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Cerennaz Bozyiğit[a, b], Kürşad Kadir Eriş[b, c], Marie-Alexandrine Sicre[d], Memet Namık Çağatay[b], Gülsen Uçarkuş[b], Vincent Klein[d], Luca Gasperini[e]

[a]Department of Climate and Marine Science, Eurasia Institute of Earth Science, Istanbul Technical University, Ayazağa, 34469, İstanbul, Turkey

[b]Department of Geological Engineering, EMCOL Applied Research Center, Istanbul Technical University, Ayazağa, 34469, İstanbul, Turkey

[c]Department of Ecology and Evolution, Eurasia Institute of Earth Science, Istanbul Technical University, Ayazağa, 34469, İstanbul, Turkey

[d]LOCEAN, Sorbonne Université, CNRS, Campus Pierre et Marie Curie, 4 place Jussieu, 75252 Paris Cedex 05, France

[e]Institute of Marine Sciences, ISMAR-Bo, CNR, Bologna, Italy

Abstract

A multi-proxy analyses was applied on the sediment core from the Gulf of Saros (GoS) to identify and characterize climate and hydrological changes during the middle-to-late Holocene. The formation of two discrete Holocene sapropel layers in the GoS sediments was documented for the first time in the sediment core based on total organic carbon analysis. According to our paleo-proxy records, the lower Holocene sapropel was deposited under warm and humid climate conditions that gave rise to high delivery of terrestrial organic matter by numerous rivers in the northern catchment of the GoS. Biomarker and μ-XRF data were used to decipher climate variations during the middle to late Holocene. The general trends of sea-surface temperature records from the GoS and Sea of Marmara (SoM) at the beginning of late Holocene are in good agreement, underlying the influence of the Black Sea inflow. A relatively warm and wet climate together with a high sedimentation rate during the mid-Holocene Climatic Optimum resulted in high organic productivity and ensuing formation of the younger Holocene sapropel between 5.4 and 3.0 cal ka BP. Late Holocene European climate periods are evident in the Saros core records. The Roman Humid Period is represented by high variation in climate, indicating an earlier (2.5-2.3 cal ka BP) dry and a later (2.3-1.55 cal ka BP) wet periods. The abrupt return to drier condition during the Dark Ages Cold Period (1.6-1.3 cal ka BP) was followed by a wetter Medieval Climate Anomaly (1.1-0.7 cal ka BP). The paleo-proxy record of the core indicates a passage from a wetter to drier climate during the cold Little Ice Age period (730-110 cal yr BP), and highlights the influence of deforestation in the catchment of the GoS as a result of human activities during the last three centuries.

Keywords: North Aegean Sea, Gulf of Saros, Marine sediment core, Geochemical proxies, Paleoclimate, Sapropels

1. Introduction

Palaeoclimatic proxies, including stable isotopes, palynological data, and lake levels, have shown that the Mediterranean region experienced climatic conditions that varied spatially and temporally throughout the Holocene (e.g., Bar-Matthews and Ayalon, 2011; Luterbacher et al., 2012; Lionello, 2012; Triantaphyllou et al., 2014, 2016; Mauri et al., 2015; Caldara and De Santis, 2015; Sadori et al., 2016a; Cheddadi and Khater, 2016). The Aegean Sea is sensitive to climate changes because of the combination of its semi-isolation from the Mediterranean Sea, small size, and proximity to the Çanakkale Strait, linking it to the Black Sea since the early Holocene (Poulos et al., 1996; Rohling et al., 2002) (Fig. 1). Previous studies focusing on the Holocene have shown that the many long and short term changes that are associated with variations in the Siberian High intensity and the Northern

Hemisphere Climate (e.g. Rohling et al., 2002; Geraga et al., 2010). Concurrently, Uk 37-SST reconstructions in both the north and south Aegean basins (Gogou et al., 2007; Kotthoff et al., 2008; Triantaphyllou et al., 2009b) reveal a warming trend that reflects the changing regional climatic conditions, coinciding with the Holocene Climatic Optimum.

The Holocene period is associated with deposition of the sapropelic sediments in the Aegean Sea as well as in the Mediterranean and Marmara seas due to substantial modifications within the surface and bottom waters. Reduced oxygen supply to bottom waters has been suggested to be a precondition for sapropel formation although increased biological productivity further promoted S1 deposition (Bianchi et al., 2006; Myers et al., 1998; Rohling, 1994; Stratford et al., 2000). The differences in its timing in different parts of the Aegean Sea was explained as a response to distinct changes in the local hydrographic regime and biogeochemical cycling linked to global and regional climatic variations (Aksu et al., 1995; Mercone et al., 2001; De Lange et al., 2008; Kotthoff et al., 2008; Triantaphyllou et al., 2009b; Filippidi, 2013). Morever, the comparison of the north and south Aegean records shows significant changes in both the productivity and the stratification of the upper water column during S1 deposition. Thus, the difference in TOC concentrations among the different segments of the Aegean Sea likely reflects variation in sedimentation and preservation rates. Two sapropel units timely coincides with the early Holocene S1 sapropel and the middle Holocene sapropel (SMH) in the southern Aegean Sea (Triantaphyllou et al., 2014; Kontakiotis, 2016). The Holocene sapropel (S1) occurs in two parts; S1a and S1b that are well dated from the Agean Sea (Geraga et al., 2000; Gogou et al., 2007; Triantaphyllou et al., 2009b; Filippidi, 2013).

NE-SW-orientedGoS is a westward-widening and -deepening triangular marine embayment that constitutes the eastern extension of the North Aegean Trough (NAT) (Fig. 1). The gulf constitutes the eastern extension of the North Aegean Trough (NAT), and is separated from the Marmara Sea by the Thrace Peninsula. The GoS was formed in the course of the postglacial transgression across the Quaternary Saros Basin fill and its basement units (Çağatay et al. 1998; Tüysüz et al. 1998). The hydrological setting of the GoS is controlled mainly by the high river discharges from the northern and southern catchment area (Fig. 2) and the regional climate conditions and notably wind forcing (Aksu et al., 1995). The gulf has been in the focus of various research groups because of its tectonic setting on the North Anatolian Fault Zone (NAFZ) (Çağatay et al., 1998; Tüysüz et al., 1998; Yaltırak et al., 1998; Saatçılar et al., 1999; Kurt el al., 2000; Yaltırak and Alpar, 2002; Ustaömer et al., 2008; Gasperini et al., 2011).

The GoS may have been affected by different paleoceanographic changes because of influences of inflows from the Mediterranean and the Black seas (Figs. 1 and 2). The connection with the Black Sea was presumably established between 4 and 5 ka BP (Tolun et al., 2001; Çağatay et al., 2001), slightly after the initiation of the S1 deposition. Although considerable work has been carried out on the Holocene paleoceanography at various sites of the Aegean Sea (e.g. Gogou et al., 2007, 2016; Kotthoff et al., 2008; Triantaphyllou et al., 2009a, b, 2014; Geraga et al., 2010; Kouli et al., 2011; Kontakiotis, 2016), only a few investigations have focussed on the Holocene climate in the gulf (e.g., Çağatay et al., 1998). Small volume and geographical position of the GoS together with the high sedimentation rates heightened sensitivity to climatic variations during the Holocene, and thus, allow us to document immediate and the short term changes for paleoclimate and paleohdyrologic reconstructions. Therefore, this study was projected to contribute towards the advance of understanding the causes of paleoceanographic variability and predicting vulnerability to potential climate change in the GoS by using a multi-proxy analyses of a sediment core. The comparision of present oceanographic settings of the GoS with rest of the Agean Sea may allow us to examine definition of the Holocene sapropel in terms of timing and source for its formation during changing paleoclimate and paleoceanographic situations in the gulf. For this purpose, we also aim to better identify general hydrologic evolution of the gulf with a special interest on formation of sapropels linked to climate variability and water exchanges between the Aegean and Marmara seas.

2. Physiography and Geology

The Aegean Sea is divided into three physiographic regions: the northern Aegean Sea, including the NAT; the central Aegean with islands, shoals, and basins; and the southern Aegean Sea, including the Cretan Trough (Fig.1). The GoS is located between Thrace Peninsula to the north and the Gelibolu Peninsula to the South, and is bounded to the north by the active main strand of the North Anatolian Fault (NAF), named the Ganos-Saros segment (Figs. 1 and 2). The gulf extends for about 60 km westwards, connecting to the main Aegean Sea basin, and reaches a maximum width of about 36 km. The bathymetry of the gulf is rather asymmetric, with a 10-km wide shelf to the north and a deep trough up to 15 km to the south. It widens and deepens toward WSW, where it becomes the easternmost part of the NAT. The shelf extends at a water depth of 90–120 m. According to the present bathymetry, the maximum depth is up to about 700 m. The deep trough starts to the southeast of Mecidiye (Fig. 2) as a wedge-shaped depression, deepening and widening toward the west. The slope leading to the deep trough has a mean gradient of 8.5° and displays an irregular morphology caused by active faulting and sediment slumping. The bathymetric map allows us to recognize several canyons cutting the slope, particularly along the northern slope of the gulf. A close-up view of these canyons indicates that it is displaced by a strike-slip fault bounding the northern slope of the gulf (Fig. 2). These canyons were presumably active during the last glacial period, when the sea level was 130 m lower than the present sea level (Çağatay et al., 1998; Gasperini et al., 2011; Vardar, 2019), and the shelf and the uppermost slopes in the gulf were exposed as subaerial.

3. Present Oceanography and Climate

The Aegean Sea is an intermittent source of deep waters for the Eastern Mediterranean (Yüce, 1994; Roether et al., 1996; Lascaratos et al., 1999). Episodic deep water formation during winter cooling known as Eastern Mediterranean Transient (EMT) have been documented (Yüce, 1994; Zervakis et al., 2000), which would have occurred over the past 500 years (Incarbona et al., 2016). In terms of hydrological features, it is divided into two sub-basins, namely the north and south Aegean basins (Fig. 1) (Lykousis et al., 2002). The inflow of Black Sea waters and from surrounding rivers together with atmosphere/ocean interactions create complex hydrological conditions within the North Aegean Sea, affecting the water circulation and subsequently the biological, chemical and depositional processes.

Climate is relatively humid in the north and semi-arid in the south. In contrast to the south Aegean Sea, the north Aegean Sea is associated with cyclonic circulation (Fig. 1). The present-day oceanographic setting in the Aegean Sea is regulate mainly by the fresh water flowing from the European rivers and the SoM. Eutrophication can take place due to the inflow of the Balkan rivers and freshwater influx from the Black Sea as well as the development of downwelling and upwelling processes caused by the presence of the cyclonic and anticyclonic eddies (Lykousis et al., 2002; Geraga et al., 2010). On the basis of historical hydrographic data, extensive production of dense water in the north Aegean was recorded in the winters of 1987 and 1992-1993 during the last decade (Theocharis and Gerogopoulos, 1993; Zervakis et al., 2000).

Lacombe et al. (1958) mentioned for the first time that the Go S is considered as a region where the deep water might be formed and ventilates the NAT and the Lemnos Basin. Pazi (2008) presented the first data suggesting that cold winter of 2002 produced by strong and cold NNE wind have given rise to the formation of this new deep water in the GoS. The dense water formation in the GoS was established by the homogenization of water column between 100 and 600 m afterwards large heat losses in January 2002 (Pazi, 2008). Three main water masses have been documented in the north Aegean: (i) the surface water layer with low salinity (38.85 psu) and temperature (13.8°C) reflecting the influence of Black Sea Water (BSW) in the upper 100-m (ii) the Levantine Intermediate Water (LIW) characterized by higher salinity (39.1 psu) and temperature (14.2°C) lying between 100-400 m, and (iii) the denser and higher salinity (39.1-39.2 psu) North Aegean Deep Water (NADW) with uniform temperature (13-14°C) (Zervakis et al., 2000; Lykousis et al., 2002; Velaoras and Lascaratos, 2005; Geraga et al., 2010; İşler et al., 2016). The warm and saline Levantine Surface Water (16-25°C; 39.2-39.5 psu) and Levantine Intermediate Water are carried by a branch of the northward flow of Asia Minor Current into the Aegean Sea. The circulation in the GoS includes longshore currents flowing over the northern shelf and anticyclonic eddies in the interior basin (Fig. 2) (Sarı and Çağatay, 2001). Nutrient concentrations, abundance of plankton and benthos and fish catch density have been recorded higher in the north-northwest Aegean Sea, including the GoS than in the south-southeast Aegean Sea (Stergiou et al., 1997; Pazi, 2008; Frontalini et al., 2015). Moreover, the Black Sea surface outflow in the NE Aegean Sea has led to the enrichment of dissolved organic carbon and dissolved organic nitrogen in the area (Polat and Tugrul, 1996). Based on historical meteorological data, the GoS has been experienced cold years in 1991, 1992, 1993 and 2002, indicating a sharp decrease of temperature down to 6°C (Pazi, 2008). Low SST data was documented during the winter of 1993 in both North Aegean and the GoS, indicating that the formation processes of dense water are predictable in these areas (Theocharis and Georgopoulos, 1993). Mean air temperature of 3.95°C was recorded in the GoS between 30 November and 31 December 2001 while low SST values were observed in winter 2002 (Pazi, 2008).

4. Materials and Methods

4.1. Core Sampling

Core SAG-14 (326.5 cm) was recovered from the GoS onboard the R/V Urania during the "MARM11" cruise at 592 m water depth with a 1.2 tons gravity corer (Table 1). The core segments, 1-m-long each, were split into two halves, photographed and described (Fig. 3) in the Istanbul Technical University (ITU)-Eastern Mediterranean Centre of Oceanography and Limnology (EMCOL). The working halves were used for lithostratigraphic studies and sampled for total organic carbon (TOC) and radiocarbon dating. The second halves archived at ITU-EMCOL core depository were used for μ-X-ray Fluorescence (XRF) and Multi-Sensor Core Logger (MSCL) analyses.

4.2. Multi-Sensor Core Logger (MSCL)

Physical properties such as magnetic susceptibility (MS) were measured by using Geotek Multi-Sensor Core Logger Analyzer (0.5 cm resolution) at ITU-EMCOL according to the standard procedures (Weaver and Schultheis, 1994). The data were used to provide information about changes in the relative amount of terrigenous inputs.

4.3. μ-XRF analysis

Core SAG-14 was analysed for multi-element composition at 0.5 mm resolution using an Itrax XRF Core scanner, equipped with XRF-EDS, X-Ray radiography and RGB colour camera at the ITU-EMCOL Core Analyses Laboratory (Croudace et al., 2006; Thomson et al., 2006). A fine-focus Mo X-ray tube was used as the source. The X-ray generator was operated at 30 kV and 50 mA, and a counting time of 20 s was applied. The relative elemental abundances were recorded as counts per second (cps) and the element-ratio profiles were used as proxies for paleoenvironmental reconstructions.

Potassium (K) is a proxy for detrital inputs, in particular illite-mica type of clays that are mainly weathering products of rock-forming minerals (mainly feldspars) during soil formation. Iron (Fe) is a redox-sensitive element, which together with sulphur (S), forms Fe-monosulphides (i.e. greigite, mackinawite) or pyrite by authigenesis or diagenesis in organic-rich anoxic sediments (Leventhal, 1983; Berner, 1985; Lyons, 1997). In oxic sediments, however, Fe occurs mainly as oxyhydroxides and in clay mineral structures, and is hence considered as a detrital mineral proxy, often showing a good correlation with Ti. Therefore, Ti and Fe are generally considered reliable proxy for paleoceanographic and paleoenvironmental reconstructions, providing insights on climate conditions prevailing in the source area as well as on the mechanisms involved in the transport of material from catchment basin to the sea floor (riverine and eolian inputs). Manganese (Mn) is another redox sensitive element. It readily precipitates as Mn-oxides under oxic conditions but remains in a dissolved form and is depleted in anoxic sediments (e.g. Calvert and Pedersen, 1993; Thomson et al., 1995). The Fe-Mn ratio was used to assess the level of oxygenation of bottom waters, with higher values of this ratio indicating stronger anoxic conditions.

Calcium (Ca) is most likely derived from endogenic calcite and is related to calcifier production (e.g. Cohen, 2003; Çağatay et al., 2014, 2015; Francke et al., 2016). Strontium (Sr) is an indicator of the presence of aragonite. The Ca-Ti ratio provides information on the relative amounts of carbonate or siliciclastic components. The Ca-Sr ratio is also used to discriminate between marine and terrestrial carbonates. This ratio is higher in terrestrial carbonates than marine ones because of the high concentration of Sr in seawater (~70 times the average river water concentration) (Angino et al., 1966; Palmer and Edmond, 1992).

4.4. Total Organic Carbon Analysis

The total organic carbon (TOC) contents was determined from freeze-dried samples using a Shimadzu TOC/TIC analyser at ITU-EMCOL. First, the total carbon (TC) content of sediments was determined based on the amount of carbon dioxide (CO_2) released by total catalytic combustion at 900°C in the presence of purged oxygen and platinum catalyst. Then, total inorganic carbon (TIC) was obtained from the amount of CO_2 produced after sediment treating with %85 phosphoric and heating at 200°C. The TOC content was calculated by subtracting TIC from TC. TOC content is indicative of organic matter production (Burdige, 2007).

4.5. Biomarker Analysis

Biomarker analyses were performed by using a Thermo Fisher Trace Ultra Gas Chromatograph (GC) Analyzer at LOCEAN, Sorbonne University. The core was sampled at a 1 cm step, and freeze-dried. Lipid extraction was performed in a mixture of dichloromethane/methanol (2:1 v/v) (Sicre et al., 1999). Alkenones were isolated from the total lipid extracted by silica gel chromatography using solvent mixtures of increasing polarity (Sicre et al., 1999). 5α-cholestane was added as an external standard prior to GC injection to calculate concentration. Detailed analytical procedure can be found in Ternois et al. (1996). Di-and tri- bounds C_{37} alkenone compounds were used to derive the C_{37} unsaturation index ($U^{K'}_{37}= C_{37:2}/ (C3_{7:2}+C_{37:3})$. Alkenone-SSTs were calculated using the global calibration of Conte et al. (2006) $T(∘C) = -0.957+ 54.293 (U^{K'}_{37})- 52.894 (U^{K'}_{37})^2 + 28.231 (U^{K'}_{37})^3$.

4.6. Radiocarbon analysis and age-depth model

Accelerated mass spectroscopy (AMS) radiocarbon ^{14}C dating of core SAG-14 was performed at TÜBİTAK-MAM facility. Three sediment samples (Table 2) selected for dating were collected from hemipelagic parts of the core, washed under distilled water and dried at 40°C before the analysis. Mostly planktonic foraminifera and small amount of epifaunal benthic and echinoderm spicules were used as dating material. AMS ^{14}C results were calibrated by using Calib v7.1 software with Marine13 ^{14}C calibration curve (Reimer et al., 2013). Reservoir ages of 149 ± 30 years were assumed for the sapropel interval (Facorellis et al, 1998), and of 58±85 outside the sapropel (Reimer and McCormac, 2002). The age-depth model of the studied core was constructed using all ages and plotted in Fig. 4. Non-Bayesian age-depth model was determined using the script "clam" on R-studio (Blaauw, 2010). The script creates a non-Bayesian, cubic spline age-depth model, calculating the %95 Gaussian confidence interval around the best model.

5. Results

5.1. Core lithology, chronology and sedimentation rates

Visual observation of core SAG-14 allowed for compilation of a lithology/texture log, indicating composite fauna of euryhaline molluscs, as well as benthic and pelagic foraminifera (Fig. 3). Although macro fossils are very scarce, rich benthic and planktonic assemblages are present, which include *Ammonia tepida, Uvigerina mediterranea, Brizalina spathulata, Elphidium crispum, Lobatula lobatula, Textularia truncata, Textularia bocki, Quinqueloculina seminula, Hyalina baltica, Spiroloculina excavata* and *Cassidulina carinata* and *Globugerinoides ruber, Globigerinoides seiglei, Globigerinoides conglobatus, Globugerinoides elongates, Globugerinita glutinata, Globigerina bulloides, Glubigerina umbilicata, Globorotaloides hexagon, Orbulina universa* and *Globorotalia* sp. At the bottom of core SAG-14, the layer until 303 cmbsf is composed of dark olive gray homogenous silty clay with Fe-monosulphide (FeS) patches and silt lense. The layer between 303-274 cmbsf is represented by olive gray homogenous clay. This is sharply overlain by dark olive gray homogenous clay, and is followed by thick layer of olive gray homogenous clay with intercalated light olive brown layer and scattered FeS patches between 196 and 101 cmbsf. The overlying unit between 101 and 29 cmbsf is composed of olive homogeneous clay with rare bioturbation and FeS patches. The uppermost 27 cm-thick layer in the core contains alternations of reddish brown clays with olive gray homogenous clay having abundant FeS patches (Fig. 3).

Our age-depth model indicates that the sedimentary sequence encompasses the last 7 cal ka BP (Figs. 3 and 4; Table 2). Based mainly on TOC analysis and physical properties, we define two sapropel layers in intervals 326.5-297.4 cmbsf (S1b sapropel) and 277.4-193 cmbsf (SMH sapropel) (see section 5.2 below). According to the age-depth models, sapropel S1b and SMH sapropels are dated 7-6.1 cal ka BP and 5.4-3.0 cal ka BP, respectively. The calculated sedimentation rate indicates a high variation between the middle and late Holocene periods. During deposition of the S1b sapropel (7-6.1 cal ka BP), the approximate sedimentation rate is around 0.31 mm/yr, whereas a slight rise to 0.35 mm/yr occurs for the younger SMH sapropel (5.4-3.0 cal ka BP). Following the SMH sapropel deposition, the sedimentation rate increases to 0.64 mm/yr and exceeds 0.75 mm/yr during the last 300 yrs.

5.2. Physical and Geochemical analyses

In core SAG-14, the two sapropel layers between 326.5 and 194.8 cmbsf interval possesses > 1 wt% TOC (Fig. 5). S1b sapropel (326.5-297.4 cmbsf) contains TOC values, ranging between 0.75 wt% and 1.42 wt%. It is characterized by a relatively high MS value and increasing μ-XRF K, Fe and Ca counts and Ca-Ti ratio in contrast to μ-XRF Ca-Sr and Fe-Mn ratios. The S.R-TOC ratio (sedimentation rate versus total organic carbon) in the S1b is very low at the base but shows a gradual increase. SSTs are relatively warm (19.8 ºC) at the base of S1b, but decrease by about 2°C together with the C_{37} alkenone concentrations (Fig. 5).

The intervening layer between S1b and SMH sapropels (297.4-277.4 cmbsf) shows SST increase and slight increase in μ-XRF K and Fe in contrast to μ-XRF Ca, TOC and MS values, together with Ca-Ti and Fe-Mn ratios. The overlying sapropel SMH (277.4-193 cmbsf) is distinct from the S1b in having strongly fluctuating and higher TOC values (0.50-1.80 wt%) as well as C_{37} alkenone concentrations and S.R-TOC ratio, although TOC content dropes below %1 between 215 and 231 cmbsf (Fig. 5). The whole layer is also marked by a decreasing trend of μ-XRF Fe-Mn ratio, and points to the almost highest μ-XRF Ca value and Ca-Ti ratio of the core with strong fluctuations that share resemblance with TOC. The elevated SST profile and μ-XRF K, Fe and MS values in the lower part of the SMH sharply decrease above 237.6 cmbsf.

Following the SMH, the interval between 193 and 172 cmbsf is marked mainly by a rising trends in μ-XRF K, Fe and MS values that negatively correlate with μ-XRF Ca value and Ca-Ti and Ca-Sr ratios as well as TOC content and μ-XRF Fe-Mn ratio. The abrupt increase in μ-XRF Fe, K and MS values as well as Fe-Mn ratio at the base of the overlying layer (172 cmbsf) is followed by strong fluctuations between 158 cmbsf and 118 cmbsf. μ-XRF Ca value and Ca-Ti and Ca-Sr ratios indicate opposite trends. The overall trend of TOC contents opposite to C_{37} alkenone concentrations that are recorded the highest between 138-125 cmbsf. The lower SST values above the SMH layer, except sharp increase at 178 cmbsf, display elevated trend until 152 cmbsf and later decline above. The progressive decreases in μ-XRF Fe and K values as well as S.R-TOC ratio between 118.6 and 112 cmbsf in the core is followed by opposite trend until 90.6 cmbsf. This interval is also associated with gradual decreasing μ-XRF Ca value and Ca-Ti and Ca-Sr ratios as well as SSTs, except for slight increases above 106 cmbsf (Fig. 5). μ-XRF Fe-Mn indicates a prominent sharp increase above 110 cmbsf.

The interval between 90.6 and 61.6 cmbsf is earmarked by increasing values of μ-XRF K and Fe in comparison to MS values and μ-XRF Fe-Mn ratio. The relatively high values of μ-XRF Ca count and Ca-Ti and Ca-Sr ratios as well as SST record indicate slight decreasing trends. Elevated TOC content in the same interval displays an inverse trend with

S.R./TOC ratio. The layer between 61.6-34 cmbsf is marked mainly by lower μ-XRF K and Fe values and Fe-Mn ratio with strong fluctuations, followed by a sharp increase until 14.3 cmbsf. The opposite trend is recorded in μ-XRF Ca value and Ca-Ti and Ca-Sr ratios. The overall TOC content in the same layer indicates high values, as opposed to S.R-TOC ratio. The highly-fluctuated relatively low SST values in contrast to C_{37} alkenone concentrations indicate a prominent increase above 14.3 cmbsf.

6. Discussion

According to the average high sedimentation rate at the core site, paleo-proxy record from core SAG-14 provides a high temporal resolution for reconstructon of paleoclimatic and palaeohydrological changes in the GoS over the last 7 cal ka BP. The overall lack of agreement about the worldwide distribution, precise timing, amplitude or cause of the Holocene climate and hydrologic changes underlines the need for additional paleo-proxy records from different areas such as the GoS. For this purpose, we compare our findings with other high-resolution marine paleo-climate records from the Aegean and Marmara seas and also regional continental records from NW Anatolia (Figs. 6 and 7). These include the palynological records from Core SL-152 in the northern Aegean Sea, located in an area neary region to the study area and the speleothem records from Sofular Cave in NW Anatolia. Even though the former study is low resolution (10 cm), it provides the analysis of multidecadal vegetation changes and moisture anomaly records during the mid-to-late Holocene that are linked with regional climate changes (Kotthoff et al. 2008), while the latter presents high-resolution changes in temperature and precipitation in the region (Fleitmann et al., 2009).

6.1. Hydrology and climate during sapropel formations

The TOC data together with chronology obtained from core SAG-14 identify the formation of two discrete Holocene sapropel layers (S1b and SMH) in the gulf, including their timing and source regarding to changing paleohydrologic and paleoclimate conditions. The Holocene S1 sapropel layer in the Aegean Sea is subdivided into two different units, the older S1a and younger S1b, by an intervening low TOC layer (Gogou et al., 2007; Triantaphyllou et al. 2009b). The reason for such interruption in the sapropel deposition is related to increased ventilation of bottom waters (Casford et al., 2003). Our core sampled only the S1b part of S1 sapropel and a younger sapropel layer (SMH) for the first time in the GoS. The sapropelic layers (S1b and SMH) in the core are recognisable as dark olive gray homogenous clay beds, containing mainly planktonic fauna with scarce or no benthic assemblages (Figs. 3 and 5). The scarcity or absence of benthic fauna in the sapropelic layers in our core is similar to the age-correlatable sapropels in the Aegean Sea and the SoM, suggesting persistent sea-floor anoxia/hypoxia in the gulf (Rohling et al., 1993, 1997; Çağatay et al., 1999; Casford et al., 2003).

6.1.1. Sapropel S1b interval (7.0-6.1 cal ka BP)

The timing of sapropel S1b in the Aegean Sea is highly debated based on various core studies, ranging from 7.8 to 6.1 cal ka BP. In this study, the core chronology indicates that termination age of S1b sapropel layer in the core is in agreement with the recent studies in the Aegean Sea, suggesting an age interval between 7.3 and 6.1 cal ka BP (Figs. 4 and 5) (Mercone et al., 2001; De Lange et al., 2008; Triantaphyllou et al., 2009b; Filippidi, 2013). In particular, the termination age of S1b sapropel at ca 6.1 cal ka BP in our core matches well with that of the eastern Mediterranean S1 sapropel (e.g., Rohling, 1994; Aksu et al., 1995; De Lange et al., 2008). Comparison of the north and south Aegean Sea records shows significant changes in both the productivity and stratification of the upper water column during S1 deposition. The TOC average values of the sapropel layer in the north Aegean Sea were previously reported between 0.7 % and 1.9 % (Triantaphyllou et al., 2009b; Filippidi, 2013; İşler et al., 2016) that is well in agreement with our TOC values (0.75 wt% and 1.42 wt%) for the S1b sapropel in the core.

Deposition of the sapropel S1b in the gulf is associated with increasing trends of μ-XRF Ca value and Ca-Ti ratio in the core (Fig. 5), suggesting an increasing production of biogenic carbonate. The general rise of μ-XRF K and Fe values together with high MS are indicative of enhanced detrital inputs during the sapropel deposition (7-6.1 cal ka BP) due to increased precipitation. In this context, the gradual decrease in C_{37} alkenone concentrations most probably reflect lower preservation or higher dilution of marine organic matter by detrital material supplied by the local delivery of freshwaters to the GoS via the numerous rivers from the northern catchment (Fig. 2). Increased precipitation during this period is also supported by the gradual decrease in $\delta^{13}C$ values at the Sofular Cave site in NW Anatolia (Fleitmann et al., 2009) and increased Arboreal type (AP) vegetation from the northern Aegean Sea (core SL-152; Fig. 6) (Kotthoff et al., 2008). However, the Holocene summer precession-related insolation maximum in the Northern Hemisphere (Laskar et al., 2004) and the monsoon intensification would have resulted in widespread humidity over the whole Mediterranean region during the S1b deposition (Rossignol-Strick, 1983; Rohling, 1994).

The relatively high μ-XRF Fe-Mn ratio in the lower part of S1b sapropel (Fig. 5) is followed by concomitant decrease upward, suggesting an increase in deep-water ventilation during the later period of sapropel formation. This may be responsible for the relatively low organic matter and alkenone levels in the core. Similar hydrological conditions during the sapropel deposition has also been reported from the north Aegean Sea by Geraga et al. (2010) who claimed that the water stratification would have been mainly restricted to the surface.

Such phenomenon demonstrates that deep water condition in the gulf was not possibly fully-anoxic during the S1b deposition, but still convenient for deposition of sapropelic sediment. Previous studies in the Aegean Sea (Triantaphyllou et al., 2009a, b; Kontakiotis, 2012, 2016) show that warm and humid climate conditions could have triggered water column stratification. Therefore, the paleoceanographic conditions in the gulf as indicated by warm and partly stratified water column together with enhanced detrital organic matter delivery could play the most important role in the deposition of S1b in the GoS. Such environmental conditions would have promoted the Holocene sapropel deposition as proposed for the SoM by earlier core studies (Çağatay et al., 2000, 2015; Tolun et al., 2002).

The progressive decrease in SST values during the S1b deposition in core SAG-14 (Figs. 5 and 7) reflects sea surface cooling upto ca. 1.5–2 °C due to the increased precipitation that could have led to surface water density decreases in the gulf. Similar SST decline has been reported over the same period in the northern Aegean Sea (Kotthoff et al., 2008) and in the SoM (Sperling et al., 2003) (Fig. 7), suggesting similar hydrologic conditions during the sapropelic deposition. According to previous observations from the Aegean Sea (Geraga et al., 2010), the elevated percentages of the species G. bulloides and T. Quinqueloba within S1b are more pronounced in the north than in south Aegean, and are related to low salinity and high fertility of the surficial waters, possibly due to the larger river inflows draining the north Aegean catchment area. However, this sea-surface cooling could also be indicative of stronger winds and enhanced mixing that would have provoked intermittent ventilation of deep waters throughout the S1b as infered from decreasing μ-XRF Fe-Mn ratio in the core (Fig. 5).

6.1.2. Post-sapropel S1b interval (6.1-5.4 cal ka BP)

The paleo-proxy record in the interval between sapropels S1b and SMH is marked by a sharp drop in the TOC content, implying diminished organic matter productivity in the gulf

(Fig. 5). This intervening layer is also associated with decreases in μ-XRF Ca value and Ca-Ti ratio, suggesting low biogenic carbonate production and organic productivity. The sharp decreases in μ-XRF Fe-Mn ratio and MS at the termination of S1b, therefore, suggest a return to fully oxygenated bottom waters and lower preservation of organic matter. Therefore, weakened primary productivity and water column oxygenation were the limiting factors for the burial of organic matter and organic-rich layer deposition. During the same interval, the gradual increases in μ-XRF K and Fe values indicate sustained detrital input to the GoS from the catchment area due to a wetter climate. Increased precipitation during this period is also depicted by the abrupt negative excursion in $\delta^{13}C$ values at the Sofular Cave site in NW Anatolia (Fleitmann et al., 2009) (Fig. 6), whereas the amount of AP in core SL-152 from the northern Aegean Sea (Kotthoff et al., 2008) is commonly high, implying warm and humid conditions. In addition, the progressive increase of SST in core SAG-14 coherently indicates warming (Fig. 5).

6.1.3. Sapropel SMH interval (5.4-3.0 cal ka BP)

The existence of a younger sapropel layer (SMH) in core SAG-14 is defined and dated between 5.4 and 3.0 cal ka BP based on the age-depth model together with TOC data (Figs. 4 and 5). According to earlier studies (Kouli et al., 2011; Triantaphyllou et al., 2014; Kontakiotis, 2016), deposition of the middle Holocene Sapropel (SMH) has only been recorded from the southern Aegean Sea during 5.4-4.3 cal ka BP. Our termination age for the SMH in the studied core differs by 1.3 ka BP from the southern Aegean Sea, but coincides with the termination of the upper Holocene sapropel reported in the SoM (Çağatay et al., 1999, 2000; Tolun et al., 2002). The differences in the timing of sapropel deposition in the gulf, relative to those of the quasi-equivalent Mediterranean sapropel, can be attributed to the intensity of environmental changes such as timing of establishment of the suboxic/anoxic bottom water conditions, rate of primary productivity, and the size and depth of the basins. The SMH layer in core SAG-14 contains a higher TOC content relative to the S1b, except for lower values between ca 4.5 to 3.5 cal ka BP. The possible reasons must be either greatly enhanced surface productivity, which would suggest a different nutrient regime compared to condition during the formation of S1b sapropel, or to a better preservation of organic matter under higher sedimentation or combination of both. However, the depth of the oxycline and hence the oxygen exposure time of the sinking material would have been variable for each sapropel interval (S1b and SMH) as indicated by a high variation in C_{37} alkenone concentration in the core (Fig. 5).

The 5.4-4.2 cal ka interval during the SMH deposition is accompanied by increases in μ-XRF K, Fe and MS values (Fig. 5), suggesting elevated detrital inputs to the GoS due to either more precipitation or weaker vegetation cover. This circumstance would have induced a relatively higher sedimentation rate (0.35mm/yr) in the GoS based on the core chronology (Fig. 4) that in turn likely provides a better preservation of organic matter. This may in part explain the higher carbonate content of the sediment as inferred from the relatively higher μ-XRF Ca value and Ca/Ti ratio in the core. During the same period, increased $\delta^{13}C$ values in the Sofular Cave record (Fleitmann et al., 2009) and decrease in AP ratio in core SL-152 (Kotthoff et al., 2008) (Fig. 6) suggests relatively drier climate and poor vegetation cover. These overall findings suggest that the warm and humid phase associated with African monsoon forcing apparently was more weakened in the north Aegean Sea and GoS during this period. On the other hand, gradual increase in SST in core SAG-14 until 4.2 cal ka BP supports prevailing warm and dry climate around the GoS during the earlier SMH deposition (5.4-4.2 cal ka). Indeed, our alkenone SST-record suggests significant climatic instability in the GoS during the overall SMH deposition, as implied by 2–3 °C SST variations. These findings are in agreement with SST records from the northern and southern Aegean Sea (Kotthoff et al., 2008) and from the SoM (Sperling et al., 2003), although temporal resolutions are much lower (Fig. 7). The relatively higher μ-XRF Fe-Mn values in comparison to later phase of the SMH deposition indicate a weaker ventilation in response to better water column stratification in the gulf. Therefore, warming of the surface water in the gulf due to a dry climate during this earlier sapropel deposition would have induced a decrease in surface density and, thus, prevented the ventilation of deeper layer, promoting the preservation of organic matter in the sediment. The termination of the humid phase during the earlier SMH deposition suggests a general trend to climatic aridification over the Late Holocene, which is in accordance with the salinity increase and oligotrophic and dry nature of the water column of the modern Aegean Sea.

The latest part of the SMH deposition in the GoS between 4.2-3.0 cal ka BP is marked by sharp decreases in μ-XRF K and Fe as well as MS values (Fig. 5), implying reduced detrital inputs. This result can be explained by different factors, including an increased vegetation cover around the catchment area that would have limited erosion and sediment delivery to the gulf. This hypothesis is supported by a prominent decrease in $\delta^{13}C$ values at the Sofular Cave site (Fleitmann et al., 2009) and increased AP ratio in core SL-152 (Kotthoff et al., 2008) (Fig. 6), indicative of the enhanced vegetation cover due to a humid climate phase, timely coinciding with the Mid-Holocene Climatic Optimum. Triantaphyllou et al. (2014) relates its deposition in the southern Aegean Sea to upper water column stratification and enhanced deep chlorophyll maximum under the Mid-Holocene wet and warm conditions resulted from weak Mid-Holocene South Asian monsoon forcing and the Etesian (Meltem) winds.

The enrichment of Ca relative to Sr in core SAG-14 indicates that the composition of the SMH sapropel is dominated by carbonate rather than aragonite, implying a lower surface water evaporation in the gulf. This conclusion is in agreement with surface freshening in the GoS after 4.2 cal ka BP due to increased precipitation as inferred from decreasing SSTs, except for a short warming event at around 3.3 cal ka BP (Fig. 5). A similar post-4.2 cal ka BP SST decline has also been documented in northern and southern Aegean Sea (core SL-152) and the SoM (core KL-71) (Fig. 7), reflecting changing regional climatic conditions during the SMH deposition. Such low salinity and high freshening of surface waters in the gulf were possibly driven by enhanced riverine discharges and land runoff from the surrounding the northern and southern catchments of the GoS that was greater towards the end of the SMH sapropel. This rapid surface water cooling during the later phase of sapropelic deposition most likely provoked intermittent ventilation of deep waters throughout the SMH deposition in the gulf. However, we cannot rule out the possible contribution of wind-driven surface water cooling as the μ-XRF Fe-Mn ratio in the upper part of the SMH in the core still shows increasing ventilation. The continuous gradual decrease in μ-XRF Fe-Mn ratio (Fig. 5) underpins better ventilated deep-waters as compared to the S1b sapropel. Such a weak stratification might have been compensated by enhanced productivity and a relatively higher sedimentation rate (0.35mm/yr) to account for the formation of SMH sapropel. The fluctuations in C_{37} alkenone concentrations together with high S.R-TOC ratios in the SMH layer indicate variable origin of the organic matter. Together with a climatic influence on freshening of the GoS waters, a possible contribution of Black Sea outflow via the SoM after 4.4 cal ka BP (Çağatay et al., 2000; Algan et al., 2001) should also be considered.

6.2. Late Holocene climate events

The late Holocene period is characterized by several climatic fluctuations that are mainly associated with historical periods documented by Büntgen et al. (2011) in central Europe. These various periods are examined here as the Roman Humid Period (RHP), the Dark Ages Cold Period (DACP), the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) are also apparent in the paleo-proxy record from the GoS (Fig. 5). Although the duration of each period is not always synchronous, our multi-proxy approach allows for the identification and discussing the timing and intensity of those climate events in the GoS (Fig. 5). The SMH termination in core SAG-14 is marked by decreases in μ-XRF Ca-Ti ratio and Ca value until the onset of the RHP at 2.5 cal ka BP (Fig. 5), likely reflecting diminished marine carbonate production in the GoS. On the other hand, μ-XRF K and Fe values indicate a pronounced increase of detrital delivery due to relatively wetter climate as supported by rising AP ratio in core SL-152 (Kotthoff et al., 2008) even though $\delta^{13}C$ values at the Sofular Cave site indicate positive excursion (Fig. 6). The lower SST values in core SAG-14 indicate sea surface freshening due to relatively cooler climate and/or continental runoff. The further decrease in μ-XRF Fe-Mn ratio evidences a change in the deep-water stratification in the GoS, suggesting suboxic to oxic conditions. During this period, increased freshwater inputs enhanced ventilation of deepwater masses and diminished organic matter production and preservation. Thus, the deep Saros Gulf basin was fully oxygenated, thus preventing the burial of organic matter and organic-rich deposition.

6.2.1. Roman Humid Period (2.5-1.55 cal ka BP)

The paleo-proxy record in core SAG-14 during the RHP indicates high climate variability in the GoS. The earlier phase of this period (2.5-2.1 cal ka BP) is characterized by decreasing trends in μ-XRF K and Fe values (Fig. 5), marking diminished detrital inputs due to enhanced dryness around the GoS. This is supported by low sedimentation rate (0.42 mm/yr) in the core in comparison to the later period as infered from relatively low S.R/TOC ratio (Figs. 4 and 5). Although the highest AP values are recorded in the northern Aegean Sea (core SL-152 in Fig. 6), the positive excursion in the $\delta^{13}C$ record at Sofular Cave in the same interval indicates diminished precipitation. This aridification trend coincides with a progressive evolution towards typical Mediterranean climate and aridity, which gradually occurs at the onset of late Holocene (e.g. Wanner et al., 2008). This remarkable dry and warm period at the beginning of the RHP has previously been documented in the Nar and Tecer lakes (Jones et al., 2006; Kuzucuoğlu et al., 2011). On the other hand, higher μ-XRF Ca-Ti ratio and Ca values (Fig. 5) suggest enhanced marine biogenic carbonate production due to possibly SST warming upto 1.5-2 °C until 2.1 cal ka BP. Nevertheless, the relatively high μ-XRF Fe-Mn ratio is followed by sharp decrease that implyies a variation in the water stratification, possbily from suboxic to oxic condition. Thus, the GoS was fully oxygenated, preventing the burial of organic matter and organic-rich deposition.

A change from warm-dry to warm-wet conditions in the latest part of the RHP (after 2.1 cal ka BP) is recorded by higher values of μ-XRF K and Fe, suggesting the higher river discharge to the gulf as a consequence of increased humidity. The higher sedimentation rate (0.64 mm/yr) based on the age-depth model of the core (Fig. 4) together with gradual increase in S.R/TOC ratio (Fig. 5) could be attributed to the increased riverine inputs in the surficial waters in the gulf. A relatively wetter phase is also documented for the same time-interval by depleted $\delta^{13}C$ values in the Sofular Cave record (Fig. 6). The freshening of sea surface waters driven by enhanced riverine discharges and land runoff was likely responsible for the SST decrease upto 1 °C after 2.1 cal ka BP (Fig. 5). In contrast to the northern Aegean Sea, a similar SST trend has been documented in the SoM, further supporting contribution of surface freshening in the GoS due to the continuous Black Sea outflow. Therefore, the combination of the inflow of water from the Black Sea and abundant rivers and the atmosphere–ocean interactions creates a complex hydrologic system within the GoS that affects its circulation and depositional process. Although decreases in μ-XRF Ca value and Ca-Ti ratio are recorded in the core, the enhanced marine organic productivity is evidenced by higher C_{37} alkenone concentration during this RHP phase (2.1-1.55 cal ka BP). The gradual increase in μ-XRF Fe-Mn ratio during this later part of the RHP (Fig. 5) indicates a change in the deep-water stratification in the GoS, suggesting suboxic to partly anoxic conditions. During this period, enhanced organic matter production together with water-stratification in the gulf water masses are likely responsbile for better organic matter preservation as indicated by relatively higher TOC ratio (Fig. 5) in compare to the following climate period after 1.55 cal ka BP.

6.2.2. Dark Ages Cold Period (1.55-1.3 cal ka BP)

The DACP is marked by initial sharp decreases in μ-XRF K and Fe values together with S.R/TOC ratio (Fig. 5), then followed by an increase witnessing drastic changes of detrital inputs. The similar variations are recorded in μ-XRF Ca value and Ca-Ti ratio till 1.3 cal ka BP, reflecting the scarcity and the later elevated biogenic carbonate production in the GoS. The overall trends in those elements attest the former dry and later humid climates in the GoS during the DACP. The general trend of AP values in core SL-152 (Kotthoff et al., 2008) (Fig. 6) is agreement with our findings, indicating high climate variability during the same period in the northern Aegean Sea. While the climate was relatively drier until 1.48 cal ka BP, SSTs cooling upto ~1 °C is consistent with earlier reports in the western and eastern Mediterranean Sea (Sicre et al., 2016; Jalali et al., 2016; 2017) and North Atlantic (Sicre et al., 2008). A progressive dryness during the DACP coincides with decreasing solar insolation in the Northern Hemisphere (Steinhilber et al., 2009) and cooler air temperatures in Greenland (Grootes and Stuiver, 1997). Although the later humid phase and the concomitant higher detrital delivery existed in the gulf, the possible reason for gradual increase in SST value could be attributed to enhanced warming of the sea surface waters of the gulf. Although μ-XRF Fe-Mn ratio is low at the beginning of the DACP, the sharp increase in the latter half indicates the poorly oxygenated deep-water condition in the GoS due to enhanced water column stratification.

6.2.3. Medieval Climate Anomaly (1.13-0.73 cal ka BP)

The most of MCA period in the GoS is represented by a relatively wetter climate and subsequent higher detrital delivery as inferred from progressive increases in μ-XRF K and Fe values in the core (Fig. 5). Although the Sofular Cave record indicates positive excursion in $\delta^{13}C$ values since the termination of RHP (Fig. 6), the broad increase in AP values in core SL-152 (Kotthoff et al., 2008) strongly indicates relatively wetter climate around the GoS. Relatively higher organic matter production was likely driven by a warmer climate that possibly gave rise to high marine carbonate production as inferred from general higher μ-XRF Ca value and Ca-Ti and Ca-Sr ratios. While climate became wetter during most of the MCA, the resultant higher river discharge to the gulf gave rise to ~2 °C progressive decrease in SST values in core SAG-14, implying continues coolling as documented from the northern Aegean (Kotthoff et al., 2008) and Marmara seas (Sperling et al., 2003; Fig. 7). Another possible reason for decreasing SSTs could be the permanent connection with the Black Sea during the late Holocene. Although the esixtence of such connection would be expected to create water column stratification, considerable high river runoff would have led to intense mixing of the surface water column that in turn gave rise to weakening of the stratification as infered from comperatively low μ-XRF Fe-Mn ratio in the core (Fig. 5). Even though, TOC enrichment of the sediment in the core indicates higher preservation of the organic matter that could only be explained by a higher sedimentation rate as documented by elevated S.R/TOC ratio during this period.

6.2.4. Little Ice Age (730-110 cal yr BP)

The LIA period is characterized by high climate variability based on the paleo-proxy record of core SAG-14 (Fig. 5). Lower μ-XRF K and Fe as well as lowest MS until 450 cal yr BP comparable to the DACP imply reduced detrital input to the gulf. The possible reason could be attributed to an extensive vegetation cover in the catchment area based on a higher

AP ratio in core SL-152 (Kotthoff et al., 2008) (Fig. 6). Relatively wetter climate in the early LIA is also evidenced by negative excursion of $\delta^{13}C$ at Sofular as well as the Soreq caves (Bar-Matthews et al., 1998). The lowest SSTs (~16 °C) in core SAG-14 during the earlier LIA period documents further sea-surface freshening that could be attributed to a higher winter precipitation and cooler climate during this earlier LIA. Such phenomenon in the gulf is consistent with other paleo-climate records from Europe and Anatolia (Türkeş and Erlat, 2005; Roberts et al., 2012; Sicre et al., 2016; Gogou et al., 2016; Ocakoğlu et al., 2016; Jalali et al., 2018). In contrast to detrital input proxies (e.g. K, Fe and Ti), the general high μ-XRF Ca-Ti ratio and Ca value indicate rising carbonate production and organic productivity. Although the water stratification was still weak as documented by a low μ-XRF Fe-Mn ratio in the core, a general high TOC content in this initial phase suggests an enhanced organic matter preservation possibly due to absence of deep water circulation in the gulf (Fig. 5).

The higher detrital input to the GoS during the late LIA (350-110 cal yr BP) as inferred from higher values in μ-XRF K and Fe (Fig. 5) could be assigned to low vegetation cover as supported by the sharp decrease of AP ratio in core SL-152 (Kotthoff et al., 2008) (Fig. 6), reflecting a shift to relatively drier climate condition around the GoS. On the other hand, the negative excursion of $\delta^{13}C$ in the Sofular Cave record at the onset of the LIA is followed by sharp increase, suggesting a shift from wet to drier climate. This is supported by a partly higher SST values in the core, reaching to ~18.5 °C. Higher soil erosion in the catchment area of the gulf could also be explained by intense deforestation due to human activities over the last 350 cal yr BP. According to Wick et al. (2003), Anatolia underwents a progressive decrease of forest cover due to human activity during the last 600 yr. Pollen record from the Aegean Sea shows heavy deforestation in southern Europe during the same time-interval (Aksu et al., 1995). The sharp decreases in μ-XRF Ca value and Ca-Sr ratio indicates limited marine organic productivity due to dry and cold climate. The strong fluctuations in μ-XRF

Fe-Mn ratio in the core suggests short-term changes in the deep-water condition (Fig. 5), which could not have provided enough time for organic matter preservation into the sediment as documented by the comparatively low TOC content in the late LIA period.

Conclusions

Multi-proxy analyses of core SAG-14 provide detailed insights into the paleoceanographic and paleoenvironmental conditions over the last 7.0 cal ka BP in the GoS. The close match between paleo-proxy data in the GoS with the marine and continental records from the northern Aegean and Black seas indicates that the timing of past climate events are in general agreement with the regional climate patterns. The middle-to-late Holocene sediment in the GoS is characterized by deposition of two discrete sapropel layers with >1% TOC values. The older sapropel layer S1b was deposited under warm and humid conditions, associated with terrestrial inputs from high river discharges from the northern catchment of the GoS. Enhanced productivity under weakly stratified surface waters together with high sedimentation rate played the most important role in the formation of S1b sapropel. The deposition of younger Holocene sapropel (SMH; 5.4-3.0 cal ka BP) initiated under relatively warm and dry conditions till 4.5 ka BP, followed by cold and wet conditions possibly associated with Black Sea outflow to the GoS. The μ-XRF Fe-Mn ratio indicates a progressive ventilation throughout the SMH from suboxic to anoxic bottom water condition and generally high and strong variable TOC content, except for lower values between ca 4.5 to 3.5 cal ka BP. Our data also show high variations during the RHP (2.5-1.55 cal ka BP), suggesting a change from dry to wet climate. Dry climate prevailed at the beginning of DACP until 1.3 cal ka BP, but evolved to relatively wetter conditions that persisted during most of the MCA (1.1-0.7 cal ka BP). Similar SST trends in the northern Aegean and Marmara seas pointed out common hydrological conditions in the region suggesting a sustained influence of the Black Sea during the late Holocene. The LIA climate indicates a shift from dry to wet climate between its early and late phases. Higher detrital delivery over the last 350 years emphasize enhanced soil erosion imputable to intense deforestation due to human activities around the GoS. This is consistent with the synchronous progradation of southern Europe delta during the coldest phase of the LIA due to growing population and land use (Maselli and Trincardi, 2013).

Acknowledgements

We would like to thank captains and all crew members of Urania R/V who attended the MARM11 cruise in 2011. We are also thankful to CNRS and the MISTRALS/PALEOMEX program for providing fundings to perform biomarker analyses and for MAS salary support. This study has been supported by the ITU BAP project (42053). We are very grateful to Dursun Acar, Asen Sabuncu and Nurettin Yakupoğlu for their help and advice during the core analyses.

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Figure Captions

Fig. 1 (a) Simplified inset map showing current tectonic setting of Turkey. (**b)** Location of the Gulf of Saros (SAG-14) and other sites discussed in the text: SL-152 in north Aegean Sea (Kotthoff et al., 2008), NS-14 in south Aegean Sea (Triantaphyllou et al., 2014), KL-71 in the Sea of Marmara (Sperling et al., 2003), Sofular cave in Black Sea (Fleitmann et al., 2009). Red arrows and black lines represent surface water circulation from Kontakiotis (2016) and the North Anatolian Fault (NAF) according to Gasperini et al. (2011), respectively.

Fig. 2 Bathymetric map of the Gulf of Saros and surroundings (yellow dots) showing the location of core SAG-14 (black dot). White arrows represent longshore currents and anticyclonic eddies in the gulf (Sarı and Çağatay, 2001). Blue lines and black lines indicate the drainage system surrounding the Gulf of Saros.

Fig. 3 Generalized lithologic logs of core SAG-14 obtained from the Gulf of Saros and its radiographic image, showing the main lithostratigraphy of the Holocene sequence. Red stars indicate the ^{14}C samples with calibrated ages.

Fig. 4 Age-depth model of the studied core SAG-14 reconstructed based on AMS ^{14}C ages and Holocene sapropels layers in the cores by using R-studio and the script “CLAM” (Blaauw, 2010).

Fig. 5 Magnetic susceptibility (MS), μ-XRF element and elemental profiles (K, Fe, Fe/Mn, Ca, Ca/Ti and Ca/Sr) for core SAG-14. Note that total organic carbon analysis and biomarker analysis were also performed in the core.

Fig. 6. Comparison of μ-XRF Ca/Ti data from core SAG-14 in the Gulf of Saros with $\delta^{13}C$ data from Sofular cave in Black Sea (Fleitmann et al., 2009) and arboreal type (AP) vegetation from north Aegean Sea core SL-152 (Kotthoff et al., 2008).

Fig. 7. Comparison of sea surface temperature (SST) profiles from core SAG-14 in the Gulf of Saros with core SL-152 in the north Aegean Sea (Kotthoff et al., 2008), core NS-14 in the south Aegean Sea (Triantaphyllou et al., 2014) and core KL-71 in the Sea of Marmara (Sperling et al., 2003).

Table Captions

Table 1 Core information for this study.

Table 2 AMS radiocarbon and calibrated ages of foraminiferal shells samples in the studied core. Radiocarbon ages are converted into calibrated ages by using Marine13 (Reimer et al., 2013) calibration curve and Calib v7.1 software (Stuiver and Reimer, 1993) with global reservoir correction of 400 years. A local reservoir age correction ($\Delta R = 149 \pm 30$ years for the sapropel interval; Facorellis et al., 1998 and $\Delta R = 58 \pm 85$ outside the sapropel Reimer and McCormac, 2002) was used for the Aegean Sea.