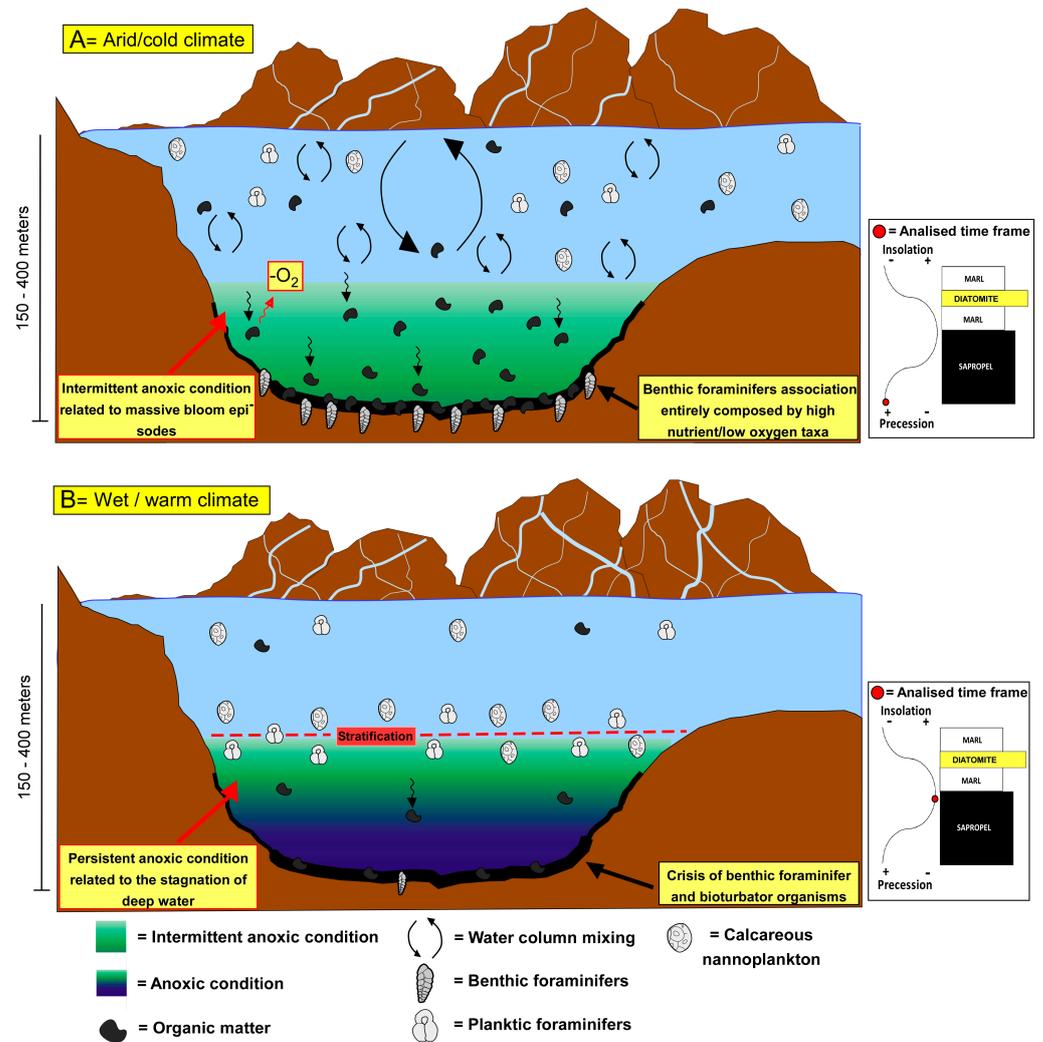


Figure 6. Sketch showing the environmental condition triggering the Messinian sapropel deposition in the Sorbas Basin based on the proxies shown in Figure 4. (A): During insolation minima (precession maxima), the cold temperature promoted vigorous vertical mixing and distributed the nutrient throughout the photic zone, thus stimulating primary productivity. This resulted in an increase of the organic carbon rain to the seafloor which, once re-mineralised, decreased the bottom oxygen content. (B): During insolation maxima (precession minima), the increase in both temperature and continental runoff favoured the stratification of the water column. Primary productivity was mostly located in the deep photic zone, where a DCM occurred. At the sea bottom, persistent anoxic conditions related to the stagnation of deep water occurred. This environmental setting led to a strong reduction or even a disappearance of benthic and bioturbator organisms.

5. Discussion

5.1. Paleoceanographic Changes of Messinian and Holocene Sapropels

Based on the data reported above, the deposition of the Messinian sapropels at Sorbas (Figure 4) started in a relatively cold context, as evidenced by the temperature indices. Cold conditions are known to promote nutrient distribution throughout the photic zone through mixing [78]. The increase of the benthic foraminiferal abundance suggests enhanced availability of organic matter on the seafloor, promoting eutrophication and the consequent oxygen consumption leading to organic matter preservation, like in the modern OMZ [79]. Thus, the Sorbas sapropels were triggered by enhanced productivity which caused oxygen deficiency at the bottom [20]. Differently, the upper portion of these sapropels is characterized by an increase in temperature and DCM indexes (Figure 4). The fine lamination characterizing the upper part of the sapropel points to an exacerbation of the oxygen starvation at the bottom, which in turn is responsible for the scarcity or absence of benthic foraminifera (Figure 6). Indeed, benthic foraminifera are able to survive in conditions of oxygen scarcity, but if these conditions are prolonged and/or alternative electron acceptors (i.e., NO_3^-) are scarce, their absolute abundance is negatively affected [67,80–82]. According to [49] and [20], the anoxic condition was the result of the increasing freshwater input and temperature, which promoted water column stratification (as indicated by the nannofossil-based DCM index and bottom water stagnation; Figures 4 and 6). The previously applied astrochronological tuning (sapropel mid-point corresponding to insolation maxima) [36,37] was also refined based on the temperature index, placing the insolation maxima at the top of the laminated portion of the sapropel [20,60].

The deep-sea sapropel S1 of the Ionian Sea featured a different record. Literature based on detailed faunal and isotopic studies showed that deep-water stagnation progressively developed from 17 Ka cal. BP onwards and that a distinct drop in $\delta^{13}\text{C}_{\text{benthic}}$ occurred around 11 Ka cal. BP, just before the collapse of benthic ecosystems [17,83,84]. Our data showed fluctuating values and a clear absence of benthic foraminifera between 10.3 Ka cal. BP and 4.8 Ka cal. BP (Figure 5). Furthermore, the increase in temperature inferred with the paleo indices slightly below the protosapropel (Figure 5) points to a surface water warming predating the onset of the sapropel S1; this is followed by a DCM productivity increase (11.4 Ka cal. BP). reflects the water column stratification because of freshening [17,76] and references therein and warming of the surface water column that, according to our data, started well before (~1.2 Ka) than the visible S1 (10.4 Ka cal. BP). This is consistent with the freshening of the water column in the eastern Mediterranean well before the S1 onset (approximately 11.5 Ka cal BP), inferred from $\delta^{18}\text{O}$ measured on planktic foraminifera [76,85–90]. The strong time correspondence between the African Monsoon intensification, causing an increase in the fluvial discharge in the eastern Mediterranean Basin mostly through the Nile River, and the sapropel occurrence was suggested to be a pre-conditioning necessary for S1 deposition [17]. The high values of the foraminiferal productivity index that we report in the sapropel S1 (Figure 5) can be seen as consequential to increased freshwater input and nutrient delivery. In fact, according to [90], the large nutrient influx delivered by summer floods of the Nile River led to a switch from oligotrophic to meso/eutrophic state in the eastern Mediterranean, which was accompanied by enhanced primary productivity in surface waters. The transition to mesotrophic/eutrophic conditions occurred around 10 ka cal. BP [87], when precipitation and runoff in the Nile River basin peaked [91,92]. From 10 ka cal. BP onwards, a drastic increase in primary productivity has been identified in the eastern Levantine Basin [93], which suggests fertilisation of surface waters by Nile-derived nutrients [90]. These features characterising S1 are consistently recorded in other areas of the eastern Mediterranean Basin (i.e., Levantine, Aegean, and Adriatic) [17,76,88–90,94–99], and collectively suggest that the thermohaline circulation at intermediate and deep settings weakened or even stopped in response to continental runoff increase.

5.2. Sorbas Shallow-Sea vs. Holocene Deep-Sea Sapropels: What Are the Differences?

Despite a single mechanism for the sapropel formation being proposed for the Neogene and Quaternary [19], our data point to a different paleoceanographic setting characterizing sapropel in the Sorbas Basin compared with Messinian sapropels recorded elsewhere [20] and the Plio-Quaternary deep-sea sapropel record. At Sorbas, the sapropel onset shows cold eutrophic planktic foraminifera and nannofossils, and benthic foraminifera characteristic of a low-oxygen/high-nutrient environment (Figure 7) [20,49,60,61]. This microfossil association led the authors of [20] to infer that the anoxic condition was related to enhanced organic carbon export to the seafloor in response to high productivity in the water column in a relatively cold context. Basically, the Sorbas sapropel sedimentation was triggered by enhanced productivity which caused bottom anoxic condition, similarly to what is observed in a modern oxygen minimum zone, such as the coast off Perù [79] and California [100], and along the north-eastern Arabian Sea [101]. Furthermore, the Messinian sapropels in the Sorbas Basin were deposited in marginal and relatively shallow environments, less than 300 m depth [102–107], where productivity and export pattern played a major role in controlling the oxygen bottom budget due to the proximity of the photic zone to the seafloor [20]. For instance, the last sapropel underlying the gypsum deposits (~5.99 Ma) characteristic of the Messinian Salinity Crisis event is thought to have been deposited from ~100 to 200 m of water depth [102,103,105]. Differently, most of the studied Plio-Quaternary sapropels were deposited at depth below 300 m [17] in response to a freshening of the surface water [17,76,86,88–90,98,99] that weakened or even stopped the oxygen delivery at intermediate and deep settings in a relatively warm/eutrophic context (Figure 7). Therefore, differently from the Sorbas sapropels, enhanced freshwater input to the basin occurred well before and preconditioned the sapropel S1 deposition through increased water stratification. Overall, the climatic and oceanographic context is completely different: at Sorbas, sapropel inception is related to high productivity in cooler condition (insolation minima) whereas the deep-sea Holocene sapropels are related to warming and freshening of the water column (insolation maxima).

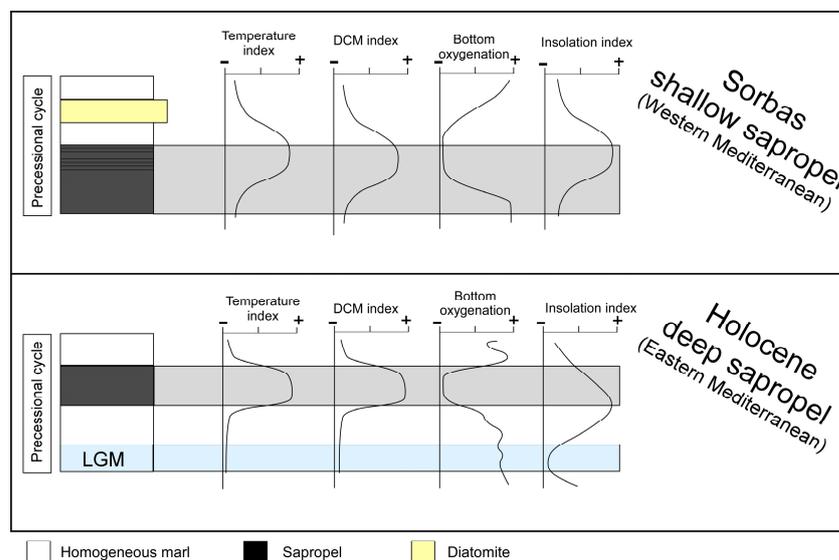


Figure 7. Comparison between the Holocene deep sapropel deposited in the eastern Mediterranean with the shallow Messinian sapropel deposited in the Sorbas Basin. The light blue rectangle at the bottom refers to the Last Glacial Maximum [LGM]. The warm/oligotrophic, cold/eutrophic, DCM, and the oxygen data are from [20,49,60,61]. These indexes were based on the distribution of planktic foraminifera and nannofossils (warm/oligotrophic, cold/eutrophic and DCM index) and on benthic foraminifera (oxygen concentration) (for more detail see the Sections 3.1 and 3.3).

5.3. A Clue on Future Deoxygenation: Are Sapropels a Good Analogue?

The Mediterranean region is considered one of the most vulnerable areas impacted by climate changes, usually referred as a climate change “hot spot” [108]. Drying and warming trends have been recorded during the last decades, and they are predicted to further exacerbate in the near future [25,27,29,109–112]. As the ocean warms, a reduction of the oxygen solubility [6], a weakening of the thermohaline circulation [113,114], and an increase in the oxygen demand for microbial activity [4] occur, leading to the so-called “ocean deoxygenation” [115]. In a semi-enclosed basin such as the Mediterranean Sea, ocean deoxygenation is exacerbated by the eutrophication phenomena and the consequent instauration of hypoxic zones, which are currently expanding in the coastal areas [21,22,25]. Ocean models project for the end of this century an increase in the global mean sea surface temperature and salinity of +3.1 °C and +0.48, respectively [27], that will lead to a slowdown of the thermohaline circulation (i.e., deep-water formation) of 40% for the intermediate water, and of 80% for the deep water [27]. In the Mediterranean, the average sea surface temperature (SST) shows an increasing trend of about 0.4 °C per decade across a 30-year time interval (1986–2015) [111]. A warming trend of about 0.12 °C during the period 1959–1988 was observed even in the deep waters of the western Mediterranean [109], increasing the deep-sea prokaryotic metabolism and thus the oxygen consumption [4]. Looking at the alkenone-based SST proxy, the temperature record of the Messinian from 6.7 to 5.9 Ma spans from 22 °C to 30 °C in the Eastern Mediterranean [116–118]. This temperature range is higher than the average SST recorded during the 1986–2015 period in the Mediterranean (14.1 °C to 24.3 °C; 111), but it fits with the temperature range predicted for the year 2100 (relative increase of 5.8 °C) [111]. This match between the Messinian SST recorded in the eastern Mediterranean and the projected temperature of the near future, further supports that the Messinian paleoenvironment may represent a time window to decipher future environmental dynamics under the current climate change.

The current warming trend impacts the oceanic realm through multiple and complex dynamics; among these, the decrease in the oxygen solubility in water, the increase in stratification episodes, and the reduced thermohaline circulation ultimately resulted in the deoxygenation of Mediterranean water [2,27,114]. All these features appear to be favourable for a decrease in the oxygen content and the consequent organic carbon accumulation in the sediment (sapropel settlement). However, the current Mediterranean setting cannot be easily compared with the Mediterranean setting at the time of S1 deposition, mostly because the Nile River discharge in the Mediterranean Basin has severely decreased after the completion of the Aswan High Dam [119]. Furthermore, a regional climate model showed an increase in the freshwater deficit of +40% for the period 2070–2099 [120], mostly due to the runoff decrease of both the Po River and the outflow from the Black Sea [27]. On the other hand, a mass balance model indicates that the Eastern Mediterranean bottom water will remain fully oxygenated on time scale >100 yr, even if deep-water formation will be strongly reduced [27,28]. Furthermore, the modern insolation intensity is close to its minimum [121] and is different from the orbital configuration characterizing the onset of S1 deposition. Based on what was reported above, the bottom condition in the Mediterranean area in the near future (decadal time scale) likely will not follow the deoxygenation dynamics characteristic of the Holocene sapropel deposited in deep environments.

Nowadays, the Mediterranean is affected by eutrophication and a consequent deoxygenation pattern in several coastal and enclosed areas (Figure 1) [7,21–25]. These environments are experiencing the spreading of seasonal bottom hypoxia, in response to primary productivity peaks (generally in summer after spring bloom, when the water column stratification is strongest), sometime fuelled by riverine runoff enriched with fertilizers [7,25,122]. Algal toxic blooms and mortality of benthic organisms are often associated with eutrophication in the Mediterranean coastal area [7,22,23,25] with negative repercussions on the marine ecosystem functioning which could preclude water resource exploitation by human activities [24]. For example, in the modern north-western Adriatic coasts, the freshwater input carrying nutrients coming from the Po River causes eutrophication and bottom anoxic

condition associated with huge mortality of fishes [22,123]. In this environment, eutrophic areas only occur along the coast near the river mouths and urban agglomerations [124], where fertilizers and other organic substances interact with the coastal realm. This part of the Adriatic is affected by a deterioration of the water quality: the abnormal colour of the water due to high concentration of suspended phytoplankton biomass results in poor transparency of the water combined with a smell of putrefaction [22]. In this perspective, this environment is experiencing a negative repercussion on the economy of the region (i.e., fisheries, decreasing tourism, etc.) related to oxygen deficiency.

The comparison presented in this paper evidences that although Plio-Quaternary sapropels remain an important feature to be explored to understand the interplay between high- and low-latitude climate [125], the Messinian sapropels of the Sorbas Basin, deposited on the shelf, appear to be the best analogue for the future deoxygenation scenario (i.e., end of this century) in the Mediterranean, as they record high productivity and organic carbon export to the seafloor which caused intermittent bottom oxygen deficiency (Figure 6). In this perspective, the shallow-water Sorbas sapropels represent an important source of information and can provide possible scenarios useful for the adaptation to the new incoming condition. In fact, such a mechanism potentially enhances the organic carbon burial in the bottom sediments, although the magnitude and the spatial distribution of this event varies according to the warming rate. The warming rate associated with Messinian precessional variation (from the sapropel base to the top, corresponding to insolation minima to insolation maxima; ~10 Ka) in the western Mediterranean was calculated through the Mg/Ca on planktic foraminifera and is on average ~ 0.001 °C year⁻¹ [20]. If we compare this warming rate to the modern one, we observe that in the interval 1986–2015, an increase in the SST of about 0.04 °C year⁻¹ was recorded; a black box model for the interval 2071–2100 indicates a further increase in the SST of 5.8 °C compared with the period 1986–2015 (predicted warming rate of ~ 0.68 °C year⁻¹) [111]. Noteworthy, the calculated Messinian warming rate is two orders of magnitude lower than the warming projected by the end of this century. Although the warming rates of the natural precession-driven (extremely slow) and the anthropogenic change (extremely fast) are clearly not comparable, important information regarding the ecosystem response could be obtained and used to predict future impact scenarios. In the Sorbas Basin, during the sapropel warming phase, a decrease in the bottom oxygen led to a disappearance of bioturbator organisms (Figure 6), as reflected by the lamination of the sediment at the top of the sapropel. This because bottom oxygen deficiency also impacts the plankton and motile bioturbator communities through reduced growth and reproduction rates, reduced activity levels, increased mortality, constrained vertical migration to the oxygenated part of the water column, habitat reduction, shifts in size structure and community composition in favour of smaller individuals and egg-carrying species, and altered predator–prey dynamics, as observed in the modern setting [12,126].

Differently from the Messinian case of Sorbas, when the natural environmental change associated with deoxygenation was slow, the current environmental change rates are exceeding the adaptation potential of marine organisms to the newly established condition [14], thus increasing the magnitude of the impact. Likely, the ongoing anthropogenic climate warming and eutrophication have the potential to severely impact the benthic and sea bottom ecosystem functioning, with possible negative repercussions on the plankton community, which in turn will impact ecosystem services and marine resources, such as fisheries [122], and therefore, also human activities.

6. Conclusions

The deposition of the shallow Messinian sapropels recorded in the western Mediterranean was triggered by high primary productivity in the water column and by high organic carbon rain to the seafloor in a relatively cold context. Conversely, in the upper part of these sapropels, the condition progressively shifted to warm/humid with the instauration of vertical stratification that separated the oxygenated condition in the upper

water column, and permanent anoxic condition on the seafloor. This upper portion of the sapropel is finely laminated, indicating the disappearance of bioturbator organisms. On the other hand, the Holocene sapropel was deposited as the result of a weakening/stopping of the thermohaline circulation, responsible for the deep-water renewal that provides oxygen at the sea bottom. As consistently recorded in other sites, these paleoceanographic changes were triggered by an increase in temperature and freshwater input, the latter mostly from the Nile River. Due to the modern oceanographic setting of the Mediterranean (i.e., closure of the Aswan Dam) and the predicted changes under the current climate warming (i.e., drying and warming trend), we infer that the Holocene sapropel setting is likely not comparable with near-future deoxygenation dynamics. Furthermore, oceanographic and mass balance models indicate that despite the thermohaline circulation losing its strength, the eastern Mediterranean abysses will remain well-oxygenated in the near future (end of this century). Instead, the eutrophication-driven bottom anoxic condition that characterised the onset of the sapropel deposition in the western Mediterranean during the Messinian could be comparable to the current situation in several marginal and enclosed basins in the Mediterranean. According to the paleoceanographic change that characterises the Messinian sapropel from the base to top, corresponding to a warming phase, an exacerbation of the bottom oxygen deficiency should be expected in the future. Indeed, the Messinian case suggests that wide areas of shelf seafloors could be affected by anoxia if the warming affects eutrophicated areas. We conclude that, as climate warming will continue in the near future, an impact on the benthic and planktic communities in response to deoxygenation should be expected, as already occurred during the cyclical warming phase of the Messinian.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse11030562/s1>, Figure S1: Core M25/4-12; Figure S2: Calcareous nannofossils relative abundance; Figure S3: Planktic and benthic foraminifers abundance; Table S1: Radiometric age of M25/4-12.

Author Contributions: Conceptualization, A.M.M. and A.N.; methodology, A.M.M., A.N., C.M. and G.B.; validation, A.M.M., R.G., F.L., C.M. and A.N.; resources, A.M.M. and A.N.; writing—original draft preparation, A.M.M.; writing—review and editing, A.M.M., R.G., F.L., C.M., G.B. and A.N.; visualization, A.M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are in submission phase to PANGEA repository (temporary ticket PDI-34011).

Conflicts of Interest: The authors declare no conflict of interest.

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