

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**PALEOCEANOGRAPHIC AND PALEOCLIMATE RECORDS IN THE GULF
OF SAROS (AEGEAN SEA) DURING THE LATE PLEISTOCENE TO
HOLOCENE**



M.Sc. THESIS

Cerennaz BOZYİĞİT

Department of Geology Engineering

Geological Engineering Programme

July 2020

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**GEÇ PLEYİSTOSEN-HOLOSEN BOYUNCA SAROS
KÖRFEZİ'NDEKİ (EGE DENİZİ) PALEOŞİNOGRAFİK VE
PALEOİKLİMSEL KAYITLAR**

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To my family,



FOREWORD

“Paleoceanographic and Paleoclimate Records in the Gulf of Saros (Aegean Sea) During the late Pleistocene to Holocene” titled graduate thesis is taken place in Istanbul Technical University, Graduate School of Science Engineering and Technology Institute, Geological Engineering between 2019-2020.

Majority of experiments and measurements are executed in East Mediterranean Centre for Oceanography and Limnology Laboratories. Biomarker Analyses are performed in Sorbonne University-Laboratoire d'Océanographie et du Climat- LOCEAN.

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ABBREVIATIONS

μ-XRF	: Micro-X-Ray Fluorescence
AD	: Anno Domini
AMS	: Accelerator Mass Spectrometry
BP	: Before Present
cmbsf	: centimeter below sea floor
cps	: count per second
EMCOL	: Eastern Mediterranean Centre of Oceanography and Limnology
LOCEAN	: Laboratoire d'Océanographie et du Climat
km	: kilometer
mm/yr	: millimeter per year
MSCL	: Multi Sensor Core Logger
yr	: year
cal	: calibre
NAF	: North Anatolian Fault
NAT	: North Anatolian Trough
SoM	: Sea of Marmara
LIA	: Little Ice Age
MCA	: Medieval Climate Anomaly
DACP	: Dark Ages Cold Period
RHP	: Roman Humid Period
SMH	: Sapropel Mid-Holocene
S1b	: Eastern Mediterranean Sapropel S1
YD	: Younger Dryas
B-A	: Bølling-Allerød
GC	: Gas Chromatography
SST	: Sea Surface Temperature
M.S.	: Magnetic Susceptibility
G.Ö.	: Günümüzden Önce
GD	: Genç Dryas
KEÇ	: Kuzey Ege Çukurluğu



SYMBOLS

Ca	: Calcium
Ti	: Titanium
Fe	: Iron
Mn	: Manganese
Br	: Bromium
Sr	: Strontium
M	: Mean
σ	: Sorting
Si	: Silisium



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PALEOCEANOGRAPHIC AND PALEOCLIMATE RECORDS IN THE GULF OF SAROS (AEGEAN SEA) DURING THE LATE PLEISTOCENE TO HOLOCENE

SUMMARY

The NE-SW-oriented Gulf of Saros is a westward-widening and -deepening, embayment in the northeastern Aegean Sea, with a water depth of 645 m. The length of the gulf is about 60 km and the width at the opening to the Aegean Sea is about 36 km. The wedge-shaped gulf extends parallel to the coasts of the Thrace Shelf to the north and the Gelibolu peninsula to the south. The gulf constitutes the eastern extension of the North Aegean Trough (NAT), and is separated from the Marmara Sea by the Thrace Peninsula. The Gulf of Saros has been in the focus of various national and international research groups for tectonic and paleoseismological studies. Although there are several paleoceanographic and paleoclimatic studies in the Aegean Sea, it is thought that the Gulf of Saros should have different dynamics from the Aegean Sea since it has a different geographic location as an inland sea. Moreover, different paleoceanographic conditions might have taken place in the Gulf of Saros because of its location on a gateway between the Mediterranean and the Black seas. Nevertheless, there is insufficient paleoceanographic and paleoclimate studies in the gulf based on the sediment core. In order to fill this scientific gap, marine survey was established in Gulf of Saros by Urania cruise in 2011 to collect sediment cores from different water depths.

In this thesis, the late Pleistocene to Holocene paleoceanography and paleoclimate of the gulf region and water exchanges between the Marmara and Aegean seas is investigated by multi-proxy approach using three sediment cores (SAG-08, SAG-14 and SAG-22) retrieved from the gulf by Urania cruise in 2011. Experiments and observations are executed in the East Mediterranean Centre for Oceanography and Limnology (EMCOL) Applied Research Center. Biomarker analysis is performed in Sorbonne University-Laboratoire d'Océanographie et du Climat- LOCEAN. Cores SAG-08 and SAG-14 represent the deeper core locations, whereas core SAG-22 is recovered from a shallower water depth. In this thesis, paleo-proxy records (sedimentologic and geochemical analyses) are established with robust core chronologies based on AMS radiocarbon datings. Beside radiochronology on the sediment cores, comparisons of XRF-Ca/Ti data between the cores and the previously well-dated sediment core from Sea of Marmara together with $\delta^{13}\text{C}$ record of Sofular Cave enable us to construct precise age-depth models. Thus, paleoceanographic and paleoclimate evolution of the gulf could be better evaluated with a robust chronology covering the period for the last 15000 cal yr BP.

According to the paleo-proxy records in the studied core, the Bølling-Allerød (B-A) took place in the gulf between 14800 cal yr BP and 12900 cal yr BP. This earliest paleoclimate period is only documented in core SAG-22, and is associated with higher paleo-productivity due to an existence of relatively warmer and wetter climate in

compare to the Younger Dryas (YD), implying higher river discharge to the gulf. High proportion of marine organic matter during the B-A due to warm climate would have given rise to deplete the available oxygen, thus, the anoxic or suboxic deep water condition prevailed at this core location. The climate shift to a cold and dry took place in the gulf at the onset of the YD period, between 12900 cal yr BP and 11800 cal yr BP based on the age-depth model. The paleo-proxy record from core SAG-22 demonstrates still high detrital input, but a lower proportion of authigenic calcite due to decreased organic productivity. However, sharp cooling of surface water and stable sea-level during the YD might have resulted in the formation of well-ventilated deep water condition as consequence of strong water circulation along the coastal region of the gulf in which the core was located.

The onset of the Holocene at 11800 cal yr BP is marked by prominent changes in the paleo-proxy record in core SAG-22. The enhanced authigenic calcite reflects increased paleo-productivity as a consequence of elevated warming around the gulf until 8900 cal yr BP. In addition to improved marine organic productivity under the warmer and wetter climate, the fast Holocene transgression gave rise to increased salinity in the gulf and establish suboxic to anoxic deep water condition, reflecting the water column stratification. The warmest climate during the early Holocene and the concomitant highest paleoproductivity is recorded at 9300 cal yr BP that timely coincides with the formation of the S1 sapropel in the Eastern Mediterranean Region as well as the Aegean Sea. The time period from 8900 to 7300 cal yr BP is associated with elevated detrital input to the gulf that would have been possibly provided by coastal erosion due to lowering of the sea-level rise rather than increased humidity. This finding is consistent with the previous study in the north Aegean Sea as well as $\delta^{13}\text{C}$ values of Sofular Cave.

The middle Holocene in the gulf is represented by deposition of the Sapropel S1b between 7300 cal yr BP and 6100 cal yr BP. During the S1b deposition, the general climate was drier until 6700 cal yr BP, then the later period until 6100 cal yr BP is recorded as warmer and wetter together with possible suboxic deep water condition, but not almost anoxic. The sea surface freshening during this later wetter period is well documented by sea surface temperature record (SST) only performed on core SAG-14. The intervening time period (6100-5300 cal yr BP) between the S1b and Mid-Holocene Sapropel (SMH) sapropels is characterized by lowering organic productivity and lower terrestrial matter delivery to the gulf due to cold and dry climate around the gulf. The SMH sapropel deposition took place in the gulf during 5300-3200 cal yr BP based on the age-depth model of core SAG-14. The climate was much drier during early period (5300-4200 cal yr BP) of the SMH deposition, whereas the highest detrital input to the gulf is recorded between 4200 cal yr BP and 3900 cal yr BP. The later period during the SMH deposition between 3900 cal yr BP and 3200 cal yr BP is marked in core SAG-14 by decreased SST value, implying sea surface freshening or cooling around the gulf. The early phase of Roman Period in the gulf between 2500 cal yr BP and 2200 cal yr BP is mainly characterized by low detrital delivery and increased SST record due to much drier climate, then it was tuned to warmer and wetter climate until 1900 cal yr BP. In the latest Holocene, the climate shift to much drier climate occurred during the Dark Age Cold Period between 1600 cal yr BP and 1100 cal yr BP. During the latest Holocene, the Medieval Climate Anomaly (1100-600 cal yr BP) is well obscured in the paleo-proxy record in core SAG-14, implying existence of enhanced sea surface freshening due to wetter climate. The cold Little Ice Age

period took place in the gulf 670 yrs ago, and is mostly associated with cold and dry climate, except a short humid period until 150 cal yr BP.





GEÇ PLEYİSTOSEN-HOLOSEN BOYUNCA SAROS KÖRFEZİ'NDEKİ (EGE DENİZİ) PALEOŞİNOGRAFIK VE PALEOKİKLİMSSEL KAYITLAR

ÖZET

Kuzey doğu Ege Denizi'nde yer alan KD-GB doğrultulu Saros Körfezi batıya doğru genişleyen ve derinleşen bir körfezdır. Saros Körfezi'nin su derinliğı 645 m'dir. Saros Körfezi'nin uzunluğı 60 km ve Ege Denizi'ne açıldığı yerde genişliğı ise yaklaşık 36 km'dir. Kama şekilli Saros Körfezi kuzeyde Trakya Yarımadası'na ve güneyde Gelibolu Yarımadası'na paralel olarak genişlemektedir. Körfez, Kuzey Ege Çukurluğı'nun (KEÇ) doğu uzantısını içermektedir ve Marmara Denizi'nden Trakya Yarımadası ile ayrılmaktadır. Saros Körfezi, tektonik ve paleosismolojik çalışmalar için çeşitli ulusal ve uluslararası araştırma gruplarının odağı olmuştur. Ege Denizi'nde birkaç paleoşinografik ve eski iklim kayıtlarına dayalı çalışma bulunmasına rağmen Saros Körfezi'nin paleoşinografik evrimini anlamaya yetmemektedir. Körfezin bir iç deniz olan coğrafi konumundan dolayı, Saros Körfezi'nin Ege Denizi'nden daha farklı dinamiğe sahip olması gerektiğı düşünülmektedir. Dahası, Saros Körfezi'nin Akdeniz ve Karadeniz arasında geçit konumunda bulunmasından dolayı körfezde farklı paleoşinografik durumlar meydana gelmiş olabilir. Bununla birlikte, körfezde sediment karotlarına dayalı yeterli paleoşinografik ve eski iklim çalışmaları bulunmamaktadır. Bu bilimsel boşluğu doldurmak amacıyla 2011 yılında Urania seferi ile farklı su derinliklerinden sediment karotları almak için denizel araştırma gerçekleştirilmiştir.

Bu tez kapsamında, 2011 yılında Urania seferi ile alınan SAG-08, SAG-14 ve SAG-22 olarak adlandırılan üç gravite sediment karotunda çoklu-parametre yöntemleri uygulanarak (çok sensörlü karot tarayıcısı analizi, tane boyu analizi, μ -XRF karot tarayıcısı analizi, toplam organik karbon ve toplam inorganik karbon analizi, biyo-işaret analizi ve AMS radyokarbon analizi gibi) körfezin, geç Pleyistosen'den Holosen'e kadar paleoşinografisi ve paleoklimi değişimleri ve Marmara Denizi ile Ege Denizi arasındaki su değişimleri araştırılmıştır. Deneyler ve gözlemler İstanbul Teknik Üniversitesi- EMCOL Uygulama ve Araştırma Merkezi'nde yürütülmüştür. Biyo-işaret analizleri ise Sorbonne University-LOCEAN Laboratuvarı'nda gerçekleştirilmiştir. SAG-08 (307 mbsl) ve SAG-14 (592 mbsl) karotları daha derin lokasyondan alınmışken, SAG-22 (100 mbsl) karotu sığ deniz derinliğinden alınmıştır.

Litostratigrafik çalışmalarla kronostratigrafik sekans sınırları ve fasiyes özellikleri gibi gözleme dayalı ana litolojik özellikler tanımlanmış ve tarif edilmiştir. Çok sensörlü karot tarayıcısı yöntemi ile sedimanın fiziksel özelliklerinden yoğunluk ve manyetik duyarlılık ölçümü elde edilmiştir. Buna ek olarak, karotlar radyokarbon yaşlandırma ve toplam organik karbon ve toplam inorganik karbon analizleri için örneklenmiştir. Sığ derinliklerde ani tane boyu değişimleri daha net gözlemlenebildiğinden, sadece SAG-22 karotunda tane boyu analizi yapılmıştır. Paleoşinografik evrim süresince meydana gelen ısınma dönemleri sonucunda ortaya çıkan organik zenginleşmenin saptanması amacıyla SAG-14 ve SAG-08 karotlarında toplam organik karbon ve toplam inorganik karbon analizi uygulanmıştır. μ -XRF

analizi (X-ışınları floresans) yöntemi ile karotlarda yüksek çönlükte (0.2 mm) majör ve eser element analizi, sayısal X-ışınları görüntülerinin (radyografi) alınması ve sayısal renk taraması yapılmıştır. Biyo-işaret analizi derinliğinden (592 mbsl) dolayı sadece SAG-14 karotuna uygulanmıştır. Bu yöntem ile iki ve üç bağlı karbon atomları kullanılarak doymamış C₃₇ indeksi elde edilmektedir. Conte vd. (2006)' da yer alan küresel kalibrasyon kullanılarak alkenon su yüzeyi sıcaklığı (SST) hesaplanmaktadır. Buna ek olarak, tek sayılı karbon atomları (C₂₇, C₂₉, C₃₁, C₃₃ ve C₃₅) toplanarak karasal girdi ile ilgili bilgilerin toplanması amaçlanmaktadır.

Son olarak, bu tez çalışmasında geçmiş belirteç kayıtlar (sedimentolojik ve jeokimyasal) radyo karbon analizleri ile oluşturulan sağlam bir karot kronolojisi ile ortaya çıkartılmıştır. SAG-14 karotundan 3 adet ve SAG-22 karotundan 1 adet radyokarbon yaş örnekleri TÜBİTAK-MAM bünyesinde bulunan laboratuvarlarda yaşlandırılmıştır. Yaşlar ¹³C düzeltmesi yapıldıktan sonra günümüzden önce (G.Ö.) ¹⁴C yılı olarak hesaplanmış ve hata payları $\pm 2\sigma$ olarak tespit edilmiştir. Radyokarbon yaşları CALIB v.7 programı (Reimer vd, 2004) kullanılarak takvim yılına göre kalibre edilmektedir. Denizel kavkıllardan alınan radyokarbon yaşları kalibre edilirken CALIB programının Marmara Denizi için rezervuar yaşı veri tabanından (Siani vd, 2000) yararlanılmıştır. Sediment karotlarındaki radyokronolijisinin yanında, Sofular mağarasının $\delta^{13}\text{C}$ kaydıyla birlikte karotlardan ve Marmara Denizi'nden alınmış ve iyi yaşlandırılmış CS-19 karotunun XRF- Ca/Ti verilerinin karşılaştırması kesin yaş-derinlik modelinin oluşturmasına olanak sağlamıştır. Saros Körfezi'nden alınan karotların Ca/Ti verileri ile Marmara Denizi'nden alınan CS-19 karotunun Ca verisi ve Sofular Mağarası'nın $\delta^{13}\text{C}$ kaydının korelasyonu ile SAG-14 karotu için 15 adet yaş-bağlantı noktası ve SAG-22 karotu için 3 adet yaş bağlantı noktası elde edilmiştir. Böylece, günümüzden önce (G.Ö.) son 15000 yılı kapsayan sağlam bir kronoloji ile körfezin paleoöşinografik ve paleoklimsel evrimi daha iyi değerlendirilebilmektedir.

Çalışılan karotlardaki geçmiş belirteç kayıtlarına göre, Bølling-Allerød (B-A) dönemi körfezde G.Ö. 14800 ve 12900 arasında meydana gelmektedir. Sadece SAG-22 karotunda gözlenen bu en erken paleoklimsel periyod, Genç Dryas (GD) dönemine kıyasla yüksek nehir girdisine işaret eden, nispeten ılıman ve yağışlı iklimsel durumun varlığından kaynaklanan yüksek geçmiş verimlilik ile ilişkili olarak SAG-22 karotunda belgelendirilmiştir. Sıcak iklime bağlı olarak B-A sırasına denizel organik malzemenin yüksek oranı mevcut oksijini tüketmeye neden olmaktadır. Bu nedenle bu karot konumunda anoksik veya suboksik derin su koşulu hüküm sürmektedir. İklimin soğuk ve kurak hale gelmesi körfezde GD döneminin başlangıcında, yaş modeline göre G.Ö. 12900 ile 11800 yılları arasında meydana gelmektedir. SAG-22 karotunun eski belirteç kayıtları hala yüksek karasal girdiyle gösterirken, organik üretkenliğin azalması nedeniyle daha düşük oranda otojenik kalsit göstermektedir. Bununla birlikte, GD sırasında yüzey suyunun keskin bir şekilde soğuması ve sabit deniz seviyesi, karotun konumlandığı körfezin kıyı bölgesi boyunca güçlü su sirkülasyonunun sonucu olarak iyi havalandırılmış derin su koşullarının oluşmasına sebep olmuş olabilir.

G.Ö. 11800 yılında Holosen'in başlangıcı, SAG-22 karotundaki eski belirteç kaydında göze çarpan değişikliklerle belirlenmiştir. Artan otojenik kalsit, körfez etrafında G.Ö. 8900 yılına kadar yükselen ılımanlaşmanın sonucunda arttırılmış paleo verimliliği yansıtmaktadır. ılıman ve yağışlı iklim koşullarındaki geliştirilmiş denizel organik verimliliğe ek olarak, hızlı Holosen transgresyonu körfezde artan tuzluluğa sebep olmuştur ve su kolonu tabakalanmasını yansıtan suboksik/anoksik derin su durumunu oluşturmuştur. Erken Holosen boyunca en ılıman iklim ve beraberinde

gelen yüksek paleo verimlilik hem Doğu Akdeniz bölgesindeki hem de Ege Denizi'ndeki sapropel oluşumuna karşılık gelen G.Ö. 9300 yıllarında kaydedilmiştir. G.Ö. 8900 yılından 7300 yılına kadarki zaman aralığı, körfeze yükselmiş nemlilikten ziyade azalan deniz seviyesinden kaynaklanan kıyı erozyonu ile sağlanmış olan artan karasal girdi ile ilişkilidir. Bu bulgular, daha önce hem Sofular mağarasında yapılmış $\delta^{13}\text{C}$ çalışması hem de kuzey Ege Denizi'nde yapılmış çalışmalarla uyumludur.

Körfezde orta Holosen G.Ö. 7300-6100 yılları arasında çökelen S1b sapropeli ile temsil edilmektedir. S1b sapropeli hem SAG-22 karotunda hem de SAG-14 karotunda tespit edilebilmiştir. G.Ö. 6500 yılının incelemesi yüksek sedimantasyon hızı ve yüksek çözünürlük özelliklerinden dolayı SAG-14 karotu üzerinden yapılmıştır. SAG-22 karotunda yer alan iklimsel belirteçlere ek olarak, SAG-14 karotunda biyo-işaret analizleri ve toplam organik karbon ve toplam inorganik karbon analizleri yapılmıştır. S1b sapropeli boyunca, genel iklim G.Ö. 6700 yılına kadar kuru iken, sapropelin geç döneminden G.Ö. 6100 yılına kadar ılıman ve yağışlı koşullar kaydedilmiştir. Bu dönem (G.Ö. 6700-6100 yılları) muhtemel olarak suboksik derin su koşulları göstermektedir; ancak tamamen anoksik olmamıştır. Bu geç yağışlı dönem boyunca, deniz yüzeyi serinleşmesi sadece SAG-14 karotunda uygulanan deniz yüzey sıcaklığı (DYS) kaydı ile iyi bir şekilde belgelenmiştir. S1b ve SMH sapropelleri arasındaki zaman dilimi (G.Ö. 6100-5300 yılları), körfez etrafındaki soğuk ve kuru iklim koşullarından kaynaklanan azalan organik verimlilik ve düşük karasal malzeme ile temsil edilmektedir. SAG-14 karotunun yaş-derinlik modeline göre, SMH sapropel çökelişi körfezde G.Ö. 5300-3200 yılları arasında meydana gelmektedir. SMH sapropelinin erken dönemi boyunca (G.Ö. 5300-4200 yılları) körfez daha fazla kurakken, körfeze en yüksek karasal girdi G.Ö. 4200-3900 yılları arasında kaydedilmiştir. SMH sapropelinin G.Ö. 3900-3200 yılları arasında geç dönemi, SAG-14 karotunda deniz yüzey serinleşmesi veya körfezin etrafının soğumasından kaynaklanan düşük DYS değerleri ile belirtilmiştir.

Körfezde, G.Ö. 2500-2200 yılları arasına karşılık gelen Roma Ilık Dönemi'nin erken evresi ağırlıklı olarak daha kuru iklimden dolayı düşük karasal girdi ve yükselmiş DYS değerleri ile temsil edilmektedir. Daha sonra bu dönem, G.Ö. 1900 yılına kadar daha sıcak ve daha yağışlı bir iklim dönüşmüştür. Roman Ilık Dönemi'ndeki değişimler jeokimyasal verilere ek olarak yüzey suyu sıcaklığı değişimleriyle de ortaya çıkarılmıştır. Geç Holosende, G.Ö. 1600-1100 yılları arasında Karanlık Çağ Soğuk Dönemi boyunca daha kuru iklim koşullarına doğru bir değişim meydana gelmiştir. Bu soğuk ve kurak iklim düşük yüzey suyu sıcaklığı ve düşük toplam organik karbon değerleri ile temsil edilmektedir. Geç Holosen boyunca, Ortaçağ İklim Anomalisi (G.Ö. 1100-600 yılları) SAG-14 karotundaki eski belirteç kayıtlarında iyi belirlenmiştir. Bu anomali yağışlı iklimden dolayı yüksek deniz yüzey soğumasının varlığına işaret etmektedir. Soğuk Küçük Buz Çağı Dönemi körfezde G.Ö. 670 yılında meydana gelmiştir ve çoğunlukla G.Ö. 150 yılına kadar olan ılıman dönem hariç soğuk ve kurak iklimle ilişkilendirilmektedir. Son dönemdeki deniz yüzey sıcaklığındaki artış yapılan diğer çalışmalarla uyumlu olarak küresel ısınmayı temsil etmektedir.



1. INTRODUCTION

Paleoclimate and paleoceanographic reconstructions have been based on geochemical proxies, because climate changes often cause significant variations in the composition of marine sediments, influenced by terrigenous input, paleocirculation, and depositional redox conditions. In order to unravel the highly diverse and interactive properties recorded in marine sediments, multi-proxy methods have been used for paleoenvironmental studies (e.g. Meyers et al, 1998; Emeis et al, 2000; Casford et al, 2003; Eastwood et al, 2007; Gogou et al, 2007; Kotthoff et al, 2008; Marino et al, 2009; Triantaphyllou et al, 2009a,b; Göktürk et al, 2011; Kouli et al, 2011; Kuzucuoğlu et al, 2011; Martín-Puertas et al, 2011; Nieto-Moreno et al, 2011; Roberts et al, 2012; Triantaphyllou et al, 2014; Rohling et al, 2015; Gogou et al, 2016; Bini et al, 2019).

The Mediterranean region is particularly sensitive to climate change due to its position within the confluence of arid northern African (i.e., subtropically influenced) and temperate and/or humid European (i.e., mid-latitudinal) climates. Paleoclimatic proxies, including stable isotopes, lipid biomarkers, 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; De Santis and Caldara, 2015; Sadori et al, 2016a; Cheddadi and Khater, 2016) and well before (eg. Sadori et al, 2016b). Evidence of abrupt events at the millennial scale during the last glacial-interglacial transition have been previously reported in the westernmost Mediterranean (e.g. Cacho et al, 1999, 2001; Moreno et al, 2002, 2005; Bout-Roumazeilles et al, 2007; Jiménez-Espejo et al, 2007, 2008), revealing that this region is highly sensitive to climate forcing and provides ultra-high-resolution records at both centennial and millennial scales.

The Aegean Sea is in itself particularly sensitive to the effects of climate changes because of the combination of its semi-isolation from the rest of the Mediterranean Sea, its small size, the proximity to the Dardanelles Straits that has linked it to the Black Sea since the early Holocene, and the abundance of local freshwater inputs

(Poulos et al, 1996; Rohling et al, 2002). This heightened sensitivity to climatic variations is especially true for the North Aegean Sea. Thus, the North Aegean is also an important locus of episodic formation of Mediterranean deep waters during winter cooling (Zervakis et al, 2000). 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 North Aegean Sea that affects its circulation and its biological, chemical and depositional processes. Sediment dispersal in the North Aegean Sea during the past 18000 yr has been controlled mainly by fluvial discharge rates, by post-glacial sea-level rise that determined the proximity of depositional basins to river mouths, and by climate-induced changes in marine circulation and productivity (Roussakis et al, 2004; Lykousis et al, 2005).

The NE-SW-oriented Gulf of Saros is a westward-widening and -deepening, triangular marine embayment in the northeastern Aegean Sea, with a water depth of 645 m. The gulf constitutes the eastern extension of the North Aegean Trough (NAT), and is separated from the Marmara Sea by the Thrace Peninsula. The Gulf of Saros 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). A NE-SW-trending dextral strike-slip fault, termed the Ganos Fault, dissects the Gelibolu Peninsula in the north and then enters the Gulf of Saros. The Gulf of Saros has been in the focus of various national and international research groups for tectonic and paleoseismological because of its tectonic setting on the North Anatolian Fault (NAF) and its earthquake risk. Moreover, the Gulf of Saros must have been faced to different paleoceanographic conditions because of its location on a gateway between the Mediterranean and the Black Sea. Although considerable work has been carried out on paleoceanographic aspects of the Aegean Sea (e.g. Gogou et al, 2007; Kotthoff et al, 2008; Triantaphyllou et al, 2009a,b; Geraga et al, 2010; Kouli et al, 2011; Triantaphyllou et al, 2014; Gogou et al, 2016; Kontakiotis et al, 2016), little has been reported from the Gulf of Saros during the time period extending from the post-glacial to the Holocene (e.g., Aksu et al, 1998; Çağatay et al, 1998; Theodore et al, 2008). Nevertheless, the overall lack of agreement about the worldwide distribution, precise timing, amplitude or cause of the past climate fluctuations underlines the need for additional regional records to reconstruct climate change.

1.1 Purpose of Thesis

This thesis was projected to contribute towards the advance of understanding the causes of climate variability and predicting vulnerability to potential climate change in the Gulf of Saros. It also aims to better identify major patterns of climate variability on centennial and longer time-scales, including natural variations and human-induced changes during the late Pleistocene to Holocene. For this purpose, marine survey was established in the Gulf of Saros by Urania cruise in 2011 to collect sediment cores from the different part of the gulf. The multi-proxy approach in this thesis allowed us for the identification and characterization of the main climate oscillations and regional changes during the late Pleistocene to Holocene, to further advance our understanding of paleoceanographic evolution of the Gulf of Saros in response to climate variability in the Aegean Sea.

Beside late Pleistocene to Holocene paleoceanography and paleoclimate of the Gulf of Saros in this thesis, water exchanges between the Marmara and Aegean seas are also aimed to investigate. For these purposes, three marine cores located along an East-West transect from different water depths are examined to make high-resolution paleoclimate and paleohydrologic reconstructions, using sedimentological and geochemical proxies. Multi-proxy analyses such as ITRAX-XRF, Multi-sensor Core Logger (MSCL), Total Organic Carbon, Biomarker analyses and grainsize from those cores allowed to investigate paleoclimate and paleoceanographic history of the gulf.

In summary, the specific aims of this thesis can be divided as followed below;

- I. Reconstructing climate variability during the Late Pleistocene to Holocene in the gulf by using a multi-proxy approach in order to identify and characterize the main climate and oceanographic oscillations.
- II. Unravelling main forcing factors driving climate variability in the gulf during this time interval.
- III. To compile and integrate a geochemical and sedimentological record for the characterization of paleoenvironmental and paleoceanographic responses.

1.2 Literature Review

The previous studies in the Gulf of Saros documented geologic record to explain mainly the basin formation with respect to morpho-tectonic setting maintained during the late Quaternary (Saner, 1985; Çağatay et al, 1998; Tüysüz et al, 1998; Yalırak et

al, 1998; Saatçılar et al, 1999; Kurt et al, 2000; Yaltırak and Alpar, 2002; Ustaömer et al, 2008) although little of them give evidence of sea-level change based on the high resolution seismic data recovered from the gulf. Saner 1985 first investigated the onshore geology of the Gulf of Saros, who subdivided the main sedimentary sequence into three different units, covering the time period from Upper Cretaceous-Lower Eocene. Based on multi-channel seismic reflection data, Saner (1985) also recommended that release faults taking place in the fold flanks enabled synclines to turn into graben when dominating by transtensional forces in the Saros region Miocene onwards.

Geological evolution of the gulf has been extensively studied by Çağatay et al. (1998) using single-channel shallow seismic reflection data and field observations. Their findings indicate that, Riss/Würm interglacial stage has occurred around 200 ka BP, causing exposition of the most of the Aegean deltaic environments. Finally, the Gulf has drowned by the Holocene transgression and have formed the current morphological stage.

On the basis of geological mapping, geomorphology, seismicity and GPS measurements, Tüysüz et al. (1998) revealed paleo- and neo-tectonic evolutions of the Gulf of Saros. In this study, three basins formation were observed around the Gulf of Saros; Trace, Enez and Saros basins corresponding to the Middle Eocene-Pliocene, Middle Miocene-Pliocene and latest Pliocene-Present, respectively.

The relationship between the evolution of the Gulf of Saros and tectonic elements have discussed by Yaltırak et al. (1998) with regard to the high-resolution shallow seismic data and the geological field observations.

The fault character of the North Aegean Sea was studied by Saatçılar et al. (1999) based on seismic reflection data used to investigate the western part of the NAF in the Aegean Sea. The active tectonism and the formation of the Gulf of Saros has been examined by Kurt et al. (2000) on the basis of multi-channel seismic reflection. Based on analysis of the seismic section and also their association with the geological, morphological and earthquake data, two main fault systems are detected in the Gulf of Saros (Kurt et al, 2000).

Yaltırak and Alpar (2002) also investigated kinematics and evolution of the Ganos Fault, northern branch of the NAF, along the Sea of Marmara and the Gulf of Saros.

They claimed that the Ganos Fault branched out from the Thrace-Eskişehir fault system at first and coevally gained dextral structures.

Based on new high-resolution swath bathymetric data and multi-channel seismics, Ustaömer et al. (2008) were studied on structural, mass-wasting and sedimentation processes throughout the dextral shear zone in the Gulf of Saros and the NE Aegean Sea.

In addition to the tectonic studies, content of heavy metals in the surface sediments of the Gulf of Saros has been investigated (Sarı and Çağatay, 2001; Uluturhan, 2010). According to Sarı and Çağatay (2001), the Gulf of Saros is comparatively unpolluted marine environments due to the absence of industry and large settlements around the gulf. The fresh water and sediment provided to the Gulf of Saros through the Meriç River in the northwest and Kavak Creek in the east. However, based on most metal and organic carbon (C_{org}) distribution, the northwestern and eastern shelves of the Gulf of Saros have been observed to be affected by anthropogenic and natural discharge from the Meriç River and the Kavak Creek (Sarı and Çağatay, 2001). Moreover, they found that the deep trough sediments have in stock probably Cu and Pb due to entering the Black Sea water to the gulf.

Besides Sarı and Çağatay (2001), Uluturhan (2010) showed that the sediments in the Gulf of Saros were contaminated by Pb, Cr, Zn, Mn and Ni. The latter study also emphasized that there were sediments not polluted by Hg, Cd, and Cu in all over of the gulf. The findings of Uluturhan (2010) are in agreement with Sarı and Çağatay (2001) about the effect of anthropogenic and natural input to the gulf from the Meriç River and the Kavak Creek.

There are limited previous studies on climatic variability in the Aegean Sea and the Mediterranean Sea covered in previous studies (Gogou et al, 2007; Piva et al, 2008; Triantaphyllou et al, 2009b; Roberts et al, 2012; Triantaphyllou et al, 2014; Gogou et al, 2016; Kontakiotis, 2016; Jalali et al, 2018; Cascella et al, 2019).

Gogou et al. (2007) investigated climate changes of the North Aegean Sea during Late Glacial-Holocene by organic geochemical proxies. Based on finding of Gogou et al. (2007), The sea surface temperature (SST) derived from $U^{K'}_{37}$. They suggested that rapid changes in the Eastern Mediterranean thermohaline circulation concur with sea SST fluctuations. Furthermore, cold intervals (e.g. the Late Last Glacial, the Younger

Dryas and interruption of deposition of the S1 Sapropel) have experienced enhanced deep-water ventilation (Gogou et al, 2007). Besides, they emphasized that a small variability of $\delta^{15}\text{N}$ values and lack of isorenieratene derivatives recommend that during the deposition of the S1 sapropel, the water column have not experienced precisely anoxic condition in the North Aegean Sea.

During the last 6000 years, climate variability in the Adriatic Sea, central Mediterranean was investigated by Piva et al. (2008). This study was performed based on planktic and benthic foraminifera assemblages collected from sediment cores recovered from the Adriatic shallow shelf and deep basin. They suggested that recurrent peaks of *Globigerinoides sacculifer* show warm-dry intervals: the 'Mediaeval Warm Period', the 'Roman Age', the late 'Bronze Age' and the 'Copper Age'. The Last Occurrence of *G. sacculifer* is about 550 yr BP coinciding with the onset of the 'Little Ice Age' leading to increase the benthic species *Valvulineria complanata*.

Triantaphyllou et al. (2009b) were studied climate variability in the south-eastern Aegean Sea using sediment core (NS-14). They documented valuable information about primary production and organic matter preservation during S1 sapropel deposition. According to Triantaphyllou et al. (2009b), the formation of S1 sapropel occurred between 10600 and 6400 yr BP in the eastern Mediterranean Sea accompanied by an interruption between 7900-7300 yr BP. Between ~10600-10000 yr BP, the fresh water input has triggered the deposition of S1 at the margin of south eastern Aegean Sea (Triantaphyllou et al, 2009b). They also documented evidence of an individual mid Holocene warm (up to 25°C) and wet period linked to the deposition of the sapropel-like layer Sapropel Mid Holocene (SMH), covering time interval between 5400 and 4300 yr BP.

Roberts et al. (2012) studied how changes climate at the east and west sub-basins of the Mediterranean Sea since AD 900 on the basis of multiple proxies derived from investigations of geochemical, sedimentological, isotopic and paleoecological.

Triantaphyllou et al. (2014) show the existence of a warm and humid Mid-Holocene period appearing in the Aegean Sea and northern Levantine Sea. Based on marine and terrestrial biological and biogeochemical indicators, three sediment cores from north and southeastern Aegean Sea and northern Levantine Sea display constant record of

warm and humid conditions between 5500 and 4000 yr BP (Triantaphyllou et al, 2014). In the shallow sites of the south eastern Aegean, the preservation of productivity is provided by swift transport and burial of organic matter as well as upper water column stratification and DCM (Triantaphyllou et al, 2014). Mid-Holocene warm and humid episode is terminated 4200 yr BP synchronous Northern Hemisphere rapid climate cooling ('4.2 ka' event) by means of evidence of Triantaphyllou et al. (2014).





2. STUDY AREA

2.1 Present Oceanography and Climate

The precipitation regime in the Mediterranean is controlled by the North Atlantic Oscillation (NAO), which is one of the major patterns of atmospheric circulation variability in the Northern Hemisphere with centers of action in the Icelandic low and the Azores high, and responsible for most of the climatic variability in the North Atlantic (Hurrell, 1995; Trigo et al, 2002). It is a transitional zone climatically influenced both by the mid-latitude westerlies and the Subtropical High pressure (anticyclone) belt, with the NAO modulating winter precipitation and the migration of the Intertropical Convergence Zone (ITCZ) affecting summer drought (Lionello et al., 2006). It stretches longitudinally from the North Atlantic Ocean to continental Eurasia.

The Aegean Sea represents high latitude variability (Rohling et al, 2002b). The Aegean Sea is in the northern sector of the eastern Mediterranean, between the Turkish coastline to the east, the Greek mainland to the north and west, and bounded on the south by the island of Crete (Figure 2.1). It is separated into two main sub basins, the north and the south Aegean, with significantly different hydrographic characteristics (Lykousis et al, 2002), which are controlled by the exchange of water masses with the Levantine and Black Seas and by the climate contrasts between more humid conditions in the north and semi-arid conditions in the south. The south Aegean is one of the most oligotrophic areas in the Mediterranean Sea (Lykousis et al, 2002), with its surface water circulation mostly affected by arid climatic conditions, while it is also modulated by the effect of the Cretan gyre (Lykousis, 2001). In the NE Mediterranean, the Aegean sub-basin has a crucial role in the Mediterranean thermohaline circulation (e.g. Theocharis et al, 1999).

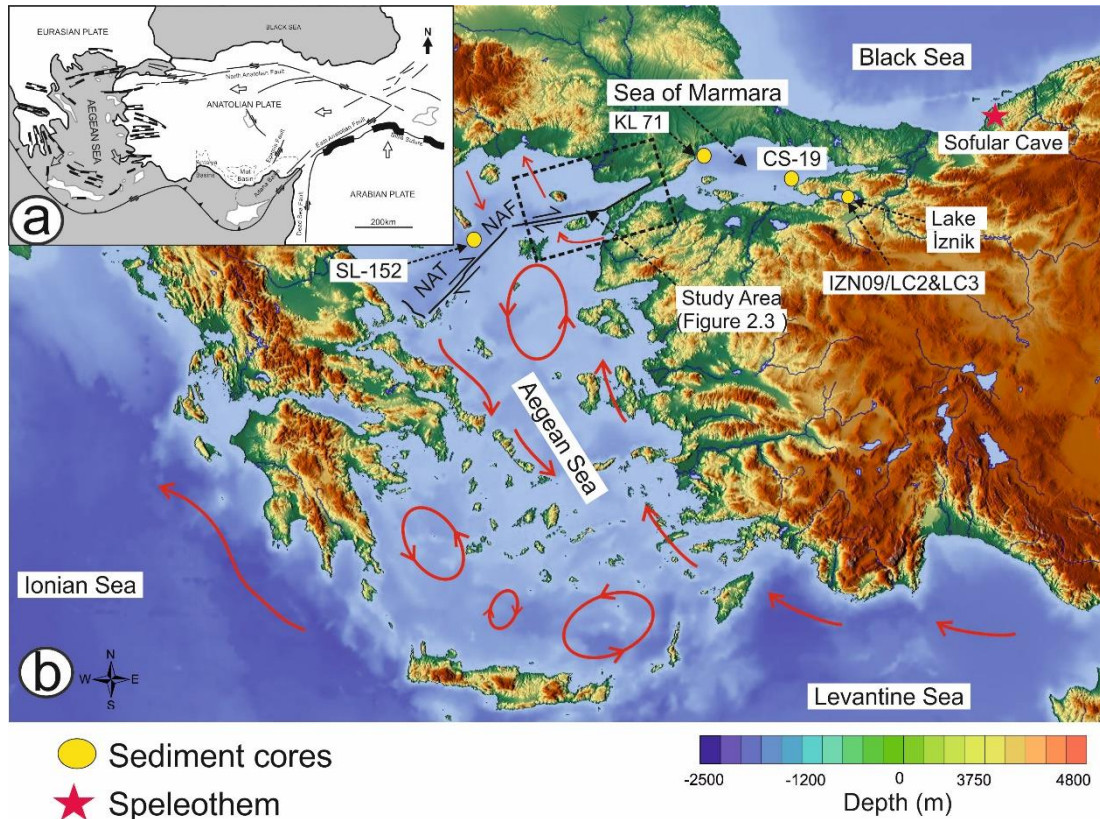


Figure 2.1 : The map of Turkey including active fault systems. b) Map of the Gulf of Saros and surroundings. Locations of cores and speleothem included in this study are marked by yellow circle and pink star respectively. The water circulation of the Aegean Sea are represented by red circles and arrows. The North Anatolian Fault is indicated with black lines. NAT: the North Aegean Trough; NAF: the North Anatolian Fault.

The Aegean Sea is characterized, in general, by a cyclonic water circulation (Lacombe and Tchernia, 1972), although the most active dynamic features are the mesoscale cyclonic and anticyclonic eddies, either permanent and/or recurrent (Lykousis et al, 2002). The circulation is affected by the Black Sea waters entering from the Çanakkale Strait as the surface flow. According to satellite observations, the Black Sea waters enter the southern part of the Gulf of Saros during the summer. The circulation in the gulf itself consists of longshore currents in the north and anticyclonic eddies (Figure 2.2). Additionally, on a seasonal time-scale, there is a major change in the Aegean Sea circulation pattern, which may be playing a significant role, not only in influencing its longer-term hydrographic properties, but also in affecting its ecosystem (Zervakis et al, 2005). The present-day Aegean Sea (Figure 2.1) is an important source of deep water for the eastern Mediterranean (Lacombe et al, 1958; Miller, 1963; Roether et al, 1996; Lascaratos et al, 1999). In the northern Aegean, influences of freshwater influx from the Black Sea (Zervakis et al, 2000) and rivers and together with winter cooling

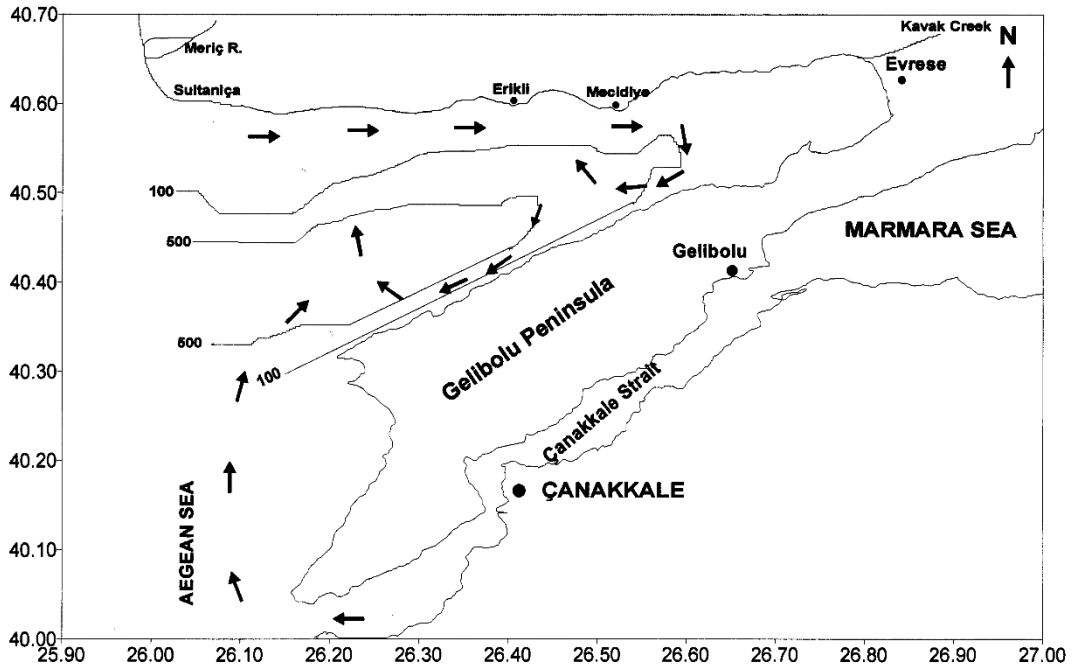


Figure 2.2 : Map showing the circulation in the Gulf of Saros including longshore current and anticyclonic eddies (adapted from Sarı and Çağatay, 2001).

determine the extent to which this basin supplies dense deep water and oxygen to the whole Mediterranean. Tokat and Sayın (2007) studied the water properties of the Gulf of Saros, considering the influences of several water masses: the warm and highly saline Levantine waters (Levantine Surface Water (LSW) and Levantine Intermediate Water (LIW), and the cold and fresh Black Sea Water (BSW). Aegean Intermediate Water (AEIW) is derived from Levantine Intermediate Water (LIW), with its source in the Rhodes Gyre. As this travels north along the Turkish Coast, prevailing offshore winds allow upwelling of the intermediate water to the surface (Lascaratos, 1989; Yüce, 1995). In these shallow eastern shelf areas, the AEIW consequently forms a single uniform water mass from the surface to the seafloor. Today, AEDW settles in the deeper parts of the Aegean Basin, below 300 m.

The North Aegean communicates with the Marmara Sea under 20 m from the surface due to the density difference. The inflow from Marmara Sea takes place in the opposite direction to the current below due to the sea level difference. The Gulf of Saros has a very distinguish water mass that is colder and denser than its environment. The reason for such cold water is the blowing wind first from NNE and then from SSW direction. Therefore, upwelling water covers the whole gulf. The intermittently formed cold and

dense upwelling water off the northern coast of Gelibolu Peninsula also has an impact on the upper water column of the Gulf of Saros. According to Pazi (2008), the amount and physicochemical characteristics of the surface waters originating from the Black Sea show great seasonal variations; the extent, distributional pattern, and depth of penetration are quite variable.

A branch of the westward-flowing Asia Minor Current deviates toward the north, out of the eastern Mediterranean basin and into the Aegean Sea, carrying the warm (16–25 °C) and saline (39.2–39.5 psu) Levantine Surface Water and Levantine Intermediate Water along the western coast of Turkey. The Asia Minor Current reaches the northern Aegean Sea, where it encounters the relatively cool (9–22 °C) and less saline (22–23 psu) Black Sea water and forms a strong thermohaline front. As a result, the water column structure in the northern and central Aegean Sea comprises a surface veneer 20–70 m thick consisting of modified Black Sea water overlying a Levantine intermediate water mass of higher salinity that extends down to 400 m. The water column below 400 m is occupied by the locally formed North Aegean Deep Water with uniform temperature (13–14 °C) and salinity (39.1–39.2 psu; Zervakis et al., 2000, 2004; Velaoras and Lascaratos, 2005). The surface and intermediate waters follow the general counter-clockwise circulation of the Aegean Sea and progressively mix as they flow southwards along the eastern coast of mainland Greece.

2.2 Morphology and Bathymetry

The Aegean Sea is divided into three physiographic regions: the northern Aegean Sea, including the North Aegean Trough; the central Aegean islands, shoals, and basins; and the southern Aegean Sea, including the Cretan Trough (Figure 2.1). The dominant bathymetric feature in the northern portion of the Aegean Sea is the North Aegean Trough. It forms a 800–1200-m-deep narrow and arcuate bathymetric depression extending from the Gulf of Saros with a WSW trend, swinging to a southwesterly trend and widening toward the west. The central Aegean Sea is characterized by a series of shallower (600–1100 m), generally NE-trending depressions, including the North Skiros, Euboea, Mikonos, and the North and South Ikaria basins, and their intervening 100–300-m-deep shoals and associated islands (Figure 2.3). The gulf is the easternmost part of the North Aegean Trough (NAT) (Figure 2.1). The Gulf of Saros is located in the Northeastern Aegean Sea and has an asymmetric bathymetry with a

10-km wide shelf to the north. The wedge-shaped gulf extends parallel to the coasts of the Thrace Shelf to the north and the Gelibolu Peninsula to the south (Figure 2.1, Figure 2.3). It widens and deepens toward WSW, where it becomes the easternmost part of the North Aegean Trough. The shelf extends at a water depth of 90–120 m. The length of the gulf is about 60 km and the width at the opening to the Aegean Sea is about 36 km. According to the present bathymetry, the maximum depth is up to about 700 m. The deep trough starts to the southeast of Mecidiye as a wedge-shaped depression, deepening and widening toward the west. The gulf is bounded from the south by the steeply faulted (the Ganos Fault) margin of the Gallipoli Peninsula (Figure 2.1, Figure 2.3). Steeply dipping sea floor along the slopes of Gelibolu Peninsula is observed in the bathymetry. The slope leading to the deep trough has a mean gradient of 8.5° and displays an irregular morphology caused by active faultings and sediment slumpings. Moreover, the Gelibolu Peninsula shows an asymmetric morphology having a watershed located close to the northern shores and extending in NE–SW.

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 (Figure 2.1, Figure 2.3). 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 et al, 2019), and the shelf and the uppermost slopes in the gulf were exposed as subaerial.

2.3 Geology

2.3.1 Stratigraphy

The Gulf of Saros was formed over the heterogeneous Eocene to Oligocene rocks with an unconformity of the fore-arc Thrace basin (Turgut et al, 1991; Ternek, 1949; Saltık, 1974; Önal, 1984; Sümengen et al, 1987; Siyako et al, 1989; Yaltırak, 1996; Görür and Okay 1997; Çağatay et al, 1998; Tüysüz et al, 1998; Yaltırak et al, 1998). A significant change in the tectonic style of the Gulf of Saros took place about 0.2 Ma ago, permitting sedimentation to resume on the shelf areas after a long hiatus. The recent sedimentation started with a transgression during the Riss-Würm interglacial stage (130—25 ka BP). Between the Würm glacial stage and the following early phase of

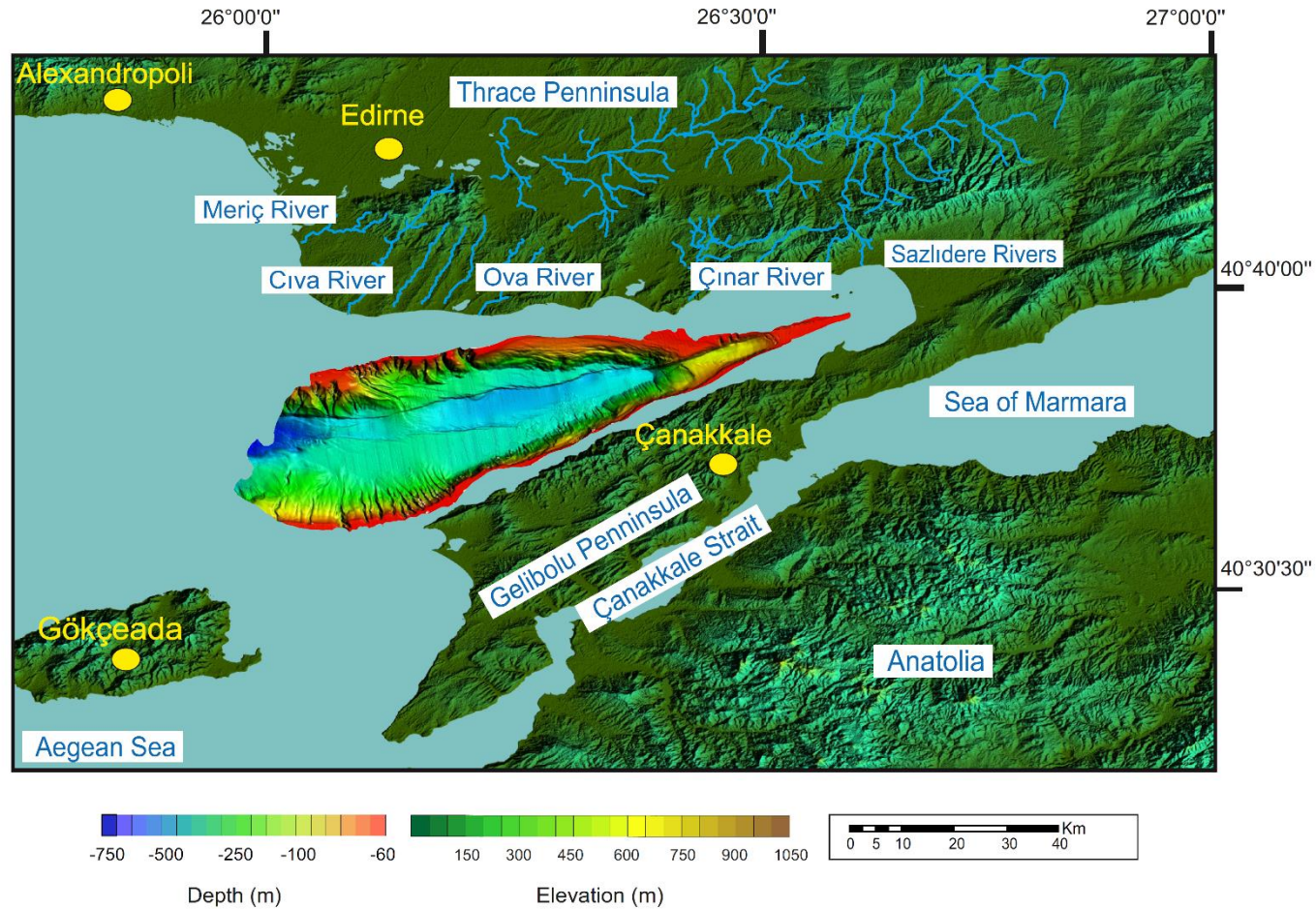


Figure 2.3 : Map showing the bathymetry and morphology of the Aegean Sea and the Gulf of Saros with the drainage system. The settlement around the gulf are indicated by yellow circles. The drainage system is displayed by blue lines.

deglaciation (25—13 ka BP), the sea level dropped as much as 130 m below the present sea level (Aksu et al., 1987), thus, caused the exposure of the shelf areas. With the beginning of the Holocene, these areas were inundated for the last time. Until the late Miocene when the westward escape tectonics of Anatolia affected the Marmara region (Dewey and Şengör 1979; Şengör et al, 1985; Dewey et al,1986), both shoulders of the gulf were uplifted and emerged and induced an erosional area, whereas the present trough was deepened along the active faults. Deepening of the basin continued due to the increased tectonic activity of the North Anatolian Fault during Plio-Quaternary when the present configuration of the basin evolved. Soon after, a widespread transgression was taking place throughout the Mediterranean and the Aegean Sea (Hsü and Bernoulli, 1978; Steininger and Rogl, 1984).

According to onshore geology and together with the seismic data, the stratigraphic sequences of both the northern and the southern margin of Gulf of Saros are formed by Neogene to Quaternary rocks separated by angular conformity (Çağatay et al, 1998; Figure 2.3). Pliocene rocks are almost absent on the northern shelf. In the Gallipoli Peninsula, these sediments with a 350 m thick consist mainly of brownish red and coarsening-upward clastic rocks, comprising locally cross-bedded and channeled conglomerate, sandstone, and shale in part with coal seams (Conkbayırı formation). The Quaternary sequence mainly outcrops on the northwestern shelf and the eastern gulf areas, as well as in the gulf as three seismostratigraphic units that are separated from one another by a disconformity characterized by a strong reflector (Çağatay et al, 1998).

There are four major unconformities in the Tertiary-Quaternary sequences, representing tectonic events, erosions and sedimentation periods (Saner, 1985; Sümengen et al,1987; Yaltrak, 1996). These unconformities are defined at the bases of the Pre-Miocene, Miocene, Pliocene and Quaternary sequences (Figure 2.4). The Gazahandere, Kirazlı, Alçitepe (Miocene units) formations that are mainly overlain uncomformably by younger units, outcrop along the Çanakkale Strait. The Miocene sedimentary sequences show some facies differences in the Thrace and Gelibolu Peninsulas (Saner, 1985; Yaltrak, 1996, Sakıncı et al, 1999). The Pliocene units (Conkbayırı, Özbek and Marmara formations) are observed at the southern part of the Gelibolu Peninsula (Figure 2.4). The alluvium formations form the current geology of

the marine and river basins and the alluvial reservoir work area of the modern river. Formations constituted by Neogene to Quaternary sediments are summarized below:

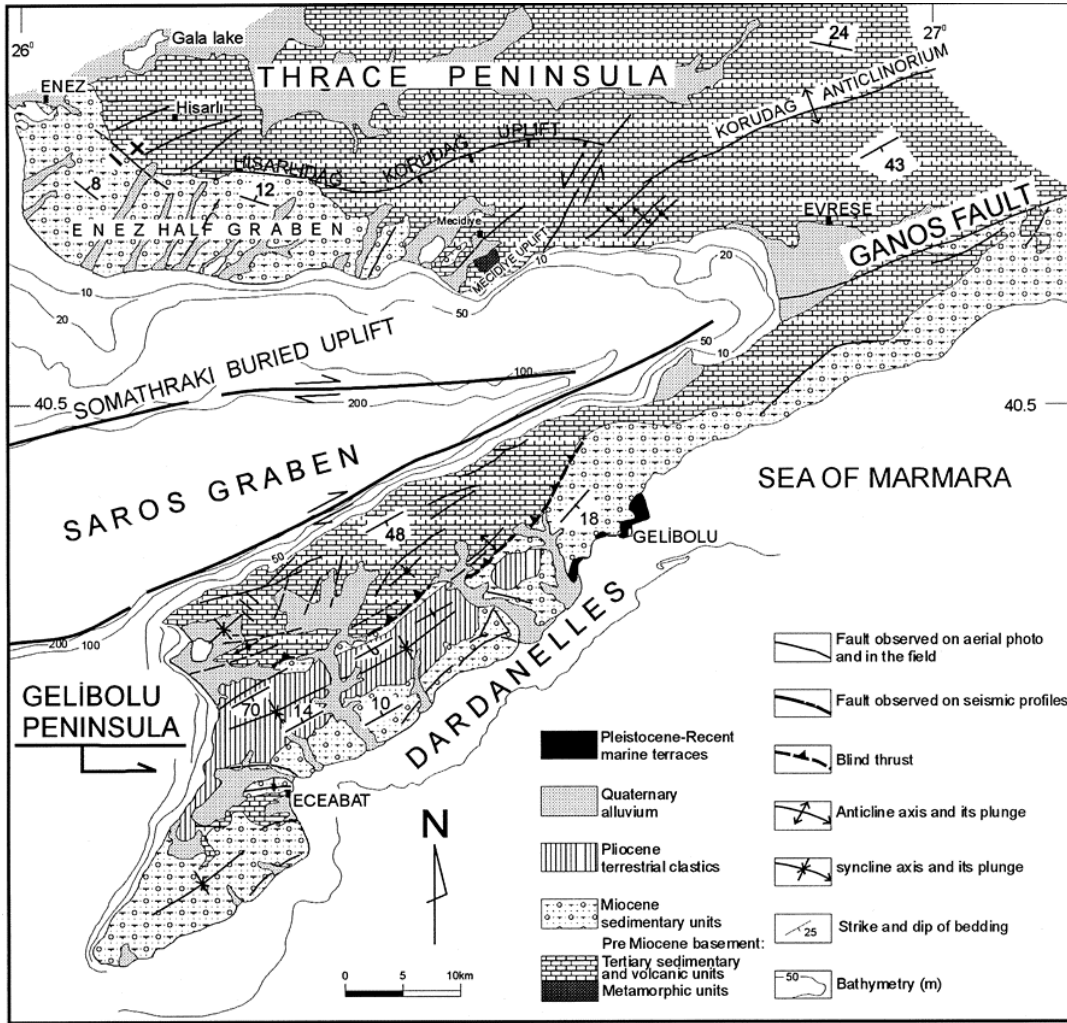


Figure 2.4 : The geological map showing the onshore geology around the Gulf of Saros together with the evolution of the NAF (adapted from Tüysüz et al, 1998).

2.3.2 Tectonic

The North Anatolian Fault splits into several NE—SW-trending strands across the Marmara Sea (Figure 2.1). One of them is the Ganos Fault, which is still active and forms the southern margin of the Gulf of Saros. The formation of the gulf has been intensively studied, and different mechanisms have been proposed for the development of the gulf, ranging from pure extension (Pfannenstiel, 1944; Saner, 1985) to strike-slip (Barka and Kadinsky-Cade, 1988; Tüysüz et al, 1998), transtensional (Görür et al, 1997; Çağatay et al, 1998; Saatçılar et al, 1999; Kurt et al, 2000; McNeill et al, 2004), or escape-tectonic processes (Yaltrak and Alpar, 2002). Çağatay et al. (1998) claimed that the Gulf of Saros was formed as a result of interactions between the NAF zone

shear activity and the Aegean extensional regime. They proposed that the southward bending of the NAF might have been increased over time as a consequence of extensional regime and resulted in development of new strands of the NAF towards south (Sengör et al, 1985). Therefore, the Saros Graben was formed between these strands (Çağatay et al, 1998).

On the basis of onshore and offshore geology, Tüysüz et al. (1998) suggested that the Gulf of Saros was mainly formed by the activation of the NAF in northwestern Turkey. A transpressional regime induced during Pliocene, resulted in the uplift of the Gelibolu Peninsula, and such a transtensional regime through the NAF resulted in opening of the Gulf of Saros as a pull-apart basin during the late Pliocene–Quaternary (Okay et al, 1999). In contrast, Yaltrak et al. (1998) claimed that the Saros graben was created as a consequence of the westerly escape of a middle block between two strike-slip faults. Saatçılar et al. (1999) mapped active submarine faults in the Gulf of Saros, who proposed a transtensional basin model. However, Kurt et al. (2000) proposed a typical negative flower structure for the Saros depression. However, they also claimed that the fault line that limits the depression to the south, marking the boundary of the Gelibolu shelf, is the main fault line and constitutes the western continuation of the Ganos fault. Based on multibeam data and seismic reflection profiles, detailed neo-tectonic reconstruction of the Gulf of Saros has been recently proposed by Ustaömer et al. (2008). Accordingly, the western extent of the NAF zone (the Ganos Fault) cuts the eastern shelf and terminates sharply at the toe of the slope with two NE-SW-oriented fault zones. The Eocene to Oligocene units on the Ganos Mountains to the north of this fault are sharply separated from Miocene and younger sediments located in the south. The Ganos Mountains are considered to have uplifted as a restraining ridge formed due to the bend along this fault (Okay et al. 2004). The Gulf of Saros is located in a complex tectonic setting where the Miocene to Recent Aegean extensional province interacts with the western extension of the Quaternary North Anatolian Fault Zone. The age and the kinematics of the opening of the Saros Basin are still being hotly debated, suggested ages ranging from Oligocene (Saner, 1985; Coşkun, 2000) to Pliocene–Quaternary (Çağatay et al, 1998; Tüysüz et al, 1998; Yaltrak et al, 1998; Yaltrak and Alpar, 2002).

The Ganos fault generated the 9 August 1912 Mürefte (Ganos) earthquake in western Turkey ($M_w = 7.4$). After the destructive $M_w=7.4$ earthquake triggered in 1912, the

Ganos fault and other secondary faults have been studied and mapped by numerous researchers (Gutzwiller, 1923; Ambraseys and Finkel, 1987; Barka and Kadinsky-Cade, 1988; Tüysüz et al, 1998; Yaltrak et al, 1998, 2000; Armijo et al, 1999, 2002, 2005; Okay et al, 1999, 2004; Kurt et al, 2000, Yaltrak and Alpar, 2002; Altınok et al, 2003; Altunel et al, 2004; Seeber et al, 2004; McNeil et al, 2004; Ustaömer et al, 2008). A seismological study for 2003 earthquakes in the Gulf of Saros (Karabulut et al, 2006) indicates that the principal deformation zone consists of a major strike-slip fault, which lies close to the northern margin of the Saros depression.



3. METHODS

In this thesis, sedimentological and geochemical analyses which were performed in İstanbul Technical University-Eastern Mediterranean Center of Oceanography and Limnology (EMCOL) Applied Research Center and Sorbonne University-Laboratoire d'Océanographie et du Climat- LOCEAN explained below in detail.

3.1 Sediment Cores

SAG-08, SAG-14 and SAG-22 were recovered from the Gulf of Saros during MARM11 Cruise by R/V Urania in 2011. The cores studied in this thesis were recovered by using gravity core method. SAG-08, SAG-14 and SAG-22 were retrieved from depth -307 m, -592 m and -100 m, in respectively (Table 3.1, Figure 3.1).

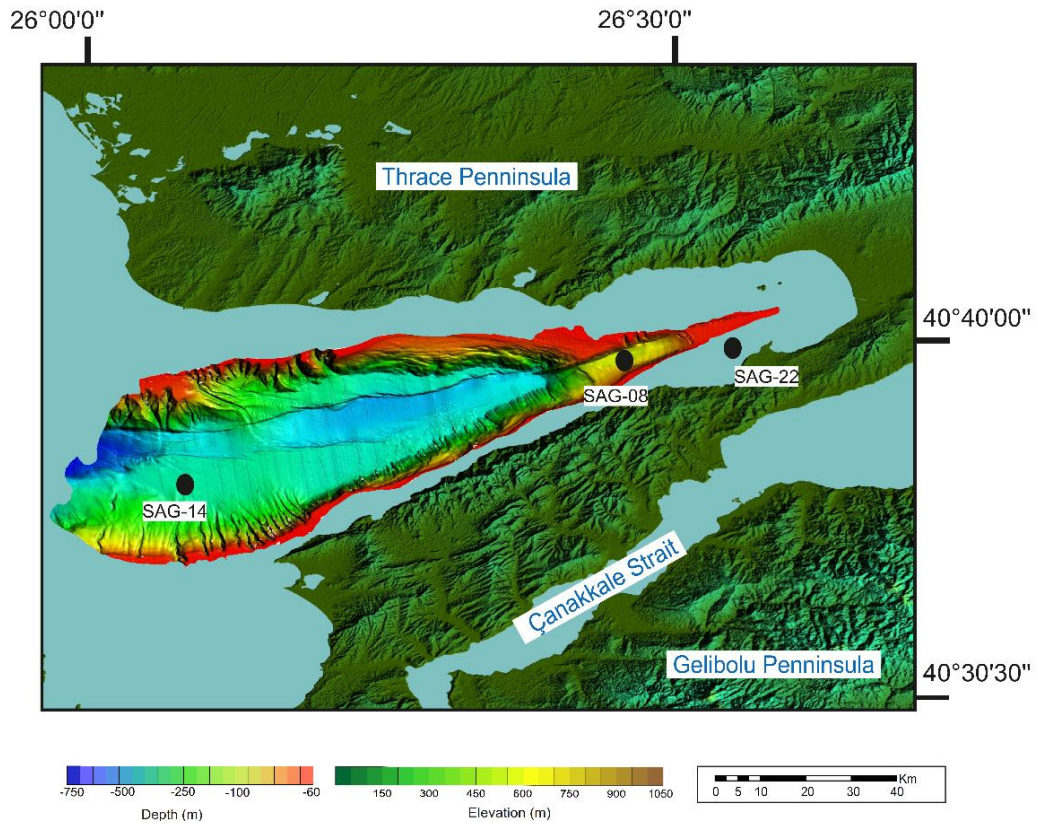


Figure 3.1 : Map showing location of cores recovered from the Gulf of Saros.

Table 3.1 : Information about the gravity cores where recovered from the Gulf of Saros, Aegean Sea (Turkey) during Urania cruise.

Core ID	Latitude	Longitude	Depth (m)	Length (cm)
SAG-08	40.503367	26.538433	-307	179
SAG-14	40.361700	26.05850	-592	326.5
SAG-22	40.55692	26.713633	-100	232.8

3.2 Sedimentologic Analysis

3.2.1 Lithostratigraphic Study

The cores were splitted into two halves into 1-meter pieces. After splitted core surfaces, sedimentological analysis was performed in order to define and describe main lithologic properties. The cores were measured in length, photographed, and the lithological properties of the cores were recorded by the logging (Figure 3.2). Purpose of these studies that determine vertical stratigraphy, lithological features based on macro observations of sediments and possible sedimentary structures. Moreover, it was aimed to detect the main chronostratigraphic sequence boundaries and to reveal characteristics of facies that were allocated by their boundaries with these studies. The sediment cores were sampled at certain intervals and specific levels for AMS ^{14}C radiocarbon analysis and total organic carbon (TOC) and total inorganic carbon (TIC) analysis.

3.2.2 Multi Sensor Core Logger (MSCL) Analysis

Physical properties of the cores, magnetic susceptibility (M.S.), gamma density, porosity, electrical resistance, temperature and p-wave velocity were measured at 1 cm resolution using Geotek Multi-Sensor Core Logger Analyzer. MSCL consist of carrier system allowing the core to pass through the sensor by taking forward on the rail, host system where sensors are mounted, microprocessor and computer (Figure 3.3). The quality of the data obtained is associated with core and ambiance temperature, the saturation of the core to water, presence of gap in the wall of the core and the sensitivity of the sensors. Before measuring, it requires to calibrate each sensor according to the characteristics of the core which will be measured.

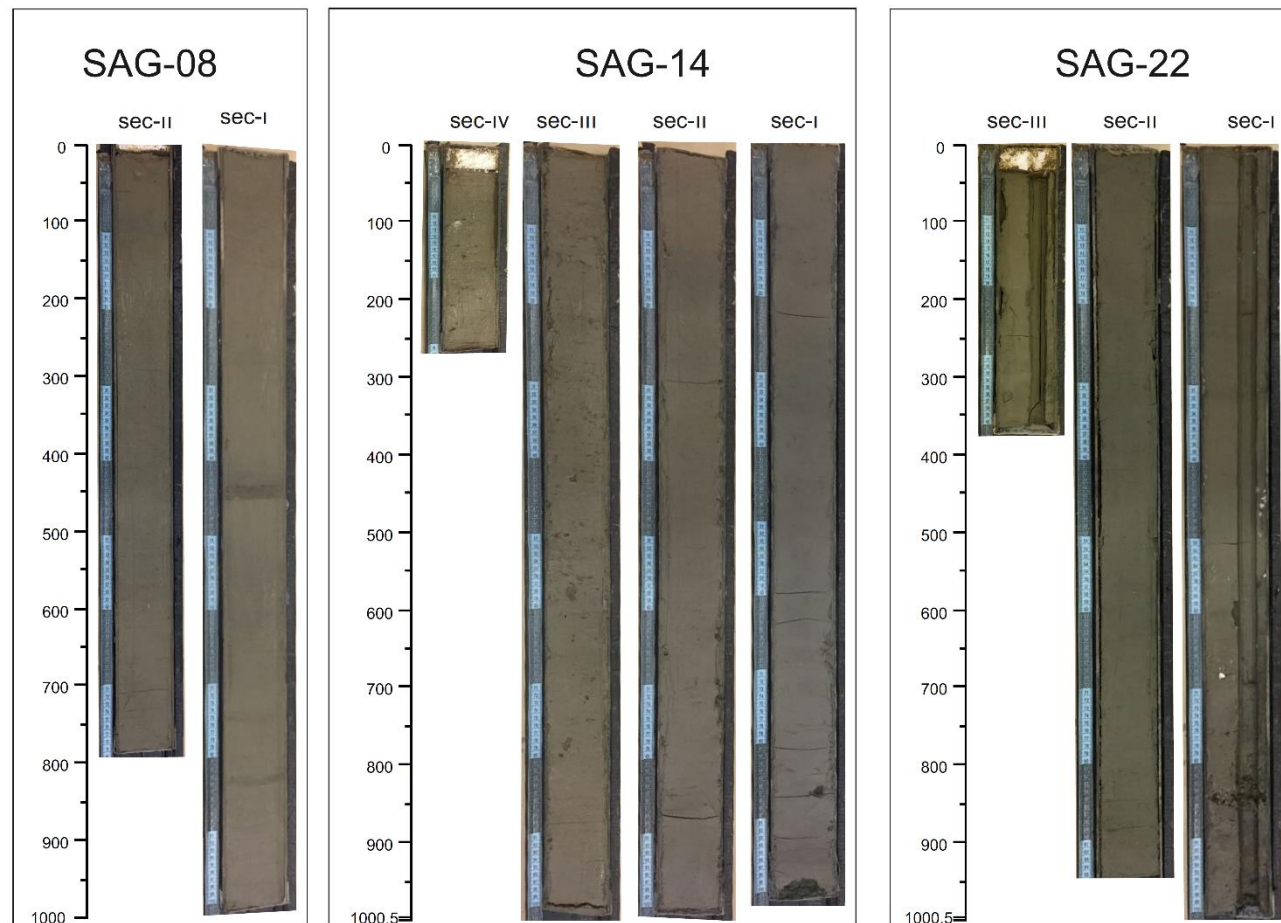


Figure 3.2 : Photographs showing the general view of the cores.

The core sections placed on the rail and carrier system on the device pass through the sensors at specified sampling interval; thus, data is collected sequentially from the sections of the same core. Measurement components of MSCL used in thesis are as follows:

Gamma density: Density is measured by absorbing of gamma rays which pass through the core based on the principle of Compton scattering. Gamma rays reach to detector where is in opposite direction by going through core. This detector quantifies the beam intensity reaching the sensor based on the gamma density properties of core thereby obtains density value of sediment. Density values are measured with an error of 1% associated with calculation time and condition of the core. Obtained density values are indicative of lithology and porosity.

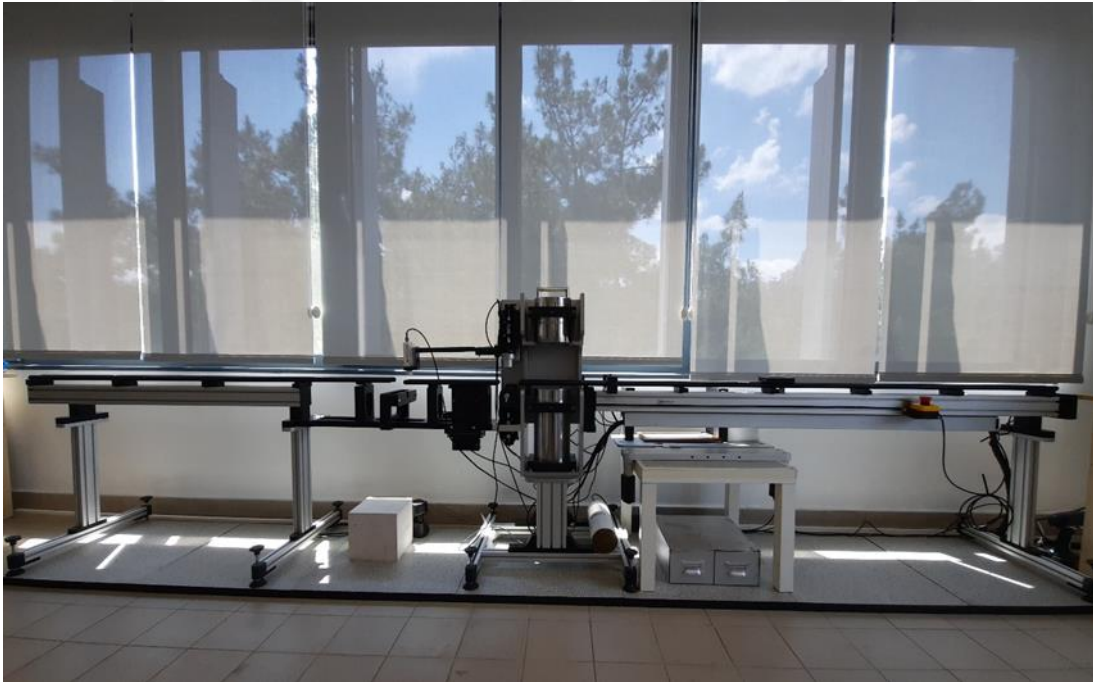


Figure 3.3 : GEOTEK Multi sensor core logger (MSCL) provides measurements of physical properties of the sediment cores. Magnetic susceptibility and gamma density are used for this study.

3.2.3 Grain Size Analysis

In this thesis, grain size analysis was only performed on core SAG-22 core by using Malvern Mastersizer 3000 Laser Granulometer Analyzer where is at ITU-EMCOL Sedimentology Laboratory (Figure 3.4) since it is located in the shallower depth, comprising a well transgressive facies from bottom to top. For the measurement, wet

sediment samples were collected with 5 cm interval. The analyzer is measured grains range between 0,1-2000 µm. It is composed of a lens and a two-way laser beam source.



Figure 3.4 : MALVERN Mastersizer Laser Particle Size Analyzer provides particle size measurements.

The grain-size fractions (sand, silt and clay) for sediment in the core were calculated according to Wentworth scale (Wentworth, 1992). According to the results of the grain size analysis, mean and sorting (Folk, 1980) were calculated by using equations displayed below:

$$M = \frac{Dx16+Dx50+Dx84}{3} \quad (4.1)$$

$$\sigma = \frac{Dx84-Dx16}{4} + \frac{Dx95-Dx5}{6,6} \quad (4.2)$$

The symbol “M” in equation 4.1 is used for determining overall size mean while the symbol “σ “ in equation 4.2 is represented by the roundness standart deviation. The symbol “Dx” in both equations 4.1 and 4.2 is associated with grain size distriburtion.

3.3 Geochemical Properties

3.3.1 Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC) Analysis

The total organic carbon (TOC) content in freeze-dried samples of the cores was analyzed by using Shimadzu TOC/TIC Analyzer at ITU-EMCOL Geochemistry

Laboratory (Figure 3.5). For TOC/TIC analysis, SAG-14 was sampled at 5 cm intervals whereas the sampling interval is determined as 10 cm for the SAG-08. Initially, total carbon (TC) analysis is based on measuring the amount of CO₂ generated by burning samples at 900°C with the detector of the analyzer in the presence of purged oxygen and platinum catalyst. The total inorganic carbon (TIC) contents of the samples were indicated by treating the samples with % 85 phosphoric acid, heating the sample to 200°C and quantifying the produced CO₂. The TOC is calculated by subtracting TIC from TC contents. The precision of the TOC analysis is better than 2% at a 95% confidence level. TOC is used to reveal organic matter production and preservation.



Figure 3.5 : Shimadzu TOC/TIC analyzer provides the information about the TOC content of sediments.

3.3.2 μ -XRF Core Analysis

Major and trace element analysis of the two gravity cores were carried out by Itrax μ -XRF Core Scanner (with Mo X-ray tube, at 30 kV, 50 mA; 1 mm resolution, 10 s for each measurement time) at ITU- EMCOL Core Analysis Laboratory (Figure 3.6). Itrax Core Scanner is a widely used to identify geochemical characteristics of different layers across the core (Rothwell and Rack, 2006). Element concentrations in the sediment are revealed with this method without damaging the core sample (Röhl and Abrams, 2000). Besides, radiography data of core is obtained from Itrax XRF Core Scanner. The elementary results are partially quantitative and expressed in units counts per second (cps; Jahn et al, 2003).



Figure 3.6 : ITRAX XRF Core Scanner provides elemental analyses on sediments core with high resolution. Instrument also provides optical and radiographic images. Study contains elemental distributions, which is provided in 1 mm measurement interval.

The elements measured by Itrax μ -XRF Core Scanner were used for paleoenvironmental reconstructions in this thesis. For instance, Ca was used for determination of endogenic carbonate production. It has been used in many studies conducted in marine and lacustrine environments (e.g. Cohen, 2003; Çağatay et al, 2014, 2015, 2019). Sr was a proxy used to detect shells of aragonite basis. The ratio of Ca to Sr gave information about salinity and temperature in marine carbonates (Russell et al, 2004; Rosenthal et al, 2006; Schöne et al, 2011). Moreover, the enrichment of Sr relative to Ca indicates that the composition of marine sediments is dominated by aragonite, rather than calcite. Due to the high concentration of Sr in sea water, marine carbonates have comparatively more Sr than the terrestrial carbonate origin (Angino et al., 1996; Palmer and Edmond, 1992). As Ti inheres in heavy minerals, it was used as a marker showing coarse silt to fine sand size detrital supply in marine and lake sediments (Piper and Calvert, 2011). Ti-normalization is commonly used to envisage

fluctuations in detrital aluminosilicate source material (e.g., Eriş et al, 2018). Thus, the Ca/Ti ratio served through the studied cores for the purpose of normalization with respect to carbonate or siliciclastic sedimentation. Ca-Ti ratio indicates whether Ca originates from marine or terrestrial input.

Mn^{2+} and Fe^{2+} are oxidized to insoluble Mn^{4+} and Fe^{3+} (Fe and Mn oxy-hydroxides) from the water column under oxic conditions, being accumulated as ferric and manganese oxides on the sediment surface. As additional sediment accumulates, thus under sub-oxic conditions, iron and manganese are reduced to soluble Fe^{2+} and Mn^{2+} and diffuses upwards. This remobilization can lead to oxidation and precipitation of Fe and Mn oxyhydroxides at the redoxcline where a post-depositional oxidation front is encountered when bottom waters are reventilated and penetrates downwards into the sediments while organic matter burns down and the redoxcline further deepens (e.g., Mangini et al, 2001). Manganese is a sensitive indicator of redox conditions; it readily precipitates as Mn-oxides in sediments deposited under oxic conditions, but remains in solution and becomes depleted in sediments of anoxic environments (e.g. Calvert and Pedersen, 1993; Thomson et al, 1995). Iron is another redox-sensitive element, which together with sulphur, 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 hence, it is considered as a detrital mineral proxy, often showing a good correlation with Ti. Several redox-sensitive trace elements such as Mn and Fe have provided information about changes in bottom water oxygenation conditions in the Gulf of Saros, being useful as paleoredox proxies because its valence can change depending on the prevailing redox conditions (e.g., Moreno et al, 2004; Rogerson et al, 2008). Besides, Mn is used for indicator of terrestrial material while Fe is proxy to reveal both terrestrial input and diagenetic process. The normalization of these two elements is used to decipher what diagenetic process is. K is another proxy to use for detrital input, especially illite-mica type of clay during the soil formation.

Organic matter is detected by using Br and the ratio Br to TOC express marine/terrestrial organic matter (Mayer et al., 1981, 2007; Ziegler et al., 2008, Çağatay et al, 2019). Furthermore, in comparison high TOC values, low Br-TOC results designate fresh pore-water and high terrestrial organic matter (Çağatay et al,

2019). Br/Ti ratio may also show a good correlation and is linked to organic matter due to bromine uptake from seawater by phytoplankton (e.g., Ziegler et al, 2008). This provides a semi quantitative estimation of sedimentary organic matter.

3.3.3 Biomarker Analysis

Biomarker analysis was carried out at Sorbonne University-LOCEAN by using a Thermo Fisher Trace Ultra Gas Chromatograph (GC) Analyzer (Figure 3.7). The sediment core was sampled at 1 cm intervals for alkenone analysis. Water was removed from the wet samples by vacuum at -60°C in freeze-dryer. The dried samples were pretreated by using an agate mortar and weighed in average 1.5 g.



Figure 3.7 : Thermo Fisher Trace Ultra Gas Chromatograph (GC) analyzer provides the C37 unsaturation index ($UK'37 = C37:2 / (C37:2 + C37:3)$), leading to sea surface temperature (SST) record.

The samples were added into a mixture of dichloromethane/ methanol (2:1 v/v) to extract lipid biomarkers. Lipid extraction were done by removing from solid phase using ultrasonic bath and centrifuge. The total lipid extracts divided into sub-fractions by silica gel chromatography using solvent mixture with increasing polarity. As an external standard, 5 α cholestane was added prior GC injection to calculate concentrations. Helium was utilized as the carrier gas. Comprehensive explanations on how to perform the analyses can be found in Ternois et al. (1996, 2000).

Di- and tri- bound C₃₇ atom carbon numbered compounds are used to produce the C₃₇ unsaturation index ($UK'_{37} = C_{37:2} / (C_{37:2} + C_{37:3})$). C₃₇ unsaturation index is formalized as a significant paleoceanographic proxy to predict sea surface temperature (Conte et al., 2006). Alkenone-SSTs were calculated with reference to the global calibration published Conte et al., 2006, which is equation 4.3.

$$T(^{\circ}C) = -0.957 + 54.293 (U^{K'}_{37}) - 52.894 (U^{K'}_{37})^2 + 28.231 (U^{K'}_{37})^3. \quad (4.3)$$

N-alkane concentrations were determined by using only the high molecular-weight homologue with an odd carbon number as C₂₇, C₂₉, C₃₁, C₃₃ and C₃₅. The sum of odd carbon atoms, also known as TERR-alkanes, was used to obtain information on terrestrial inputs (Jalali et al, 2016, 2017).

3.4 AMS Radiocarbon Analysis

The studied two sediment cores SAG-14 and SAG-22 were dated by an accelerator mass spectrometry (AMS) ¹⁴C analysis that were carried out at TUBİTAK-MAM facility (Turkey) (Table 3.2). The samples for dating were selected from hemipelagic parts of the cores, and were washed under distilled water and dried at 40°C. The samples contain epifaunal benthic and planktonic foraminifera and echinoderm spicules. AMS ¹⁴C results are calibrated by using Calib v7.1 software (Stuvier and Reimer, 1993) with Marine13.¹⁴C calibration curve. Their calibrations were calculated according to the reservoir age corrections of 149 ± 30 years for sapropel interval (Facorellis et al, 1998), and 58±85 for normal hemipelagic part (Reimer and McCormac, 2002). All ages reported in this thesis are reservoir corrected and calibrated to calendar years and expressed as cal age BP unless otherwise stated. Non-

Bayesian age-depth model is created by using the script “clam” on R-studio (Blaauw, 2010). Cubic-spline interpolation was generated in 95% Gaussian confidence interval.

Table 3.2 : Uncalibrated and calibrated AMS ^{14}C ages in foraminiferal samples collected from the gravity cores.

Core ID	Depth (cm)	Dated Material	Radiocarbon yrs $\pm 2\sigma$ error	Calibrated age (yrs before 1950 $\pm 2\sigma$ error)
SAG-14	91.5	<i>Globigerina</i> sp. <i>Globorotalia</i> sp. <i>Globigerinoides</i> sp. <i>Orbulina</i> sp.	1642 $\pm$ 34	1118 $\pm$ 179
SAG-14	185.5	<i>Globigerina</i> sp. <i>Globorotalia</i> sp. <i>Globigerinoides</i> sp. <i>Orbulina</i> sp.	3076 $\pm$ 26	2820 $\pm$ 225
SAG-14	293.5	<i>Globigerina</i> sp. <i>Globorotalia</i> sp. <i>Globigerinoides</i> sp. <i>Orbulina</i> sp.	5597 $\pm$ 35	5939 $\pm$ 226
SAG-22	217.3	Non-deformed bivalve	10410 $\pm$ 30	11437 $\pm$ 314



4. RESULTS

4.1 Sedimentologic Properties

4.1.1 Sediment Cores

Within the scope of this thesis, three sediment cores (SAG-08, SAG-14 and SAG-22) were examined for sedimentological purpose, which were recovered from the Gulf of Saros in Aegean Sea (Turkey) at depths of -307, -592 m and -100 m, respectively (Table 4.1, Figure 3.1, Figure 4.1). The visual observations on the sediment cores were performed by using lithology and color changes through the cores. Color for each different lithology is described by using Munsell color scheme. Detailed lithostratigraphic and faunal analyses of the sediment cores suggests that deposition took place under marine condition. In addition to lithologic properties, density and magnetic susceptibility analyses were also performed on the cores in order to correlate their lithologic properties, thus, it enables us to establish lithostratigraphic correlations among the cores. Magnetic susceptibility (M.S.) provides a useful proxy indicator of changes in the relative intensity of terrigenous input into the Gulf of Saros. According to the lithological, paleontological and physical data (density and magnetic susceptibility), the description and interpretation of each cores are explained separately below.

4.1.1.1 Core SAG-14

Core SAG-14 with a 3265 mm length was recovered from western part of the Gulf of Saros (Table 3.1, Figure 3.1, Figure 4.1). Since this sediment core is comparatively longer than the two others examined in this thesis, the relative stratigraphic age of the sedimentary record presumably is much older (Table 3.1, Figure 4.1). Therefore, core SAG-14 is studied in detail, in terms of sedimentology and faunal assemblages together with AMS radiocarbon dates through the core (Table 3.2). The lower part of the core between 3265-2330 mm represents dark olive gray homogenous clay, except the layer between 3030-2750 mm, which is characterized by olive gray homogenous clay.

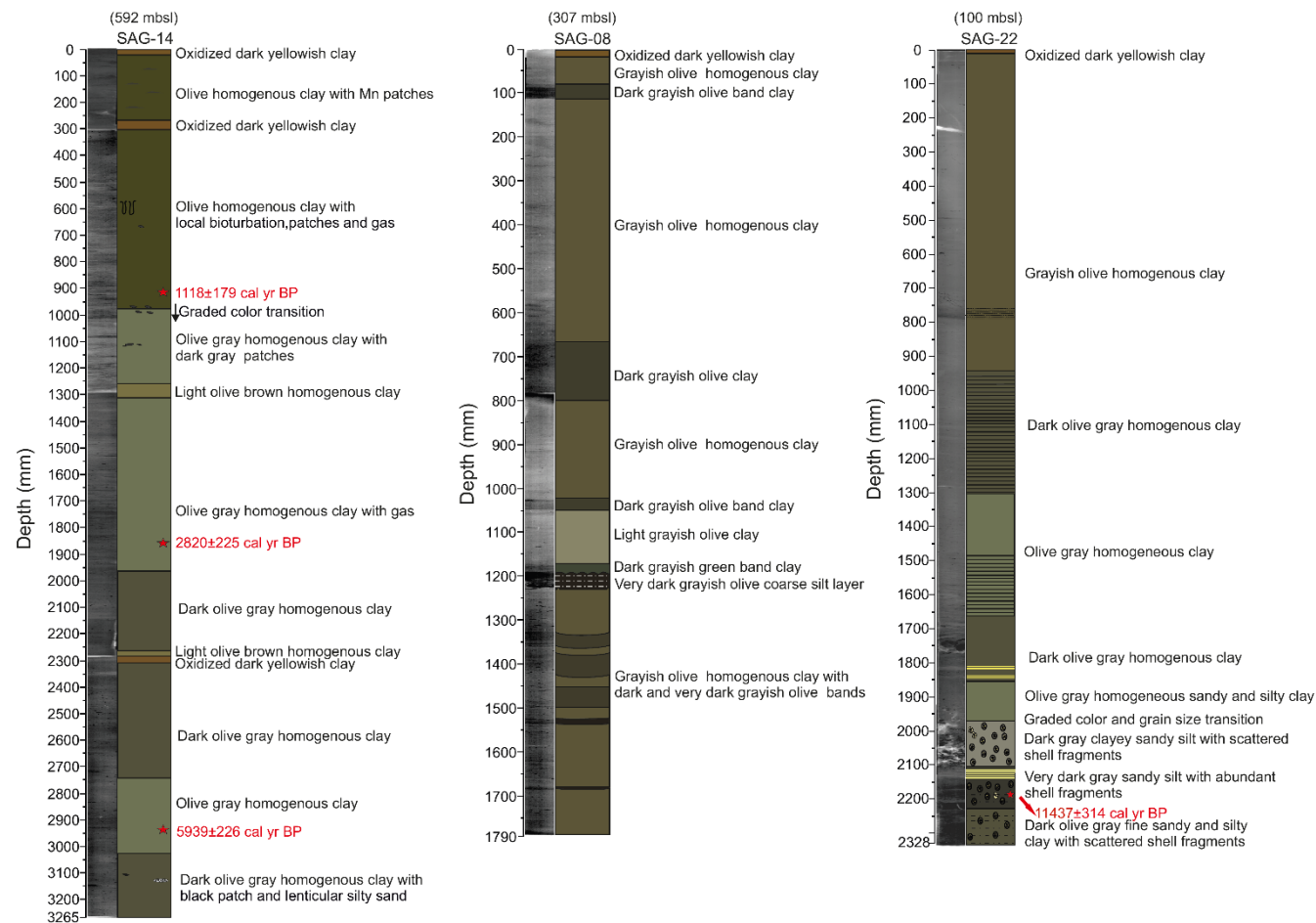


Figure 4.1 : The general lithostratigraphic units of the gravity cores SAG-14, SAG-08 and SAG-22. Red stars indicate the AMS ^{14}C sample locations with calibrated ages.

The lower part of the core includes black patch and lenticular silty sand at the 3100 and 3150 mm, respectively. The main benthic and planktonic assemblages are *Ammonia tepida*, *Uvigerina mediterranea*, *Brizalina spathulata*, *Elphidium crispum*, *Lobatula lobatula*, *Textularia truncata*, *Textularia bocki*, *Quinqueloculina seminula*, *Hyalina baltica*, *Spiroloculina excavata* and *Cassidulina carinata* and *Globigerinoides ruber*, *Globigerinoides seiglei*, *Globigerinoides conglobatus*, *Globigerinoides elongates*, *Globigerinita glutinata*, *Globigerina bulloides*, *Glubigerina umbilicata*, *Globorotaloides hexagon*, *Orbulina universa* and *Globorotalia* sp. The corresponding M.S. and gamma density values could be examined into three parts from bottom to top until 2330 mm (Figure 4.2). The lowermost layer is associated with the lowest density values, whereas MS is comparatively higher due to presence of lenticular silts. The overlying layer is marked by a sudden increase in density and decrease in MS values. The uppermost layer in this part displays a highly fluctuated density and MS values with reverse tendencies in comparative to the underlying layer. AMS ^{14}C age is obtained from planktonic foraminifera at 2930 mm, giving an age of 5939 ± 226 cal yr BP.

Upward in the core above 2330 mm, 3 cm-thick oxidized dark yellowish clay appears, then it is sharply overlain by light olive brown homogenous clay between 2270-2300 mm. The layer between 2300-1960 mm displays dark olive homogenous clay accompanied with relatively high gamma density values and slightly increasing trend in M.S. The rest of the core up to 1320 mm consists of olive gray homogenous clay with common gas escape structures. In contrast to homogenous appearance, density values are highly fluctuated with a general upward increase, whereas M.S. values indicate much lighter fluctuations with the same upward tendencies. Another AMS ^{14}C date is obtained from planktonic foraminifera that gives an age of 2820 ± 225 cal yr BP (Table 3.2, Figure 4.1). Thin layer of light olive brown homogenous clay is observed between 1320-2270 mm, and this is overlain by a light olive gray homogenous clay between 980-1260 mm, comprising dark gray patches. Based on the radiographic image, this part of the core displays thin laminations and a relatively higher M.S. values together with an increasing density. The color transition into olive homogenous clay occurs above 980 mm, at which M.S. value indicates a sharp decrease upward due to presence of intense bioturbations within this overlying part of the core. The youngest AMS ^{14}C date is obtained from planktonic foraminifera at 935 mm that gives an age

of 1118 ± 179 cal yr BP (Table 3.2, Figure 4.1). The layer between 980-300 mm is represented by a continuous sequence with olive homogenous clay with relatively low MS values, which is overlain by a thin layer (3 cm thick) of oxidized dark yellowish clay, implying a sharp increase in MS value. The uppermost part of the core above 270 mm consists of olive homogenous clay with rare Mn patches that corresponds to the highest M.S. values through the core. The overlaying oxidized dark yellowish clay appears at the top with 2 cm-thick layer.

4.1.1.2. Core SAG-08

Core SAG-08 with a 1790 mm length was recovered from eastern part of the Gulf of Saros (Table 3.1, Figure 3.1, Figure 4.1). According to visual observation on the splitted part of the core together with its radiography, the main lithology is described from bottom to top (Figure 5.1). The lower most part of the core between 1790-1230 mm consists of grayish olive homogenous clay with dark and very dark grayish olive bands that are also visible on the radiography record. This part of the core is characterized by highly-fluctuated magnetic susceptibility (M.S.) values, ranging from 3 to 15 SI (Figure 4.2). The reason for a higher M.S. values could be presence of FeS content. This homogenous lower part is overlain by a very dark grayish olive coarse silt layer between 1200-1230 mm. This thin veneer of coarser part is marked by the highest magnetic susceptibility value through the cores. The most remarkable lithostratigraphic boundary in the core is documented in both splitted part and radiography at 120m mm as a truncation surface. It is overlain by alternations of dark grayish green clay bands and light grayish olive clay between 1200-1030 mm. This part of the core is associated by low magnetic susceptibility values in compare with the underlying layers, except one layer between 1050-1030 mm due to FeS content. Between 1030 -800mm in the core, a light grayish olive homogenous clay is obscured with lower magnetic susceptibility values. Until the top of this layer, the overall gamma density values indicate slight gradual decrease. The overlying layer between 800-670 mm comprises a dark grayish olive homogenous clay, base of which coincides with a sudden decrease in gamma density and increase in M.S. values. The rest of the core from 670 mm up to 120 mm consists of grayish olive homogenous clay that is characterized by a gradual decrease in gamma density, whereas M.S. value indicate a slight increase upward in the core. The other marked increase in M.S. value of the core is discernable into dark grayish olive clay band between 120-90 mm, implying

presence of FeS content. The uppermost part of the core above 90 mm contains grayish olive homogenous and the overlaying dark yellowish clay with an intense oxidation. This part of the core corresponds to a lower M.S. values and gradual increase in gamma density.

4.1.1.3. Core SAG-22

Core SAG-22 with a 2328 mm length was recovered from eastern part of the Gulf of Saros (Table 3.1, Figure 3.1, Figure 4.1). Unlike the other two sediment cores, grainsize analysis (Figure 4.3) is also performed in addition to magnetic susceptibility (M.S.) and density measurements (Figure 4.2) through core SAG-22 in order to reveal detailed sedimentary facies, while its visual sedimentologic properties at the lower part of the core resemble paleo-shoreline sediment. The reason for having coarser grainsize composition is possibly shallow water depth (-100 m) of the core location in the gulf. Based on grain-size measurements, clay, silt and sand percentages together with mean grainsize and sorting through the core could be calculated (Figure 4.3).

The lowermost part of the core until 2225 mm is represented by a dark olive gray fine sandy and silty clay that is associated with a higher density, but decreased MS values due to scattered shell fragments (Figure 4.2). This part is sharply overlain by a very dark gray silty clay with lamination appeared the top of the same layer, implying a low density values due to high molluscan shells. Upward increase in M.S. value within this part can be explained by higher amounts of silt and sand contents that are also supported by mean grain size measurement, displaying a reverse grading with a moderate to poor sorting until 2100 mm (Figure 4.3). An AMS ^{14}C date is obtained from marine bivalve at 2178 mm that gives an age of 11437 ± 314 cal yr BP (Table 3.2, Figure 4.1). According to grainsize analyses of the core together with a visual observation on the splitted core and its radiographic image, the most remarkable lithologic change occurs at 2100 mm that corresponds to decreasing M.S. value and grainsize, implying a normal grading with moderate to well sorting. This transgressive lithologic unit begins with a dark gray clayey sandy silt with scattered mollusc shells, and grades into an olive gray homogenous sandy and silty clay at 1850 mm. Based on the grainsize measurements, this normal grading unit continues with a grayish olive homogenous silty clay that is represented by a lower density and relatively higher MS values. This transgressive lithologic unit is overlain by dark olive gray homogenous

clay with lamination at the bottom. The same layer corresponds with a sharp decrease in density and low M.S. values. Upward in the core from 1660 to 1300 mm consists of an olive gray homogenous clay layer with an increasing value of density and high MS values. This layer is overlain by dark olive gray homogenous clay between 1300-940 mm while the same layer is characterized by decreasing trend in both density and M.S. The rest of the core comprises grayish olive homogenous clay intercalated with thin silt laminations as obscured from density and M.S. values together with mean grainsize, implying very poor sorting. Within this part, sharp density changes are documented in two parts, although mean grainsize does not indicates any difference upward through the core. At the core top, an oxidized dark yellowish clay appears with unchanged values either in density and grainsize, whereas M.S. value displays upward decrease.

4.2 Chronostratigraphy

In order to reveal chronology of the sediment cores, three ^{14}C AMS datings are obtained from core SAG-14 (Table 3.2 and Figure 4.1), whereas only one ^{14}C age can be provided in core SAG-22 (Table 3.2 and Figure 4.1) due to difficulty in finding available material for dating analysis. Since scarcity of AMS ^{14}C dating in the studied cores, it is needed to establish more precise chronologic framework in order to investigate the paleoceanographic and paleoclimate evolution of the Gulf of Saros since the late Pleistocene Holocene based on the sedimentologic and geochemical analyses. For this purpose, the better chronology of the cores could be obtained by comparison of the geochemical records (XRF-Ca/Ti ratio) of the cores in the gulf with previously studied core CS-19 by Makaroğlu et al. (2020) in the Sea of Marmara (SoM) (Figure 4.4). In addition to that comparison in this thesis, the studied cores are also compared with Sofular $\delta^{13}\text{C}$ isotope record (Fleitmann et al., 2009) due to proximity with the studied region (Figure 2.1; Figure 3.1, Figure 4.4).

In a recent study, Makaroğlu et al. (2020) dated the core CS-19 in the SoM by AMS ^{14}C dating, tephrochronology, and tuning of determined Ca concentrations with stadials and interstadials observed in Greenland ice core oxygen isotope data. According to the age model, core MRS-CS19 date back to 32000 yr and inherently represents a continuous sedimentation with an average sedimentation rate (S.R.) of 68 cm/ka.

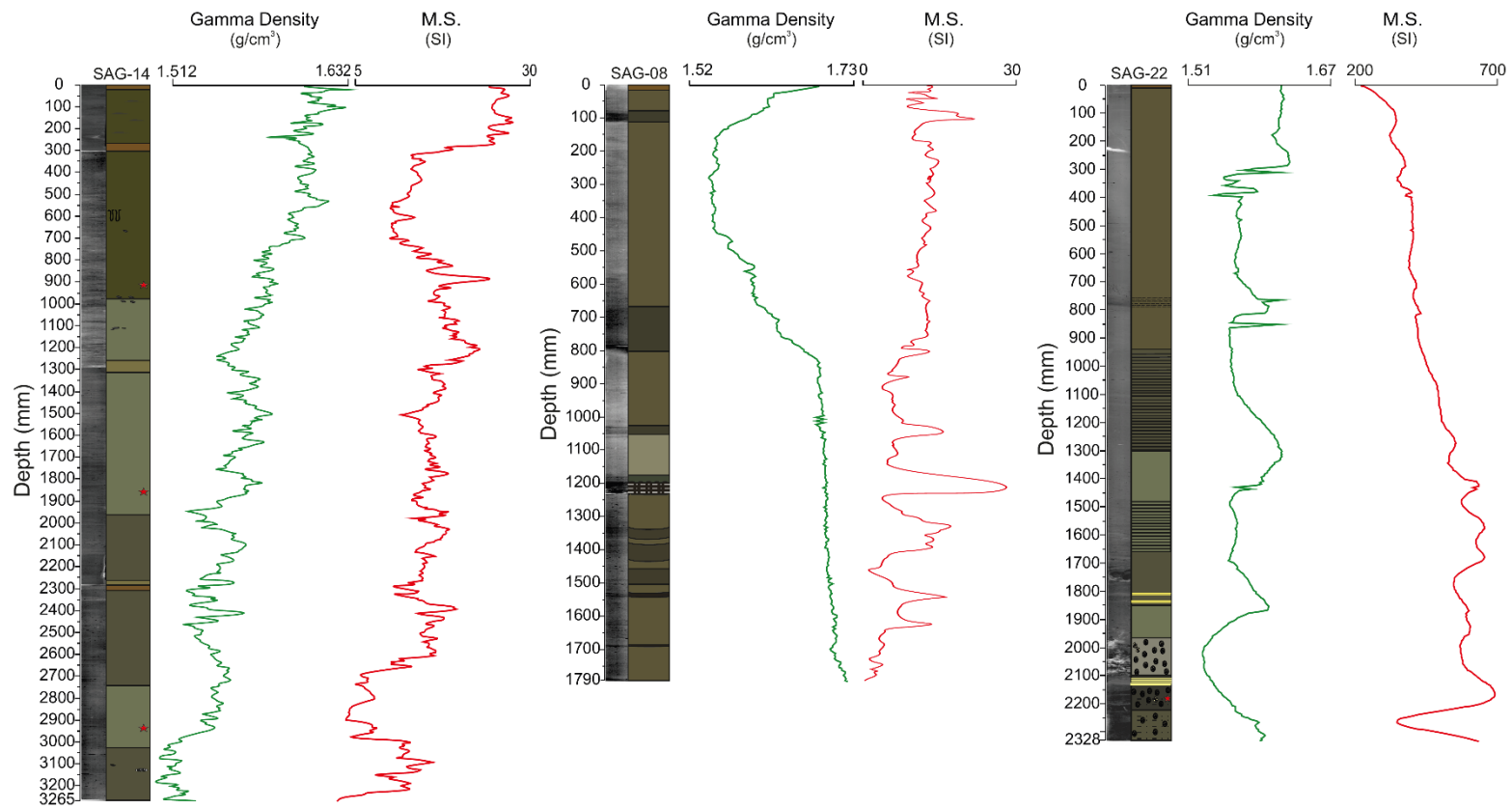


Figure 4.2 : The gamma density and the magnetic susceptibility results of cores SAG-14, SAG-08 and SAG-22.

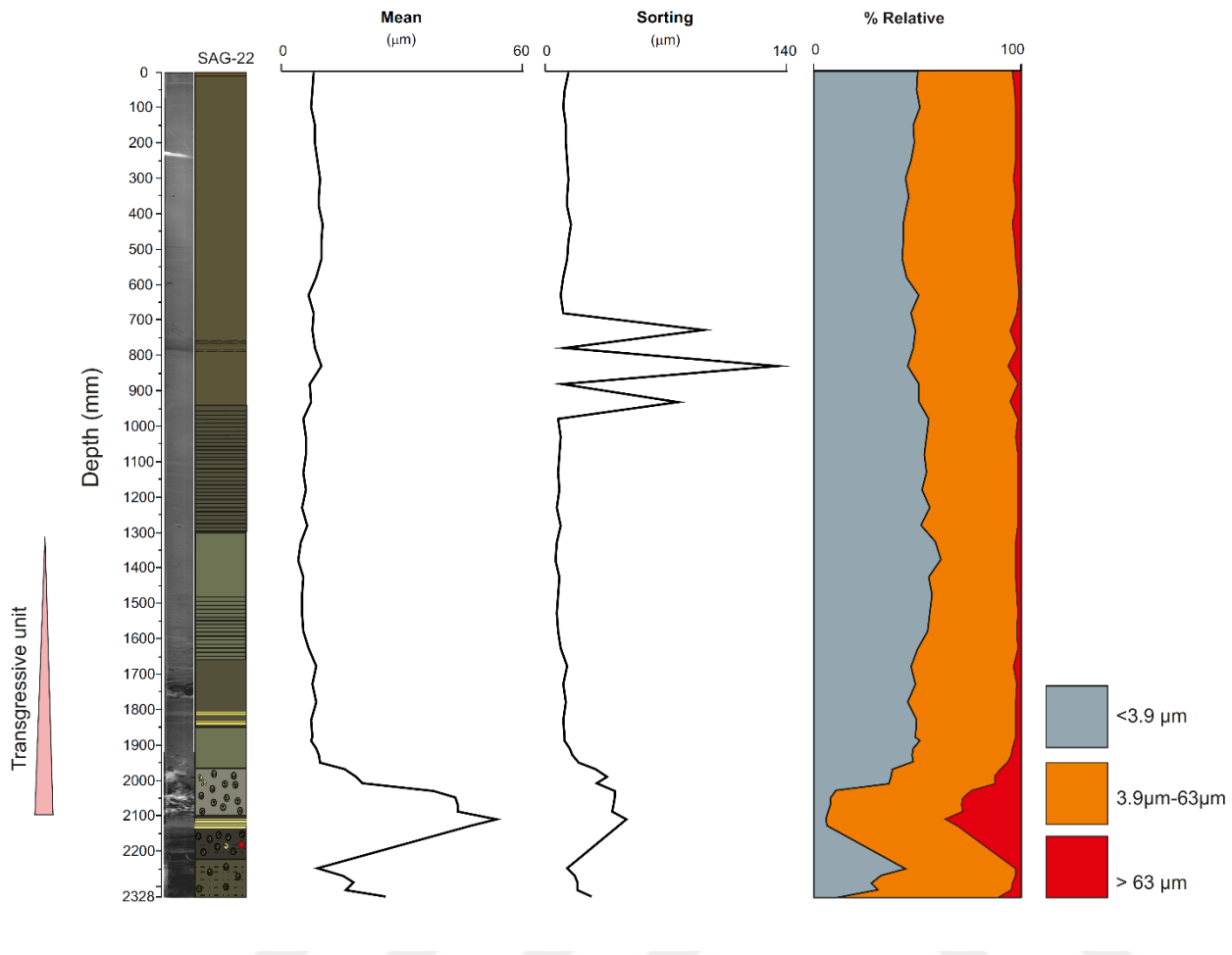


Figure 4.3 : The results of the grain size analysis performed on the core SAG-22. The grain size parameters are obtained as mean, sorting and relative grain size distribution.

The same approach of dating sediment cores from the Sea of Marmara (SoM) was applied by Çağatay et al. (2015, 2019), who linked the Ca-record (XRF counts) from the sediment cores from the SoM to Greenland interstadials (GIs). They proposed that the GIs in the SoM are well expressed by high Ca (carbonate) concentrations, relatively high total organic carbon (TOC) contents and negative oxygen isotope excursions, suggesting high organic productivity under relatively high temperatures. Therefore, the GIs in the SoM is characterized by endogenic carbonate precipitation, resulting from high primary production in surface waters (Çağatay et al, 2015). Çağatay et al. (2019) argued that the Sea of Marmara and Eastern Mediterranean isotope records indicate synchronicity with the NGRIP record. Furthermore, a similar study by Grant et al. (2012) shows that the polar temperatures from the Greenland ice cores and ice volume/ sea level from marine cores are closely coupled within centennial response time.

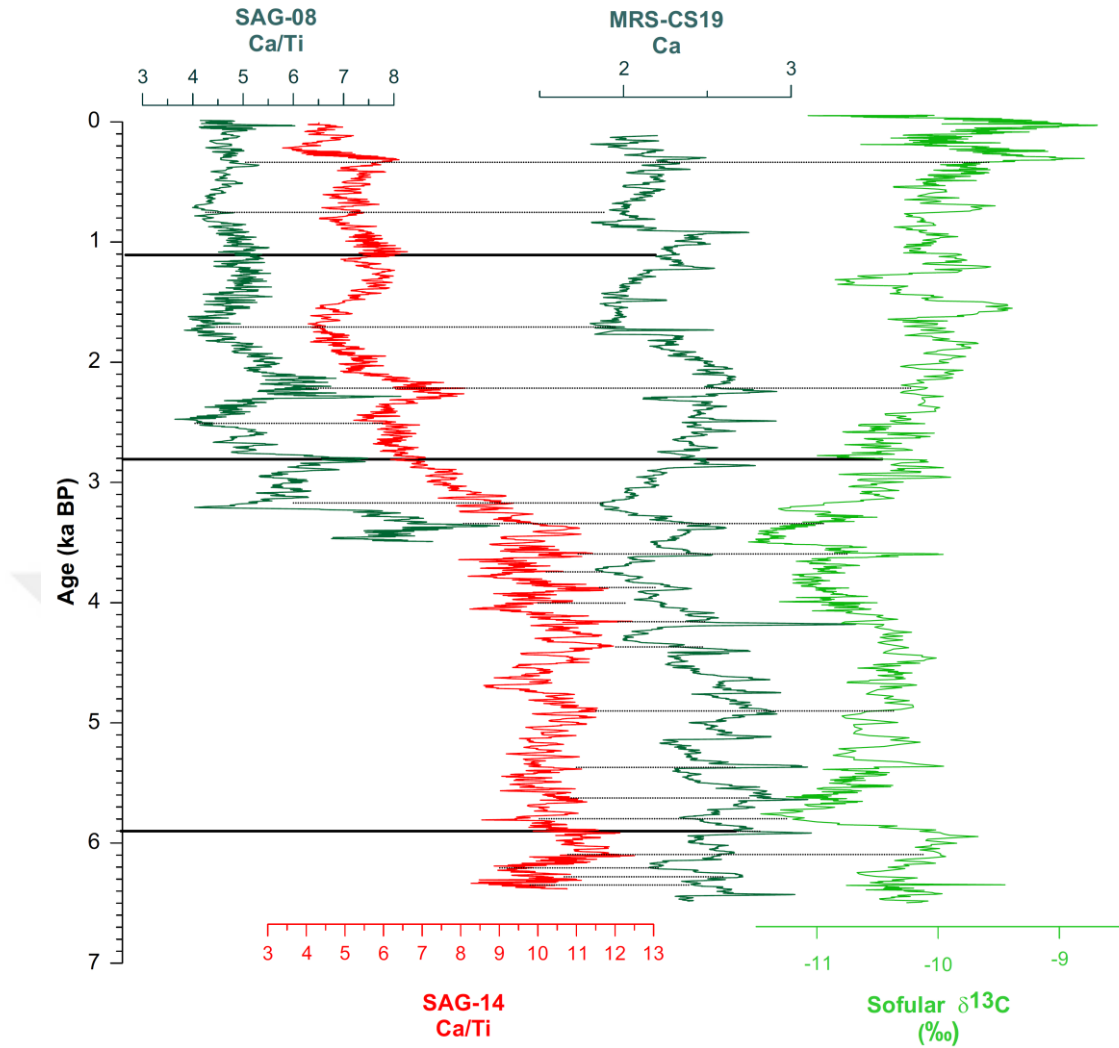


Figure 4.4 : The correlation of the cores SAG-14 and SAG-08 with the core CS-19 from the Sea of Marmara and the speleothem from Sofular Cave, which is performed by using an interactive computer software called “extended tool for correlation” (xtc). Blank lines indicate the matched ages.

In this thesis, we used the same approach and wiggle-matched (tuned) the μ - XRF Ca/Ti data of cores SAG-14 and SAG-08 with XRF Ca data of core CS-19 from the SoM and synthetic Sofular carbon isotope data. The wiggle matching of the Ca/Ti data with $\delta^{13}\text{C}$ C isotope record and Ca data of core CS-19 was made by using an interactive computer software called “extended tool for correlation” (xtc), provided by courtesy of Norbert Nowaczyk (Deutsches GeoForschungs Zentrum-GFZ, Potsdam, Germany) (Figure 4.4). Considering proximity of the surrounding catchment areas around the Gulf of Saros, it is assumed that the origin of the carbonate fractions through the cores SAG-14 and SAG-08 could not only be an authigenic, but also an allogenic that were presumably derived as riverine detrital input to the gulf. Therefore, Ca/Ti ratios are

used in the comparisons as being served for the purpose of normalization with respect to carbonate or siliciclastic sedimentation.

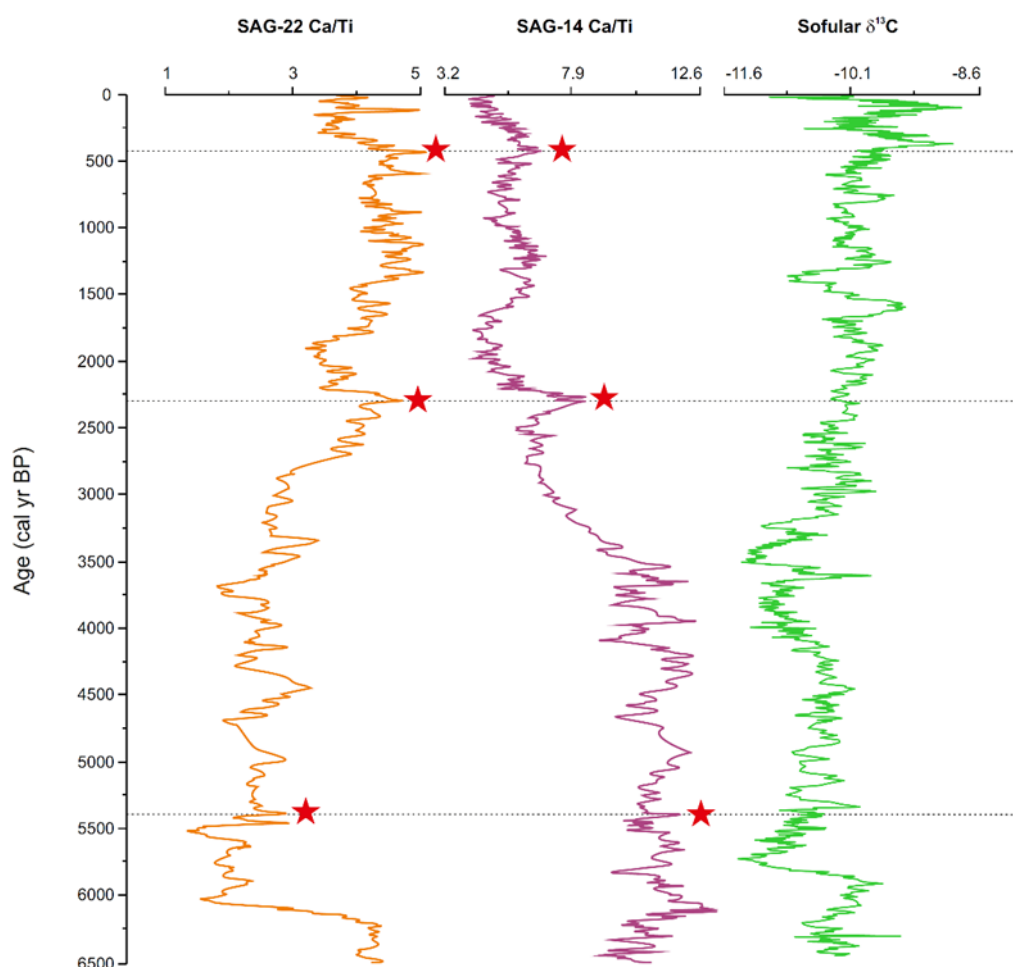


Figure 4.5 : The correlation of core SAG-22 with the core SAG-14 and the speleothem of Sofular Cave. Matched ages between cores SAG-22 and SAG-14 are marked by red stars and dashed lines.

Based on the geochemical comparisons between SAG-14 and CS-19 and Sofular isotope record, fifteen age tie-points were obtained from the core in addition to three radiocarbon analysis (accelerator mass spectrometry), thus, an age-depth model of core SAG-14 is constructed by a Non-Bayesian model that is established by using the script “clam” on R-studio (Blaauw, 2010). Therefore, the age-depth model of core SAG-14 allows us to examine the $\sim 6500 \pm 350$ yr long sedimentary record of the Gulf of Saros (Figure 4.6). Therefore, the age-depth model of this longer core reveals the precise timings of abrupt changes of paleoceanography of the gulf and climate periods since the early-to-middle Holocene. Similarities on the Ca/Ti data of both cores SAG-14 and SAG-08 from the gulf enables us to construct an age-depth model for core SAG-08

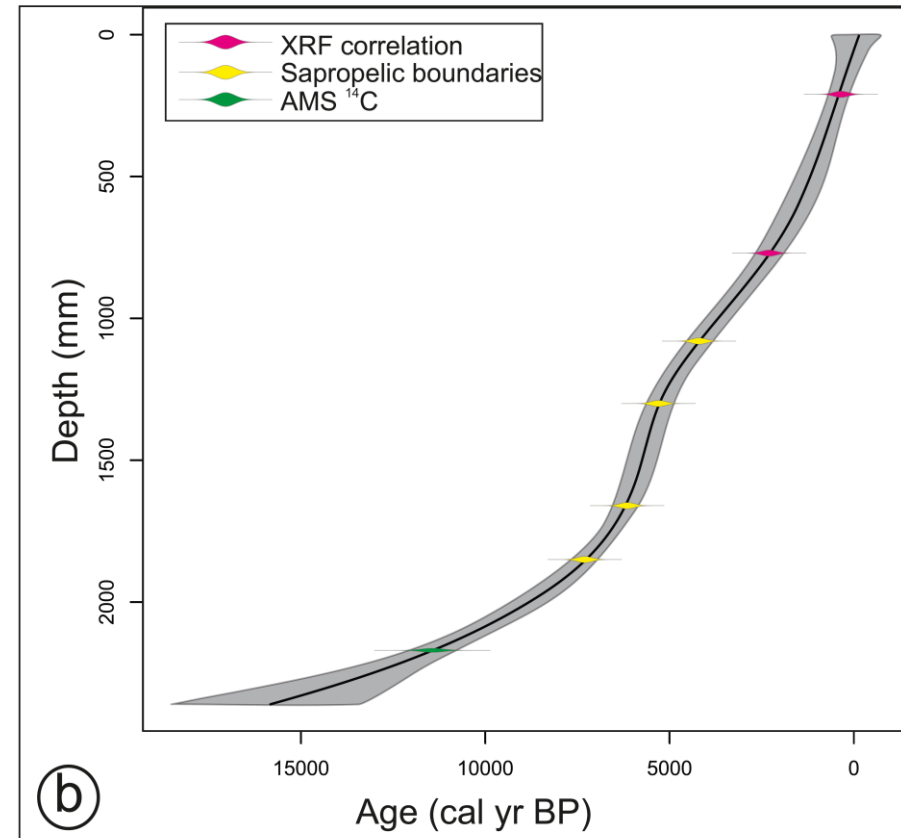
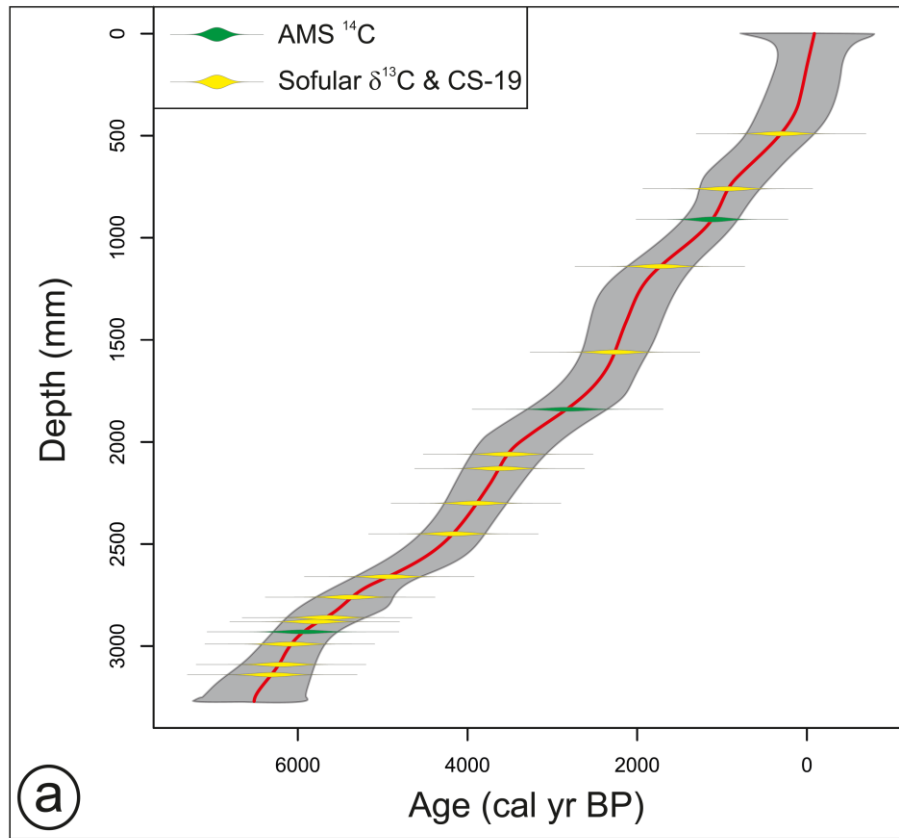


Figure 4.6 : Age models which are executed on R-studio, by using the script “clam” for a) SAG-14 based on three AMS ^{14}C samples and fifteen ages tie-points with CS-19 and Sofular $\delta^{13}\text{C}$ b) SAG-22 based on AMS ^{14}C , comparisons of XRF Ca/Ti data between SAG-14 and SAG-22 and two sapropelic boundaries.

that reveals presence of much younger sediment due to its shorter recovery, covering the time period of ~3600 cal yr BP. Since the age-depth model of core SAG-14 provides us precise chronology at least for the last 6500 cal yr BP, comparison on Ca/Ti records between SAG-14 and SAG-22 together with Sofular $\delta^{13}\text{C}$ isotope record (Fleitmann et al, 2009) is established, which reveals three main age tie-points among the cores. Thus, obtained three dates from that comparison together with ^{14}C age close to the base of core SAG-22 enables us to construct an age-depth model, displaying nearly 15000 cal yr BP recovery from the gulf sediment (Figure 4.5, Figure 4.6).

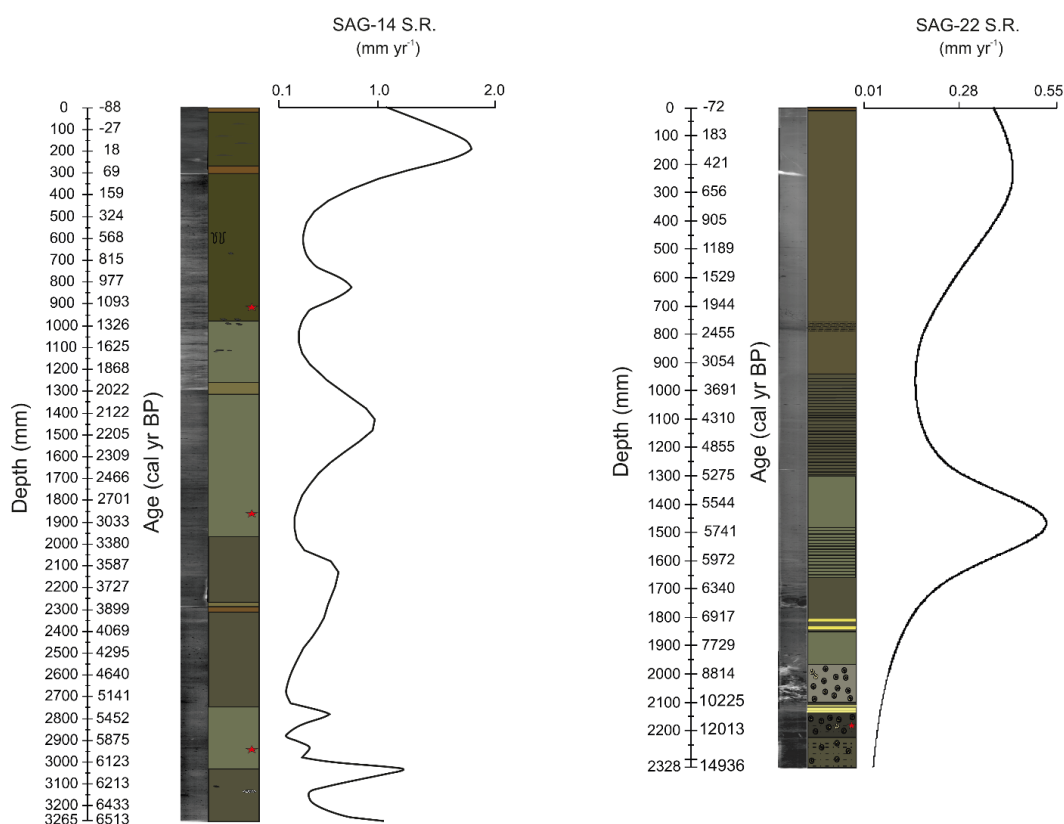


Figure 4.7 : The sedimentation rate of cores SAG-14 and SAG-22 are calculated according to the age-depth model. S.R. is used as abbreviation for sedimentation rate.

According to the age-depth model of core SAG-14, the calculated average S.R. through the core is ~50 cm/kyr that is almost consistent with regions elsewhere from the Northern Aegean (Figure 4.7). According to the İşler et al. (2015, 2016), S.R. of the eastern border of the Aegean Sea is below 40 cm/kyr. In contrast, Gogou et al. (2016) calculated S.R. up to ~80 cm/kyr based on the 48 cm long core from the Athos basin (northwestern coast of the Aegean). The reason is presumably related to nature

of the catchment areas and the drainage system of the east-west Aegean coastline. In terms of S.R. during the last 6500 yr BP, the age-depth model of the core could be divided into three parts from base to top of the core. The lowermost part between 3265 and 2600 mm in the core (6500-4640 cal yr BP) is associated with a mean S.R. of 0.35 mm/yr (Figure 4.7). This rate increases up to 0.49 mm/yr in the overlying part between 2600 and 600 mm (4640-568 cal yr BP). The highest S.R. through the core is observed within the uppermost part (600-0 mm), which is around 0.91 mm/yr, almost twice as much of the earlier periods in the core (Figure 4.7).

4.3 Geochemical Properties

4.3.1 Total Organic Carbon (TOC) and Total Inorganic Carbon TIC Analysis

The TOC ratio of marine sediments is the reflection of input and maintenance of endogenous and exogenous organic matter that is mainly influenced by aquatic biology and terrestrial vegetation (Fischer and Wefer, 1999). In other words, TOC is a proxy of paleo-productivity within the water column, which is related to organic matter preservation during settling and burial. However, sedimentation rates, bottom-water conditions (i.e. oxic, suboxic, dysoxic, anoxic/euxinic), the amount of export production, and bioturbation are the primary factors controlling the deposition of organic carbon in the oceans. High concentrations of organic carbon in marine sediments might be attributed to deposition beneath an O₂-free (euxinic) water column (Demaison and Moore, 1980), where anaerobic processes of organic carbon decomposition are less efficient than decomposition in the presence of dissolved oxygen.

Total Organic Carbon (TOC) and Inorganic Carbon contents of cores SAG-14 and SAG-08 are analyzed in this thesis and discussed separately below. The TOC values through the graphs are evaluated with respect to average threshold value (ca 1 wt%) for defining a sapropel deposition in the Aegean Sea. S1 sapropel layer appears at multiple sites in the Aegean Sea, where it represents a period of elevated organic matter accumulation during a period of wetter climate (Aksu et al, 1995a; Triantaphyllou et al, 2009b, 2014; Martinez et al, 2015; Filippidi, 2013; İşler et al, 2015; Gogou et al, 2007). Holocene sapropel deposited in the Aegean Sea is referred as S1 that is subdivided into two different units, S1a and S1b, respectively. Gogou et al. (2007) proposed the average TOC value of 1.9 % for S1a and 1.3 % for S1b,

whereas Triantaphyllou et al. (2009b) documented the same values as 0.9 % and 0.7 %, respectively. However, Filippidi (2013) argued that the highest TOC values for the South and the North Aegean Sea are as 1.09 % and 0.9 %, respectively. Recently, TOC value for S1sapropel from the North Aegean Sea was obtained greater than 1.1 % by İşler et al. (2015). The amount of organic carbon preserved in sediments is primarily controlled by the sedimentation rate and the amount of primary production within the photic zone. This difference in TOC concentrations likely reflects the disparity in sedimentation rate from South to North Aegean Sea, which is assumed to be the main control on preservation of organic matter.

The timing of Holocene sapropel (S1) in the Aegean Sea is highly debated in various core studies. The onset of the sapropel deposition ranges from 9700 cal yr BP to 9200 cal yr BP, whereas time period for its termination ranges from 6300 cal yr BP to 6900 cal yr BP (Filippidi, 2013; Triantaphyllou et al, 2014; Martinez et al, 2015; Perissoratis and Piper, 1992; Aksu et al, 1995a; Geraga et al, 2000; Mercone et al, 2000, 2001; Roussakis et al, 2004; Kotthoff et al, 2008a, b). The differences in the timing of sapropel deposition can be attributed to the intensity of environmental changes that took place during sapropel formation, although precision on stratigraphic position of dated samples and methods in previous core studies in the Aegean Sea are still questionable.

4.3.1.1. Core SAG-14

According to the age-depth model of the core, total organic carbon (TOC) contents through the core enable us to estimate changing organic productivity with respect to paleoceanographic situations of the Gulf of Saros during the last 6500 ± 350 cal yr BP. However, inorganic carbon content (TIC) of the core sediment reveals amount of dissolved carbon via erosion or detrital input from the surrounding catchment area of the gulf. This finding could also be comparable with other geochemical proxies documented in this thesis (Chapter 4.3.2.1). TOC ratio of the core is compared with plots of a mean S.R. and S.R./TOC content in order to assess both bottom-water oxygenation and sea-surface primary productivity (Figure 4.8) (Fischer and Wefer, 1999). Such plots are only valid for the marine component of the organic carbon fraction, since the terrestrial component has no bearing on sea-surface productivity.

TOC and TIC graphs of the studied core are examined in different parts based on an average threshold value (1 wt%) for defining a sapropel deposit in the Aegean Sea.

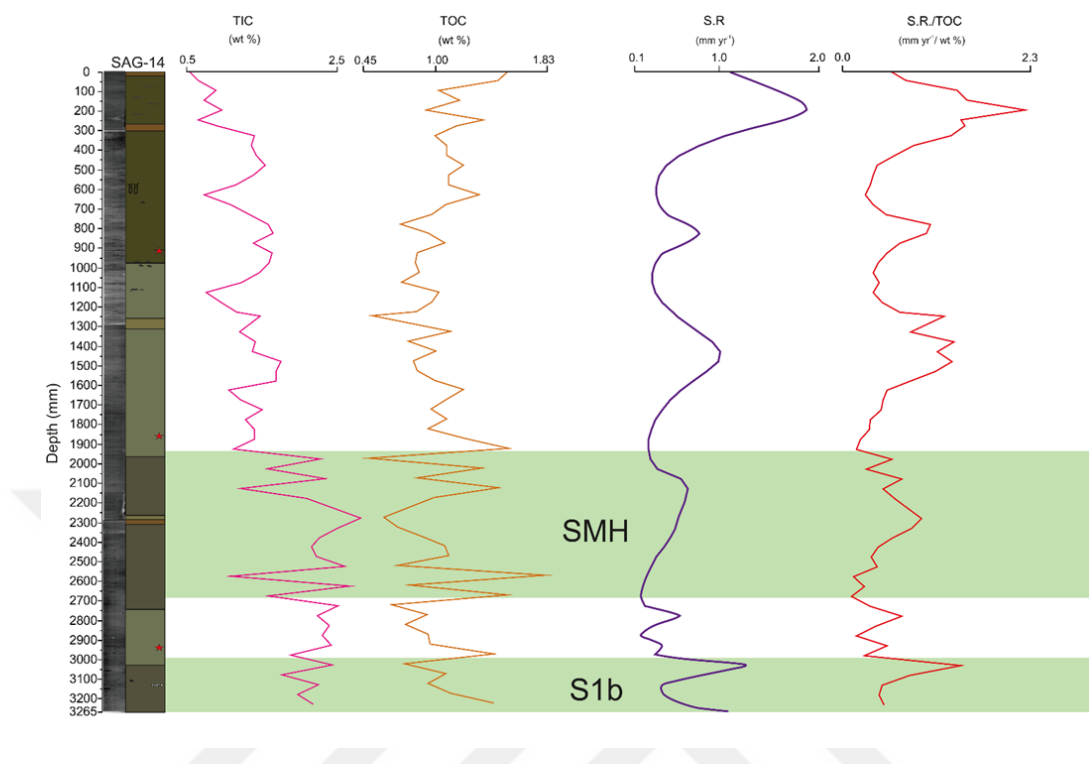


Figure 4.8 : Total organic carbon and total inorganic carbon results of core SAG-14 and its sedimentation rate (S.R.)-ratio profiles

The lowermost part of the core between 3265-2995 mm displays fluctuated TOC and TIC values, ranging from 0.76 to 1.43 wt % and 1.64 to 2.09, respectively. Such rate of TOC content reveals existence of a sapropel layer at the base of the core. According to the age-depth model of the core, the top of this layer could be dated at 6110 cal yr BP. Therefore, this peculiar layer in core SAG-14 timely coincides with the S1b sapropel that was previously documented in the Aegean Sea (Filippidi, 2013; Triantaphyllou et al, 2014; Martinez et al, 2015; Kotthoff et al, 2008a, b). TIC content in the same layer is comparatively low with high fluctuations, but still higher compared to average values through the core. The S.R. in the S1b layer is highly fluctuating, but mostly higher in close to top of this layer. This trend is almost compatible with the S.R./TOC content. Upward in the core between 2940 and 2740 mm is represented by a decrease in TOC content, ranging values from 0.7 to 0.95 wt %. TIC content within the same layer display a comparatively higher values, whereas the sedimentation rate indicates almost its lowest value through the core. The most remarkable increase in TOC content is observed between 2740 and 1855 mm in the core, reaching a value of

1.81 wt %. The TOC values with strong fluctuations are inversely correlated with TIC content, ranging from 0.99 to 2.40 wt %. The S.R. and S.R./TOC content (Sr) are lower than counterparts in the underlying part. Such a high TOC ratio in core SAG-14 attests existence of a younger sapropel layer. According to the age-depth model, deposition of this layer took place between 5300 and 3200 cal yr BP that coincides with the timing of mid-Holocene sapropel (SMH) documented in the Aegean Sea by Triantaphyllou et al. (2009b, 2014) and Kontakiotis (2016). The similar youngest Holocene sapropelic layer was previously documented as an upper sapropel (US) in the Sea of Marmara deposited between 5000 and 3100 cal yr BP (Çağatay et al, 1999; Tolun et al, 2002) and in the Gemlik Gulf dated between 5400 and 2700 cal yr BP (Çağatay et al, 2015; Filikçi et al, 2017). The same layer also includes the lowest TOC values around 1980 mm, ranging from 0.50 to 0.97 wt % whereas the highest TIC content is observed at 2290 mm that in turn indicate increasing

The upward core until 680 mm, TOC contents are never observed above the threshold value (1 wt%) for the sapropel definition. S.R./TOC ratio displays high fluctuations and ranges from 0.52 to 1 wt%. In the same layer, TIC contents with strong fluctuations are almost lower than the underlying part of the core, whereas sedimentation rate indicates strong fluctuations with increasing trend. S.R/TOC content have a similar trend with the TIC profile. The uppermost part of the core above 680 mm is associated with TOC content that ranges from 0.92 to 1.53 wt%. This reveals that TOC values partly exceed the threshold value for the sapropelic layer. On the other hand, TIC content in the core displays a comparatively higher value as well as the S.R. that indicates sharp increase above the top 300 mm in the core, over the last few decades based on the age-depth model.

4.3.1.2 Core SAG-08

The chronology of core SAG-08 is provided by comparison of its geochemical properties (Ca/Ti ratio) with the other longer and deeper core SAG-14 (Figure 4.4).

Therefore, the age-depth model of core SAG-08 is established by several age-tie points obtained from the core (Figure 4.4). Accordingly, TOC and TIC analyses of core SAG-08 provides information about total organic carbon and inorganic contents of the Gulf of Saros during the last 3602 cal yr BP (Figure 4.9). The bottom part of the core between 1790-1550 mm displays relatively low TOC and the highest TIC values

between 0.65-0.71 wt % and 1.33-1.81 wt %, respectively. This layer corresponds to sapropelic layer which is newly documented in the gulf as well as in core SAG-14, coincides with the upper sapropel documented in the SoM (Çağatay et al, 1999; Tolun et al, 2002). The same layer is represented by almost the lowest S.R. and together with the low S.R./TOC content. A remarkable change in TOC content (0.63-0.92 wt %) is observed between 1550 and 1350 mm accompanied by the lowest TIC values (1.00-1.15 wt %) with opposite sign. The same layer in the core characterized by low S.R.

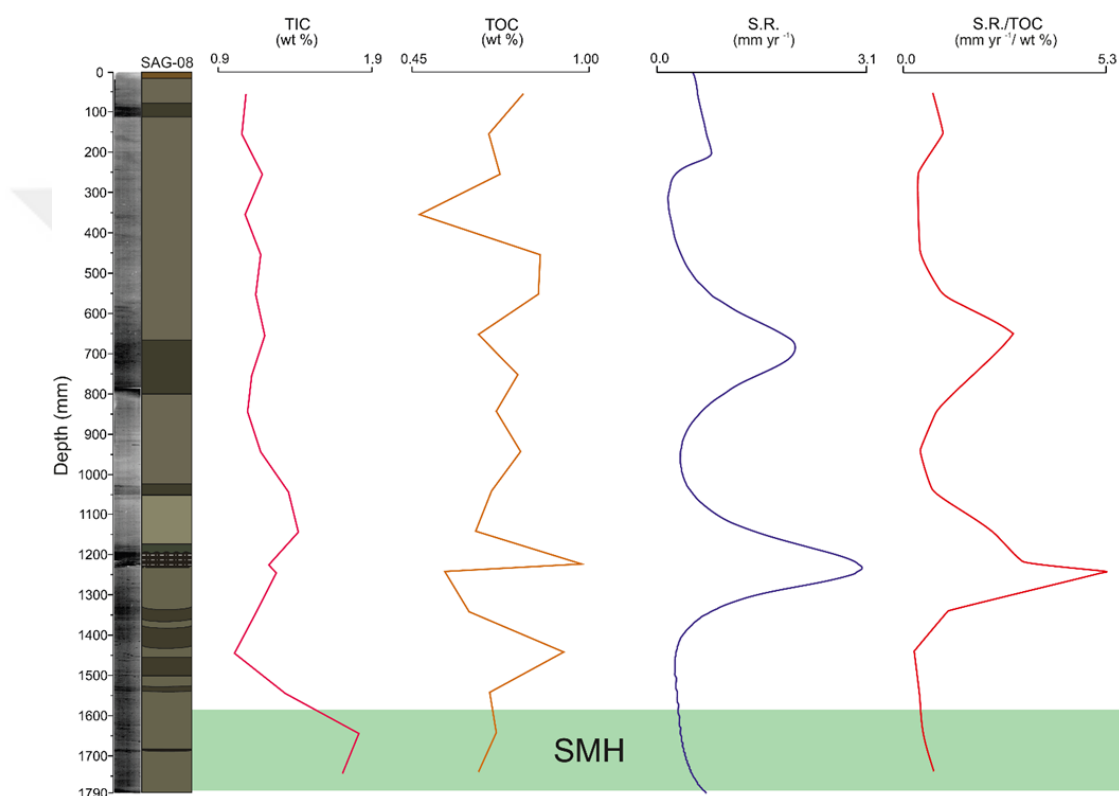


Figure 4.9 : Total organic carbon and total inorganic carbon results of core SAG-08 and its sedimentation rate (S.R.)-ratio profiles

and S.R./TOC content. TOC content displays a decrease down core to 0.55 wt % between 1350 and 1250 mm, whereas TIC content displays an increasing trend. The S.R. in this layer shows an increasing value up to 3 mm yr⁻¹. S.R./TOC content has a similar trend with the sedimentation rate. The most remarkable increase in TOC content is observed at 1250-1150 mm in the core with values of up to 0.92 wt % that is accompanied with a reverse trend in TIC values. This layer is also represented by the highest S.R. and S.R./TOC content, but lower in close to top of this layer. In the upper 655 mm of the core, TOC content ranges from 0.65 to 0.79 wt % with high fluctuations, whereas TIC content is marked by relatively low values, ranging from

1.09 to 1.42 wt%. This layer is associated with a quite low S.R. that is also represented by the lowest S.R./TOC ratio. From 655 mm to 355 mm, TOC content displays relatively high values, reaching up to 0.85 wt %, whereas the lowest value of TOC content in the core is observed at 355 mm by weight 0.47 %. On the other hand, TIC content in the same layer indicates slight fluctuation with low values, varying between 1.07-1.20 wt %. In the same layer, the S.R. and S.R./TOC content display a decreasing trend. The uppermost part of the core above 355 mm is marked by increasing TOC values, ranging from 0.47 to 0.80 wt %. TIC content shows the same trend as the underlying part. Besides, the S.R. indicates lower values accompanied by low S.R./TOC content in similar tendency.

4.3.2 μ -XRF Analysis

The chemical composition and elemental ratios of deep marine sediments provides a wide range of information on paleoenvironmental changes, sediment sources, primary organic production, sedimentary oxygenation and post-depositional changes in the sedimentary record (Calvert and Pedersen, 2007). Such properties through sediment cores could be used as appropriate proxies, which are precisely measured by X-ray Fluorescence (XRF) core scanners (ITRAX). In this thesis, the studied sediment cores were analyzed by the core scanner ITRAX in order to reveal relative supply of some major elements such as K, Fe, Mn, Ca, Sr, Ti and Br (Figure 4.4). The relative elemental abundances through the cores were recorded as counts per second (cps) in the element-ratio profiles. These elemental records of the studied cores (SAG-14 and SAG-22; Figure 4.10, Figure 4.11) is expected to provide important paleoclimate information, mostly reflecting the intensity of precipitation and erosional processes linked to climate conditions prevailed during the last 15000 cal yr BP.

The resolution of ITRAX-XRF analyses (Chapter 4.3.2.1) of core SAG-14 allow us to document environmental changes at the millennial to centennial time scale due to high-sedimentation rates in the core locations. On the other hand, the same elemental analysis of core SAG-22 gives us much older environmental record, covering the time period of the last 14936 cal yr BP due to a very low sedimentation rate.

In this study, K and Ti elements together with Fe are used to estimate the abundance of terrestrial materials, the detrital fraction of deep sea sediments is a reliable proxy for paleoceanographic and paleoenvironmental reconstructions (e.g., Çağatay et al,

2019), providing an insight regarding the climate condition prevailing in source area and the mechanisms involved in the transport of material from the catchment to sea (riverine and eolian input). However, Fe/Mn ratios are calculated to indicate changing of bottom water conditions in the gulf. Sr/Ca is used to discriminate between marine and terrestrial carbonates, with marine carbonates having relatively higher ratios than the terrestrial carbonates. The Ca/Ti ratio is used to normalize with respect to carbonate or siliciclastic sedimentation. Ca is most likely derived from endogenic calcite that is related to productivity into the water column. The records of elemental profiles of the studied cores are examined separately below;

4.3.2.1 Core SAG-14

The elemental composition of the core is examined with respect to marked changes in the elemental profiles from base to top (Figure 4.10). The lower part of the core between 3265 and 1948 mm contains two different sapropelic layers that is well documented by TOC analyses (Figure 4.8), named here as S1b and SMH (middle Holocene sapropel). The oldest sapropel in the core (S1b) is mainly associated with gradual increases in K, Ca, Sr and Ca/Ti, whereas Br/Ti values are comparatively low. Ca/Sr ratio displays almost its highest values through the core. In this core, particular attention is given to the distribution of redox sensitive elements (Fe and Mn), while Fe/Mn plays a key role for estimating deep-water oxygen condition during the deposition of sapropel layers in the gulf. The highest Fe/Mn ratio is detected at the base of S1b sapropel, then displays gradual decrease upward. Its trend is inverse to Ca, Sr and K values. In the intervening layer between S1b and SMH sapropel layers, the marked changes are documented in Fe/Mn, Ca and Ca/Ti profiles, whereas Br/Ti ratio is comparatively higher within the same layer as well as Sr and K values. The overlying sapropel layer SMH is distinct from the older S1b with having higher K, Ca and Sr values. Their trends are compatible with higher Ca/Ti and Br/Ti ratios with high fluctuations, and inverse decreasing trend in Fe/Mn and Ca/Sr ratios. The layer between 2446 and 2148 mm is marked by sharp increases in K value and Fe/Mn ratio, indicating gradual decreases upward. In the same layer decreases in Ca and Sr values are positively correlated with Ca/Sr ratio, but inversely correlated with lower Ca/Ti and Br/Ti ratios with high fluctuations. The youngest sapropel layer SMH in the core is marked by sharp increases in Ca and Sr values together with Ca/Sr and Ca/Ti ratios,

all of which are inversely correlated with K value and Fe/Mn ratio. Br/Ti ratio remains the similar values with the underlying layer (Figure 4.10).

Apart from the sapropel layers, remarkable changes in the elemental profiles could be distinguished in different layers in the rest of the core. Such a pronounced layer until 1610 mm above the youngest sapropel (SMH) is marked by sharp increases in K value and Fe/Mn ratio, whereas Ca and Sr values together with Ca/Sr and Ca/Ti ratios display gradual decreases as well as Br/Ti ratio with a high fluctuation. Another remarkable changes in the elemental profiles are documented at 1610 mm, indicating sharp increases in Ca and Sr values and Ca/Ti ratio in contrast to Fe/Mn ratio. K value displays a slight decrease, but then attains the highest values above 1415 mm. In the same layer of the core, Br/Ti values are comparatively higher with high fluctuations. The most progressive decreases in K values in the core is obscured in the layer between 1260 and 1060 mm. The similar sharp decreases are documented in Ca and Sr values and Fe/Mn, Ca/Sr and Ca/Ti ratios, but then remarkable increases are recorded upward. In contrast to K element, Br/Ti profile indicates gradual increase. Until 540 mm in the core, although Ca and Sr values together with Ca/Sr and Ca/Ti ratios are inversely correlated with K values, all having comparatively higher values with moderate to strong fluctuations. The basal of this layer in the core is associated with a sharp increase in Br/Ti ratio, whereas Fe/Mn displays higher values only until 820 mm. The rest of the core above 540 mm is accompanied with remarkable changes in Ca and Sr values and Ca/Sr and Ca/Ti ratios, implying gradual decreases upward. In contrast to K value, Br/Ti ratio attains its highest value with strong fluctuations as well as Fe/Mn ratio.

4.3.2.2 Core SAG-22

The paleoceanographic and paleoclimatic changes in the Gulf of Saros during the last 14936 yr BP is documented in the elemental profiles of the core SAG-22 (Figure 4.11). The lower part of the core until 2200 mm is represented by relatively high K and Ca values and Ca/Ti ratio, while Ca/Sr ratio is marked by the highest value through the core. The same layer also displays low Sr value and low Br/Ti ratio with a decreasing trend in Fe/Mn ratio. The top of this layer is documented by remarkable changes in elemental profiles, representing the lowest Ca, Sr, Ca/Sr, Ca/Ti and Fe/Mn along the core. The upward in the core between 2200 and 1960 mm is associated with the highest

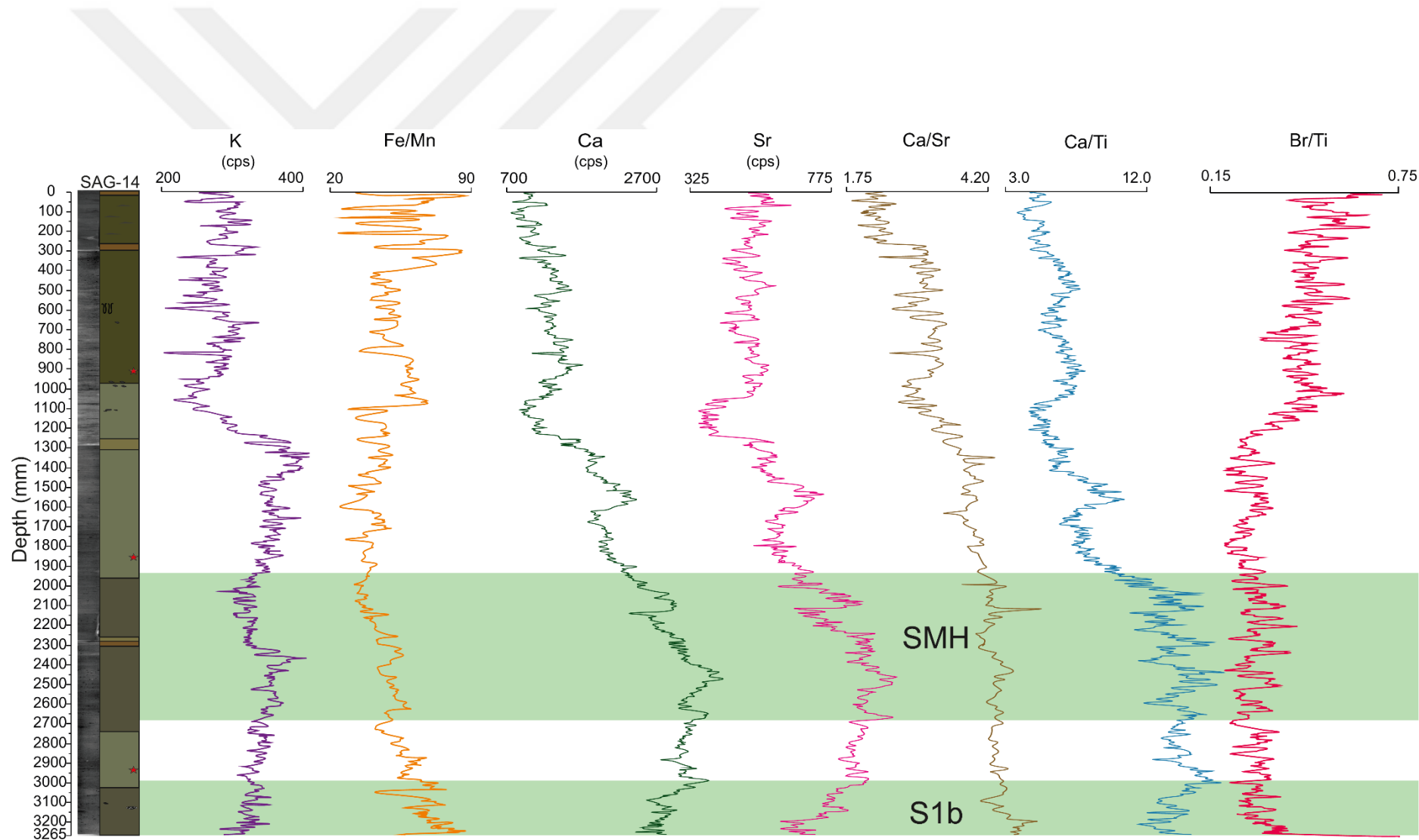


Figure 4.10 : μ -XRF geochemical element and element-ratio profiles (K, Fe/Mn, Ca, Sr, Ca/Sr, Ca/Ti and Br/Ti) for core SAG-14. Green bands indicate sapropel layers. SMH and S1b are used as abbreviations for Sapropel Mid-Holocene and the Eastern Mediterranean Sapropel S1b.

Sr and Ca/Ti that is inversely correlated with low Ca/Sr ratio. In the same layer, K profile displays the lowest value with an increasing trend, and Fe/Mn ratio is linked to low values. The highest Br/Ti value in the core occurs at 2100 mm. The layer between 1960 and 1650 mm displays relatively high Ca and Sr values, and Ca/Ti ratio with the same tendency coupled with increasing trend of K. In addition, the same layer is correlated with low Br/Ti ratio excluded from 1845 to 1765 mm while Fe/Mn and Ca/Sr ratios display relatively low values with the fluctuations.

The remarkable change in Fe/Mn profile together with the highest value of K with a decreasing upward trend is documented between 1650-1180 mm. In the bottom of the same layer, the sharp decreases in Ca and Sr values and Ca/Ti ratio are detected, but then attain the lowest values through the core (Figure 4.11). Br/Ti ratio remains the similar values with the underlying layer until the sharp increase around 1325 mm, whereas Ca/Sr shows rising values with strong fluctuation within this layer. Between 1180 and 755 mm in the core is characterized by the similar trend of Ca, Sr and Ca/Ti with underlying layer until 870 mm, whereas the values of Ca and Sr and Ca/Ti ratio display an increasing trend in close to top of this layer. This layer is also associated with low K value and low Fe/Mn ratio. On the other hand, trend of Ca/Sr ratio resembles with the underlying layer, while Br/Ti ratio displays the similar values after 1325 mm until top of this layer. In the contrast to Br/Ti ratio, the upper part of the core above 755 mm is represented by gradual decrease in K values, Ca/Sr and Fe/Mn ratios. In addition, Ca and Sr values and Ca/Ti ratio display increasing values in the same tendency.

4.3.3 Biomarker Analysis

The most worldwide proxy based on organic fossil used in paleoclimatology for SST reconstructions is the Uk' 37 index (Brassell et al, 1986), This index quantifies the degree of unsaturation (two, three or four double bonds) of long chain ketones with 37 carbon atoms (alkenones) biosynthesized by haptophyte algae (coccolitophorids, mainly *Emiliana huxlei*). This index has a direct relationship with the water temperature when the algae grew. The degree of unsaturation increase, and so that the relative proportion of the three double bonds ketone biosynthesized, as temperature of the water decreases (Prahl and Wakeham, 1987). This proxy has also been successfully tested in the Mediterranean Sea, showing a good correlation with the $\delta^{18}\text{O}$ record from

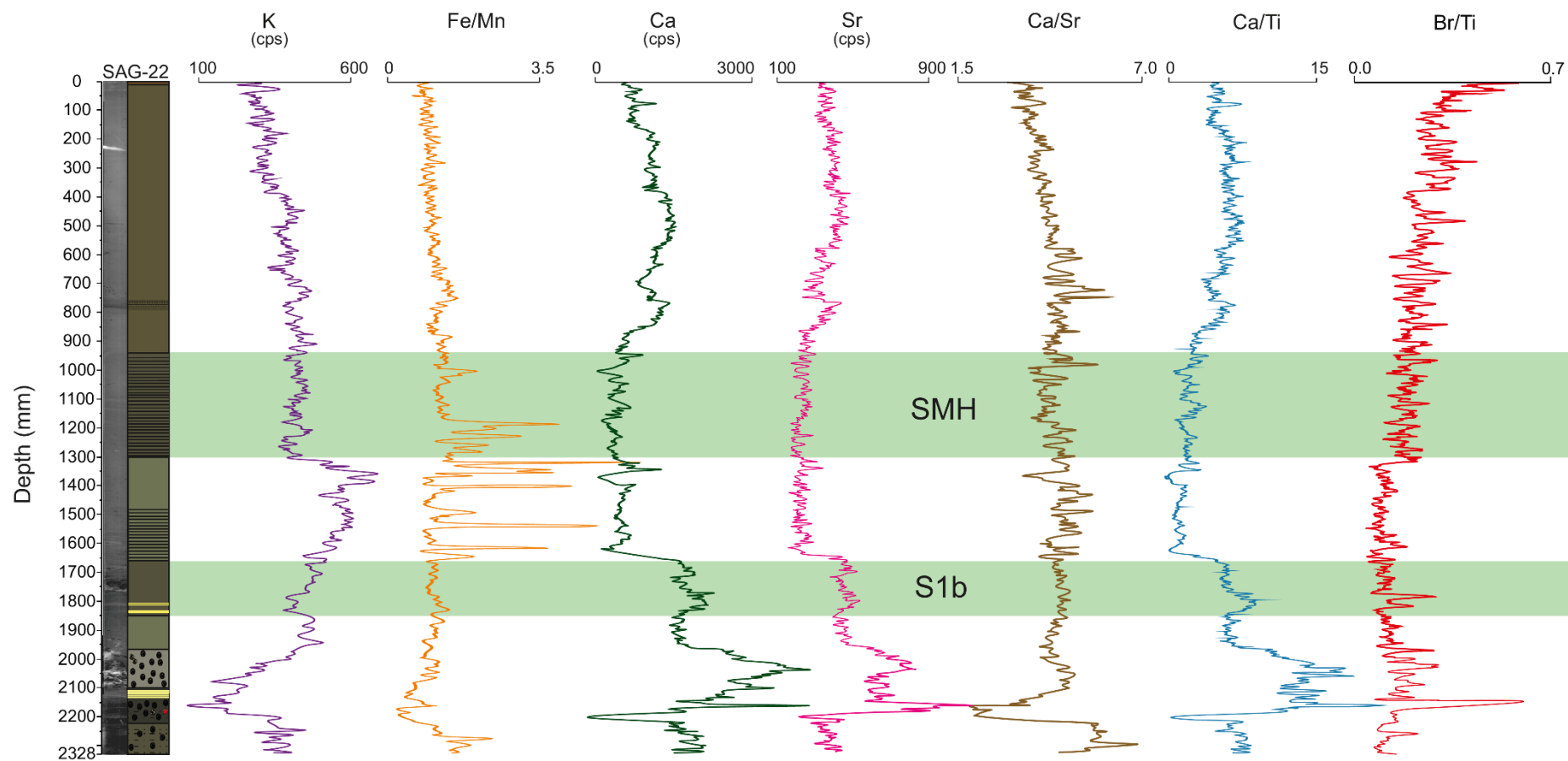


Figure 4.11 : μ -XRF geochemical element and element-ratio profiles (K, Fe/Mn, Ca, Sr, Ca/Sr, Ca/Ti and Br/Ti) for core SAG-22. Green bans indicate sapropel layers. SMH and S1b are used as abbreviations for Sapropel Mid-Holocene and the Eastern Mediterranean Sapropel S1b.

the GISP2 ice core to abrupt events during the last deglacial cycle (Cacho et al., 1999, 2001; Marchal et al, 2002; Martrat et al, 2004, 2007). Past SST is one of the most common approach for the reconstruction of climate variability beyond the instrumental record. Alkenone analysis of core SAG-14 is the first attempt to provide a SST record in the Gulf of Saros during the last 6500 cal yr BP in that region (Figure 4.12). The Gulf of Saros is in itself particularly sensitive to climate changes because of the combination of its semi-isolation from the rest of the Aegean Sea, its small size and the abundance of local freshwater inputs.

The bottom part of the core is marked by high SST record (19.9°C) low TERR-alkanes value (~105 ng/g) around 3230 mm. The SST values display a decreasing trend down to 16°C towards present except for the last warm value at the top of the record, and are accompanied by a sharp increase in TERR-alkanes values (1000 ng/g) at 3030 mm. Between 3030 and 2600 mm, SST is characterized by highly-fluctuated and relatively increased (up to 19°C) while TERR-alkanes show low values. SST values display an increasing trend to the highest value (20°C) at 2415 mm. There is superimpose decadal to multidecadal fluctuations. Besides, Terr-alkanes are outstandingly high and variable between 1700-1100 mm.

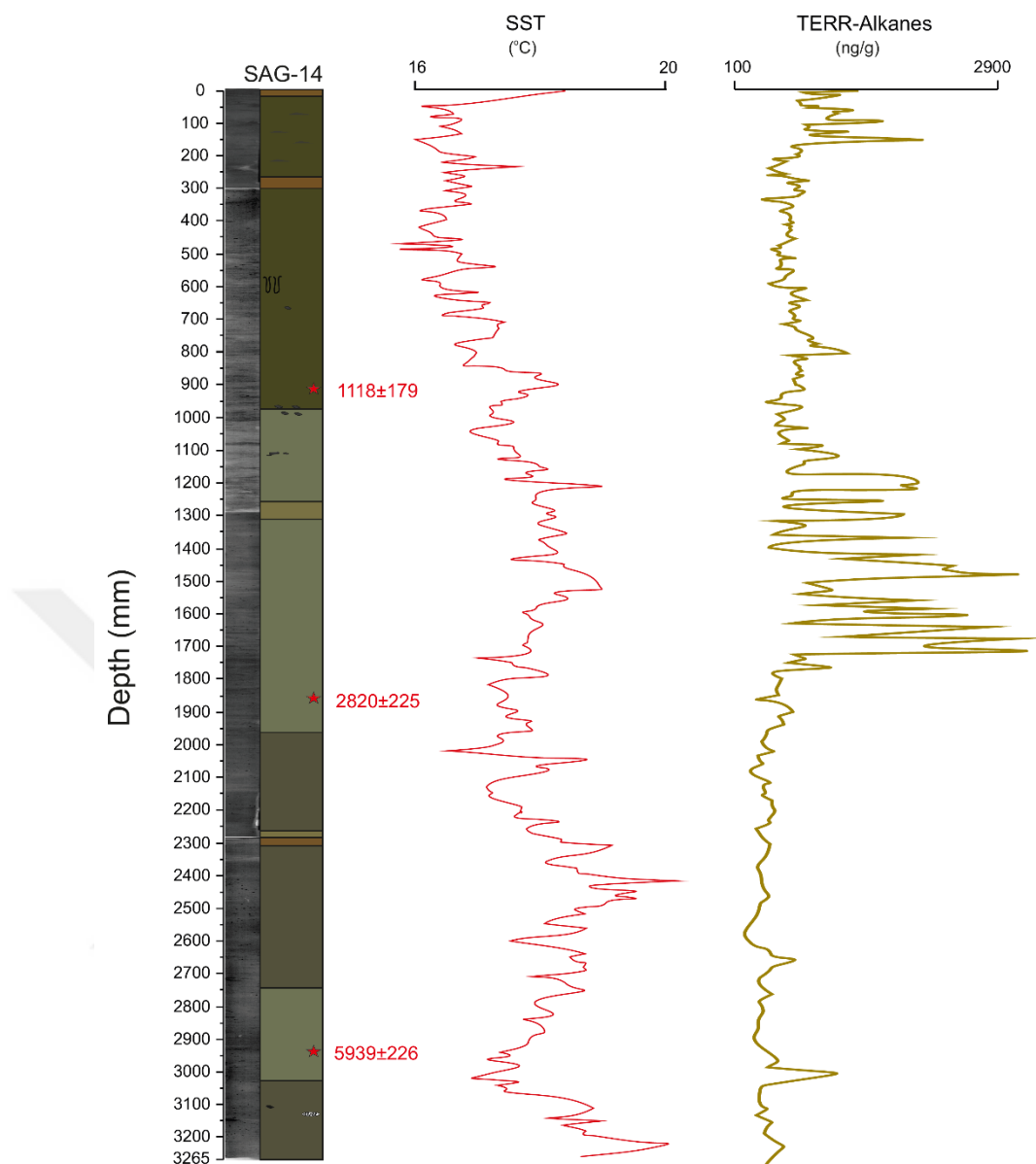


Figure 4.12 : The results of biomarker analysis performed on the core SAG-14. Sea surface temperature (SST) record and TERR-alkanes are derived from the C_{37} unsaturation index ($UK_{37} = C_{37:2} / (C_{37:2} + C_{37:3})$) by using the global calibration (Conte et al., 2006) displayed equation 4.3.



5. DISCUSSION

5.1 Paleoclimate and Paleohydrology

5.1.1 Pre-Holocene

Previous studies focusing on the last Glacial period and Holocene have shown that the Aegean Sea has been subjected to many long and short term variations 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). Small volume and geographical position of the Gulf of Saros together with the high sedimentation rates allow us to document the short term changes of reconstructions paleoclimate and paleohydrologic in the gulf. Moreover, the hydrological setting of the Gulf of Saros is controlled mainly by the high river discharges from the northern and southern catchment area and the regional climate conditions (Aksu et al, 1995).

In this thesis, three sediment cores from the gulf were examined following a multi-proxy approach that allows the identification and characterization of the paleoceanographic changes prior to the Holocene in the Gulf of Saros. This time interval is of particular interest because of the significant climate and paleoceanographic re-organization that presumably took place after the Last Glacial Maximum (LGM), such as Bølling-Allerød (B-A) and the Younger Dryas (YD). These pre-Holocene climate periods can only be documented in core SAG-22 covering the the last 14936 cal yr BP on the basis of the age-depth model (Figure 4.5, Figure, 5.1). Besides the geochemical analyses of the core, comparison of their records with the Sofular Cave $\delta^{13}\text{C}$ isotope data (Figure 4.5) provide much promising chronology of these past climate periods (B-A and YD).

In the Mediterranean region, significant climate variations during B-A oscillations and YD have been described (e.g., Cacho et al, 1999; von Grafenstein et al, 1999; Cacho et al, 2000; Cacho et al, 2001; Martrat et al, 2004; Sierro et al, 2005; Essalami et al, 2007; Martrat et al, 2007; Naughton et al, 2009; Sprovieri et al, 2012), demonstrating a strong link between the Mediterranean and North Atlantic climates, and with the monsoon regim (e.g., Sprovieri et al, 2012). According to the age-depth model of core

SAG-22 together with the main lithologic and geochemical changes, the Bølling-Allerød (B-A) took place in the gulf between 14800 and 12900 cal yr BP. This period corresponds to decreasing trend in MS value and higher proportions of clay and silt contents that are supported by higher K value in compare with the overlying YD period, implying higher detrital delivery to the gulf (Figure 5.1). Sediment dispersal at the core location in the gulf would have been controlled mainly by fluvial discharge rates and sea-level rise that determined the proximity of depositional basin to the river mouth, and by climate-induced changes in marine circulation. A decrease in MS values was recorded from core IZN09/LC2&LC3 between 15000 cal yr BP and the onset of the Younger Dryas in İznik Lake, coincident with the Bølling-Allerød (Roeser et al, 2012). Roeser et al. (2012) suggest that a decreasing trend MS value was related to the higher carbonate precipitation as suggested by the detrital input corresponding to high Ca/Ti. According to end-member modelling of the grainsize distribution on core GoeTü SL148 from the northern Aegean, providing discrimination between aeolian and fluvial transports of the sediments, Hamann et al. (2008) emphasized that the increase in the fine grain concentrations (EM3) are observed during the Bølling-Allerød (B-A) in the Aegean Sea and the Levantine Sea. Increased riverine influx of clay size sediments is associated with more humid climate condition during the Bølling-Allerød (B-A) (Neev and Emery, 1995; Severinghaus and Brook, 1999; Bar-Matthews et al, 2003; Hamann et al, 2008). Accordingly, the higher Ca/Ti values compare to the overlying YD period points to a higher carbonate-productivity due to an existence of relatively warmer and wetter climate. The increased wetness during this period (B-A) has also been documented from Sofular Cave at 14600 yr cal BP based on negative excursion of $\delta^{13}\text{C}$ values (Fleitmann et al, 2009). Bahr et al. (2005) also argued that Black Sea was experienced wetter climate and high paleo productivity during the B-A based on the gravity core GeoB 7608-1, displaying high Ca and low Ti/Ca accompanied with a decrease in grain size distribution. Palynological study based on the sediment core (GeoTü SL152; Figure 5.2) retrieved from the Mount Atos Basin in the northern Aegean Sea (Kotthoff et al, 2008) shows changes in environmental condition based on ratio of Arboreal type vegetation (AP; Figure 6.2) during the last 15000 cal yr BP. Since XRF-Ca/Ti ratio can be assumed to be very reliable paleo-proxy for the past climate change, comparison of its ratio in core SAG-22 with ratio AP in core SL-152 seems to be much consistent, supporting wetter climate during the B-A period in the northern Aegean Sea as well as the Gulf of Saros

(Figure 5.2). However, pollen record from Lake İznik indicates remarkable change in vegetation composition, suggesting warmer and moister climatic conditions for the Marmara region (Miebach et al, 2016). Almost highest Ca/Sr value in the same layer of the core indicate higher proportion of calcite deposition rather than aragonite due to a low salinity as a result of excess of fresh water in the gulf supplied from the surrounding catchment area. On the other hand, considerably high Fe/Mn value in the same interval of the core strongly indicates existence of anoxic or suboxic deep water condition at the core location in the gulf. Considering the water depth at this location (100 mbsl), such low oxygen content could not have been produced by a water stratification in the gulf, while global sea-level was around -110 m at the onset of the B-A. The most possible reason for decreased oxygen content may be explained by high organic productivity due to warm and wet climate, consuming the oxygen content in the water column. High proportion of marine organic matter is also explained by rising Br/Ti ratio during the B-A period. Our results are in agreement with findings of Khunt et al. (2007) in core SL-148 that after abruptly changing in faunal assemblage at approximately 16000 yr BP, *Brizalina dilatata* and *Bolivina variabilis* are situated in the northern Aegean Sea, implying a shift in deep-water oxygenation from oxic to dysoxic values and maximum oxygen reduction occurs between 14500- 1300 yr BP.

According to the core chronology of SAG-22, the YD period took place in the gulf between 12900 and 11800 cal yr BP, and is marked by an abrupt decrease in Ca/Ti, implying not a higher detrital input but a lower proportion of authigenic calcite due to decreased calcareous productivity during cold and dry climate. Such low calcareous productivity is compatible with a sharp decrease in Br/Ti ratio. Accordingly, comparatively low K value supports a lower detrital delivery to the gulf due to decreased precipitation during the YD. The Younger Dryas commonly is depicted as a reappearance of glacial conditions, with enhanced drought and an increment in global dust rates (e.g. Bottema, 1995; Gasse, 2000; Kohfeld and Harrison, 2001; Hamann et al, 2008). On the basis of findings of Hamann et al. (2008), the minor increase in aeolian influx based on end-member modelling and an increase in grain size distribution (EM1) display increasing dust rates and a diminish in riverine input of fine grain sediments in the Aegean Sea, leading to a short-term cold and dry conditions during the Younger Dryas. This situation could be observed in core SAG-22 by a

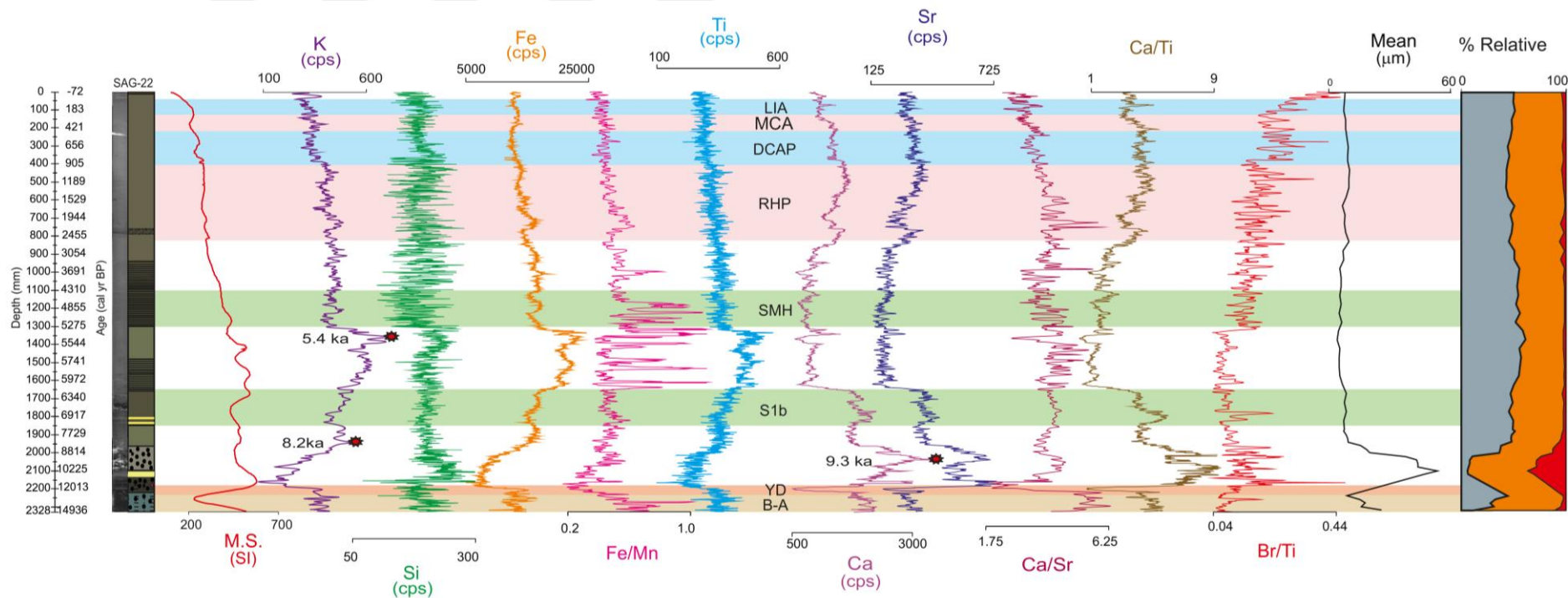


Figure 5.1 : Magnetic susceptibility (M.S.), μ -XRF geochemical element and element-ratio profiles (K, Si, Fe, Fe/Mn, Ti, Ca, Sr, Ca/Sr, Ca/Ti) and grain size parameters for core SAG-22. (LIA: the Little Ice Age, MCA: the Medieval Climate Anomaly, DCAP: the Dark Cold Ages Period, RHP: the Roman Humid Period, SMH: the Sapropel Mid-Holocene, S1b: the Eastern Mediterranean Sapropel S1b, Y-D: the Younger Dryas, B-A: the Bølling-Allerød).

slight increasing trend in grain size distribution and reduction in detrital input derived from riverine influx (e.g. low Ca/Ti). Accordingly, low ratio of AP in core SL152 together with high percentage of Chenopodiaceae (Kotthoff et al, 2008) indicates that YD period was considerably dry, supporting XRF-Ca/Ti record of core SAG-22 (Figure 5.2). The YD in the Eastern Mediterranean was expressed by the retreat of mesic forests and the spread of steppic vegetation, implying dry and cold climate conditions (Bottema, 1995; Rossignol-Strick, 1995). This climate period is known as cold and dry period from lake records elsewhere in Anatolia (Landmann et al, 1996, 2011; Wick et al, 2003; Robert et al, 2008; Jones et al, 2007; Litt et al, 2009; Çağatay et al, 2014; Eriş, 2013, 2018; Biltekin, 2018). Similarly, a positive excursion in ^{13}C isotope record of Sofular Cave indicate the retreat of trees and shrubs at the southern Black Sea coast since 12900 cal yr BP (Fleitmann et al, 2009). This period is recorded from the Marmara region as drier and/or cooler climate, resulting in decline of several trees and shrubs (Miebach et al, 2016). Such dry climate and the resultant high evaporation gave rise to higher aragonite than calcite as inferred from a low Ca/Sr in core SAG-22. In accordance with the results of SAG-22, gravity core GeoB 7608-1 recovered from the Black Sea displays low Ca, high Ti/Ca and increase in grain size distribution, leading to periods of cold conditions and reduced phytoplankton activity during the YD (Bahr et al, 2005). Moreover, global sea-level increased up to -65 m during the YD, and still stand sea-level took place at its termination (Figure 5.6), giving rise to formation of marine terraces as documented in the Sea of Marmara (Çağatay et al, 2003; Eriş et al, 2007 and 2011). Such a still stand sea-level may have given rise to deposition of coarsening-up sequence in the core as inferred from increases in grainsize and MS value. On the other hand, increased clastic sediment delivery with relatively coarse grains during the YD can be attributed to weak vegetation cover due to dry climate that may have possibly resulted in enhanced physical degradation over the catchment area of the gulf. Progressive decrease in Fe/Mn during the YD period implies existence of oxic deep water condition during the deposition that is attributed to intense deep water circulation at that time. According to Khunt et al. (2007), the reappearance of the *Brizalina dilatata* fauna in the northern Aegean (core SL148) and the increase in *Cassidulina crassa* fauna in the southern Aegean (core SL123) are evidence for bottom water oxygen in the overall the Aegean Sea during the YD. Sharp cooling of surface water and stable sea-level during the YD could have resulted in the formation of down welling that gave rise to strong water

circulation along the coastal region of the gulf. On the other hand, remarkable change in deep water ventilation might be expected during the increase of deglacial meltwater at 14700 cal yr BP (Termination 1a) (Rogerson et al., 2008). It is well known that the African monsoon regime would yield an impact on Mediterranean thermohaline circulation, affecting intermediate and deep-water formation as well as water column stabilization (Myers et al, 2003).

5.1.2 Holocene

The climate in the Holocene is defined as the time span between the termination of the YD and present, which was the final stadial of the last glaciation and ended about 11700 yr BP ago.

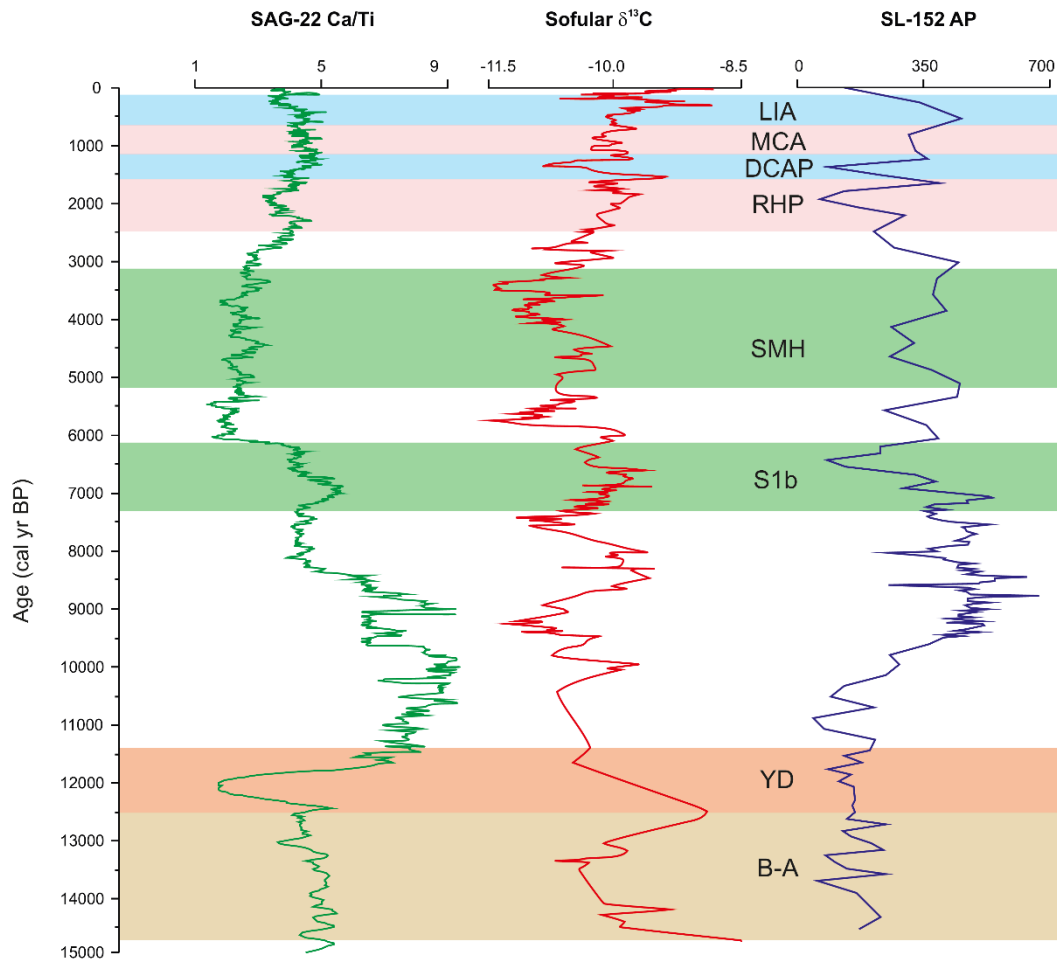


Figure 5.2 : Correlation between μ -XRF Ca/Ti profile and the Sofular Cave $\delta^{13}\text{C}$ together with the core SL-152 recovered from the North Aegean Sea. (LIA: the Little Ice Age, MCA: the Medieval Climate Anomaly, DCAP: the Dark Cold Ages Period, RHP: the Roman Humid Period, SMH: the Sapropel Mid-Holocene, S1b: the Eastern Mediterranean Sapropel S1b, Y-D: the Younger Dryas, B-A: the Bølling-Allerød, AP: arboreal pollen).

It was previously described as a climatically stable period (Dansgaard et al., 1993). This conclusion was in contrast with isotope record described in Mediterranean region, implying rapid climate variability including polar cooling, aridity, and changes in the intensity of atmospheric circulation (Casford et al, 2001; Rohling et al, 2009; Mayewski et al, 2004; Wanner et al, 2008). Nevertheless, recent studies from the Anatolian lakes show well-dated distinct climate variations during the Holocene (Landmann et al, 1996, 2011; Wick et al, 2003; Robert et al, 2008; Jones et al, 2007; Litt et al, 2009; Çağatay et al, 2014; Eriş et al, 2013, 2018; Miebach et al, 2016; Biltekin et al, 2018), although their amplitudes and timings are still under discussion. Marine and lake core records indicated that the winter precipitation signal was strongest in the northeastern Mediterranean during the early Holocene and that there was a drying trend in the Mediterranean from the early Holocene to the late Holocene, particularly in the east (Brayshaw et al, 2011a; Roberts et al, 2011).

Early to Mid-Holocene is only recorded in core SAG-22 based on the age-depth model, whereas mid-to-late Holocene is documented in cores SAG-14 and SAG-08. Low sedimentation rate in SAG-22 restricts the resolution of geochemical analyses through the core in order to define short term (centennial) climate and hydrologic changes in compared to other two deep sediment cores (SAG-14 and SAG-08). Nevertheless, very well promising matching of XRF-Ca/Ti data between core SAG-22 and others together with Sofular Cave ^{13}C isotope record (Figure 5.2) provide enough chronology of the core sediment for defining the main long lasting paleoclimate and paleohydrologic changes during the Holocene.

5.1.2.1 Early Holocene (11.500-8200 yr BP)

Transition from the YD to early Holocene at 11800 cal yr BP is represented by sharp changes nearly in all paleo-proxy data in core SAG-22 (Figure 5.1). The progressive increases in Ca/Ti and Ca values until 9000 cal yr BP reflect excess of authigenic calcite due to increased calcareous-productivity as a consequence of warming. This finding is supported by increased ratio in Br/Ti that is used as the ratio of marine/terrestrial organic matter (Mayer et al, 1981, 2007; Ziegler et al, 2008). The evidence of warming around 11000 cal yr BP compatible with the findings from cores SL152 (northern Aegean) and SL148 (southern Aegean) that indicate a shift to lighter values of the planktic $\delta^{18}\text{O}$ records (Kuhnt et al, 2007; Kotthoff et al, 2011). In

addition, such an abrupt warming at the onset of the Holocene is also documented by increased AP ratio in SL-152 core from the northern Aegean Sea (Figure 5.2) Kotthoff et al. (2008, 2011). However, on the basis of a rapid decrease in $\delta^{13}\text{C}$ of Sofular Cave record, an increase in effective moisture and a fast revegetation with trees and shrubs began at 11600 yr BP. Previous core studies from the Marmara and Black seas show that higher paleo-productivity was documented commonly during the warmer period and higher sea-level (Bahr et al, 2005; Çağatay et al, 2009, 2015, 2019).

In core SAG-22, sharp decreases in K, Fe, Ti and Si are recorded until 11100 cal yr BP, but lower than the B-A and YD periods. Although the earliest Holocene (~11700 and 9500 cal yr BP) is known as wetter based on various lake and marine records from the Mediterranean region including AP pollen record of core SL-152 and $\delta^{13}\text{C}$ values of Sofular Cave, this interval was interrupted by minor climate deterioration, known as “11.2 cal ka event” described from central Europe and the Mediterranean region (Hoek and Bos, 2007; Magny et al, 2007; Dormoy et al, 2009). The same short cold interface was also documented from the northern Aegean Sea as decrease in the detrital input that reveals a low mean annual temperature and low mean annual precipitation (Kotthoff et al, 2011). The one reason for a lower detrital delivery to the core location during this short time period (11800-11100 cal yr BP) might be a dense vegetation cover around the catchment area of the gulf due to wetter climate, limiting the detrital input as a result of lower physical degradation and erosion. Another possible reason could be the fast transgression and concomitant deepening based on the sea-level curve (Figure 5.6). Increases in the accommodation space on the coastal region gave rise to retreat of the clastic system further landward and restrain receiving terrigenous sediment to the core location. In the same interval of the core, sharp increase in Sr and decrease in Ca/Sr imply that the composition of the sediment is dominated by aragonite rather than carbonate. Ca/Sr ratio is used to discriminate between marine and terrestrial carbonates, with marine carbonates having relatively higher ratios than the terrestrial carbonates, because of the high concentration of Sr in seawater (Angino et al, 1966; Palmer and Edmond, 1992). Therefore, the fast marine transgression together with warmer climate, salinity in the gulf may have been raised, giving rise to enrichment of aragonite during the deposition. However, comparatively high ratio of Fe/Mn until 11100 cal yr BP may demonstrate suboxic to anoxic deep water condition due to water column stratification and increased marine organic productivity that might be related

to the fast Holocene transgression. This likely suggests that process driving the deep water formation in the Gulf of Saros was more sensitive even to smaller climate and sea-level changes, which in turn possibly affect the deep water circulation of the basin. On the other hand, higher MS value in the same interval of the core suggests the formation of Fe monosulfides during the diagenesis under the suboxic or anoxic deep water condition.

According to the paleo-proxy record of core SAG-22 (Figure 5.1), the time interval from 11100 cal yr BP until 8900 cal yr BP is marked by progressive increases in Ca/Ti and Ca/Sr, whereas Ca almost reaches its highest value at 9300 cal yr BP, implying elevated biogenic carbonate deposition due to an enhanced marine paleo-productivity as a result of increasing warming in compare to the onset of the Holocene. Such climate amelioration can be inferred from rising Br/Ti ratio. In the same interval of the core, increases in K, Ti and Fe, and particularly sharp rising grain-size and Si value, indicate increases in detrital input to the core location due to wetter climate. This conclusion is supported by progressive increases in AP pollen ratio recorded in core SL-152 and negative excursions in $\delta^{13}\text{C}$ values of Sofular Cave, implying increased precipitation from 11100 cal yr BP to 9300 cal yr BP (Figure 5.2). Increased river discharge to the gulf as a result of wetter climate might be gave rise to an active re-ventilation in the water column that is supported by low Fe/Mn ratio in compare to the earliest Holocene. The improved oxygenation would have promoted organic-matter degradation and post depositional oxidation (Thomson et al, 1999). During the same period, the reason for upward decrease in MS value might be related to high amount of carbonate fraction and organic matter. On the basis of the data from core NS-14, southern Aegean Sea adduces for increased freshwater input and higher productivity between 9900-9300 yr BP (Triantaphyllou et al, 2009b). Moreover, an increase in both deciduous and evergreen taxa between 9300-9000 yr BP in the Aegean Sea indicates the beginning of vegetation derived from warm and humid conditions in this time interval (Triantaphyllou et al., 2009b). On the other hand, between 11200 and 10200 cal yr BP, temporary increase in percentage of Spiniferites species and *L. machaerophorum* attest the high paleo-productivity in the Aegean Sea (cores SL152 and SL148) as these taxon exits under elevated sea-surface productivity (e.g. Wall et al, 1977; Combourieu-Nebout et al, 1998; Marret and Zonneveld, 2003).

According to paleo-proxy records in core SAG-22, the Boreal climate period between 8900 cal yr BP and 7300 cal yr BP is represented by higher values of K, Fe and Ti, implying increasing detrital input to the core location in the gulf. In the same period, Ca, Ca/Ti and Sr values indicate gradual decreases, but the most prominent changes took place after 8400 cal yr BP. Although Si value indicates slight decrease, there may be two possible reasons for such enrichment of lithogenic fractions in the core sediment; one is related to sea level change as discussed above, and other can be explained by regional climate affect. According to global sea-level curve of Siddal et al. (2003), this time period is associated with decreasing rate of sea-level rise with prevailing short periods of lowering. In this case, considering the water depth (between 20-30 m) at the core location during this period (8900-7300 cal yr BP), sediment delivery due to enhanced erosion along the coastal plain is assumed to be higher. Based on the findings of core NS-14 (southern Aegean Sea) Triantaphyllou et al. (2009b) emphasized that terrestrial environment displays slight increase of steppe vegetation between 8600-7600 cal yr BP derived from dry and relatively cold condition correspond to the interruption of S1 Sapropel. These conditions are supported by concurrent enhanced Chenopodiaceae, Artemisia, Ephedra and Olea accompanied with a decrease in deciduous Quercus, Pistacia and Pinus, indicating drier climate condition (Triantaphyllou et al, 2009b). $\delta^{13}\text{C}$ values of Sofular Cave indicate positive excursion during 8900-8400 cal yr BP, implying drier climate prevailed in the NW of the Anatolia. Similar trend is documented in pollen record of core SL-152 from the northern Aegean Sea. Therefore, such high delivery of detrital sediments during the first half of this period (8900-8400 cal yr BP) might have been consequence of decreasing global sea-level rise, rather than enhanced humidity. According to paleo-proxy record of core SAG-22, the subsequent period (8400-7300 cal yr BP) is considerable increases in Fe and Ti, whereas K value indicates remarkable shift at 8.2 cal ka BP. A positive shift in AP ratio of core SL-152 together with a negative trend in $\delta^{13}\text{C}$ values of Sofular Cave after 8400 cal yr BP indicate enhanced vegetation cover as a result of increased precipitation. Thus, the reason for the enhanced values of lithologic elements in the core might possibly be the result of rising precipitation or humidity between 8400-7300 cal yr BP. However, the same period is represented by abrupt decreases in Ca and Sr values together with Ca/Ti ratio, implying decreased carbonate production due to low marine organic productivity. This is supported by considerable decrease in Br/Ti ratio, supporting lower marine organic matter

production in the gulf after 8400 cal yr BP. Such circumstance in the water column can be linked to improved oxygenation as inferred from lowering Fe/Mn ratio in the core. Rohling and Pälike (2005) suggested that time interval between 8500-8000 cal yr BP is consistent to multi-century cooling associated with solar output fluctuations, including “8.2 ka BP event”. The same records are documented in speleothems from Soreq cave, Eastern Mediterranean (Bar-Matthews et al, 1999, 2000, 2003). On the other hand, based on the marine sediments, a decrease in the percentage of warm species indicate that the Sicillian Channel and Aegean Sea experienced cooler condition between 8500-8000 cal yr BP (Rohling et al, 2002; Sprovieri et al, 2003) in agreement with the findings of Triantaphyllou et al. (2009) in the southern Aegean Sea. This discrepancy might have been resulted from the location of the core SAG-22, which can be influenced by coastal region with enhanced drainage system.

5.1.2.2 Middle Holocene (8200-4200 yr BP)

The middle Holocene in the Gulf of Saros is recognized in the sediment cores by expression of the sapropel layer on the basis of sedimentologic observation. Accordingly, two different sapropel layers are identified in core SAG-22, which can be recognized as dark olive gray homogenous to laminated clays. Based on the age-depth model of the core, the lower one is dated between 7300 and 6100 cal yr BP. The similar age of sapropel layer was previously dated and defined as S1b from the northern and southern Aegean Sea (De Rijk et al, 1999; Geraga et al, 2000; Mercione et al., 2000, 2001; Roussakis et al., 2004; Casford et al., 2007; Gogou et al., 2007; Kontakiotis et al, 2009; Triantaphyllou et al, 2009a, b; Kontakiotis et al, 2012; Kouli et al., 2012). The tendencies of the same paleo-proxy records in the S1b layers in both cores SAG-22 and SAG-14 are almost consistent. This strongly indicates chronologic matches of these cores are well established. In contrast to core SAG-22, additional paleo-proxies are used in core SAG-14, which enable us to better document paleoclimate and paleoceanographic changes in the gulf (Figure 5.3). This time (7300-6100 cal yr BP) almost coincides with the base of the S1b sapropel in core SAG-14 based on the age-depth model, which is documented well by visual sedimentologic observation and TOC analysis of the core. The S1b layer in core SAG-14 is synchronous to the upper half of the same sapropel (between 6500-6100 cal yr BP) in core SAG-22. Although formation of these unique layers are discussed below in a

discrete chapter of this thesis, we aim to emphasize here the main paleoceanographic and paleoclimate condition during their formation in the gulf.

In core SAG-22, sapropel S1b is associated with abrupt increases in Ca and Ca/Ti, implying rising marine carbonate production due to warm climate prevailed during the S1b formation (7300-6100 cal yr BP). However, Fe/Mn ratio indicates considerably high value at the base of the S1b, then progressively decrease towards to top, although its intensity is still higher than the younger sapropel layer (SMH). This suggests that deep water condition became much oxic from 7300 cal ka BP to 6100 cal yr BP. In core SAG-22, MS and K, Si, Ti and Fe profiles demonstrate lower values until 6700 cal yr BP, then abrupt shifts to gradual increases towards to the top of S1b layer. Such trend in those paleo-proxies strongly suggests the climate much drier between 7300 and 6700 cal yr BP, then later increased precipitation took place until 6100 cal yr BP. This finding is also supported by lowering SST record in core SAG-14, implying sea surface freshening because of increasing river discharges during the same period (6700-6100 cal yr BP). The similar decreasing trend in SST record was also documented in core SL-152 from the northern Aegean Sea (Figure 5.5; Kotthoff et al, 2008), implying higher discharge rate from the surrounding catchment area due to wetter climate. It can be concluded that the climate presumably was drier at the onset of the S1b sapropel deposition until 6700 cal yr BP, than the later period possibly became much wetter. Moreover, Gogou et al. (2007) documented remarkable decrease in the SST during the deposition of S1, especially at the upper part of sapropel deposition in the North Aegean Sea (core MNB-3). A similar cooling conditions are identified in the different regions almost the same time such as Adriatic Sea between ~6800-6000 cal yr BP (Sangiorgi et al., 2003), the South Aegean between 8000-6500 cal yr BP (Geraga et al., 2005) and Ionian Sea at the age of 7000 cal yr BP (Geraga et al., 2008). In contrast, SST records from the southern Aegean (NS-14) and Marmara (KL-71) seas are almost opposite, implying different paleoclimate and paleohydrologic conditions prevailed in both different parts of the Aegean Sea.

Although mid-to-late Holocene is recorded in core SAG-22, sedimentologic and geochemical analyses in core SAG-14 retrieved from the deeper part of the gulf provide much precise paleoclimate record due to a higher sedimentation rate. However, considerable difference in the water depths of these studied cores reveals that paleohydrologic situations might have been considerably different during the

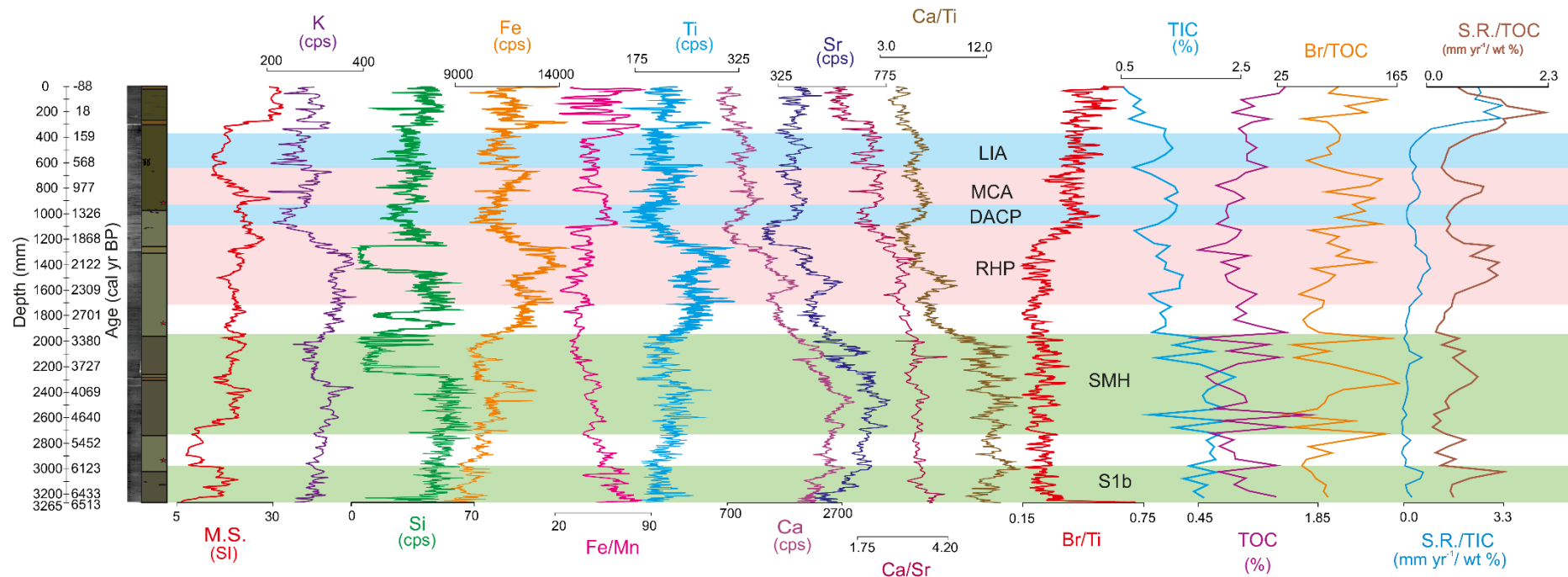


Figure 5.3 : Magnetic susceptibility (M.S.), μ -XRF geochemical element and element-ratio profiles (K, Si, Fe, Fe/Mn, Ti, Ca, Sr, Ca/Sr, Ca/Ti, Br/Ti, TIC, TOC, Br/TOC, S.R./TIC, S.R./TOC) for core SAG-14. Note that Br in cps and TOC is in wt % units. (LIA: the Little Ice Age, MCA: the Medieval Climate Anomaly, DACP: the Dark Cold Ages Period, RHP: the Roman Humid Period, SMH: the Sapropel Mid-Holocene, S1b: the Eastern Mediterranean Sapropel S1b).

same time period of deposition. Such discrepancy may possibly give rise to remarkable differences in lithologic and geochemical compositions of the cores. Although the top of the S1b sapropel in both cores (SAG-22 and SAG-14) is associated with abrupt changes in paleo-proxy records (Figure 5.1, Figure 5.3). Since the location of core SAG-22 might have been much close to the shore due to its lesser water depth, the intensity of changes in composition of some elements is comparatively strong. Thus, the multi-proxy data in core SAG-22 is the most sensitive regarding to environmental changes on the catchment area of the gulf.

The time period between termination of the S1b sapropel and onset of the middle Holocene sapropel (SMH) is dated as 6100-5300 cal yr BP in both cores (SAG-22 and SAG-14) based on the age-depth models of the cores. In core SAG-22, this period is associated with abrupt decreases in Ca, Ca/Ti and Sr due to low biogenic carbonate production as a consequence of decelerated organic productivity. The similar trend in those elements is also documented in core SAG-14. This finding is compatible with lower amount of TOC and Br/Ti ratio in core SAG-14, implying decreasing organic productivity and concomitant lower amount of marine organic matter in the gulf. In the same time period (6100-5300 cal yr BP), however, slight decreases in K, Si, Fe and Ti values are recorded in cores SAG-14, whereas and the same elements together with MS value in core SAG-22, reveals the existence of higher detrital input to the gulf. The reason for such conflict on the trend and intensity of those elements in both cores is that the shallower core SAG-22 would have been much sensitive to the clastic delivery due to its proximity to the coastal region at that time. According to pollen record of core SL-152, AP ratio in the same period is comparatively lower even strong fluctuation occurs, indicating diminished humidity around the northern Aegean Sea (Kotthoff et al, 2008). The small rising SST record in core SAG-14 supports existence of drier climate during 6100-5300 cal ka BP. The same period is marked by improved oxygenation as inferred from gradual decrease in Fe/Mn ratio in core SAG-14. Triantaphyllou et al. (2009b) proposed that between 6400-5200 cal yr BP is described as a decrease in temperature and precipitation which is represented by enhanced steppic elements such as *Chenopodiaceae* and *Poaceae* accompanied with decrease in deciduous *Quercus* and *Picea*. A dry phase is recorded in the Eastern Mediterranean after 6600 yr BP (Roberts et al, 2011) whereas the forest withdrawal in İznik region took place about 6500 cal yr BP (Miebach et al, 2016). Based on isotope records, SW

Anatolia displayed drier climatic conditions from 6000 to 5300 yr BP (Eastwood et al, 2007). Prior to the SMH deposition, abrupt decreases in MS, K, Fe, Si and Ti values imply reduced detrital input to the gulf due to short period of dryness prior to 5300 cal yr BP (Figure 5.3).

Deposition of the middle Holocene Sapropel (SMH) in the gulf took place between 5300 cal yr BP and 3200 cal yr BP based on the age-depth models of cores SAG-14 and SAG-22. In addition to two cores, core SAG-08 includes the SMH layer at the base of core dating from ~3600 cal yr BP. This time period is well consistent with the deposition of upper Holocene sapropel in the Sea of Marmara (Çağatay et al, 2000; Tolun et al, 2002), whereas the termination of this peculiar layer was previously dated at 4300 cal yr BP in the core studied from the northern Aegean Sea (Kouli et al, 2011; Triantaphyllou et al, 2014; Kontakiotis et al, 2016). In compare to core SAG-22, the paleo-proxy record in core SAG-14 provides remarkable changes with better resolution. Considering decelerated the global sea-level during the SMH deposition in the gulf, the S.R. might have been much slower with decreasing water depth, since the available accommodation space restricts for further sedimentation along the coastal part in compare to the deeper basin. The calculated sedimentations rates for those studied cores reveal that the sedimentation rate during the SMH deposition (5300-3200 cal yr BP) was around 0.37 mm/yr in core SAG-14 and 0.18 mm/yr in core SAG-22, implying twice S.R. in the deeper basin of the gulf.

The SMH layer in core SAG-22 can only be defined by a visual lithologic observation together with chronologic matching with core SAG-14. The onset of the SMH in the core is recognized by abrupt increase in Br/Ti ratio that continues to increase gradually upward, implying enhanced production of marine organic matter at the onset of the SMH deposition. In core SAG-14, the slight increases in K, Si, Ti and Fe values in the SMH layer is documented until 4200 cal yr BP as well as in core SAG-22. In the same part of the SMH layer (5300-4200 cal yr BP), the rising $\delta^{13}\text{C}$ values of Sofular Cave (Fleitmann et al, 2009; Figure 5.4) and decreasing amount of AP ratio in core SL-152 (Kotthoff et al, 2008; Figure 5.4) indicate that the climate was drier at the onset of the SMH deposition. This conclusion is supported by the elevated SST in core SAG-14 that reaches its maximum value at 4200 cal yr BP, implying warming up of the surface layer or diminished freshwater discharge into the gulf. Rohling et al. (1997) and Triantaphyllou et al. (2009b) claimed that the presence of high amount of *G. sacculifer*

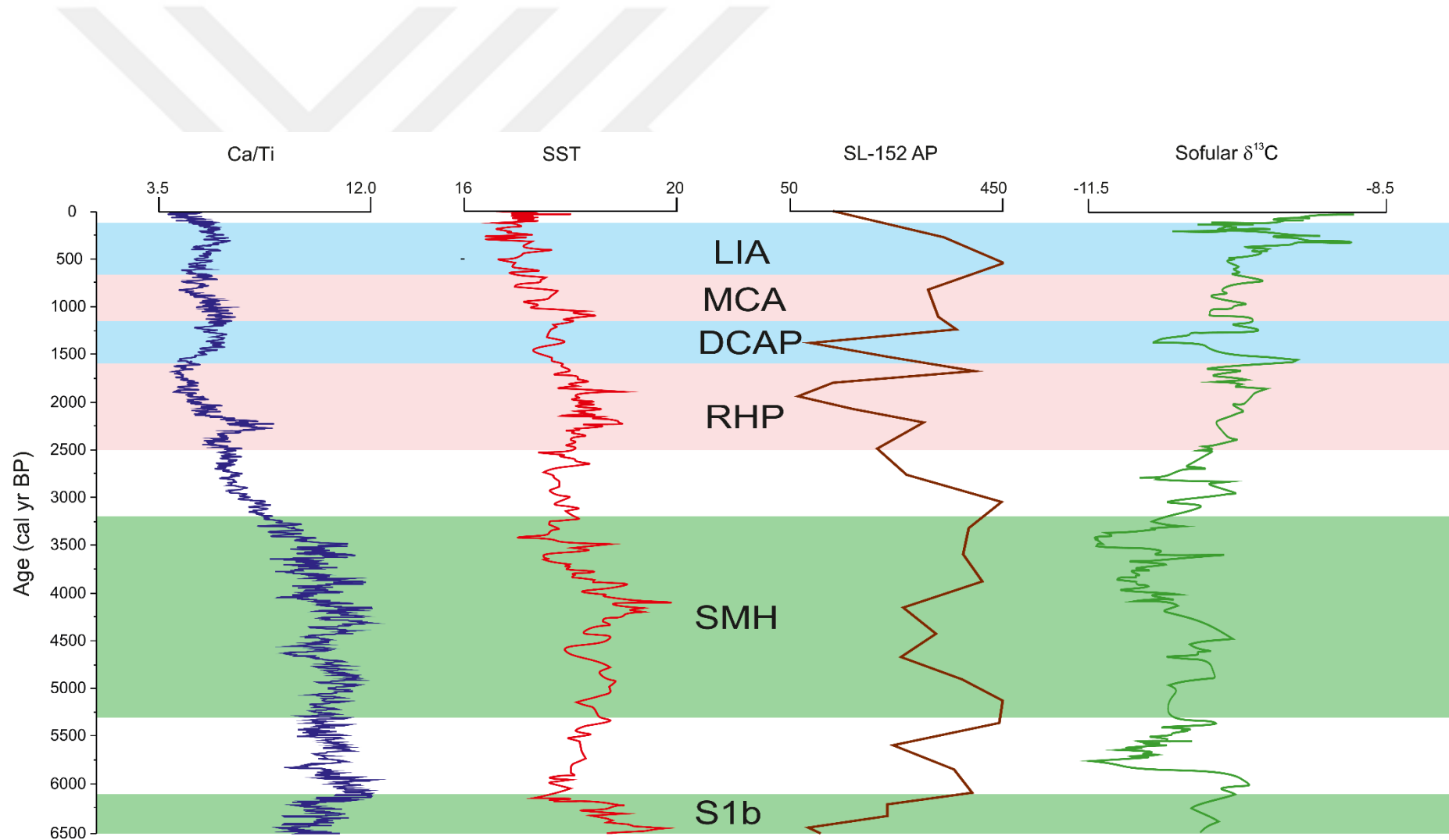


Figure 5.4 : μ -XRF Ca/Ti and SST record of core SAG-14 are correlated with the core SL-152 and Sofular Cave $\delta^{13}\text{C}$. (LIA: the Little Ice Age, MCA: the Medieval Climate Anomaly, DCAP: the Dark Cold Ages Period, RHP: the Roman Humid Period, SMH: the Sapropel Mid-Holocene, S1b: the Eastern Mediterranean Sapropel S1b, Y-D: the Younger Dryas, B-A: the Bølling-Allerød, AP: arboreal pollen).

and the existence of *T. quinqueloba* indicate elevated freshwater input in the Aegean Sea in this time interval. Our findings are in agreement with the results derived from core NS-14 of Triantaphyllou et al. (2009b) based on the foraminiferal paleoclimatic curve. They claimed that the time interval between 5200 and 4200 cal yr BP is characterized by an increase deciduous *Quercus*, *Abies* and *Picea* together with a decrease in *Chenopodiaceae* and *Artemisia*, leading to very humid and warm conditions. The most elevated values of K, Ti, Si and Fe during the SMH deposition are recorded between 4200-3900 cal yr BP displaying the enhanced precipitation due to wetter climate condition. This time (4200-3900 cal yr BP) coincides with lowering $\delta^{13}\text{C}$ values of Sofular Cave (Fleitmann et al, 2009) and rising AP ratio in core SL-152 (Kotthoff et al., 2008), supporting existence of enhanced humidity during this time. Such climate condition would have induced surface freshening in the gulf as inferred from rapid decrease in SST record of core SAG-14 after 4200 cal yr BP.

5.1.2.3 Late Holocene (4200 yr BP-present)

The time interval between 4200-3200 yr BP is in response to 4.2 ka BP event (Kuzucuoğlu and Marro, 2007; Kuzucuoğlu, 2007, 2009; Mayewski et al, 2004; Kaniewski et al, 2018). Although 4.2 ka BP event is generally known as global mega-drought episode (Bond et al, 1997; Eastwood et al, 1999; Wick et al, 2003; Kuzucuoğlu and Marro, 2007; Mayewski et al, 2004), the Aegean Sea could have been excluded from this generalization. According to Bini et al. (2019), the Aegean Sea does not experience drier conditions during the “4.2 ka BP event”. Our results attest accuracy of Kotthoff et al. (2008) and Bini et al. (2019) that the borderlands of the Aegean Sea display wetter condition synchronously with 4.2 ka BP event. Although the SST values progressively declined until the termination of the SMH deposition (3200 cal yr BP), abrupt decreases in K, Ti, Fe and Si values are documented after 3900 cal yr BP can be explained by extensive vegetation cover around the catchment area, restricting the detrital sediment delivery to the gulf. This finding is also supported by the abrupt decrease in the SST record after 4200 cal yr BP (Figure 5.5) that attest to beginning of sea surface cooling in the gulf. In the SMH layer in core SAG-14, strong fluctuation in Ca/Ti, Ca and Sr values strongly indicate the high frequency oscillations in marine carbonate between 5300 cal yr BP and 3200 cal yr BP. During the SMH deposition the general upward decreases in Fe/Mn values in core SAG-14 demonstrate that the deep water condition changed from anoxic to suboxic, possibly due to enhanced freshwater

discharges as a consequence of wetter climate after 4200 cal yr BP. Such climate change to much humidity at this time corresponds to similar shift in the SST record obtained from the Sea of Marmara (SoM), indicating sea cooling in both different basins. Considering the Marmara and Black seas connection after 4500 cal yr BP (Çağatay et al, 2000; Algan et al, 2001; Eriş et al, 2011), such freshening in the SoM might have been provided by the Black Sea connection, whereas the same outflow into the Aegean Sea was previously reported by Çağatay et al. (2000) Algan et al. (2001) and Eriş et al. (2011). The sudden sea surface freshening of the gulf as inferred from progressive decline in SST record in core SAG-14 may be attributed to such Black Sea connection, rather than regional climate effect on the surface water temperature.

The termination of the SMH deposition in the gulf is recognized by marked decreases in Ca/Ti, Ca and Sr until the onset of the Roman Period at 2500 cal yr BP. Such declines in those elements can be attributed to diminished marine carbonate production in the gulf. Although slight increases in K, Ti, Si and Fe values are recorded during this earlier period (3200-2500 cal yr BP), rising $\delta^{13}\text{C}$ values of Sofular Cave and lower amount of AP ratio in core SL-152 (Kotthoff et al., 2008) indicate existence of drier climate condition, whereas slight SST rising in core SAG-14 suggests sea surface warming as a result of this dryness in the gulf.

The beginning of Roman Period between 2500 and 2200 cal yr BP, comparatively low values in K, Fe and Ti are recorded, implying a low detrital delivery to the gulf as a result of existence of drier climate. On the other hand, gradual increases in Ca/Ti, Sr and Ca values demonstrate enhanced biogenic carbonate production due to warming up at the beginning of the Roman Period. Evidence of such warm and dry climate is documented by rising SST record in core SAG-14 and lowering amount of AP ratio in core SL-152 (Kotthoff et al, 2008) together with higher $\delta^{13}\text{C}$ values of Sofular Cave. The most remarkable change in paleo-proxy record during the Roman Period is obscured between 2200 cal yr BP and 1950 cal yr BP, when the abrupt increases in K, Ti and Fe values are recorded, implying higher detrital input to the gulf due to wetter climate. This time also coincides with the highest sedimentation rate recorded in the Roman Period. The existence of wetter and warmer climate during the same period is also discernable from rising amount of AP ratio in core SL-152 (Kotthoff et al, 2008) together with negative excursion in $\delta^{13}\text{C}$ values of Sofular Cave (Figure 5.4). In the Roman Period between 1950 and 1650 cal yrs BP, considerable decreases in K, Fe, Ti

and Si values attest likely to lowering detrital input. On the other hand, the almost lowest Ca/Ti, Ca/Sr, Ca and Sr values suggests low marine carbonate production during the drier later phase of the Roman Period (1950 cal yr BP and 1650 cal yr BP). In the same period SST record indicates lowering values, implying sea surface cooling rather than freshening. In the same period, the reason for enhanced Br/Ti value can be considered as a result of considerable low value of Ti element, rather than increased marine organic matter. These overall records reveal that the climate was cool and dry during the latest phase of the Roman Period. This period as a whole is associated with general rising tendency in Fe/Mn ratio. This finding indicates that deep water condition became much anoxic through the time in the gulf.

In the latest Holocene, the Dark Age Cold Period took place in the gulf between 1600 cal yr BP and 1150 cal yr BP based on the age-depth model of core SAG-14. This period is mainly represented by diminished values in K, Fe, Si and Ti, whereas Ca and Sr values together with Ca/Ti ratio is highly accelerated in compare to the latter phase of the Roman Period. These finding are documented as the similar trend in core SAG-14 corresponding to the DCAP at the same time interval. Such paleo-proxy record demonstrates that detrital input to the gulf was considerably decreased in contrast to marine carbonate production. This conclusion is supported by elevated Br/Ti ratio in the same core. On the other hand, this period is marked by general decreasing trend in SST, implying sea surface cooling as a result of dominant dry climate during the Dark Age period. This finding is supported by lower amount of AP ratio in core SL-152 (Kotthoff et al., 2008) in contrast to the same record from İznik Lake (Miebach et al, 2016), which also conflict with a negative excursion in $\delta^{13}\text{C}$ values of Sofular Cave. Considering the cold and dry climate during the Dark Age Cold Period and nearly stable the global sea-level, formation of an anoxic deep water condition as inferred from abrupt increase in Fe/Mn is unusual, although the Black Sea connection with the gulf would have possibly created the water stratification that in turn gave rise to such anoxic deep water condition. According to the age-depth model and paleo-proxy record of core SAG-14, the Medieval Climate Anomaly took place between 1150 cal yr BP and 670 cal yr BP. This period is mostly marked by considerable decrease in SST record with strong fluctuations in core SAG-14 that could be attributed to the enhanced sea surface cooling in the gulf. The similar SST trends are recorded in core SL-152 from the northern Aegean Sea (Kotthoff et al, 2008) and in core GeoTü-KL71

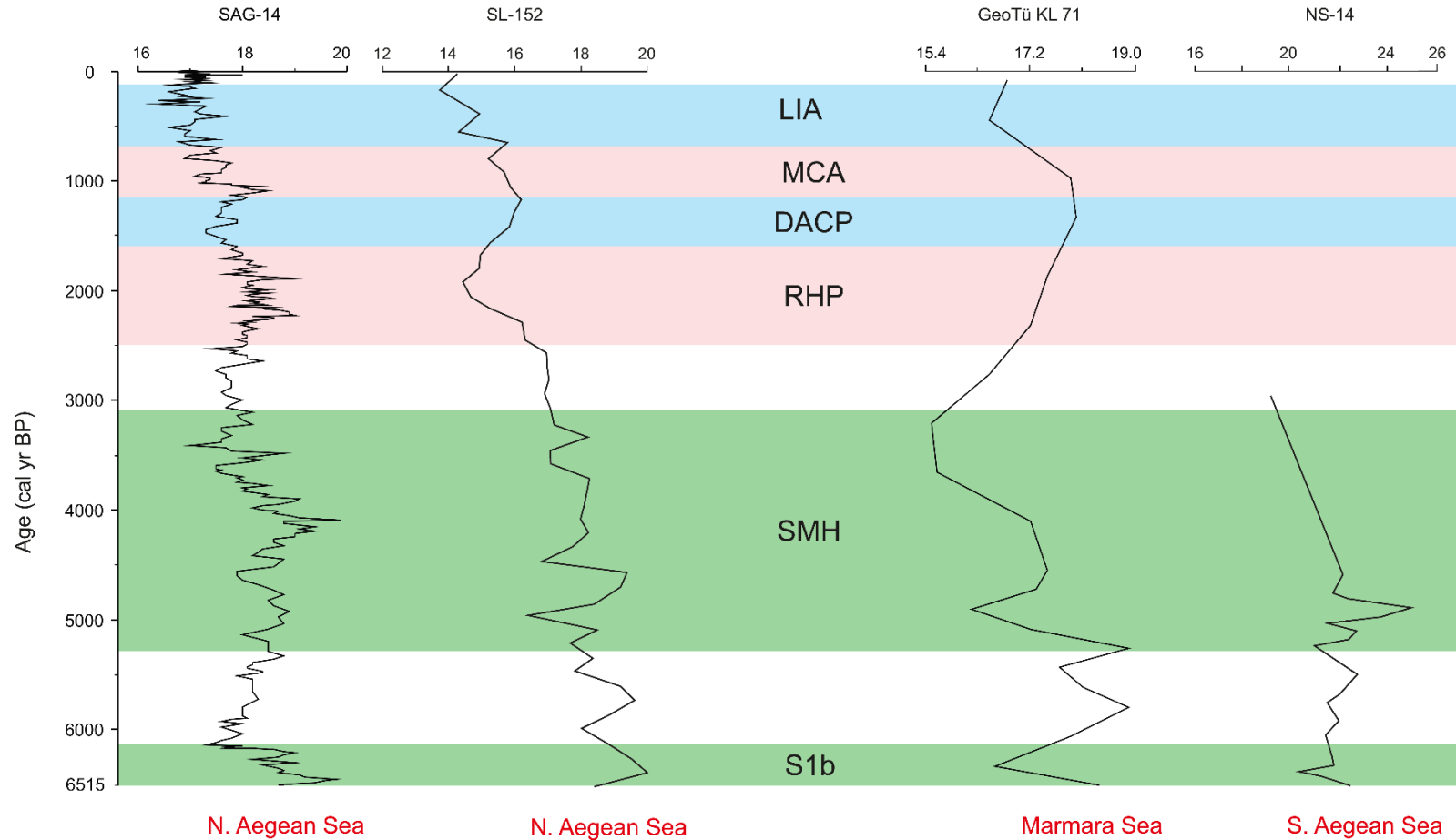


Figure 5.5 : Sea surface temperature profiles of cores SAG-14 and SL-152 (Kotthoff et al., 2008) from the north Aegean Sea, core GeoTü KL71 (Sperling et al., 2003) from the Sea of Marmara and core NS-14 (Triantaphyllou et al., 2014) from the south Aegean Sea.

from the Sea of Marmara (Sperling et al, 2003), implying overall sea surface cooling in both different basins. On the other hand, the same period is also associated with almost higher values in Ca, Sr and Ca/Ti, implying marine carbonate production due to warmer and wetter climate in core SAG-14. However, the remarkable excursion in Ca/Sr ratio attest an existence of decrease in sea water salinity as in core SAG-14. Pollen record in core SL-152 (Kotthoff et al, 2008) that displays considerable rising in AP ratio, implying extensive vegetation cover during the Medieval Climate Anomaly. Moreover, Roberts et al. (2012) recorded a wetter climate condition during the MCA. Kuzucuoğlu (2011) described the MCA as a dry/wet alternation since the first period of the MCA (1130-1100 yr BP) persisted dry condition due to the summer temperature whereas the latter part of the period displayed enhanced rainfall and cooler temperature until 800 yr BP. According to the age-depth model of core SAG-14, the Little Ice Age (LIA) covers the time period from 670 cal yr BP until 150 cal yr BP. This last climate period is remarkable mostly by abrupt decreases in K, Ti, Si and Fe, implying lowering detrital input to the gulf. According to the SST record in core SAG-14, first half of this period until 300 cal yr BP is mainly represented by high values in compare to the latter half due to much drier climate. As LIA period is known as cold period elsewhere from the Europe and Anatolia, lower values of lithogenic proxies (K, Fe, Si and Ti) together with SST record attest existence of cold but dry climate at least during the first half of the LIA. Its latter half until 150 cal yr BP in core SAG-14 is recognized by higher values in K, Ti, Si and Fe, whereas Ca value and Ca/Ti and Ca/Sr ratios are high in compare to the first half. These findings together with an abrupt cooling SST record in the core reveals that the climate during the later period of the LIA was presumably colder and wetter climate. The similar conclusion is supported by negative excursion in $\delta^{13}\text{C}$ values of Sofular Cave, implying wetter condition. In contrast, pollen record from core SL-152 indicates diminished amount of AP. The reason for lower vegetation cover can be explained by intense deforestation due to human impact for the last 150 cal yr BP. The humidity conditions are evidenced by precipitation curve from Soreq Cave (Bar-Matthews et al, 1998) and mineralogy and grain-size distribution from Tecer Lake between 380-200 yr BP (Kuzucuoğlu, 2011) whereas Nar Gölü is represented by dry condition until the termination of the LIA (Jones et al, 2006). Jones et al. (2006) suggested that this discrepancy in Nar Gölü is derived from major effect the North Sea-Caspian Sea climatic system. According to Wick et al. (2003), Turkey is characterized by a decrease of woodland resulted from human activity for the last 600 yr. Furthermore, pollen records from the Aegean Sea pointed out to deforestation in the southern Europe in the same interval (Aksu et al, 1995).

5.2 Formation of Holocene Sapropels (S1 and SMH)

5.2.1 Definition from Adjacent Seas

Sapropels were described as organic-rich, dark-colored layers by Kidd et al. (1978), who studied sapropel layers in cores recovered from the Eastern Mediterranean, and gave the first definition of these layers: “a discrete layer more than 1 cm thickness, set in open marine pelagic sediments and containing greater than 2% organic carbon by weight”. A less restrictive definition for sapropels was given by Hilgen (1991): brownish, often laminated deposits that are interbedded with more marl sediments. Sapropel deposition requires substantial modifications within the surface and bottom waters, which are thought to have occurred in response to changes in the local hydrographic regime and biogeochemical cycling linked to global and regional climatic variations (Rohling et al, 2004). The sapropel layers record episodes of elevated organic matter deposition and the concomitant production and preservation under conditions very different from those prevailing today. Sapropels often display obvious sub-millimeter to millimeter-scale lamination. This is especially the case for sapropels from areas with enhanced sediment accumulation rates, such as occasional ones in marine cores (e.g., Moller et al, 2012). This lamination may represent preserved original sedimentary lamination, due to a lack of bioturbation. This agrees with observations that sapropels are commonly marked by an absence of benthic foraminifera, which suggests persistent sea-floor anoxia (Rohling et al, 1993b; Nijenhuis et al, 1996; Rohling et al, 1997; Jorissen, 1999; Casford et al, 2003; Schmiedl et al, 2010).

The eastern Mediterranean has been the subject of a larger number of geochemical studies than the western Mediterranean, mainly focused on the origin of sapropels. They are organic-rich sediments were cyclically deposited as a result of the combination of climatically induced increases in primary productivity and changes in bottom- water oxygenation (e.g., Calvert et al, 1992; Emeis et al, 2000a; Meyers and Arnaboldi, 2005; Rohling et al, 2006). Sapropel 1 is the most recent sapropel, deposited during the Holocene and hence the most easily retrieved and accurately dated. Therefore, it has been studied in great detail and its features have been linked directly or indirectly to processes taking place in the water column, as well as in the sediments. Reduced oxygen supply to bottom waters has been suggested to be a precondition for sapropel formation although increased biological productivity further promoted S1 formation (Bianchi et al, 2006; Meyers et al, 1998; Rohling, 1994; Stratford et al, 2000). In a commonly accepted model, recurrent Mediterranean sapropel formation is attributed to a stratified water column

and anoxic deep water conditions that developed as a consequence of enhanced fresh water inputs (Rossignol-Strick et al, 1982; Rohling, 1994; Emeis et al, 2000). Therefore, surface water density decreases due to excess freshwater inputs have played an important role in reducing Mediterranean Sea thermohaline circulation during sapropel formation (Myers et al, 1998; Rohling, 1994; Stratford et al, 2000). The influence of a freshwater source, possibly Black Sea outflow, has been estimated to be minor, since the time of the Black and Mediterranean Sea connection (9000–8000 cal yr BP; Soulet et al, 2011; Vidal et al, 2010) was later than the onset of S1 deposition.

On the other hand, the sapropel formation in the Mediterranean is believed to have been controlled by sea level rise and precession minima with the former causing preconditioning and prevention of deep water formation, and the latter enhanced monsoon intensity and runoff from North Africa, resulting in density stratification and stagnation (Rohling et al, 2015). Stable oxygen isotopes, faunal/floral assemblages, and pollen records from the Mediterranean region documented existence of the general warming in the onset of the S1 deposition (e.g., Aksu et al, 1995a; Emeis et al, 2000; Geraga et al, 2000; Casford et al, 2003; Giunta et al, 2003). This warming trend reflects the changing regional climatic conditions in which the Eastern Mediterranean became warmer and more humid into the Holocene Climatic Optimum following the cooler/drier Younger–Dryas. Deposition of S1 sapropel in the Mediterranean Sea was dated between 10800–6100 cal yr BP (De Lange et al, 2008). Sapropel S1 exhibits the same characteristics as the older sapropels and therefore it has been used as diagnostic for other sapropels.

Sapropel S1 formation did not take place under a stable, persistently anoxic environment, but fluctuations in the oceanographic regime as a whole occurred repeatedly, interrupting the accumulation of high amounts of organic matter. Its development has been linked to cold and dry air masses acting from Northeast Europe (Rohling et al, 1997; 2002; Mercone et al, 2000; Rohling and Palike, 2005). Despite its short duration of 200 years, the 8.2 cal. ka BP event that is included in the S1 interval, has been preserved explicitly in marine and terrestrial records. The significant lowering of the organic matter content manifests the resumption of bottom-water formation in both Aegean and Adriatic Seas (Rohling et al, 1999; De Rijk et al, 1999; Crasford et al, 2003; Kuhnt, et al, 2007; Kothoff et al, 2008; Schmiedl et al, 2010; Siani et al, 2010). The end of the sapropel formation in the Eastern Mediterranean is marked with the re-establishment of oligotrophic conditions, similar to present (Kuhnt et al, 2007; Kothoff et al, 2008).

The sapropel deposition in the SoM appears to have been triggered by marine flooding events, the timing of which is determined by the rate of sea level rise and the sill depth of the connecting shallow straits of Bosphorus and Çanakkale (Dardanelles) at the time (Çağatay et al, 2009, 2015). The marine flooding of the fresh-brackish basins of the SoM and Black Sea would cause a density stratification of the water column, decreased renewal of deep waters and increased organic matter preservation, all leading to the sapropel formation (Çağatay et al, 2009, 2015). The formation of sapropels in the SoM being earlier than those in the Mediterranean sapropels does not necessarily indicate a causal link between the Black Sea outflow and the sapropel formation in the Eastern Mediterranean, as claimed by some earlier studies (Olausson, 1991; Aksu et al, 1995). Instead, the differences in timing of the sapropel deposition in the silled SoM and Black Sea marginal basins, relative to those of the quasi-equivalent Mediterranean sapropel, are likely related to timing of establishment of the suboxic/anoxic bottom water conditions, which would in turn be controlled by the sill depth of the connecting shallow straits, rate of primary productivity, the rate and extent of sea level rise, and the size and depth of the basins. The Holocene lower and upper sapropel units in the SoM have been previously radiocarbon dated at 10600–6400 ^{14}C yr BP (ca. 11100– 6900 cal yr BP) and 4750–3200 ^{14}C yr BP (ca. 5.0–3.1 cal ka BP), respectively (Çağatay et al, 1999, 2000; Tolun et al, 2002).

5.2.2 Aegean Sea and the Gulf of Saros

S1 sapropel layer appears at multiple sites in the Aegean Sea, where it represents a period of elevated organic matter accumulation during a period of wetter climate that persisted from about 9500 yr to 6000 yr BP (Perissoratis and Piper, 1992; Aksu et al, 1995a; Geraga et al, 2000; Merccone et al, 2000, 2001; Roussakis et al, 2004; Gogou et al, 2007; Triantaphyllou et al, 2009, 2014; Gogou et al, 2016). However, in the Aegean Sea, S1 is found at (modern) water depths as shallow as 120 m (Perissoratis and Piper, 1992), which implies only about 80–110 m water depth at the onset of deposition (e.g., Siddall et al, 2003). Moreover, the comparison of the north and south Aegean records shows significant changes in both the productivity and stratification of the upper water column during S1 deposition. The SST record from the North Aegean Sea shows that the cool interval of S1 interruption is coeval with a marked decrease of TOC contents (Geraga et al, 2000; Merccone et al, 2000; Gogou et al, 2007; Kotthoff et al, 2008; Triantaphyllou et al, 2009b; 2014). Thus, the Holocene sapropel (S1) has been differentiated into two parts; S1a and S1b that are well dated from the Aegean Sea (De Rijk et al, 1999; Geraga et al, 2000; Merccone et al, 2000, 2001; Giunta et al, 2003; Roussakis et al, 2004; Casford et al, 2007; Gogou et al, 2007; Kontakiotis et al, 2009; Triantaphyllou et al, 2009a, b;

Kontakiotis et al, 2012; Kouli et al, 2012). The reason for such interruption could be related to different preservation rates of organic material due to intermittent ventilation to greater depths (Casford et al, 2003). They were rather short-lived and did not give rise to well expressed “interruptions”, but they may have had important impacts on hydrographic and ecosystem processes throughout deposition of the S1 sapropel in the Aegean Sea. The comparison of present oceanographic settings of the Saros Gulf with rest of the Aegean Sea may allow us to examine definition of the Holocene sapropel, including its timing and source during changing paleoclimate and paleoceanographic conditions in the gulf. For this purpose, two sediment cores are studied to analyze for investigating the Holocene sapropels together with prevailed paleoceanographic setting during their formations.

The whole S1b layer is only documented in core SAG-22 due to its older age recovery. Nevertheless, the oldest Holocene sapropel S1a (~9.6-8.2) in the Northern Aegean Sea could not be documented in core SAG-22 (Figure 5.1) due to its very shallow core location, while deposition of a sapropelic layer requires a particular paleohydrologic situation that needs a significant increase of water depth in order to extent of the thermocline in the water column (Calvert and Fontugne, 2001; de Lange et al, 2008; Rohling et al, 2009). In marine cores from the Levantine, Ionian and Aegean Sea basins the organic-rich S1 sapropel layer exists below ~300 m water depth, whereas the lower Holocene sapropel from the Sea of Marmara could not be documented in the sediment cores having water depth less than 100 m (Çağatay et al, 2009).

Based on the age-depth model of the core SAG-22, the S1b sapropel was deposited in the gulf between 7300 cal yr BP and 6100 cal yr BP. Based on the age-depth model together with TOC analysis in core SAG-14, only the upper half of S1b sapropel is well documented, covering the last 400 yrs of this sapropel deposit. The onset of the S1 sapropel coinciding with between 7600-6900 cal yr BP in the southern Aegean is characterized by an increase deciduous *Quercus* and *Pinus* together with an abrupt decrease in *Chenopodiaceae* and lack of *Artemisia*, implying a humid period at the base of the sapropel whereas a decrease in *G. ruber rosea*, *O. universa* and *G. rubescens* in response to the decrease of warm condition is revealed after 6900 cal yr BP which leads to the cessation of sapropelic layer (Triantaphyllou et al, 2009b). There is 300 yr BP lag between our data and Triantaphyllou et al. (2009b) in terms of the onset and cessation of S1b sapropel and associated with changes in climatic condition. Combined plankton data from suggested that climate cooling occurs before the termination of the S1b sapropel.

According to the TOC analysis in core SAG-14, TOC ratio in the upper half of the S1b sapropel ranges between 0.70 % and 1.42 % (Figure 5.3). This percentage is considerably low with com-

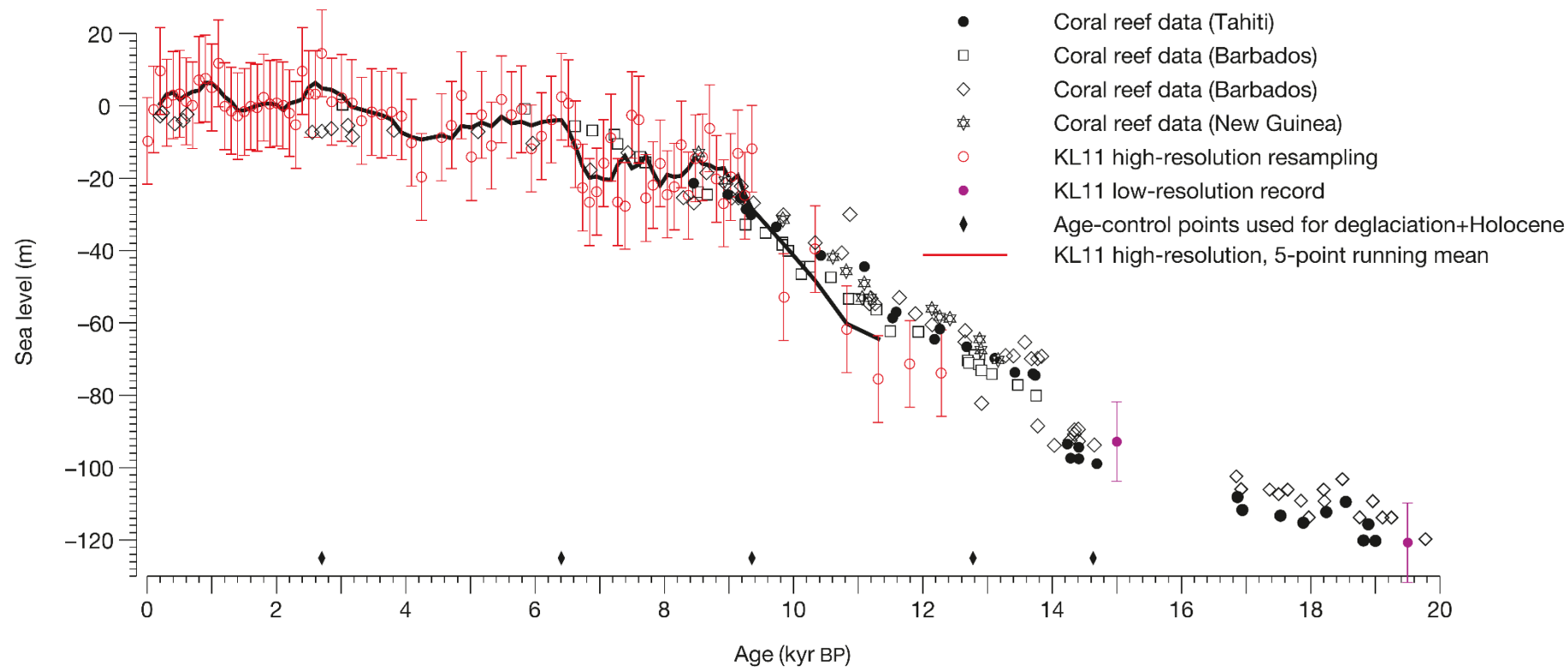


Figure 5.6 : Sea-level curve derived from core KL11 based on the $\delta^{18}\text{O}$ record (adapted from Siddall et al., 2003).

pare to the SMH (0.50 % and 1.81 %) recorded in the same core. According to paleo-proxy record in both cores (e.g., K, Si, Fe and Ti elements), the climate during the formation of the S1b sapropel in the gulf was drier at the beginning, became wetter. This reveals an enhanced detrital input to the gulf during its formation. However, the sea surface freshening as a consequence of higher river discharge during the S1b deposition and decreasing SST in core SAG-14 is seen as well as in core SL-152 from the northern Aegean Sea (Kotthoff et al, 2008). This conclusion is in agreement with previous observation on the same sapropel layer (S1b) from the Aegean Sea (Geraga et al, 2010) that low salinity and high freshening of surface waters were more pronounced in the north than in south Aegean, possibly due to the larger river inflows draining the north Aegean catchment area. Outflows by numerous rivers from the surrounding the northern and southern catchments of the Gulf of Saros might have increased during the time of S1b sapropel deposition in the gulf. Increased humidity during the S1b deposition is also proved by $\delta^{13}\text{C}$ record Sofular Cave (Fleitmann et al, 2009) and pollen record from core SL-152 (Kotthoff et al, 2008). However, the comparison of the north and south Aegean records shows significant changes between the north and south Aegean basins in both the productivity and the stratification of the upper water column during this time period (Triantaphyllou et al, 2014; Kontakiotis, 2016). They claimed that the warm and humid climatic conditions initiated upper water column stratification and development of the deep chlorophyll maximum deposition (DCM).

In comparison to the SMH, the marine organic matter production is lower in the S1b layer in core SAG-14, shows a very strong correlation to TOC in the core (Figure 5.3). The evidence of the increased terrestrial organic matter as a result of enhanced detrital input is also documented by lower Br/TOC ratio. This finding is also supported by gradual increase in S.R./TOC ratio, displaying the increased amount of sediment supply to the gulf. Since the deep water condition plays a critical role on the preservation of organic matter, particular interest in record is given to Fe/Mn ratio in the cores. The progressive decreases from the base to top of S1b layer indicate that the deep water condition in the gulf during the S1b deposition was possibly much oxygenated compared to the earlier Holocene period. Thus, it can be concluded that the deep water condition during S1 deposition in the gulf possibly was suboxic, but not anoxic due to a weak water column stratification. In contrast to southern Aegean

Sea, such weak stratification might be mainly restricted to the surface, and still enhanced productivity that plays the most important role in the formation of S1b. Similar to the northern Aegean Sea, this overall climatic and oceanographic setting in the gulf, as indicated by productive and enough stratified water column gave rise to increased preservation of organic matter and the deposition of S1b in the entire Aegean Sea. On the other hand, the presence of benthic foraminiferal faunas in the earlier studied cores from elsewhere in northern Aegean Sea strongly imply continuation of some deep-water formation throughout S1 (Kuhnt et al, 2007). Beside the water column stratification, high S.R. would possibly play important role on the preservation of the organic matter as inferred from low values of TOC in core SAG-14 compared to the younger SMH sapropel layer. The overall record here indicates that the deposition of sapropel S1b in the Gulf of Saros is mainly accompanied by humid conditions and the weak stratification of the upper water column, as a result of the climatic amelioration at Early Holocene and throughout the Holocene Climatic Optimum until 6100 cal yr BP.

Another younger sapropel layer in both cores are dated between 5300-3200 cal yr BP based on the age-depth model of the cores. This sapropelic layer likely corresponds to the Middle Holocene Sapropel that was previously defined from the Northern Aegean Sea (Triantaphyllou et al, 2014) deposited between 5400-4300 cal yr BP. The younger age for the termination of the SMH sapropel in the gulf could be related to bottom water condition that was possibly much more anoxic than in areas elsewhere in the northern Aegean Sea having bottom-water formation with improved oxygenation or a diminished primary production. Since the timing of the SMH layer in the cores (SAG-14 and SAG-22) give much younger deposition, this youngest sapropel in the gulf might timely coincide with the upper Holocene Sapropel deposited between 4700-3200 cal yr BP in the Sea of Marmara (Çağatay et al, 1999, 2000, 2009; Algan et al, 2001).

The resolution of paleo-proxy record for the SMH sapropel layer is better documented in core SAG-14, since the location of the core has a higher sedimentation rate due to decelerated sea-level rise during 5300-3200 cal yr BP. Beside the lithologic observation on the cores, the presence of the SMH is documented by TOC analysis only in core SAG-14. The amount of TOC demonstrates wide range of values between 0.49 % and 1.81 %. This could be related to high fluctuations in the paleohydrologic

and paleoclimate conditions during the early to middle Holocene as clearly inferred from the paleo-proxy records in the cores (SAG-14 and SAG-22). However, SST record from core SL-152 suggests significant climatic instability in the North Aegean Sea during the Holocene. This instability is consistent with paleoclimate records from the central Mediterranean (Rohling et al, 2003). These conditions during the SMH deposition in the gulf can be evaluated into two different parts based on the paleo-proxy record in the cores.

According to the general trend of the paleo-proxy record together with $\delta^{13}\text{C}$ record Sofular Cave and pollen record from core SL-152 (chapter 6.1.1.2), the general climate between 5300 and 4100 cal yr BP was wetter at the beginning, but later it became considerably drier when the SST record from the gulf reached its maximum value. According to general higher Fe/Mn ratio in this first half of the SMH in the cores, deep water condition might be much anoxic in compare to the later period of the sapropel. Diminished detrital input to the gulf is also supported by low S.R./TOC ratio in compare to the upper half of the SMH. The general trend and intensity of highly-fluctuated Br/TOC ratio indicate a lesser amount of marine organic matter production, but became much higher towards to 3900 cal yr BP. These findings indicate that marine organic production was still enough even the paleoclimate was not convenient for high terrestrial organic matter delivery. The preservation of organic matter for the sapropel formation during this first half would possibly be established as a result of strong water column stratification that likely created poorly ventilated deep water condition. Although diminished input of terrestrial material to the gulf during the SMH formation, weak water stratification and an increased in S.R. may have contributed to the higher preservation of the organic matter in the sediments.

In the second half of the SMH sapropel (4100-3200 cal yr BP), the paleohydrologic condition in the gulf was considerably changed. This part of the sapropel layer was deposited under the wetter climate condition as supported by higher AP ratio in pollen record from core SL-152 (Chapter 5.1.2.2) and negative excursion in $\delta^{13}\text{C}$ record Sofular Cave. High river discharge to the gulf possibly induced surface freshening progressive decrease in SST record in core SAG-14. Our findings reveal that pronounced SST-cooling, at least in the Saros Gulf, was much more frequent during the latter part of the SMH deposition. Such rapid cooling events are known to provoke

intermittent ventilation of deep waters throughout the S1 (Casford et al, 2003). It could explain decreasing trend of Fe/Mn during the deposition of S1.

Although diminished lithogenic elements (K, Ti, Si and Fe) are recorded in the cores, increase in S.R./TOC ratio together with higher TIC value demonstrate higher terrestrial input and elevated inorganic carbon during the second half of the SMH deposition. Therefore, the freshening of sea surface waters driven by enhanced riverine discharges to the gulf and land runoff due to intensified rainfall was greater towards the end of the SMH sapropel. The general gradual decrease in Fe/Mn ratio indicates that the deep water condition changed possibly from anoxic to suboxic. One possible reason for improved oxygenation of the deep water in the gulf can be considered as a result of high river discharge that would have generated a hyper pycnal mixing, penetrating into the deeper part of the gulf. Another reason might be the Black Sea connection of the gulf during the later period of the SMH that might have given rise to freshening of the persistent saltier gulf water as inferred from the progressive decreases in SST record after 4100 cal yr BP. Such connection would have provided much oxygenated waters to the gulf, and created enhanced ventilation within the thermocline.

According to previous core studies from the Sea of Marmara, the connection with the Black Sea was documented between 5000 and 4000 yr BP on the basis of faunal evidences from the sediment cores (Çağatay et al, 2000; Tolun et al, 2002). This is also supported by considerable decrease in SST record in core GeoTü KL71 from the Sea of Marmara. Although Br/TOC ratio together with Ca/Ti ratio provide us an evidence for excess of marine organic matter production, the lower ratio of TOC in the latter half of the SMH deposition indicates lesser amount of the preserved organic matter in compare to the earlier period. This would be related to formation of weak water column stratification due to better ventilated water column that is possibly consequence of the interaction between the Mediterranean Sea and the gulf. On the other hand, higher sedimentation rate during this later period of the SMH would have played most important role on the formation of the sapropel in the gulf even there was not well established water column stratification as occurred in the Sea of Marmara (Çağatay et al, 1999, 2000). In the southern Aegean Sea, the fast transport and burial of organic matter together with the stratification in upper part of the water column and enhanced DCM leads to deposition of the SMH (Triantaphyllou et al, 2014;

Kontakiotis, 2016). In contrast, the North Aegean Sea did not accomplish bottom-water condition, although it experienced the upper water column stratification. Unlike the North Aegean Sea, the Gulf of Saros provides conditions for the deposition of the sapropelic layer due to being semi-enclosed basin and a constant supply of fresh water into the gulf via surrounding rivers. In addition to such basin characteristic, the formation of a present dual-flow regime in the gulf after 4500 cal yr BP would have contributed to the deposition of SMH in the gulf during the mid-to-late Holocene (Çağatay et al, 2000; Algan et al, 2001 and Eriş et al, 2011).





6. CONCLUSIONS

In this thesis, we focused on ~15000 yr BP climatic and oceanographic history of the North Aegean region. This study presents three gravity cores (SAG-14, SAG-22 and SAG-08) that have been recovered from the Gulf of Saros in order to reconstruct its climatic evolution. To evaluate climatic events, we used multi-proxy approach, containing physical, textural and geochemical traces thus, these proxies reveal precursors for Late Pleistocene- Holocene main climatic periods and events such as the B-A, the YD, the, S1b sapropel, the SMH, the RHP, the DACP, the MCA and the LIA. Furthermore, we compiled a series of criteria to characterize the climatic and oceanographic events with their sedimentological and geochemical responses by using multi-parameter analysis on the sediment cores.

The Gulf of Saros has formed at Upper Miocene as a transtensional basin, having a northern catchment area. The region has been hugely affected by the western tip of the NAF activity in the Aegean Sea thus the N-S extensional regime of the Western Anatolia. Although there are several paleoceanographic and paleoclimatic studies in the Aegean Sea, it is thought that the Gulf of Saros should have different dynamics from the Aegean Sea since it has a different geographic location as an inland sea. In the Gulf of Saros.

In this thesis, sedimentological (lithostratigraphic studies, multi sensor core logger analysis (MSCL) and grain size analysis) and geochemical analyses (ITRAX- XRF analysis, total organic carbon (TOC) and total inorganic carbon (TIC) analyses and biomarker analysis) performed in İstanbul Technical University-Eastern Mediterranean Center of Oceanography and Limnology (EMCOL) Applied Research Center and Sorbonne University-Laboratoire d'Océanographie et du Climat-LOCEAN. Three gravity cores SAG-08, SAG-14 and SAG-22 recovered by R/V Urania in 2011 during Cruise MARM11. Physical properties of the three core (magnetic susceptibility (MS) and gamma density) revealed by using Geotek Multi-Sensor Core Logger Analyzer at 1 cm resolution. Grain size analysis uses to unravel the grain size distribution and sorting. Unlike to cores SAG-08 and SAG-14, grain size analysis was only performed in core SAG-22. Itrax Core Scanner is generally used to

identify geochemical properties of different layers through core. We used Itrax μ -XRF Core Scanner to reveal the relative supply of major and trace elements such as K, Fe, Mn, Ca, Ti, Sr, and Br of core SAG-14 and SAG-22. TOC was conducted in three cores to indicate paleo-productivity within the water column associated with the preservation of organic matter whereas biomarker analyses were only performed in SAG-14 to reconstruct the climate variability of the gulf because of a direct relationship with sea surface temperature (SST). Lastly, the studied two sediment cores SAG-14 and SAG-22 were dated by an accelerator mass spectrometry (AMS) ^{14}C analysis that has been carried out at TUBİTAK-MAM facility (Turkey) for age model by using Bayesian statistics method.

Three sediment cores from the gulf were examined by multi-proxy approach that allows for the identification and characterization of the main climate oscillations and paleoceanographic changes prior to the Holocene in the Gulf of Saros. Previous studies focusing on the Last Glacial period and Holocene have shown that the Aegean Sea has been subjected to many long and short term variations that are associated with variations in the Siberian High intensity and the Northern Hemisphere Climate. Relatively small morphology and geographical position of the gulf together with the high sedimentation rates allowed us to document immediate and the short term changes for reconstructions paleoclimatic and hydrological changes. Therefore, we documented the presence of the B-A and the YD main climatic periods in core SAG-22 by using age-depth modelling and correlation of Sofular Cave $\delta^{13}\text{C}$ isotope data. Based on paleo-proxy records, the B-A occurs between 14800-12900 cal yr BP and is characterized by elevated paleo-productivity in comparison with the YD. In the same period, the location of the core SAG-22 was dominated by anoxic or suboxic deep water condition, since high amount of marine organic matter could have brought about diminish of available oxygen.

After the termination of the B-A, cold and dry climatic condition occurred between 12900-11800 cal yr BP during the YD period. According to paleo-proxy records, the YD was associated with high detrital input together with low organic productivity and dry climate conditions. This period was experienced by oxic deep water condition resulted from an abrupt cooling surface water and still stand sea-level. The climate in the Holocene is defined as the time span between the termination of the YD and present, which was the final stadial of the last glaciation and ended about 11800 cal yr

BP ago. Moreover, we presented a robust correlation between XRF-Ca/Ti data between core SAG-22 and Sofular Cave $\delta^{13}\text{C}$ isotope record.

The onset of the Holocene (11800 cal yr BP) was associated with elevated paleo-productivity in the gulf lasting until 8900 cal yr BP, except climatic setback around 11200 cal yr BP. “11.2 cal ka event” have been documented in SAG-22 by correlating Sofular $\delta^{13}\text{C}$ profile and AP pollen records of the core SL-152. Thus, in Boreal climatic period, we encountered higher values of K, Fe and Ti in core SAG-22, suggesting increasing detrital input to the core location. It has been followed by the drastic change in the detrital input as a cold period which is interpreted as an interruption of the S1 sapropel. Geochemical proxies showed the abrupt change at 8.2 cal ka event in the core SAG-22 in terms of high Fe, Ti and K values. The fast Holocene transgression might have caused enhanced salinity in the gulf and led to suboxic to anoxic condition owing to the water column stratification. The warmest climate together with highest paleoproductivity was marked at 9300 cal yr BP corresponds to the deposition of S1 sapropel in the Eastern Mediterranean and the Aegean Sea. We encountered increased detrital input to the gulf between 8900-7300 cal yr BP as a consequence of coastal erosion. These findings were conformed with previous studies from the Aegean Sea.

In the mid-Holocene, we have documented the presence of Holocene sapropelic layers in the cores SAG-22 and SAG-14. Based on the age-depth model, the formation of S1b sapropel takes place between 7300-6100 cal yr BP in core SAG-22 whereas S1b in core SAG-14 occurs between 6500-6100 cal yr BP. The early phase (between 7300-6700 cal yr BP) of S1b sapropel displayed drier condition whereas the latter part of S1 sapropel until 6100 cal yr BP is related to the warm and wet condition accompanied with suboxic deep water condition. The sea surface cooling due to the wetter condition is recorded well by sea surface temperature record in core SAG-14. Moreover, the resemble decrease in SST record was observed in core SL-152 from the northern Aegean Sea. On the other hand, significant difference in the water depths of cores SAG-14 and SAG-22 discloses that paleo-hydrologic situations might have been noticeably different during the same time period. According to the paleo-proxy, deep water condition progressively turned into oxic during deposition of S1b sapropel between 7300-6100 cal yr BP. The time interval between the end of S1b sapropel and the onset of SMH sapropel (6100-5300 cal yr BP) was associated with low organic

matter and low detrital input owing to cold and dry climate condition around the gulf. The deposition of the youngest sapropel SMH occurred between 5300 and 3200 cal yr BP in the Gulf of Saros. In addition to cores SAG-14 and SA22, core SAG-08 comprised the SMH layer at the bottom of core accompanying from ~3600 cal yr BP. This time period was well correlated with the upper Holocene sapropel in the Sea of Marmara. On the basis of the paleo-proxy records, the early period of SMH indicated by dry climatic condition until 4200 cal yr BP. The highest terrestrial matter delivery to the gulf was documented in the cores from 4200 cal yr BP to 3900 cal yr BP. The latter part of the SMH between 3900-3200 cal yr BP was represented by decreased SST values from core SAG-14 in relation to sea surface freshening or cooling in the vicinity of the gulf. The first part of the Roman Warm Period between 2500-2200 cal yr BP was marked by low detrital input accompanied with the elevated SST record due to the prevailing drier climate. After this period, climate remained warmer and wetter until 1950 cal yr BP while the latter part of Roman Warm Period until 1650 cal yr BP was associated with dry and cool climate condition. Based on the paleo-proxy record, the overall period displayed anoxic deep water condition in the gulf. The time interval between 1600-1100 cal yr BP was linked to the transition to much drier climate, corresponding to the Dark Ages Cold Period. This period was mainly interpreted by low terrestrial matter delivery and relatively high marine organic matter in compatible with the latter part of the Roman Warm Period. On the basis of the age-depth model, the Medieval Climate Anomaly came into existence between 1150-670 cal yr BP. The MCA was indicated by significant decrease in SST record owing to increased sea surface freshening and/or cooling in the Gulf of Saros. This SST record was supported by in core SL-152 from the northern Aegean Sea and in core GeoTü KL71 from the Sea of Marmara. The MCA was concluded with warmer and wetter in core SAG-14, leading to high marine carbonate production. The Little Ice Age occurred between 670-150 cal yr BP as inferred from the age-depth model. The LIA was considered by cold and dry climate between 670-300 cal yr BP whereas the upper part of the LIA displayed a short humid period until 150 cal yr BP.

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

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- Çağatay, M. N., Eriş, K. K., Makaroğlu, Ö., Yakupoğlu, N., Henry, P., Leroy, S. A., Uçarkuş, G., Sakınç, M., Yalamaz, B., Bozyigit, C. & Kende, J. (2019). The Sea of Marmara during Marine Isotope Stages 5 and 6. *Quaternary Science Reviews*, 220, 124-141.
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