

Marine nitrogen cycling dynamics under altering redox conditions: Insights from deposition of sapropels S1 and the ambiguous S2 in the Eastern Mediterranean Sea

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ABSTRACT

The eastern Mediterranean Sea (EMS) sedimentary record is periodically interspersed with organic-rich 'sapropel' layers. Sapropels are characteristic of basin-wide anoxic events, triggered by precession-forced insolation maxima. Relatively subdued insolation maxima, however, are not always expressed as distinct sapropel events. The EMS sedimentary record is thus useful to investigate feedbacks between marine anoxia and the nitrogen (N) cycle and offers an analogue for modern deoxygenation and past oceanic anoxic events. To this end, we investigated a ~68 kyr sedimentary record from the EMS containing the well-established sapropel S1 (deposited in two phases: S1a [~10.5–8.5 ka BP] and S1b [~7.8–6.1 ka BP]) and sediments timed to the ambiguous S2 sapropel (~53 ka BP). We used lipid biomarkers of microorganisms to reconstruct key N-cycle components: (1) anaerobic ammonium oxidation (anammox) using ladderanes and a stereoisomer of bacteriohopanetetrol (BHT-x), (2) dinitrogen gas (N₂) fixation using heterocyte glycolipids, and (3) nitrification by Thaumarchaeota using crenarchaeol. Additionally, benthic foraminifera and trace metals (U, Mo, Mn) were used to reconstruct redox conditions. During S1a, abundances of Thaumarchaeota increased, likely promoted by elevated high-nutrient freshwater discharge. At this time, a combination of phosphorus supply and intensified loss of bioavailable N via water column anammox, may have reinforced anoxia by favoring diatom-diazotroph associations. During S1b, anammox is equally intense. Yet, no positive feedback on N₂-fixation is observed, likely because diazotrophs were phosphorus limited. Instead, anammox may have provided negative feedback on anoxia by quenching primary production. Ladderanes suggest additional episodes of anammox between ~69 to 39 cal ka BP, corresponding to brief periods of water column deoxygenation. Anoxia likely occurred at the sediment–water interface in S2-timed sediments (53–51 cal ka BP). During these episodes, ladderanes co-occur with the later eluting BHT-34R stereoisomer. δ¹³C_{BHT-34R} indicate an anammox source, potentially synthesized by marine sedimentary anammox bacteria. No corresponding increase in diatom-diazotroph associations is observed, likely due to the oligotrophic conditions and the limited effect of sedimentary anammox on N-availability in the euphotic zone. Our results highlight various modes of operation of the N-cycle at different degrees of deoxygenation, which depend amongst others on nutrient-availability and the niche-segregation of N-loss and N₂-fixating microorganisms.

1. Introduction

In the Eastern Mediterranean Sea (EMS), the cyclic occurrence of dark, organic-matter rich sediment layers, known as sapropels, are

diagnostic of basin-wide anoxic events. Sapropels typically have an elevated total organic carbon (TOC) content of >2% (Kidd et al., 1978), which has been attributed to: (1) enhanced primary productivity in response to increased terrestrial nutrient-runoff (Calvert, 1983), (2)

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better preservation of organic matter (OM) under anoxic conditions (Rossignol-Strick, 1982), or (3) a combination of both (Howell and Thunell, 1992). The timing of sapropel deposition is associated with precession-forced insolation maxima, driving an intensified North-African monsoon (Rossignol-Strick, 1985). The strengthened monsoonal climate fueled increased freshwater discharge into the Mediterranean Sea, causing density stratification and increased input of nutrients. The resulting cessation of the thermohaline deep-water mass circulation ultimately led to the formation of oxygen depleted deep-waters (e.g., Rossignol-Strick, 1982; Rohling et al., 2015). Because of their (quasi-) periodicity and excellent preservation, sapropels are ideally suited to evaluate the marine nitrogen (N) cycle under low oxygen conditions. Furthermore, throughout the late Quaternary, not all precession minima are associated with distinct sapropel deposits. These periods of likely less intense deoxygenation have been poorly studied for N-cycle dynamics, despite potentially providing useful information on feedback mechanisms.

At the time of the most recent precession minimum, during which sapropel S1 was deposited (~10.5–6.1 ka BP; Grant et al., 2016), evidence for bottom water anoxia, based on redox sensitive trace metals (e.g., molybdenum, 'Mo' and uranium, 'U'; e.g., Thomson et al., 1995) and benthic foraminifer assemblages (e.g., Abu-Zied et al., 2008) is clear. In contrast, during the precession minimum at ~60 ka BP (Laskar et al., 2004), the corresponding sapropel unit (S2), has not been distinguished unequivocally based on redox and paleo-productivity proxies (e.g., the barium to aluminum ratio, 'Ba/Al'; van Santvoort et al., 1997). Yet, around ~55–52 cal ka BP, a minimum $\delta^{18}\text{O}$ event has been recorded in Soreq cave speleothems (Bar-Matthews and Ayalon, 2007), and in multiple cores recovered from the Levantine Basin (Vergnaud-Grazzini et al., 1977; Rossignol-Strick, 1982; Cornuault et al., 2016; this study), which have been associated with insolation driven increased rainfall (Rossignol-Strick, 1982). Also, a weakened intermediate thermohaline circulation at ~53–51 ka BP (i.e., the approximate timing of S2; Muerdter et al., 1984), is thought to have resulted in reduced bottom water oxygenation in the EMS at this time (Di Donato et al., 2022). As such, some reduced ventilation may be inferred, but the corresponding levels of deoxygenation and associated N-cycling dynamics are still poorly elucidated. Thus, by reconstructing key processes of the N-cycle and redox conditions during the S1 and S2 intervals (from here on referred to as 'S2' due to its ambiguity), potential feedbacks between the N cycle and anoxia, may be exposed.

The availability of dissolved oxygen has a large impact on how N is cycled in marine systems (Fig. 1a). Lipid biomarkers of organisms involved in the N cycle are useful tools in the reconstruction of the different components of the marine N cycle and associated redox conditions (Fig. 1b). Under anoxic conditions, bioavailable N (i.e., nitrate NO_3^- , nitrite NO_2^- and ammonium NH_4^+), is lost through anaerobic ammonium oxidation (anammox; van de Graaf et al., 1997; Kuypers et al., 2003) and denitrification (Kuenen and Robertson, 1988). Ladderane lipids (Sinninghe Damsté et al., 2002c) have been used as biomarker lipids for the past presence of anammox bacteria during sapropel deposition (Rush et al., 2019). In addition, while bacteriohopanetetrol (BHT)-34S is ubiquitously synthesized by bacteria, a later eluting stereoisomer (BHT-x) has been proposed to be uniquely synthesized by marine anammox bacteria, i.e., *Ca. Scalindua* spp. (Rush et al., 2014; Schwartz-Narbonne et al., 2020). Since then, BHT-x has been successfully applied as a biomarker for anammox in a modern marine setting (van Kemenade et al., 2022) and in late Quaternary and Pliocene sapropels (Rush et al., 2019). A third BHT stereoisomer (BHT-34R) is known to be synthesized by freshwater anammox bacteria and various aerobic terrestrial microbial species (Peiseler and Rohmer, 1992; Rosa-Putra et al., 2001; Schwartz-Narbonne et al., 2020).

In Plio-Pleistocene sapropels, lipid biomarkers have also been used to detect the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) by Thaumarchaeota (Menzel et al., 2006; Castañeda et al., 2010; Polik et al., 2018), using crenarchaeol (Sinninghe Damsté et al., 2002b) and N_2 -fixation by heterocytous cyanobacteria (Bale et al., 2019; Elling et al., 2021), using heterocyte glycolipids (HG). Pentose HGs (C_5 HGs) are synthesized by cyanobacteria living in symbiosis with diatoms (diatom-diazotroph associations, 'DDAs'; Schouten et al., 2013; Bale et al., 2015), while hexose HGs (C_6 HGs) are synthesized by freshwater/brackish cyanobacteria of the order Nostocales (Bauersachs et al., 2009; Wörmer et al., 2012). The occurrence of DDAs during sapropel events has been proposed to sustain high mineralization rates, hereby providing a positive feedback on anoxia (Kemp et al., 1999; Sachs and Repeta, 1999). Unsaturated BHT-cyclitol ether (BHT-CE), amongst others synthesized by the filamentous N_2 -fixating non-heterocytous cyanobacterium *Trichodesmium* sp. (Talbot et al., 2008), has also been used to infer past N_2 -fixation (Handley et al., 2010). Applying lipid biomarkers may thus provide us with detailed information on the evolution of the various components of the marine N cycle during sapropel formation.

Here, we explore a ~68 kyr sedimentary record from the EMS

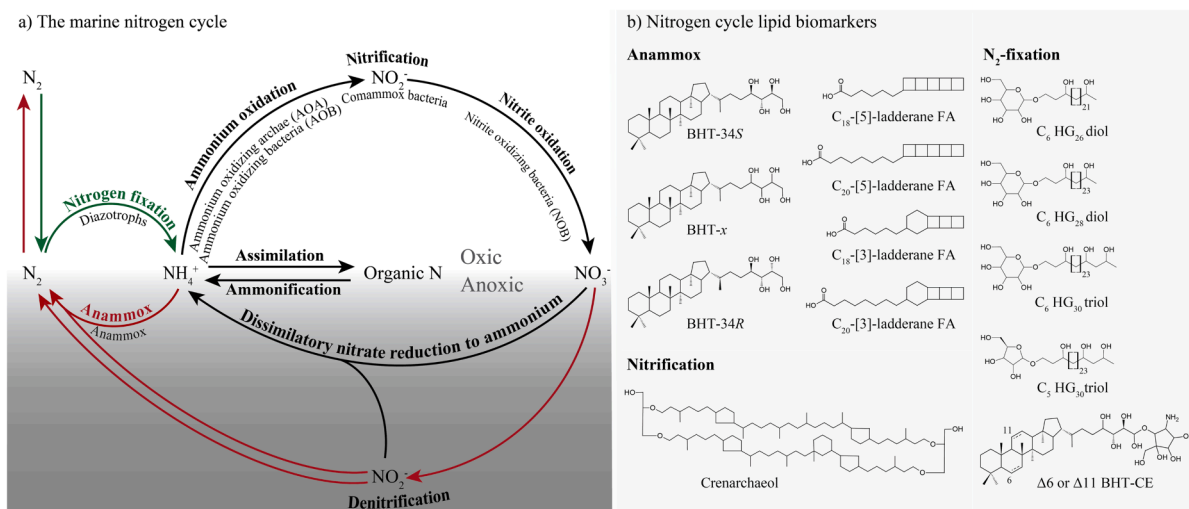


Fig. 1. a) The marine nitrogen (N) cycle. Red arrows indicate the N-loss processes anammox and denitrification. Green arrows indicate N_2 -fixation. Key microorganisms associated with a specific pathway are indicated. b) Lipid biomarkers of N-cycling microorganisms applied in this study. Anammox biomarkers: stereoisomers of bacteriohopanetetrol (BHT)-34S, BHT-x and BHT-34R), and ladderane fatty acids (FAs) with 5 or 3 cyclobutane moieties and 18 or 20 carbon atoms. Nitrification biomarker: crenarchaeol. Diazotrophy biomarkers: heterocyte glycolipids (HG) with C_6 or C_5 sugar head groups and alternating C_{26} to C_{30} alkyl chain lengths and $\Delta 6$ or $\Delta 11$ BHT-cyclitol ether (BHT-CE).

(64PE406-E1; Fig. 2), which includes the well-established Holocene sapropel S1 as well as the ambiguous ‘S2’ event of the late Pleistocene. We provide an overview of the N cycle and associated redox conditions, using a broad scope of lipid biomarkers (Fig. 1b) and compound specific carbon (C) and bulk sediment C and N stable isotopes. Moreover, complementary data in this core obtained from bulk sedimentary redox-sensitive trace metals (Mo, U, and manganese to Al, Mn/Al), Ba/Al ratio (partially published earlier in: Hennekam et al., 2020; Clarkson et al., 2021), and foraminiferal assemblages provide additional insights in the redox conditions and productivity during the studied interval. Comparing the different nitrogen–oxygen feedback modes occurring within and between the more intensely deoxygenated S1 and the ambiguous ‘S2’ ultimately allows us to constrain the feedback of N cycling processes and redox conditions. This provides further insights on biogeochemical responses to marine deoxygenation.

2. Materials and methods

2.1. Sample collection and chronology

A multicore (containing sapropel S1) and piston core (containing onset S1 and ‘S2’) were collected during the Netherlands Earth System Science Centre (NESSC) research cruise (64PE406) onboard the R/V Pelagia, and are collectively referred to as core 64PE406-E1. The cores were recovered in January 2016 at site 64PE406-E1 (33°18.14898′N, 33°23.71998′E; water depth 1760 m below sea surface ‘mbss’) in the Levantine basin, located in the EMS (Fig. 2). For biomarker and bulk isotope analysis, a total of 49 samples were collected from core 64PE406-E1, forming a (near-)continuous record of the last ~68 kyr, which includes the two most recent insolation maxima (Fig. 3a). High resolution sampling was conducted between 5–15 cal ka BP (16 samples; covering S1) and between 49–59 cal ka BP (18 samples; covering ‘S2’). Sediments were freeze-dried and stored at –40 °C until further analysis.

The age model (see supplementary material S1.1 for details) of multicore 64PE406-E1-MC and piston core 64PE406-E1-PC was obtained by correlating Ba/Al excursions and $\delta^{18}\text{O}$ values of *Globigerinoides ruber* to those of other well-dated nearby cores (Grant et al., 2012; Zwiép et al., 2018; Hennekam et al., 2020; Clarkson et al., 2021) and to Soreq speleothem $\delta^{18}\text{O}$ (Grant et al., 2012).

2.2. Total organic carbon and total nitrogen

Freeze-dried sediments were analyzed for total organic carbon

(TOC), total nitrogen (TN) and their stable isotopic composition, $\delta^{13}\text{C}_{\text{TOC}}$ and $\delta^{15}\text{N}_{\text{TN}}$, respectively, using a ThermoScientific Flash EA coupled to a Delta V Plus IRMS. For analysis of TOC and $\delta^{13}\text{C}_{\text{TOC}}$ (but not TN and $\delta^{15}\text{N}_{\text{TN}}$), aliquots of freeze-dried sediment were first acidified to remove calcium carbonate (CaCO_3), using hydrochloric acid (HCl). Sediment aliquots were weighted into tin capsules before combustion. Isotopic compositions were peak size-corrected and offset-corrected using the following certified standards: benzoic acid ($\delta^{13}\text{C}$, –27.4; C%, 68.80), acetanilide ($\delta^{13}\text{C}$, –29.53; C%, 71.09; $\delta^{15}\text{N}$, 1.18; N%, 10.36%), urea ($\delta^{15}\text{N}$, 20.17; N%, 46.65%) and casein ($\delta^{15}\text{N}$, 5.94; N%, 13.32%). Isotopic ratios are reported in ‰ relative to Vienna Pee Dee Belemnite (VPDB) for C, and relative to air for N.

2.3. Benthic foraminiferal analysis

Samples from the multi- and piston cores were sieved over 63 and 150 μm meshes for foraminiferal-based analysis. The >150 μm fraction of all key intervals was studied continuously with a 1 cm resolution (supplementary material 1 Table S2). All low oxygen indicators (Jorissen, 1999) were determined at the species level (*Globobulimina* spp., *Chilostomella* spp., *Cassidulinoides bradyi*, *Ellipsopolymorphina fragilis*, *Fursenkoina* spp., *Stainforthia* spp., *Bulimina exilis* and *Bulimina costata*). On the basis of the cumulative percentage of these low oxygen indicator species (LOS), a semi-quantitative index to estimate bottom water oxygenation (BWO), ranging from 0.0 (anoxia) to 1.0 (100% oxygen saturation) was applied (based on Jorissen et al., 2007), using:

$$\text{BWO} = e^{(-0.0625 \times \% \text{LOS})} \quad (1)$$

Samples with a total number of foraminifera less than were considered sterile due to anoxia, and BWO was set to zero.

2.4. Lipid extraction, derivatization and analysis

2.4.1. Bligh and Dyer extractions

Sediments were extracted using a modified Bligh and Dyer extraction (BDE) method (Bligh and Dyer, 1959; Sturt et al., 2004; Bale et al., 2021). Homogenized sediments (~2–10 g) were dispersed in a solvent solution of 2:1:0.8 (v:v; ~4–20 mL) methanol (MeOH), dichloromethane (DCM) and phosphate buffer. The monophasic mixture was then sonicated for 10 min and centrifuged for 2 min at 3000 rpm after which the supernatant was collected in a centrifuge tube. This procedure was repeated three more times. For the last two repeats, the phosphate buffer was replaced with trichloroacetic acid, after which the supernatant was

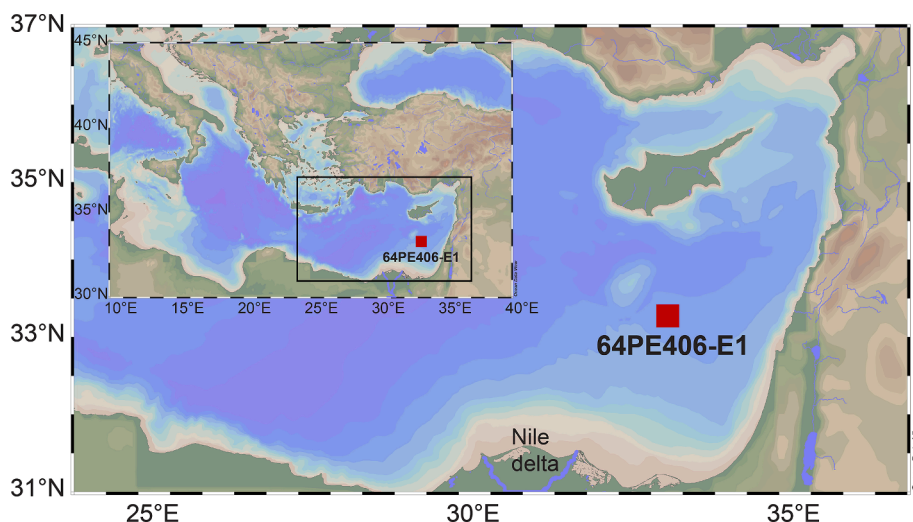


Fig. 2. Location of multi-, and piston core 64PE406-E1 (33°18.14898′N, 33°23.71998′E; indicated with red square) in the Levantine basin, Eastern Mediterranean Sea. Core was recovered from a water depth of 1760 mbss. Rivers are indicated in purple. Map was created using ODV (Schlitzer, R., Ocean Data View, 2021).

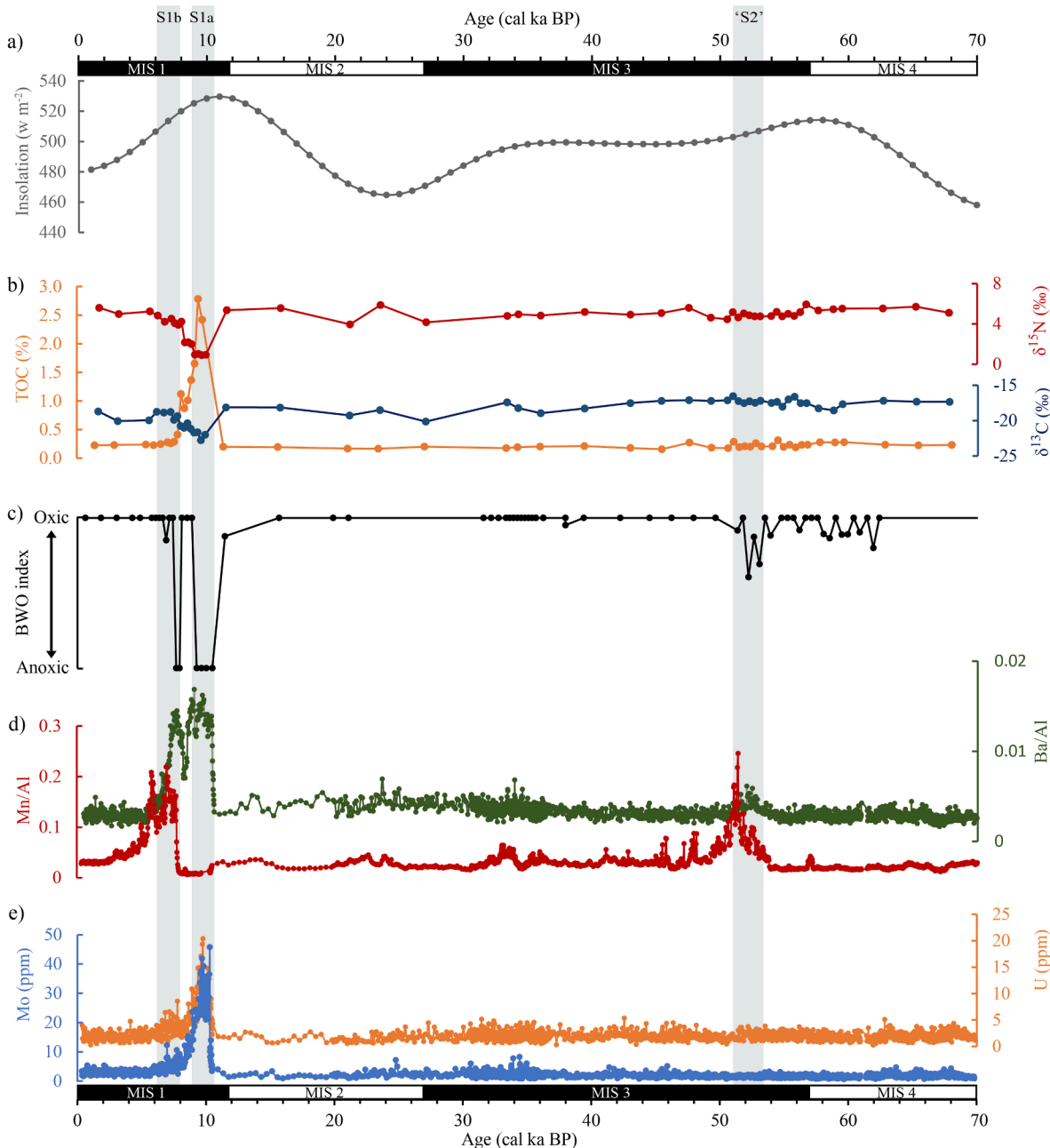


Fig. 3. a) 21st of June 65°N insolation curve (Laskar et al., 2004); data from record 64PE406-E1; b) Total organic carbon (TOC) in orange, sedimentary bulk $\delta^{15}\text{N}$ in red and $\delta^{13}\text{C}$ in blue; c) Benthic foraminifer derived bottom water oxygen (BWO) estimate; XRF scanning data partially published earlier in Hennekam et al., 2020; Clarkson et al., 2021; d) ratio of Manganese (Mn) to Aluminum (Al) in red and the ratio of Barium (Ba) to Al in green; and e) concentrations of Molybdenum (Mo) in blue and Uranium (U) in orange. Timing of S1a, S1b (Rohling et al., 2015; Grant et al., 2016) and 'S2' (Muerdter et al., 1984), are shown in grey. Glacial and interglacial marine isotope stages are indicated in white and black, respectively.

collected in a separate centrifuge tube. Phase separation was then achieved in the collected supernatant by adding additional DCM and phosphate buffer, to obtain a new ratio of 1:1:0.9 ($\nu:\nu$), MeOH, DCM and phosphate buffer, respectively. The biphasic mixture was centrifuged (2 min at 3000 rpm), after which the bottom DCM layer was collected. The remaining solvent phase was washed two more times with DCM, using the same procedure. The combined DCM layers were dried under N_2 gas. Freeze-dried biomass of *Ca. Scalindua* spp. (van de Vossenberg et al., 2008) and *Ca. Brocadia* spp. (Kartal et al., 2007) was extracted similarly, and used as a reference standard for the analysis of $\text{C}_{18}[3]$ -, $\text{C}_{18}[5]$ -, $\text{C}_{20}[3]$ - and $\text{C}_{20}[5]$ -ladderanes and BHT stereoisomers.

2.4.2. Saponification and methylation for ladderane fatty acid analysis

BDE aliquots were saponified in 2 N potassium hydroxide (in MeOH 96%) by refluxing for 1 h. After, 2 mL of bidistilled water was added to the saponified extracts. The fatty acid (FA) fraction was obtained by acidifying the reaction mixture to a pH of 3 with 2 N hydrochloric acid/MeOH (1:1, $\nu:\nu$), and partitioning three times with DCM. The DCM layer was collected each time after centrifuging for 2 min at 3000 rpm. The FA fraction was dried over a sodium sulphate (Na_2SO_4) column, using DCM as an eluent. Following this, the fractions were methylated with diazomethane (CH_2N_2) and air dried overnight. Polyunsaturated fatty acids were removed by eluting the methylated fractions with DCM over a silica impregnated silver nitrate (AgNO_3) column. Samples were dissolved in acetone and filtered over 0.45 mm PTFE filters (4 mm; BGB,

USA), before analysis.

2.4.3. Purification and acetylation for $\delta^{13}\text{C}_{\text{BHTs}}$ compound specific stable isotope analysis

Nine core sediment depths (Table 1) were selected for compound specific $\delta^{13}\text{C}$ analysis of BHT-34S ($\delta^{13}\text{C}_{\text{BHT-34S}}$), BHT-x ($\delta^{13}\text{C}_{\text{BHT-x}}$) and BHT-34R ($\delta^{13}\text{C}_{\text{BHT-34R}}$), using the method described in Lengger et al., (2019). BDE aliquots were subjected to column chromatography using Isolute NH₂ 500 mg/3mL solid phase extraction (SPE) columns. The columns were preconditioned with 2 × 3 mL hexane. Fraction 1, 2 and 3 were eluted with hexane, DCM, and MeOH, respectively, with the latter containing BHT. All fractions were dried under N₂. Fractions were acetylated using a 1 mL mixture of acetic acid anhydride and pyridine (1:1, v:v) at 50 °C for 1 h, and left overnight at room temperature. Acetylated fractions 3 (MeOH) were dried under N₂ and dissolved in ethyl acetate before analysis on the GC-IRMS.

2.4.4. Analysis of intact polar lipids

Deuterated diacylglyceryltrimethylhomoserine (DGTS D-9; Avanti® Polar Lipids, USA) was added as an internal standard to BDE aliquots. Aliquots were dissolved in a MeOH: DCM 9:1 (v:v) and filtered over 4 mm True generated cellulose syringe filters (0.45 µm, BGB, USA). Filtered aliquots were analysed on an Agilent 1290 Infinity I ultra-high performance liquid chromatographer (UHPLC) with a thermostatted auto-injector, coupled to a Q Exactive Orbitrap MS with an Ion Max source and heated electrospray ionisation probe (HESI; ThermoFisher Scientific, Waltham, MA), according to Hopmans et al. (2021; modified from Wörmer et al., 2013). Briefly, chromatographic separation was achieved with an Acquity BEH C18 column (2.1 × 150 mm, 1.7 µm, Waters), with A) MeOH / H₂O / formic acid / 14.8 M NH₃aq (85:15:0.12:0.04 [v:v]) and B) IPA / MeOH / formic acid / 14.8 M NH₃aq (50:50:0.12:0.04 [v:v]) at a flow rate of 0.2 mL min⁻¹. Compounds were eluted with 5% B for 3 min, followed by a linear gradient to 40% B at 12 min ending at 100% B at 50 min. Lipids were detected using positive ion monitoring of m/z 350–2000 (resolution 70,000 ppm at m/z 200), followed by data dependent MS² (isolation window 1 m/z ; resolution 17,500 ppm at m/z 200) of the 10 most abundant ions.

For the analysis of BHT and unsaturated BHT-CE, optimal fragmentation was achieved with a stepped normalized collision energy of 22.5 and 40 (isolation window 1.0 m/z). Identification and integration was based on their exact masses (within 3 ppm) and diagnostic

fragmentation spectra (Hopmans et al., 2021). The protonated ($[\text{M}+\text{H}]^+$ adduct (m/z 706.525) was used for integration of unsaturated BHT-CE. The combined mass chromatogram of the ammoniated ($[\text{M}+\text{NH}_4]^+$) and sodiated ($[\text{M}+\text{Na}]^+$) adducts (m/z 564.499 and m/z 569.454, respectively) were used for integration of BHT-34S, BHT-x and BHT-34R. The ratio of BHT-x and BHT-34R over BHT-34S was then calculated as:

$$\text{BHT-x ratio} = \frac{\text{BHT-x}}{(\text{BHT-x} + \text{BHT-34S})} \quad (2)$$

$$\text{BHT-34R ratio} = \frac{\text{BHT-34R}}{(\text{BHT-34R} + \text{BHT-34S})} \quad (3)$$

For the analysis of HGs and crenarchaeol, optimal fragmentation was achieved with a stepped normalized collision energy of 15, 22.5 and 30 (isolation window 1.0 m/z). Identification and integration of analyzed compounds was based on their exact masses (within 3 ppm) and diagnostic fragmentation spectra (Bauersachs et al., 2009; Schouten et al., 2013; Bale et al., 2019). The combined mass chromatograms of the $[\text{M}+\text{H}]^+$ and $[\text{M}+\text{NH}_4]^+$ adducts were used to integrate hexose and pentose HGs. Identified and integrated HGs were: C₆ HG₂₆ diol (m/z 577.467 and m/z 594.494), C₆ HG₂₈ diol (m/z 605.499 and m/z 621.517), C₆ HG₃₀ triol (m/z 649.525 and m/z 666.552) and C₅ HG₃₀ triol (m/z 619.514 and m/z 636.541). Mass chromatograms of the $[\text{M}+\text{H}]^+$, $[\text{M}+\text{NH}_4]^+$ and $[\text{M}+\text{Na}]^+$ adducts and their first isotopologue were used to integrate crenarchaeol (m/z 1292.244, 1293.252, m/z 1309.271, 1310.279, m/z 1314.226, 1315.234).

The integrated peaks were corrected for matrix effects and variations in MS performance using the internal DGTS-D9 standard. Due to a lack of authentic standards for absolute quantifications, concentrations are reported as their relative integrated peak area response unit (ru), and normalized against their accumulation rate (ru g⁻¹ cm⁻² kyr⁻²). Normalized concentrations per gram TOC (ru gTOC⁻¹) are also reported (supplementary material 1 Fig. S2). Although this does not allow for quantification of absolute concentrations, it does allow for relative quantification, as the response factor should be identical across the sample set.

2.4.5. Analysis of ladderane fatty acids

Filtered FAME fractions were analyzed on an Agilent 1290 Infinity I UHPLC equipped with a thermostatted auto-injector and column oven, coupled to a Q Exactive Plus Orbitrap MS, with a positive ion

Table 1

$\delta^{13}\text{C}$ values [‰ V-PDB] and standard deviations (s.d.; 1-sigma) of (from left to right) BHT-34S, BHT-x, BHT-34R and TOC in nine samples from core 64PE406-E1, with corresponding age (in cal ka BP). Additionally, $\delta^{13}\text{C}$ values for BHT-x and BHT-34R were determined for *Ca. Scalindua* spp. and *Ca. Brocadia* spp., biomass (above the upper dotted line) recovered from an anoxic sequencing batch reactor at Radboud University, the Netherlands. Samples below the lower dotted line reflect median values of entire datasets, with datasets from a: this study, recovered from core PE406-E1 in the Levantine basin; b: Lengger et al. (2019), recovered from core P900 in the Arabian Sea; c: Elling et al., (2021), recovered from ODP sites 964 in the Ionian Sea and 967 in the Levantine basin.

Sample	Age (cal ka BP)	$\delta^{13}\text{C}$ values [‰ V-PDB]							
		BHT-34S	s.d.	BHT-x	s.d.	BHT-34R	s.d.	TOC	s.d.
Ca. Scalindua	–	–71.8	0.2	–73.7	0.4	n.d.*	–	–	–
Ca. Brocadia	–	–63.1	0.3	n.d.	–	–62.7	0.1	–	–
PE406-E1, S1	7.8	–24.7	0.4	–41.5	0.9	n.d.	–	–20.7	<0.1
PE406-E1, S1	8.9	–24.1	1.0	–42.7	0.8	n.d.	–	–21.7	<0.1
PE406-E1, S1	9.7	–24.5	0.3	–38.9	0.2	n.d.	–	–22.0	0.2
PE406-E1, non-sapropel	45.3	–22.6	0.4	n.d.	–	–32.8	0.7	–17.2	0.1
PE406-E1, 'S2'	51.3	–25.1	0.3	n.d.	–	–43.0	1.2	–17.2	<0.1
PE406-E1, 'S2'	52.2	–24.7	0.5	n.d.	–	–41.2	0.9	–17.3	0.2
PE406-E1, 'S2'	52.6	–25.3	1.3	n.d.	–	–41.5	0.6	–17.5	0.3
PE406-E1, non-sapropel	62.6	–23.5	0.3	n.r.**	>2.0	–33.6	1.5	–17.2	0.2
PE406-E1, non-sapropel	65.2	–22.2	0.3	n.d.	–	n.d.	–	–17.3	0.1
PE406-E1 ^a	–	–24.1	1.1	–41.5	1.9	–41.2	4.8	–18.7	2.1
P900 ^b	–	–26.6	1.4	–46.1	3.4	–	–	–20.9	0.8
ODP 964 and 967 ^c	–	–27.2	1.1	–47.1	2.1	–	–	–22.0	1.5

* n.d.: not detected.

** n.r.: not reproducible (when the s.d. of measurements is >2.0).

atmospheric pressure chemical ionization (APCI) probe (Thermo Fischer Scientific, Waltham, MA), as previously described by van Kemenade et al., (2022). Separation was realized with a ZORBAX Eclipse XDB C18 column (Agilent, 3.0 × 250 mm, 5 μm), using MeOH as an eluant at 0.4 mL min⁻¹. Target lipids were detected using a positive ion monitoring of *m/z* 225–380 (140,000 ppm resolution), followed by a data dependent MS² (isolation window 1 *m/z*; resolution 17,500 ppm at *m/z* 200) of the 10 most abundant ions. The stepped normalized collision energy was set at 15, 22.5, 30. Mass chromatograms of the protonated molecules were used to integrate C₁₈[3]-, C₁₈[5]-, C₂₀[3]- and C₂₀[5]-ladderane FAMES (*m/z* 291.232, 289.216, 319.263, 317.248, respectively), reported within 5 ppm mass accuracy. Quantification was performed using external calibration curves of isolated of C₂₀[3]- and [5] ladderane FAMES standards (Hopmans et al., 2006). Concentrations are reported in accumulation rates (ng⁻¹ cm⁻² kyr⁻¹; supplementary material 1 Table S7). Identification of ladderanes was achieved by comparing retention times and spectra with in-house isolated C₂₀[3]- and [5] ladderane FAME standards (supplementary material 2, Fig. S3) and with C₁₈[3]-, C₁₈[5]-, C₂₀[3]- and C₂₀[5]-ladderane FAMES in a biomass sample of *Ca. Kuenenia* (Ratray et al., 2008). Additionally, although PUFAs were removed during the sample preparation (see Section 2.4.2), commercially available C₁₈:3- and C₂₀:3-polyunsaturated fatty acids (PUFAs; Reagecon Diagnostics Ltd.; *m/z* 291.232 and 319.263) were derivatized and analyzed using the same method to assess potential interference with the identification of the ladderane FAMES of the same *m/z*. The PUFA standards differed significantly in retention time (supplementary material 2, Fig. S4).

2.4.6. δ¹³C analysis of BHT stereoisomers

Compound specific stable isotope analysis of δ¹³C values of the BHT stereoisomers (δ¹³C_{BHT-34S}, δ¹³C_{BHT-x}, δ¹³C_{BHT-34R}) was performed on a GC-C-IRMS system (Trace 1310 GC coupled to a Delta V MS via a GC Isolink II and Conflo IV, ThermoScientific), equipped with a CP Sil-5 column (25 m length, 0.32 mm OD and 0.12 μm film thickness; Agilent,). Helium was used as a carrier gas with a flow rate of 2 mL min⁻¹. The programmed temperature was set at 70 °C and followed the next program: 20 °C min⁻¹ to 130 °C, 10 °C min⁻¹ to 190 °C and 1 °C min⁻¹ to 320 °C where it remained for 10 min. Monitoring CO₂ gas with a predetermined stable carbon isotope value was measured at the beginning and end of each run to be able to assign isotope values to the compounds of interest. Performance of the entire system including the combustion interface was monitored using an in-house mixture of C₂₀ and C₂₄ perdeuterated *n*-alkane standards (IAEA) (STD < 0.5%). The isotopic composition of the acetyl group used in the acetylation of the BHT stereoisomers was determined by acetylation of *myo*-inositol with a predetermined stable carbon isotope value, which was then subtracted from the δ¹³C BHT values, using a mass balance correction. Isotopic compositions are reported relative to the VPDB standard for C.

3. Results

3.1. Total organic carbon and total nitrogen

Throughout the record, sedimentary bulk total organic carbon (TOC) content ranges from 0.2 to 2.8%, showing a δ¹³C value (δ¹³C_{TOC}) of -16.5 to -22.7‰ (Fig. 3b). Total nitrogen (TN) content ranges from 0.02 to 0.20%, with δ¹⁵N values (δ¹⁵N_{TN}) of 0.9–5.0‰. TOC and TN content are relatively stable in the time interval between 67.8 and 11.3 cal ka BP (TOC: 0.2–0.3%; TN: 0.02–0.03%), while δ¹³C_{TOC} and δ¹⁵N_{TN} values range from -20.1 to -16.5‰ and from 4.0 to 5.9‰, respectively (Fig. 3b). Between 10.4–8.1 cal ka BP, TOC and TN are relatively elevated (TOC: 0.9–2.8%; TN: 0.10–0.20%), while δ¹³C_{TOC} and δ¹⁵N_{TN} values are lower (δ¹³C_{TOC}: -22.7 to -20.4‰; δ¹⁵N_{TN}: 0.9–2.2‰). Maximum TOC and TN content and minimum δ¹³C_{TOC} and δ¹⁵N_{TN} values are observed at 9.4 cal ka BP. Between 7.8–1.4 cal ka BP, TOC is 0.2–0.4% (δ¹³C_{TOC}: -20.7 to -18.7‰) and TN is 0.02–0.05% (δ¹⁵N_{TN}:

3.9–5.6%).

3.2. Lipid biomarkers

3.2.1. Bacteriohopanetetrols

Unsaturated BHT-CE was not detected in this study. BHT-34S was present throughout the sedimentary record, with accumulation rates (ARs) ranging between 6.7 × 10⁶–7.0 × 10⁹ ru g⁻¹ cm⁻² kyr⁻¹ (supplementary material 1, Table 2). BHT-*x* (Fig. 4a) was present in sediments from 67.8 to 53.9 and 49.2 to 1.4 cal ka BP (except at 42.9 cal ka BP), at ARs between 2.6 × 10⁷–5.6 × 10⁹ ru g⁻¹ cm⁻² kyr⁻¹ (BHT-*x* ratio: 0.03–0.59). BHT-*x* ARs peaked (in relation to background values) between 9.7–5.4 cal ka BP. BHT-34R stereoisomer was detected in sediments between 67.8–56.6 cal ka BP (Fig. 4a), with values of 1.0 × 10⁷–5.0 × 10⁸ ru g⁻¹ cm⁻² kyr⁻¹ (BHT-34R ratio [3]: 0.02–0.68) and between 54.3–42.9 cal ka BP (except at 53.9 cal ka BP), with values of 4.0 × 10⁶–1.1 × 10⁹ ru g⁻¹ cm⁻² kyr⁻¹ (BHT-34R ratio: 0.02–0.76).

In the nine sediment horizons selected for compound-specific δ¹³C stable isotope analysis of the BHT stereoisomers (Table 1), δ¹³C_{BHT-34S} values range from -25.3 to -22.2‰ (median, 'MD': -24.1 ± 1.1‰). In the three horizons recovered from the S1 time interval (7.8, 8.9 and 9.7 cal ka BP), δ¹³C_{BHT-x} values range from -42.7 to -38.9‰ (MD: -41.5 ± 4.8‰). In the three horizons recovered from the 'S2' time interval (51.3, 52.2, 52.6 cal ka BP), δ¹³C_{BHT-34R} values range from -43.0 to -41.2‰. At 45.3 and 62.6 cal ka BP, δ¹³C_{BHT-34R} was -32.8 and -33.6‰, respectively (δ¹³C_{BHT-34R} MD: -41.2 ± 1.9‰ for all five horizons). At 65.2 cal ka BP, BHT-34R concentrations were insufficient for δ¹³C_{BHT-34R} analysis. δ¹³C_{BHT} values were also determined in a *Ca. Scalindua* spp. and *Ca. Brocadia* spp. biomass enrichment culture, with the former showing values of -71.8‰ for δ¹³C_{BHT-34S} and -73.7‰ for δ¹³C_{BHT-x}, and the latter showing values of -63.1‰ for δ¹³C_{BHT-34S} and -62.7‰ for δ¹³C_{BHT-x}.

3.2.2. Ladderane fatty acids

Identified ladderane fatty acids were C₁₈[5]-, C₂₀[3]- and C₂₀[5]-ladderanes (concentrations reported in supplementary material 2, Table 3). Throughout the record, summed ladderane FA concentrations (Fig. 4c) were 0–2.4 ng⁻¹ cm⁻² kyr⁻¹, with higher concentrations observed between 62.6–42.9 cal ka BP (maximum at 53.9–53.0 cal ka BP) and between 9.1–6.5 cal ka BP (maximum at 7.8–7.3 cal ka BP). C₁₈[5]-ladderanes were solely detected in the younger sediments, at 9.1 cal ka BP (0.3 ng⁻¹ cm⁻² kyr⁻¹) and between 8.3–7.0 cal ka BP (0.1–1.1 ng⁻¹ cm⁻² kyr⁻¹). C₂₀[3]- and C₂₀[5]-ladderanes were detected in sediments between 62.6–42.9 cal ka BP, except at 55.2 and 54.8 cal ka BP sediments, both at ARs of 0.1–0.3 ng⁻¹ cm⁻² kyr⁻¹. The C₂₀[3]-ladderane was additionally present at 33.3 cal ka BP sediments (0.3 ng⁻¹ cm⁻² kyr⁻¹). The C₂₀[3]- and C₂₀[5]-ladderane ARs in the younger sediments (9.1–6.5 cal ka BP) were 0.3–1.2 ng⁻¹ cm⁻² kyr⁻¹ (maximum at 9.1 cal ka BP) and 0.2–2.2 ng⁻¹ cm⁻² kyr⁻¹ (maximum at 8.9 cal ka BP), respectively.

3.2.3. Heterocyte glycolipids

Identified heterocyte glycolipids were: C₅ HG₃₀ triol, C₆ HG₂₆ diol, C₆ HG₂₈ diol and C₆ HG₃₀ triol (concentrations reported in supplementary material 2, Table 4). The C₅ HG₃₀ triol (Fig. 4d) was present in sediments from 11.3 to 5.4 cal ka BP (except at 7.5 and 6.5 cal ka BP) at ARs of 1.0 × 10⁷–5.6 × 10⁹ ru g⁻¹ cm⁻² kyr⁻¹ (max. at 8.6 cal ka BP). C₆ HGs were detected in sediments from 62.6 to 50.9 cal ka BP (except at 53.1 and 53.0 cal ka BP) with ARs of 8.7 × 10⁶–1.2 × 10⁸ ru g⁻¹ cm⁻² kyr⁻¹ (max. at 56.2 cal ka BP) and in sediments from 11.3 to 1.4 cal ka BP (except at 7.0 cal ka BP), at ARs of 2.2 × 10⁷–3.7 × 10⁹ ru g⁻¹ cm⁻² kyr⁻¹ (max. at 8.6 cal ka BP). C₆ HGs are reported as their summed abundance (Fig. 4d): they were detected in sediments of 47.5, 34.2 and 33.3 cal ka BP with ARs of 8.3 × 10⁶, 2.0 × 10⁷ and 4.2 × 10⁷ ru g⁻¹ cm⁻² kyr⁻¹, respectively.

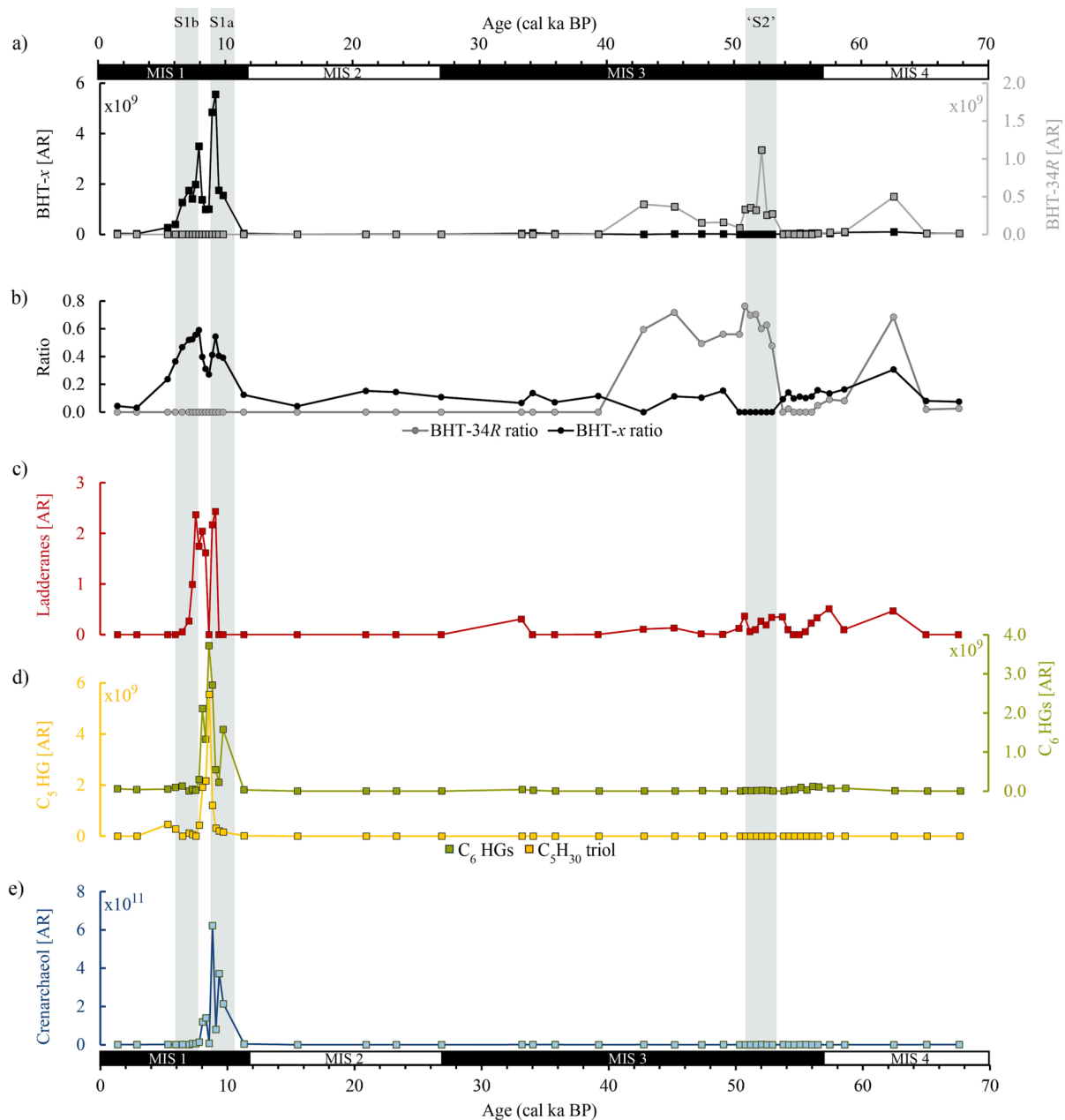


Fig. 4. Lipid biomarker accumulation rates (ARs) at site 64PE406-E1: a) bacteriohopanetetrol (BHT)-x and BHT-34R [$\text{ru g}^{-1} \text{cm}^{-2} \text{kyr}^{-1}$]; b) BHT-34R ratio in grey and BHT-x ratio in black; c) summed $\text{C}_{18}[3]$ -, $\text{C}_{18}[5]$ -, $\text{C}_{20}[3]$ - and $\text{C}_{20}[5]$ -ladderane FAs [$\text{ng}^{-1} \text{cm}^{-2} \text{kyr}^{-1}$]; d) Heterocyte glycolipids (HG) with summed C_6 HGs (C_6 HG₂₆ diol, C_6 HG₂₈ diol and C_6 HG₃₀ triol) plotted on the right y-axis and C_5 HG₃₀ triol plotted on the left y-axis [$\text{ru g}^{-1} \text{cm}^{-2} \text{kyr}^{-1}$]; and e) crenarchaeol [$\text{ru g}^{-1} \text{cm}^{-2} \text{kyr}^{-1}$]. Timing of S1a, S1b (Rohling et al., 2015; Grant et al., 2016) and 'S2' (Muerdter et al., 1984), are shown in grey. Glacial and interglacial marine isotope stages are indicated in white and black, respectively.

3.2.4. Crenarchaeol

Crenarchaeol was detected throughout the sedimentary record at ARs of 2.4×10^7 – $6.2 \times 10^{11} \text{ ru g}^{-1} \text{cm}^{-2} \text{kyr}^{-1}$ (Fig. 4e; supplementary material S2, Table 5), with peak ARs at 9.7 to 7.8 cal ka BP (7.1×10^9 – $6.2 \times 10^{11} \text{ ru g}^{-1} \text{cm}^{-2} \text{kyr}^{-1}$; max. at 8.9 cal ka BP).

3.3. Benthic foraminiferal bottom water oxygenation index

Low oxygen indicator species (LOS) varied throughout the core in abundances of 0–8%, relative to the total number of benthic foraminifera (supplementary material 1 and 2, Fig. S5 and Table 6, respectively). Based on the LOS cumulative percentage and the absence of foraminifera (where the BWO index was set to 0), the benthic foraminiferal BWO index was determined for the entire record (Fig. 3c), with values

ranging between 0.0 (i.e., anoxic bottom waters) and 1.0 (i.e., fully oxygenated bottom waters). Through most of the record, the BWO index indicates fully oxygenated conditions (BWO \sim 1) with the exception of two periods: i) during 'S2', the BWO index shows a decrease (reaching 0.6) indicating oxygen depleted waters without reaching anoxia, ii) at 11.3 cal ka BP the BWO index was 0.9 and decreased to 0 during S1. During S1, the BWO index was 0 between 10.4–8.8 and 7.8–7.5 cal ka BP, with the amount of total foraminiferal counts <4 , indicating anoxic bottom water conditions. At 8.8 to 8.0 cal ka BP (between S1a and S1b), an interval was observed where the BWO index was 1.0.

4. Discussion

EMS sapropels, characteristic of basin-wide deoxygenation events,

are valuable for the investigation of past marine nitrogen cycling under low oxygen conditions. In the following sections, lipid biomarkers of microorganisms involved in the nitrogen cycle are analysed with redox sensitive trace metals and benthic foraminifer assemblages to constrain past nitrogen cycling activities and redox conditions during the Holocene sapropel S1 (~10.5–6.1 ka BP; Section 4.1) and the 'S2' event of the late Pleistocene (53–51 ka BP; Section 4.2). Ultimately, by assessing the shifts in the N-cycle occurring during the different depositional environments of S1 and 'S2', further insights can be obtained on feedback mechanisms between the nitrogen cycle and water column deoxygenation (Section 4.3).

4.1. Nitrogen cycling dynamics under altering redox conditions during deposition of the Holocene sapropel S1

4.1.1. Loss of fixed N throughout the S1 event

The presence of anammox biomarkers indicate loss of bioavailable N via marine anammox bacteria (*Ca. Scalindua* spp.) throughout S1 deposition (Fig. 4a, c). The BHT-x ratio [1] reflects the relative contribution of BHT-x synthesized by the anaerobe *Ca. Scalindua* spp. (Rush et al., 2014; Schwartz-Narbonne et al., 2020; van Kemenade et al., 2022), over the total BHT-34S pool, ubiquitously synthesized by mostly aerobic bacteria. From 9.7 cal ka BP onwards, the BHT-x ratio is >0.2 (Fig. 4b), suggesting a dominant presence of *Ca. Scalindua* spp. within the total pool of BHT-34S synthesizing bacteria (van Kemenade et al., 2022). Ladderane FA and BHT-x ARs further suggest *Ca. Scalindua* spp. was most abundant at ~9.1 cal ka BP (Fig. 4a, c).

At the onset of S1a (~10.5 cal ka BP), the abrupt disappearance of benthic foraminifera reflects a quick establishment of anoxic bottom waters at site 64PE406-E1. The depth at the core location (1760 mbss) is at the edge of the stagnant and euxinic deep-water (DW) during S1 (<1800 mbss; De Lange et al., 2008) and anoxic intermediate water, which were more frequently ventilated (sapropel intermediate water; SIW; ~500–1800 mbss; Zirks et al., 2019). During S1, SIW is believed to have flowed from the Aegean Sea towards the Levantine basin, becoming progressively depleted in oxygen in response to the increased remineralization of the sinking OM (Zirks et al., 2019; 2021). Indeed, the Ba/Al profile (Fig. 3e) points to increased export productivity between ~10.5–6.1 cal kyr BP, typically thought to be a response to enhanced Nile River discharge (see review Rohling et al., 2015), recorded from ~11.3 cal ka BP onwards (Hennekam et al., 2014; 2015; Weldeab et al., 2014). Mild DW euxinia is also recorded during S1a (Azrieli-Tal et al., 2014; Andersen et al., 2020). This is thought to be the result of a slowdown of the Mediterranean thermohaline overturning system, resulting in a cessation of DW renewal (e.g., Sarmiento et al., 1988; de Lange et al., 2008). As our site is located at the boundary of the anoxic non-euxinic SIW (Matthews et al., 2017; Zirks et al., 2019) and euxinic DW, the concurrent increase in Mo and U (Fig. 3e), indicative of euxinic conditions (Tribovillard et al., 2006; Algeo and Liu 2020), likely reflects a euxinic sediment–water interface, and possibly euxinic bottom waters. As anammox bacteria are inhibited by the presence of free sulfide (Jensen et al., 2008), *Ca. Scalindua* spp. likely occupied a niche in the anoxic SIW, but not in the euxinic DW or sediments. Hence, the more progressive oxygen-depletion of the SIW may have resulted in a gradual expansion of anammox into the SIW, causing maximum anammox to occur with a lag (of ~1.4 kyr) after the onset of bottom water anoxia.

A dip in anammox biomarkers is observed at ~8.6 cal ka BP. At this time, the BWO index records a return of oxygenated bottom water conditions (~8.6–8.1 cal ka BP; Fig. 3c). This oxygenation period (8.5–8.0 cal ka BP; Grant et al., 2016) relates to the well-known S1 interruption, corresponding to the re-ventilation of the EMS, which may be associated to the 8.2 ka BP global cooling event (Rohling et al., 1997). Likely, the return of more oxygenated SIW (Zirks et al., 2021) led to a crash of *Ca. Scalindua* spp. population in the water column. However, after 8.3 cal ka BP, anammox biomarker ARs increase again. While the anammox process is inhibited by oxygen concentrations as low as 1 μM

(Strous et al., 1997), in the marine environment *Ca. Scalindua* spp., are known to inhabit anoxic micro-niches, allowing them to thrive at ambient oxygen concentrations up to ~20 μM (Woebken et al., 2007). In addition, evidence for anammox bacterial presence has been detected in marine environments with oxygen levels up to ~9–50 μM (Kuypers et al., 2005; Hamersley et al., 2007; Jensen et al., 2008; Kalvelage et al., 2011; Hamasaki et al., 2018; van Kemenade et al., 2022). (Pore) waters in the Levantine basin during the S1 interruption must thus have been sufficiently oxygen-deficient (at least < 50 μM ; van Kemenade et al., 2022) to provide a suitable niche for *Ca. Scalindua* spp.

A progressive down-ward moving oxidation front has affected the composition of the upper part of the original S1b layer. Previously described discrepancies between the TOC and Ba/Al profiles (Thomson et al., 1995; van Santvoort et al., 1996; de Lange et al., 2008), in which the latter is thought to reflect the original primary productivity, and hence C-deposition signal, is indicative of the post-depositional oxidation ('burn-down') of sapropels. Burn-down of the upper part of S1 at our site occurred from ~7.8 cal ka BP onwards (Fig. 3b, d). The lower Mn/Al peak (start at ~7.8 cal ka BP; Fig. 3d) is thought to mark the depth of the currently active oxidation front (Higgs et al., 1994; Thomson et al., 1995; van Santvoort et al., 1996), as Mn precipitates under oxygenated conditions (Tribovillard et al., 2006). The upper Mn/Al peak (start at ~6.1 ka BP; Fig. 3d) is thought to mark the time of re-introduction of oxygenated bottom waters at the end of S1, as a response to the resumption of DW formation (Filippidi and de Lange et al., 2019). The BWO index is thought to largely withstand post-depositional diagenesis (Jorissen et al., 2007). A near-absence of benthic foraminifera shows anoxic conditions between 7.8–7.5 cal ka BP, and their re-occurrence the establishment of fully oxygenated conditions from ~6.5 cal ka BP onwards (Fig. 3c).

This post-depositional oxidation likely also affected biomarker concentrations (Sinninghe Damsté et al., 2002a), suggesting the original ARs of anammox biomarkers in the oxidized section of S1b must have been higher than reported here. Despite this, ladderane ARs in S1b still surpass those of S1a, suggesting that loss of bioavailable N via anammox was probably more intense during S1b than during S1a. This is supported by the observation that anammox biomarker concentrations normalized against TOC (which should retain the original signal better as both TOC and lipids are sensitive to oxic degradation) are also higher in S1b than in S1a (supplementary material 1, Fig. S2). Unexpectedly, however, while ladderane lipids undergo β -oxidation under the influence of low amounts (<3 μM) of oxygen, their corresponding short-chain (SC) degradation products (SC-ladderanes; Rush et al., 2011; 2012), were not detected in the oxidized section of S1b, nor in the rest of the record.

The BHT-x ratio (which is likely not affected by diagenesis) is substantially elevated (>0.2) across the S1 interruption and during S1b, showcasing a similar relative abundance of *Ca. Scalindua* spp. in the total bacterial pool as during S1a (Fig. 4b). In the contemporary Benguela oxygen minimum zone, where similar BHT-x ratio values have been observed as in S1 (>0.2; van Kemenade et al., 2022), the total amount of N loss via anammox was estimated to be 1 Tg N yr⁻¹ (Kuypers et al., 2005). Accordingly, loss of bioavailable N via anammox is thought to have been substantial from ~9.1 cal ka BP (~1.4 kyr after the onset of anoxia) until the end of the S1 event.

4.1.2. N₂-fixation during S1a and S1 interruption

Hexose HG ARs are elevated across S1a (from 9.6 cal ka BP onwards), and during the S1 interruption, with peak values at 8.6 cal ka BP (Fig. 4d). The C₆ HG₂₆ diol, C₆ HG₂₈ diol and C₆ HG₃₀ triol observed in this study are biomarkers for freshwater/brackish cyanobacteria of the order Nostocales (Bauersachs et al., 2009; Wörmer et al., 2012). The presence of C₆ HGs in sapropel S5 has been attributed to the presence of a brackish surface layer formed because of enhanced Nile outflow into the EMS (Bale et al., 2019). The presence of C₆ HGs in S1 suggests that, at least occasionally, the surface waters must have been sufficiently

brackish to provide a suitable niche for Nostocales cyanobacteria. Indeed, maximum intensities of Nile River discharge into the EMS occur around 9.5 ka BP and gradually decrease after the S1 interval, from 6.5 cal kyr onwards (Hennekam et al., 2014; 2015; Weldeab et al., 2014). Modern Nile floods are known to reduce salinity in the EMS basin. The much larger flooding occurring during S1a (Woodward et al., 2022) could have resulted in the brackish water conditions inferred from this study.

A peak in C₅ HG₃₀ triol is observed in the S1 interval, slightly surpassing C₆ HG ARs (factor 1.5; Fig. 4d). C₅ HGs are synthesized by marine DDAs, with the C₅ HG₃₀ triol being specifically associated with the heterocytous cyanobacterium *Richelia intracellularis* (Schouten et al., 2013; Bale et al., 2015). Its corresponding host diatom, *Hemiaulus hauckii*, has previously been reported to occur in sapropel S5 sediments (Kemp et al., 1999). Potentially, C₆ HG-producing Nostocales inhabited the upper photic zone, where conditions were likely fresher, while C₅ HG derived from DDAs may have inhabited the lower photic zone, where conditions were more saline compared to the brackish surface waters. Alternatively, intermittent periods with brackish surface layer conditions, favoring Nostocales, could have alternated with more saline conditions that favored DDAs. During S1b, C₆ HGs and the C₅ HG remain present at background levels, with a slight elevation of the C₅ HG at 6.0 to 5.3 cal ka BP, possibly reflecting the return of more saline conditions in surface waters after the re-ventilation of the EMS that occurred after sapropel deposition (e.g., de Lange et al., 2008).

No biomarker evidence for the occurrence of the filamentous cyanobacterium *Trichodesmium* spp. (unsaturated BHT-CE; Talbot et al., 2008) was detected. Potentially, low amounts of unsaturated BHT-CE might have remained below the detection level of our method, as *Trichodesmium* spp. has been found to occur in low abundances in the contemporary Mediterranean (Yogev et al., 2011). Even so, *Trichodesmium* spp. are known to be outcompeted by DDAs at higher phosphorus and iron levels (Follett et al., 2018). Hence, no substantial N₂-fixation by *Trichodesmium* spp. is thought to have taken place during S1.

In the modern EMS, δ¹⁵N values of suspended particulate matter (δ¹⁵N of −0.2‰; Pantoja et al., 2002) are similar to those observed in S1 sediments (Fig. 3b), while the surface sediments are similarly enriched (>5‰; Fig. 3b) as non-sapropel sediments (Sachs and Repeta, 1999). This resulted in the hypothesis that N₂-fixation during sapropel deposition is similar to the present-day EMS (Sachs and Repeta, 1999), and that elevated δ¹⁵N levels in non-sapropel sediments reflect diagenetic isotope enrichment (Sachs and Repeta, 1999; Möbius et al., 2010). Later, Higgins et al. (2010) showed that the offset between δ¹⁵N values found in chlorins and in total N is 5‰ in both sapropel and non-sapropel sediments (reflecting isotopic fractionation during chlorophyll biosynthesis by eukaryotes; Higgins et al., 2011), indicating that δ¹⁵N_{TN} values reflect the original biomass, and not diagenetic isotopic alteration.

Modern-day N₂-fixation rates are, however, low (Yogev et al., 2011) and do not explain the depleted δ¹⁵N values observed in the water column and surface sediments. These low rates are thought to be caused by the extremely low bioavailability of phosphorus (P), whereas iron (Fe) is not considered a limiting factor (Ridame et al., 2011). Mara et al., (2009) showed that the depleted δ¹⁵N values observed in the modern EMS result from atmospheric deposition of exogenous aerosol N (δ¹⁵N of −3.1‰). The influx of reactive N species (e.g., via atmospheric deposition and rivers) is thought to account for >50% of total bioavailable N in the modern EMS (Krom et al., 2004).

A different mechanism seems to have occurred during sapropel deposition. Discrepancies between the HG (max. at 8.6 cal ka BP) and TOC profile (max. at 9.4 cal ka BP), indicate that increases in the concentrations of HGs during S1 are not simply a preservation signal. This provides evidence for enhanced N₂-fixation by heterocyte cyanobacteria during especially the later S1a stages and the S1 interruption, in comparison to non-sapropel sediments and S1b. At maximum Nile flooding (~9.5 cal ka BP; Hennekam et al., 2014), increased Nile input led to increased P influx as dissolved, particulate, reactive and detrital P

(Slomp et al., 2002; Zirks et al., 2021). Deposition of organic- and iron bound-P and subsequent release under anoxic conditions is thought to have resulted in the enhanced availability of reactive P species in SIW (500–1800 m), which could be recycled into shallower waters (200–500 m; Zirks et al., 2021). In turn, turbulent mixing of the surface and intermediate waters is thought to lead to a dispersal of N and P (van Capellen et al., 2014). Less intense P-release occurs after the 8.2 ka BP ventilation event, as pre-sapropelic oligotrophic conditions slowly returned (Zirks et al., 2021). P-recycling into intermediate water depths may have favored DDAs in the later S1a stages and during the S1 interruption. In addition, loss of bioavailable N via anammox may have promoted growth of diazotrophs over other primary producers (Kuypers et al., 2004). *Ca. Scalindua* spp. are typically most abundant at the secondary nitrite maximum, below the oxycline (Rush et al., 2012). This implies that the most extensive N-loss likely occurred at the upper margin of the anoxic SIW, which may have affected N-availability in the euphotic zone.

4.1.3. Aerobic ammonium oxidation by *Thaumarchaeota*

The AR of crenarchaeol, uniquely synthesized by autotrophic aerobic ammonium oxidizing archaea (AOA) *Thaumarchaeota* (Sinninghe Damsté et al., 2002b) is substantially elevated across S1a (Fig. 4e). Nonetheless, crenarchaeol is detected throughout the record showing a continuous presence of *Thaumarchaeota*. As such, it is possible that the elevated crenarchaeol accumulation rates during S1a reflect enhanced preservation under anoxic conditions, rather than an increase in the abundance of *Thaumarchaeota*. Lower crenarchaeol ARs in non-sapropel sediments may simply be the result of oxygen exposure (Sinninghe Damsté et al., 2002a). However, crenarchaeol concentrations normalized to TOC (supplementary material 1 Fig. S2), also show increased crenarchaeol from 11.3 cal ka BP, with a peak at 8.9 cal ka BP. A similar S1 trend in crenarchaeol concentration was observed by Castañeda et al. (2010). These authors proposed that the increase in NH₄⁺ oxidation was a response to enhanced supply of high-nutrient freshwater discharge into the Levantine basin. Indeed, our observed elevated crenarchaeol concentrations are congruent with a recorded increase in river discharge from 11.5 ka BP onwards, remaining high until 6.5 ka BP (Hennekam et al., 2014; 2015; Weldeab et al., 2014). Crenarchaeol remains present throughout the S1 interruption and S1b, but with markedly lower ARs. Reduced nutrient-influx and remineralization rates in these later S1 stages may have limited NH₄⁺ supply, and hence, *Thaumarchaeota*.

Potentially, the increase in *Thaumarchaeota* abundance may have contributed to providing anammox bacteria with the necessary NO₂⁻ to perform the anammox reaction. In the Black Sea euxinic basin, AOA and ammonium oxidizing bacteria (AOB) have been suggested to provide up to 40% of the NO₂⁻ for anammox bacteria (Lam et al., 2007). As anammox bacteria are inhibited by the presence of free sulfide (Jensen et al., 2008), the *Ca. Scalindua* spp. population in the Black Sea is located right above the sulfidic-anoxic boundary (at ca. 110 mbss). Here, they co-inhabit the suboxic-anoxic zone with *Thaumarchaeota* (Lam et al., 2007). A similar niche-partitioning likely occurred during sapropel S5, where anammox bacteria inhabited the upper water column, due to the occurrence of photic zone euxinia (Rush et al., 2019). In contrast, in the Arabian Sea, *Thaumarchaeota* inhabit the upper suboxic chemocline and anammox bacteria the lower anoxic chemocline (Pitcher et al., 2011). The large depth segregation of anammox bacterial and *Thaumarchaeota* niches (>400 m) is thought to indicate that no direct coupling of their metabolism, nor competition for substrates, takes place.

Ca. Scalindua spp. can be found over a much larger O₂ range than previously assumed (<50; Woebken et al., 2007; Hamasaki et al., 2018; van Kemenade et al., 2022), being mainly limited by NO₂⁻ availability (Rush et al., 2012). More recently, oxygen assays showed that anammox and aerobic nitrifying bacteria share a large overlapping range in O₂ concentrations (>0–20 μmol/L; Kalvelage et al., 2011). Hence, we propose *Ca. Scalindua* spp. likely inhabited the upper SIW, at the depth

of the secondary nitrite maximum where Thaumarchaeota (and potentially also aerobic nitrifiers) may have provided the necessary NO_2^- for the anammox process. Also, as anammox bacteria are known to have an extremely high affinity for NH_4^+ (<1 μM ; Strous et al., 1999), competition for NH_4^+ with Thaumarchaeota was possibly limited.

4.2. N-cycling during the Late Pleistocene (~70–11 cal ka BP), including ‘S2’ deposition (~55–52 cal ka BP)

4.2.1. Lipid biomarker evidence for the occurrence of anammox bacteria during MIS 3/4

Elevated ladderane FAs (in relation to background values) between ~63–56 (MIS 3/4), 54–39 (MIS 3), and at 34 cal ka BP (MIS 3) show the increased presence of anaerobic ammonium oxidizing bacteria over these time intervals. However, no corresponding BHT-x elevations, as observed for S1, are observed. Curiously, the BHT-34R stereoisomer was detected at 67.8–56.6 and 54.3–42.9 cal ka BP (Fig. 4b). BHT-34R is known to be synthesized by freshwater/brackish anammox bacteria *Ca. Brocadia* spp., (Schwartz-Narbonne et al., 2020), but also by species of acetic acid bacteria (Peiseler and Rohmer, 1992), the aerobic terrestrial nitrogen-fixing bacteria *Frankia* spp. (Rosa-Putra et al., 2001) and the aerobic methanotrophic bacterium *Methylocella palustris* (van Winden et al. 2012). While BHT-x does not show a significant correlation with the ladderane FA distribution in the MIS 2–4 sediments, BHT-34R does ($p < 0.05$).

To further explore the source organism of the detected BHT-34R, compound specific $\delta^{13}\text{C}$ measurements were conducted. Median $\delta^{13}\text{C}_{\text{BHT-x}}$ and $\delta^{13}\text{C}_{\text{BHT-34R}}$ values were -41.5‰ ($\pm 1.9\text{‰}$) and -41.2‰ ($\pm 4.8\text{‰}$), respectively (Table 1). $\delta^{13}\text{C}_{\text{BHT-34R}}$ values are close to expected values, if anammox bacteria were the source organisms, given the stable carbon isotope fractionation effect with which *Ca. Brocadia* spp. synthesizes BHT-34R ($^{13}\text{C}_{\text{CO}_2(\text{aq})\text{-BHT-34R}}$: ca. -36.3‰ at a temperature of 35 °C; Schouten et al., 2004) when assuming dissolved carbon dioxide (DIC) was +1 (modern EMS; Rohling et al., 2015) to 4‰ (reconstructed value during sapropel deposits; Elling et al., 2021). Also, the equally depleted $\delta^{13}\text{C}$ values of BHT-x and BHT-34R suggest a similar carbon fixation pathway, which in the case of *Ca. Scalindua* spp., is thought to be the acetyl-CoA pathway (Schouten et al., 2004; Strous et al., 2006; Kartal et al., 2013). Additionally, values recorded during ‘S2’ are similar (-43.0 to -41.2‰ ; Table 1) to those recorded for marine anammox bacteria in the Arabian Sea (Lengger et al., 2019) and the EMS (Hemingway et al., 2018; Elling et al., 2021). Potentially, relatively low $\delta^{13}\text{C}_{\text{BHT-34R}}$ values could also be synthesized by the methanotroph *M. palustris*. Yet, Type II methanotrophs do not have consistently $\delta^{13}\text{C}$ -depleted lipids (Kool et al., 2014). Together with the co-occurrence of ladderane lipids, it is more likely that anammox is the source of the BHT-34R detected in ‘S2’. Future work is nonetheless required to differentiate the $\delta^{13}\text{C}_{\text{BHT-34R}}$ values of the different producers.

So far, inventories of BHT stereoisomer synthesis by marine anammox bacteria have focused solely on pelagic *Ca. Scalindua* spp. (Rush et al., 2014; Schwartz-Narbonne et al., 2020; van Kemenade et al., 2022), and little is known on the synthesis by sedimentary marine anammox bacteria. Marine anammox candidate genus, *Ca. Bathyanammoxiabiaceae*, was recently described in marine sediments and terrestrial environments (Zhao et al., 2022). *Ca. Bathyanammoxiabiaceae* have been detected predominantly in the nitrite-ammonium transition zones of marine sediments (Zhao et al., 2022), which would likely also be the niche of anammox at site 64PE406-E1 during the intermittent periods of MIS3/4, where anammox biomarkers were detected. However, lipid characterization of *Ca. Bathyanammoxiabiaceae* is required to determine whether this genus might synthesize BHT-34R.

Peaks in ladderane lipids coincide with minor fluctuations in the benthic foraminifera-derived BWO index. This would indicate intermittent bottom water deoxygenation during MIS3/4. The BWO index dips during MIS3/4, most perspicuous from 53.0 to 52.2 cal ka BP (Fig. 3c), are based on the increased relative abundance of the deep

infaunal low-oxygen indicator taxon *Globobulimina* spp.. Reduced bottom water oxygen concentration may have culminated in anoxia at the sediment surface, allowing anammox.

When anoxic conditions are introduced, Mn^{2+} diffuses upwards and is either lost to the water column if bottom waters are anoxic, or precipitates as Mn oxides in the sediments if pore water oxygen is encountered (see review Tribouillard et al., 2006). Mn oxides are reductively removed when sedimentary redox conditions become anoxic again (e.g., this type of post-depositional diagenesis likely occurred after the ‘S2’ interval), but the original signal may be preserved when dissolution provides enough Mn^{2+} for Mn-carbonate formation (Chiu et al., 2022). As such, the Mn/Al peak at 53 to 49 cal ka BP (Fig. 3d), likely suggests enhanced Mn cycling related to sedimentary anoxia occurred prior to 53 cal ka BP, and subsequent re-ventilation from 53 cal ka BP onwards.

The BWO index fluctuations, Mn/Al peak values and the occurrence of anammox biomarkers correspond to the timing reported for bottom water deoxygenation between 53–51 cal ka BP (attributed to the ‘missing’ S2 sapropel), associated with a reported weakening of the intermediate circulation in the Sicily channel, which in turn slowed intermediate water ventilation in the EMS (Di Donato et al., 2022). The weakening of the thermohaline circulation might have been a response to enhanced stratification due to an activation of North-African coastal wadis advected by Mediterranean storms during MIS3/4 (Blanchet et al., 2021). Possibly these short-lasting and less intense humid events during MIS3/4 (Blanchet et al., 2021), might not have been sufficient for complete development of bottom water anoxia, but still affected the biogeochemical cycling in the EMS. Only around ~55–52 cal ka BP (i.e., the timing of ‘S2’), the nutrient load may have been sufficient to allow an appreciable increase in productivity (as indicated by the minor Ba/Al elevation at this time; Fig. 3d), resulting in enhanced bottom water deoxygenation (as indicated by the BWO index and Mn profile). This may be caused by the only Nile flood recorded to occur at this time; Ducassou et al., (2008; 2009) detected clastic mud facies associated with Nile floods at ~55 cal ka BP in a record recovered from the Levantine basin (FKSO4). While the absence of persistent fully anoxic bottom waters means that ‘S2’ does not qualify as a (typical) sapropel, we hypothesize that the abovementioned short periods of water column deoxygenation resulted in an anoxic sediment–water interface that provided a niche for anammox bacteria.

4.2.2. No evidence for enhanced N_2 -fixation and aerobic ammonium oxidation

C_6 HGs were present from 63 to 51, at 48, and from 34 to 33 cal ka BP (Fig. 4d), albeit with very low ARs, suggesting limited increases in the abundance of Nostocales occurred at these time periods (Schouten et al., 2013; Bale et al., 2015). C_5 HGs and unsaturated BHT-CE were not detected, indicating DDAs and *Trichodesmium* spp. were absent or too low in abundance for detection. Although crenarchaeol is detected throughout the 64PE406-E1 record, no elevation in relation to background levels is observed over ‘S2’ (Fig. 4e). The relatively low (in comparison with S1 sediments) HG and crenarchaeol ARs throughout the late Pleistocene, might indicate these lipids were degraded, as enhanced preservation was not warranted by bottom water anoxia (Sinninghe Damsté et al., 2002a). Nonetheless, HG and crenarchaeol concentrations normalized to TOC (supplementary material 1 Fig. S2) are also continuously low, remaining far below S1 levels. This likely suggests ammonium oxidation by Thaumarchaeota and N_2 -fixation by DDAs was markedly more limited in the late Pleistocene, than during S1 deposition.

The EMS water column throughout most of MIS 2–4 seems to reflect modern oligotrophic conditions. In the modern EMS, Thaumarchaeota are known to also occur in the oxic mesopelagic waters (De Corte et al., 2009). Measured nitrification rates in the Mediterranean Sea are 72–144 $\text{nmols N l}^{-1} \text{d}^{-1}$ (Bianchi et al., 1999). As such, ammonium oxidation by Thaumarchaeota is likely to have contributed significantly to N-

recycling throughout the late Pleistocene in the EMS. In contrast, only low rates of N_2 -fixation ($\leq 0.5 \text{ nmols N l}^{-1} \text{ d}^{-1}$; [Ibello et al., 2010](#)) have been measured in the modern Mediterranean Sea ([Ibello et al., 2010](#); [Yogev et al., 2011](#)). Diazotrophs thus provide only a minor source of the bioavailable N. These low rates are likely caused by an extreme P depletion, resulting from an accumulation of N as anammox and denitrification seem not to occur in the modern EMS ([Krom et al., 2010](#)). Even so, at brief periods during MIS 3/4, the co-occurrence of C_6 HGs and anammox biomarkers might indicate that loss of bioavailable N via anammox (and potentially denitrification) drove N_2 -fixation rates by heterocyte cyanobacteria at intermittent periods of bottom water deoxygenation (see [Section 4.2.1](#)).

4.3. Insights on feedbacks between the nitrogen cycle and anoxia, based on the S1a, S1b, and 'S2' deoxygenation events

Sapropel depositions record information on paleoclimatic and paleoceanographic changes during anoxic events, linked to the orbital cycle of the Earth's precession ([Rossignol-Strick, 1985](#); [Hilgen, 1991](#)). They are considered potential analogues for modern ocean deoxygenation ([Mancini et al., 2023](#)). Additionally, sapropels reveal sequences of biogeochemical processes in response to climate change, and have therefore been proposed as a more recent framework to assess Mesozoic anoxic events ([Meyers and Negri, 2003](#)). The S1 and 'S2' deoxygenation events of the EMS offer insights on biogeochemical feedbacks under different depositional conditions, which enables better constraints of biogeochemical models. Below we outline the proposed feedback modes between the N-cycle and marine (de)oxygenation during deposition of S1a, S1b and 'S2', which offer a framework for nitrogen cycling responses to changing redox conditions.

First of all, during the S1a deposit in the Levantine basin, a positive N-cycling feedback on anoxia is thought to occur. Based on modern-environmental distributions, *Ca. Scalindua* spp. is expected to predominantly inhabit the upper SIW at the depth of the secondary nitrite maximum. In the contemporary EMS, limited mixing is thought to occur between EMS intermediate (150–600 m) and deep water (>600 m) layers ([Powley et al., 2016](#)). Turbulent mixing of the surface and intermediate waters, however, is thought to lead to a dispersal of N and P ([van Capellen et al., 2014](#)). Increased *Ca. Scalindua* spp. abundance in the upper SIW could thus have led to N-limitation in the euphotic zone. During Cretaceous anoxic events, loss of bioavailable N via anammox and denitrification has been proposed to drive N_2 -fixation rates, by providing diazotrophs with a competitive advantage over other primary producers ([Kuypers et al., 2004](#)). In the EMS, peak DDA abundance in S1 occur ~0.5 kyr after peak *Ca. Scalindua* spp., abundance ([Fig. 4](#)). Loss of bioavailable N via anammox may therefore have contributed to an increased presence of DDAs. The same mechanism was also proposed to occur in the Ionian Sea, where [Elling et al. \(2021\)](#) suggested that during S4, S5 and S74 sapropels, anammox promoted the occurrence of DDAs, which in turn sustained anoxia via enhanced degradation rates of the sinking OM. Furthermore, increased P availability during S1a in response to Blue Nile floods ([Slomp et al., 2002](#); [Zirks et al., 2021](#)) may have favored the presence of DDAs over smaller-sized diazotrophs ([Follett et al., 2018](#)). Remineralization of the sinking DDAs would further promote anoxia in the SIW. In the Levantine basin, however, HGs derived from the smaller-sized Nostocales and larger-sized DDAs are more or less equally abundant (this study; [Elling et al., 2021](#)). Consequently, this would lead to a lower OM flux to the seafloor than in Ionian Sea sapropels, where HGs were solely sourced from DDAs ([Elling et al., 2021](#)). It must also be noted that the positive feedback of DDA abundance on anoxia was likely negligible compared to thermohaline circulation changes in response to the 8.2 ka BP global cooling event, which resulted in a re-ventilation and oxygenation of the EMS basin ([Rohling et al., 2015](#)).

Secondly, the decoupled peaks in abundance of cyanobacteria and anammox bacteria during S1b (*i.e.*, HG concentrations are relatively

low, whereas anammox biomarker concentrations are as high as in S1a) shows that loss of bioavailable N was not sufficient to promote N_2 -fixation by DDAs. We also propose that a return to more oligotrophic conditions during S1b, where P is no longer supplied in excess, limited the presence of DDAs at this time.

During the S2 interval, when Mn and benthic foraminifers indicate water column hypoxia and anoxic sediments, the intermittent deoxygenation events triggered enhanced N-loss via anammox (see [Section 4.2](#)). Yet, this N-loss during 'S2' did not trigger increased N_2 -fixation via heterocyte cyanobacteria. This decoupling was probably caused by the large niche-segregation of anammox bacteria (proposed to inhabit the sediments at this time; see [Section 4.2.1](#)) and diazotrophs (in the euphotic zone). Also, the brief intervals of increased river runoff ([Ducassou et al., 2008](#); [2009](#); [Langgut et al., 2018](#); [Blanchet et al., 2021](#)) and the associated moderate water column deoxygenation (see [Section 4.2.1](#)) were likely not sufficient to provide the P (via riverine influx or a release of P from anoxic sediments) necessary to promote high DDA abundances. Under these more oligotrophic conditions, the negative feedback of the N-cycle on anoxia would likely have been stronger than the positive feedback.

Based on the results of this study, loss of bioavailable N via anammox can impose both i) negative feedback on anoxia via quenching of primary production and ii) positive feedback on anoxia via the promotion of DDA growth. The relative importance of either feedback mode depends on local conditions and is affected by niche segregation of N-loss and N_2 -fixating microorganisms and nutrient availability (*e.g.*, phosphorous) in the euphotic zone. Our findings highlight that disentangling the coupling between N-loss processes and N_2 -fixation is imperative to understanding the cascading effects of marine deoxygenation on biogeochemical cycling and potential feedback mechanisms on water column oxygenation.

5. Conclusions

By comparing biomarker information with redox proxies (redox sensitive trace metals and benthic foraminifer assemblages) in the presented EMS record, we show that a cascade of N-cycling shifts with various feedback modes on anoxia occurred during S1a, S1b and 'S2'. Lipid biomarkers show that Thaumarchaeota were predominantly present in S1a, potentially promoted by enhanced nutrient availability via increased river discharge. Anammox intensity increased during S1, likely in response to the progressive deoxygenation of the SIW. Associated loss of bioavailable N may have fueled the ensuing increase in diatom-diazotroph associations (DDAs). In turn, this may have promoted enhanced remineralization rates via an increased flux of OM to the sea-floor, providing a positive feedback on anoxia (as has been proposed to occur in S4, S5 and S74 sapropels). During S1b, however, while anammox biomarker concentrations are equal to S1a, no evidence for such feedback is observed. A return to more oligotrophic conditions likely resulted in a P-limitation for diazotrophs. Under such conditions, the occurrence of anammox bacteria may have induced a negative feedback on anoxia, by quenching primary production, and hence, limiting the OM flux to the seafloor.

From ~69 to 39 cal ka BP, the occurrence of ladderanes and hexose HGs suggests episodes of bioavailable N removal via anammox bacteria and N_2 -fixation by Nostocales, respectively, corresponding to recorded intervals of enhanced river activation. The low Ba/Al ratio indicates limited organic C export, and consequently, no significant increase in primary production. Hence, the short-lasting humid events recorded during this interval may not have been sufficient to reach the tipping point for true sapropel formation. Yet, foraminifer assemblages and Mn/Al do suggest brief periods of anoxia during these intervals (maximum deoxygenation at ~53–52 ka BP, *i.e.* timing of 'S2'), with the redoxcline being located around the sediment–water interface. During these intervals, ladderanes co-occur with BHT-34R. Compound-specific $\delta^{13}C_{BHT-34R}$ values indicate an anammox source, potentially synthesized by

marine anammox bacteria living in the nitrite-ammonium transition zone of marine sediments. As such, the large niche-segregation with primary producers likely resulted in a decoupling between N-loss and N₂-fixation at this time. In addition, the oligotrophic conditions (with extreme P-depletion) are thought to have also limited the presence of DDAs, as no pentose HGs were detected. Our results show various modes of operation of the N-cycle during different states of deoxygenation. Nutrient-availability and microbial niche-segregation are thought to strongly impact feedbacks of the N-cycle, which therefore necessitates considerations when assessing biogeochemical responses to marine deoxygenation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data related to this article is available online via doi: <https://dataportal.nioz.nl/doi/10.25850/nioz/7b.b.fd>.

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Appendix A. Supplementary material

The supplementary material includes two files. The first file (supplementary material 1) describes the core chronology (S1.1) and figures of $\delta^{18}\text{O}$ values of *G. ruber* (Fig. S1), lipid biomarker concentrations normalized against TOC (Fig. S2), mass chromatograms and MS² of ladderanes (S3), mass chromatograms of FAME standards (Fig. S4), relative abundances of benthic foraminifers (Fig. S5). The second file (supplementary material 2) provides six tables with the data presented in the manuscript, in which table 1 presents the bulk sedimentary carbon and nitrogen data, table 2 to 5 the lipid biomarker accumulation rates and table 6 the benthic foraminiferal data. Supplementary material to this article can be found online at <https://doi.org/10.1016/j.gca.2023.06.018>.

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