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Paleolimnological Investigations in Coastal Sarıkum Lagoon, Sinop, Turkey*

Sinop, Türkiye, Kıyısal Sarıkum Lagünü'nde Paleolimnolojik Araştırmalar

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Abstract: *Lagoons are dynamic systems, making ecosystem management difficult. Paleolimnological approach is the only way to track past long term environmental changes and background conditions that are essential to build environmental management plans. Here, we investigated a sediment record from Sarıkum Lagoon, on the Black Sea coastal plain in North Anatolia, through a multiproxy paleolimnological approach to reveal long term environmental change and background conditions in the lake. For which, dry weight, organic and carbonate carbon, chlorophyll a (including its main diagenetic products), magnetic susceptibility and ostracod analysis were undertaken. The core was dated via radionuclide technique. At around 30 cm of the sediment record, there are abrupt transitions in all proxies, indicating a massive sediment input, a transition from transitional water to lacustrine environment, and lake's biota also changed. Biological proxies preserved in the sediments suggest that the latest zone, after this event, is represented by lacustrine and hydrologically more isolated conditions from the Black Sea. Whatever the reason of that event (e.g. earthquake, flood), Sarıkum Lagoon has had lacustrine conditions during the last ~ 2 and half centuries following that abrupt event. This long term environmental change information should be considered while making future ecosystem management and conservation plans for the lake. (e.g. keep the lake connected with the Black Sea).*

Keywords: *Transitional Waters, Paleolimnology, Multiproxy Approach, Black Sea, Turkey*

Özet: *Lagünler ekosistem yönetimini zorlaştıran dinamik sistemlerdir. Paleolimnolojik yaklaşım, çevre yönetim planlarının oluşturulması için gerekli olan geçmiş uzun vadeli çevresel değişiklikleri ve referans koşullarını izlemenin tek yoludur. Burada, Kuzey Anadolu, Karadeniz kıyı düzlüğündeki Sarıkum Lagünü'nden alınan sediman karotunu göldeki geçmiş koşullar ve uzun süreli çevresel değişimi ortaya çıkarmak için, çoklu indikatör kullanılan plaeolimnolojik bir yaklaşımla araştırdık. Bunun için kuru ağırlık, organik ve karbonat karbon, klorofil a (ana diyajenetik ürünleri dahil), manyetik duyarlılık ve ostrakod analizleri yapıldı. Karotun tarihi radyonüklid tekniği ile belirlendi. Sediman kaydının yaklaşık 30'uncu cm'sinde, bütün indikatörlerde büyük bir sediman girişini, geçiş sularından gölsel çevreye geçişi ve göl biyotasının da değiştiğini gösteren ani geçişler vardır. Sedimanda korunan biyolojik indikatörler bu olaydan sonraki en geç zonun gölsel ve Karadeniz'den daha izole koşullarla temsil edildiğini düşündürmektedir. Bu olayın nedeni ne olursa olsun (deprem, su baskını vb.) Sarıkum Lagünü gölsel koşulları son 2.5 yüzyıl boyunca, bu ani olayın ardından kazanmıştır. Göl için gelecek ekosistem yönetimi ve koruma planları yapılırken bu uzun süreli çevresel değişim bilgileri dikkate alınmalıdır (örneğin, gölün Karadeniz'le bağlantısını koruyun).*

Anahtar kelimeler: *Geçiş Suları, Paleolimnoloji, Çoklu-indikatör Yaklaşımı, Karadeniz, Türkiye*

1. Introduction

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Paleoecological records via natural archives (e.g. lake sediments), spanning centuries to thousands years, are useful when long term monitoring data are lacking. Such data provide information about background conditions, clues as to the causes, trends and future responses of the environmental changes which are vital for remediation plans (Smol 1992; Smol 2019). It can also address specific conservation issues such as habitat naturalness and disturbance regimes (Wills and Birks 2006). Instrumental, ecological monitoring data usually include short period of time in the environmental history and hence, provide insufficient perspective in the history of long term environmental change. Lake and lagoon sediments are an important natural archive recording environmental changes in timescales longer than the instrumental records. Paleolimnology uses lake sediments as a natural archive to track long-term environmental change by means of proxy data. The diagnostic tools used by paleolimnologists are the physical, chemical, and biological proxies preserved in the sediment profiles. Since biotic and abiotic interactions in an ecosystem can be very complex, it is necessary to work with as many proxies as possible to get a broad view of past ecosystem changes (Smol 2008). Podocopid (freshwater) ostracods, which are small, bivalved, benthic, micro-crustaceans living in all aquatic environments and preserved in the sediments of lagoon, lakes, and wetlands, are useful paleolimnological proxies (Boomer et al. 2003; Ruiz et al. 2013; Viehberg 2006) together with other biological indicators.

Coastal ecosystems in Turkey are rarely utilized sources for palaeolimnological studies. They are dynamic systems. Short-term physical processes (flood, tsunamis, storms etc.) or longer-term changes in climate, eustatic sea level and isostatic land level are possible driving forces for many of the biological, chemical and sedimentological processes that occur in these coastal systems. They can also be preserved in the sedimentary records. The Black Sea has amazed people with its giant waves and severe storms since the antiquity. As an example, for short term physical process, for instance, severe storms can create extreme waves (Kuznetsov et al. 2006). Between 1836 and 1998, the average storm frequency in the Azores region was 3.1 storms per year, lasting 2.3 days on average, and on average once every seven years an extreme storm occurs (Andrade et al. 2008). Sediments from coastal lakes located on the coastline in the southern part of the Black Sea are also expected to contain records of past massive storm events, such as the ones in November 10-12, 2007 and November 1854, which had catastrophic impact along the northern Black Sea coast. The Balaklava storm in 1854 was one of the most disastrous storms that ever happened in the Black Sea. Storminess over the north-east part of the Black Sea, during most of the last two centuries was partially due to NAO (North Atlantic Oscillation) mode of circulation (Andrade et al. 2008). The winter NAO (North Atlantic Oscillation) show anti-correlation with storminess indices in the Azores region for a century between the late 19th and late 20th centuries, however it was vanished after 1960 (Andrade et al. 2008). Negative precipitation anomalies arise when positive phases of the NAO occur during winter in the Black Sea region (Trigo et al. 2004). Stronger negative correlation coefficients between precipitation in Turkey and North Atlantic Oscillation (NAO) indices in winter and autumn were revealed by Türkeş and Erlat (2003). There are negative correlation coefficients between North Atlantic Oscillation (NAO) indices (in winter and autumn) and precipitation between 1930 and 2000 in Turkey (Türkeş and Erlat 2003). During the strong phase of the Arctic Oscillation (AO), a strong anticyclonic anomaly circulation also dominates Turkey, with northerly and northeasterly airflows from polar regions dominating over the Black Sea (Türkeş and Erlat 2008). Mid-latitude storm tracks over Europe and Mediterranean are a main impact on the hydroclimate of the Mediterranean region during winter (Brayshaw et al. 2010). Increase in storm activity would be also associated with precipitation (Brayshaw et al. 2010). Storminess (most of the time together with intense precipitation) can create landslide, freshwater flooding (through freshwater inlets), coastal flooding, temporary marine incursions from wave over wash and sea salt aerosols off wave tops, with minimal sand inputs, or as a barrier breach with significant marine influx and sand deposits over a multi-year period. According to Ceyhunlu et al. (2021), current climate crisis will likely increase wind speed and coastal flooding in the Black Sea shores of Turkey, creating mixing of freshwater resources with salt water in the near future.

The North Anatolian fault (NAF) is one of the three main fault zones in Turkey that make this region seismically quite active. The NAF extends from eastern Anatolia to the north of the

Aegean Sea, paralleling the Black Sea coast about 50-80 km inland (Kuran and Yalçiner 1993). Tsunamis in the Sea of Marmara, northern Aegean, and the Black Sea, triggered by large earthquakes along the NAF, are common (Kuran and Yalçiner 1993), with 134 tsunamis reported on or around Turkish coasts during the last 3500 years (Altinok et al. 2011). According to Yalçıner et al. (2004), 22 tsunami events have occurred in the Black Sea since the 1st century AD. At least one tsunami is known to have reached our study site in the last 500 years. In 1598 AD, a major earthquake in north central Anatolia, the Amasya and Çorum earthquake (Yalçiner et al. 2004; Altınok and Ersoy 2000), created a tsunami in the gulf between Sinop and Samsun (Nikonov 97., adopted from Altınok and Ersoy 2011). However, we haven't seen any peculiar tsunami deposits in a four-meter-long sediment core taken from Sarıkum Lagoon.

Many inland lake sediments and cave deposit were used to reveal long term environmental and climatic changes in this region. The last major climatic transition, like in most cool-temperate regions, occurred around the Pleistocene-Holocene boundary (Sekeryapan et al. 2020) as a result of complex interactions between orbital forcing, atmosphere, ocean and land surface conditions. During the early Holocene, climate was warm (Göktürk et al. 2011; Roberts et. al. 2001; Wick 2003; Woldring and Bottema 2002); however, it was drier during mid-Holocene (Roberts et al. 2001). Water level fluctuations have been observed in Anatolia during the Holocene (Roberts et al. 2001; Sekeryapan et al. 2020;). Seasonal water shortages and drying up of many inland water bodies have also been a problem especially in the central Anatolia. Nevertheless, a Holocene climatic and environmental condition in the coastal zone of the eastern Mediterranean region is less clear and needs further studies. The aim of this study was to track Holocene environmental and climate changes by means of podocopid ostracoda fauna and other physical proxies preserved in the sediment record along the Black Sea coast of Turkey and to differentiate the effects of climate change, tsunami and synoptic storm events by means of multi-proxy approach. Our objective was to identify any regional or local catastrophic events preserved in the sedimentary record. To accomplish this aim, sedimentary archive from coastal Sarıkum Lagoon was used. It was part of a PhD study (Sekeryapan 2011).

2. Study Site

Sarıkum Lagoon (but locally called Sarıkum Gölü, i.e. Sarıkum Lake) (42° 00'N, 34°55'E) is located in Sinop on the Black Sea cost of Turkey (Fig. 1 and Fig. 2A). It is a small (~ 100 ha), oval shaped shallow brackish lagoon with a maximum water depth of ~1 m deep in the main basin (Fig. 2B) and 1.8 m deep in the channel (Fig. 2C-D) (in July 2008). The lagoon is located within a natural conservation area (nature reserve) since 1987 and surrounded by marine, wetland, forest and dune ecosystems. Sarıkum Lagoon is separated from the Black Sea with a flat, sandy barrier (Fig. 2E) and a narrow channel (Fig. 2C-D) (which is between 3-6 m in width, 1.1-1.8 m in deep). Because of the low-lying sand barrier sea water can easily intrude into the lake. Connection to the sea is closed by sand but in winter/spring outflowing water creates an outlet and storm waves break the barrier and push salt water to the lake. The tidal range in the Black Sea is low (up to 18 cm) (Medvedev et al. 2016). In July 2008, we experienced an inundation event from the sea, as a result of a multi-day storm blowing seawater against the coast during a high tide period. Maximum water level, pH, dissolved oxygen and conductivity data in the channel were measured (Table 1) before and after the storm during a full moon period. The lagoon is fed by seasonal streams from south-east and south-west (Yılmaz 2005). Along the Black Sea coast of Turkey, rainfall is relatively uniform during the year with a maximum in autumn (Türkeş 1998). Between 1930 and 1993, mean annual rainfall was 656 mm for Sinop (Türkeş 1996). The mean winter temperature at the study site was 6°C between 1929 and 2003 (Türkeş and Erlat, 2008). Sarıkum Lagoon which was formed via the closure of an earlier bay by a sand bar has been turned in to Sarıkum Lagoon environment following alluvial depositions via freshwater inputs (Ozaner 1998). It is unknown when Sarıkum turned to a lagoon. It is an International Wetland Ecosystem, a stopover point for migratory birds.

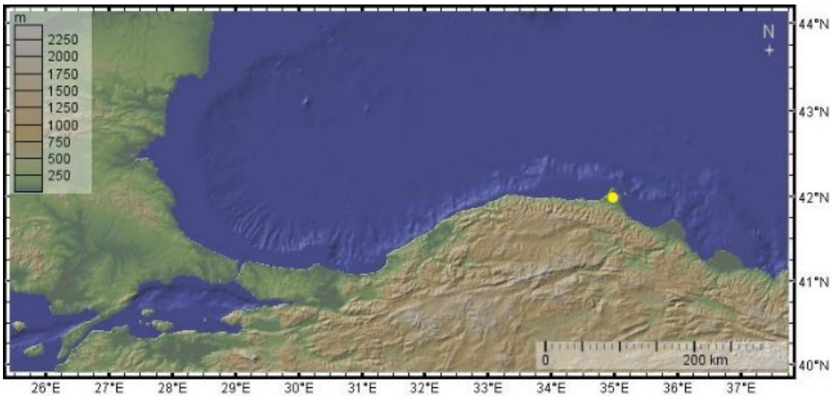

Figure 1. A map of study site. Sarıkum Lagoon is indicated via yellow circle. Figure made with GeoMapApp (www.geomapapp.org) / CC BY.

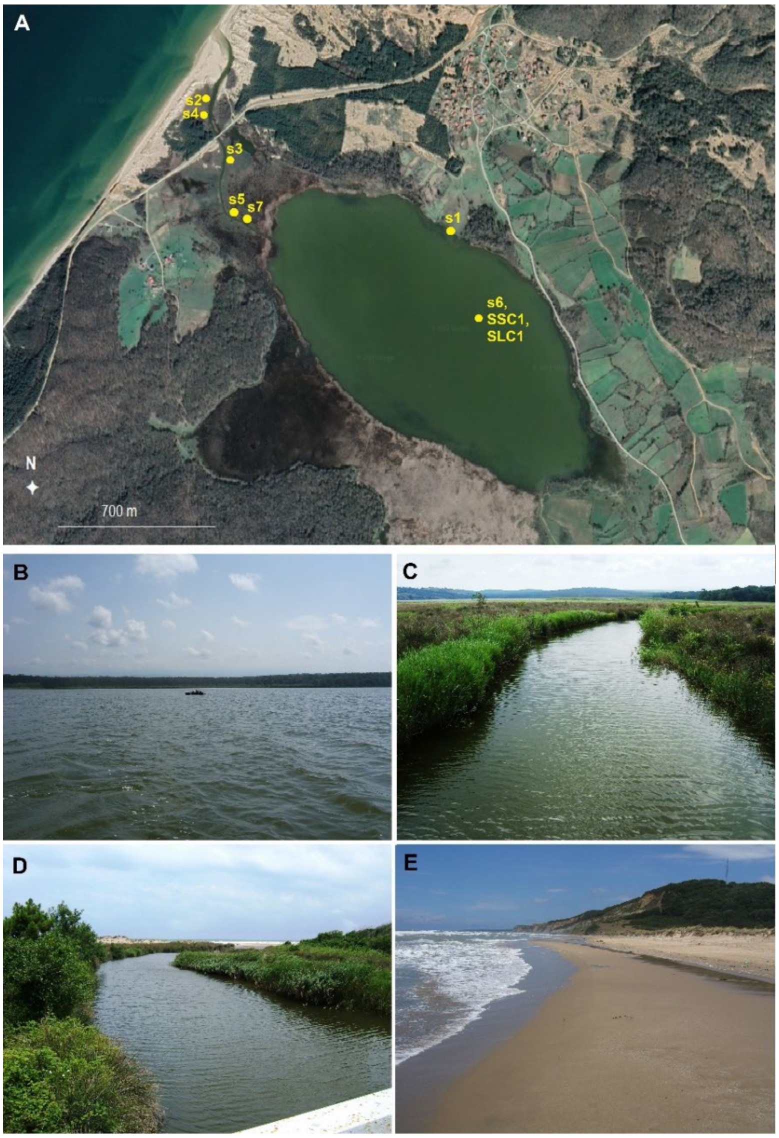

Figure 2. Study sites in Sarıkum Lagoon. A) Google Earth image of Sarıkum Lagoon, with short core (SSC1), long core (SLC1), and monitoring sampling sites (s1-7). B) The main lake basin, near sampling site 6, where SSC1 and SLC1 were also collected. C) Channel by the lake side. D) Channel by the sea side, near sampling site 2. E) Sand barrier between the lake and the Black Sea.

3. Materials and Methods

3.1. Coring and Sampling

A 40 cm short core (SSC1) was collected in July 2007 using a Kajak corer. It was extruded and subsampled in 1 cm intervals in the field. A 4 meter-long core (SLC1) was collected in July 2008 using a 50 mm diameter, modified square-rod Livingstone Piston Corer (Wright 1967). Changes in sediment characteristics prevented retrieval of deeper-lying sediments, perhaps because of the presence of sand or dry clay. The long core from Sarıkum Lagoon was split, photographed, described and sampled at 1-cm intervals at Middle East Technical University (METU). Samples were stored in the dark, at +4°C. Observations on the uppermost one meter of the long core (SLC1) and short core (SSC1) have been studied and presented in this paper. Physical limnological variables such as water temperature, dissolved oxygen concentration, pH, and conductivity were recorded at sampling site (Fig. 2A, s6; Table 1) and at different water property measurement sites in 2007 and 2008 (Fig. 2A, s1-5, s7; Table 1).

3.2. Radionuclide chronology

Lead-210 and 137Cs were used to determine sediment chronologies of recent sediments and accumulation rates in the upper sedimentary deposits of Sarıkum Lagoon. Lead-210 is a naturally produced radionuclide, primarily enters lake environments by atmospheric fallout (termed unsupported 210Pb). With the decay of unsupported 210Pb in the sediments, the activities become less and less with time. In this study, to calculate sediment chronologies and accumulation rates, we used the constant rate of 210Pb supply (CRS) dating model (Appleby and Oldfield 1978). Cesium-137 enters to the lakes via atmospheric fallout from nuclear reactor accidents and nuclear weapons testing. This artificially produced radionuclides can provide time markers in sediment dating if they are available. Sediment samples were freeze-dried for determination of dry density and water content for 210Pb dating and for initial detection of changes in the water and organic content of the sediments. Freeze-dried subsamples from SSC1 were analysed for 210Pb and 137Cs in the Environmental Radiometric Facility at University College, London (UCL), using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector in April 2008. Obtained dates were also used for dating the uppermost long core (SLC1) by cross-correlating using the Loss-on-ignition (LOI) profiles of SSC1 and SLC1 cores.

3.3. Loss-on-ignition analyses

Percentages of LOI at 550°C, representing total organic matter (TOC) and loss at 950 °C, representing total inorganic carbon (TIC, or carbonate), were calculated by the following procedure: 1-2 grams of wet sediments were heated in a muffle furnace at 105 °C for at least 12 hours to calculate the percentage of dry weight. To measure TOC and TIC carbon amounts, the dried sediment samples were placed in pre-weighed crucibles and heated in a furnace to 550°C for 2 hours. Samples were cooled and weighed, then reheated to 925°C for 3.5 hours (Dean 1974). This procedure was applied to every 1 cm of SLC 1and SSC 1 cores.

3.4. Chlorophyll *a* determination

Spectrally inferred chlorophyll *a* content was determined using the visible reflectance spectroscopy method (Michelutti et al 2010; Michelutti and Smol 2016; Rydberg et al 2020) at PEARL (Paleoecological Environmental Assessment and Research Laboratory, Queen's University, Kingston, ON, Canada). In this method, freeze dried sediment samples are sieved at 125 μm, in order to remove the influence of particle size and water content on the spectral signal (Michelutti et al. 2010). Approximately 1 g of dry sediment is used. Each sample encompasses 1 cm depth. 5 cm-interval samples from SLC1 and 1 cm-interval samples from the uppermost 8 cm of SSC1 were analysed for spectrally inferred chlorophyll *a* content.

3.5. Magnetic susceptibility

Magnetic susceptibility (MS) measures the magnetisability of material from Fe-bearing minerals in sediment samples (Dearing 1994) and can be used to help understand past changes in the delivery of detrital magnetic material transported to the lake by water or wind. For each sediment interval, MS of discrete sediment subsamples from SLC1 were measured at PEARL (Paleoecological Environmental Assessment and Research Laboratory, Queen's University, Kingston, ON, Canada) using a Bartington MS2 meter with a MS2B dual-frequency sensor (Bartington Instruments Ltd.) (Dearing 1994). This portable sensor facilitates the measurements at two different frequencies. We selected the low frequency to take five measurements from each sample; the average of each was reported in Fig. 4.

3.6. Ostracod analysis

Ostracods are aquatic micro-crustaceans. Their bivalve calcite shells are excellent fossils preserved in the lake sediments. They have been used as a potentially valuable proxy for the past salinity, temperature, and dissolved oxygen level (Boomer et al. 2003; Boomer and Eisenhauer, 2002; Frenzel and Boomer 2003). In this study, the compositions of ostracod assemblages at different sediment depths of SLC1 and SSC1 were identified to species level, taking account of taphonomic considerations. Sample sizes aimed to be about >300 specimens per sample. For this, approximately 3 cc of wet sediment per sample were sieved through a 63 µm sieve using a gentle jet of water. The last wash included pre-treatment with methanol to prepare the shells for trace element analyses (Mischke et al. 2008). The coarse residue was dried and weighed. The differences of the weights of the dried coarse residue including ostracoda and wet samples used for sieving through a 63 um sieve were calculated and plotted. All ostracod valves in the dry coarse residue fraction were counted.

Ostracod specimens were picked and mounted on slides, then identified to species level according to Meisch (2000) using stereo microscopes under 80x magnification. Samples were analysed for ostracods in SLC1 at 5 cm intervals. In the uppermost sediments of SSC1 several subsamples were used for ostracod analyses. *C. torosa* are photographed under Scanning Electron Microscopy (Fig. 8).

4. Results

4.1. Water property measurements and core description

Sarıkum Lagoon is very shallow, alkaline, oxygen rich, macrophyte dominated, and transparent brackish coastal lagoon (Table 1). Dissolved oxygen concentrations in the surface waters of the main lake basin and channel were 10.2 mg L-1 and 8.7-8.6 mg L-1 respectively. In the bottom waters dissolved oxygen concentrations were 10.9 mg L-1 in the lake, and 8.2 - 8.4 mg L-1 in the channel. Both in the main lake basin and in the channel, pH is slightly alkaline. Following a multi-day storm blowing seawater against the coast during a high tide period in 2008, salinity didn't change much in the channel close to the main lake side (site 7 in Table 1 and Fig. 2A). However, dissolved oxygen and pH of both surface and bottom water decreased, and water level was increased by ~ 10 cm (it was measured through the ruler attached to the bridge over the channel). The colour of the SLC1 sediment was olive black (Hue 10Y, 3/2 and Hue 5Y, 2/2 according to Oyama 1970) silts and sand, interrupted with bluish black (Hue 5BY, 1.7/1 according to Oyama 1970) (clay & silt) event layer (Fig. 4). Bottom most part of the long core includes lots of bivalve shells.

4.2. Chronology

The 137Cs activity through depth shows a peak at 5 cm in SSC1 (Fig. 3). The simple 210Pb CRS dating model placed 1986 at about 5.5 cm, suggesting the 137Cs peak was derived from the fallout of 1986 Chernobyl accident, and the 1986 137Cs fallout has obscured the 1963 peak from the nuclear weapon testing. The final 210Pb chronologies and sediment accumulation rates were corrected by assuming that sediments at 5.5 cm were formed in 1986 and calculated using the CRS model. Corrected dates of SSC1 are given in Table 2. The CRS model suggests that sedimentation rates gradually increased from 0.025 g cm-2 yr-1 in the 1900s to 0.096 g cm-2 yr-1 in the 1960s, followed by a dip to around 0.055 g cm-2 yr-1 in the 1970s, and then gradually increased again to 0.12 in the 2000s (Table 2). Our obtained chronology can also be used for cross-correlation of dates to SLC1 by tied to SSC1 via loss-on-ignition data.

Table 1. Water measurements at different locations (including the sampling location) at Sarıkum Lagoon.

Sample Sites	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**		**Site 7**
Date	14th of July 2008					14th July 2007	16th of July 2008	17th of July 2008
Time	11:00 am	11:30 am	1:50 pm	1:50 pm	11:00 pm			
N	36T0659080 UTM	36T0658012 UTM	36T0658060 UTM	36T0657994 UTM	36T0658083 UTM	42º00′58,2″	36T0659282 UTM	36T0658140 UTM
E	4653680 accuracy: 5m	4654129 accuracy: 7m	4653933 accuracy: 4 m	4654081 accuracy: 5 m	4653712 accuracy: 5m	34º55′23,6″	4653277 accuracy: 9 m	4653686 accuracy: 6 m
Elevation						10 m		
Weather	very windy and cloudy (50 %, 6 cumulus), beaufort 3-4		windy and cloudy (80 %)	windy and sunny		cloudy	sunny	very windy
Water depth			110 cm	180 cm	110 cm	~105 cm	80 cm	110 cm
Turbidity (Sechi depth)						> max. water depth		
Aquatic plants						very dense		
Surface water:								
Temperature	27.25 ° C	26.5 °C	26.7 °C	26.2 °C	26.8 ˚C	25 °C	27.8 °C	25.9 °C
Ph	8.69	8.19	8.11	8.11	8.10	10.38	8.58	7.97
Dissolved oxygen content	12.1 mg/L	9.3 mg/L	9.0 mg/L	8.7 mg/L	8.6 mg/L		10.2 mg/L	5.7 mg/L
Salinity						5.1 ‰		
Conductivity	12.92 µS/cm	13.13 µS/cm	13.40 µS/cm	13.22 µS/cm	13.53 µS/cm	9.17 Ms	12.87 µS/cm	13.42 µS/cm
TDS						5030 mg/L		
Bottom water:								
Temperature			26.5 °C	26 °C	26.7 °C			25.9 °C
Ph			8.1	8.07	8.10		8.6	7.97
Dissolved oxygen content			8.2 mg/L	7.7 mg/L	8.4 mg/L		10.9 mg/L	5.3 mg/L
Salinity								
Conductivity			13.41 µS/cm	13.34 µS/cm	13.55 µS/cm		12.90 µS/cm	13.45 µS/cm
Site description:		On the sea side of the bridge next to some reeds.	Inlet channel midpoint, on the lake side of bridge. Channel width~ 6-7 m.	On the sea side of bridge, mid-channel, near to sand barrier on sea. Seems to be the deepest point.	In outlet/inlet channel near lake, mid-channel.	Main lake basin. SSC1 was collected.	Main lake basin.	Channel to sea opened in the last night of storm. Possibly still open. Lake level increased by ~ 10 cm in the channel.

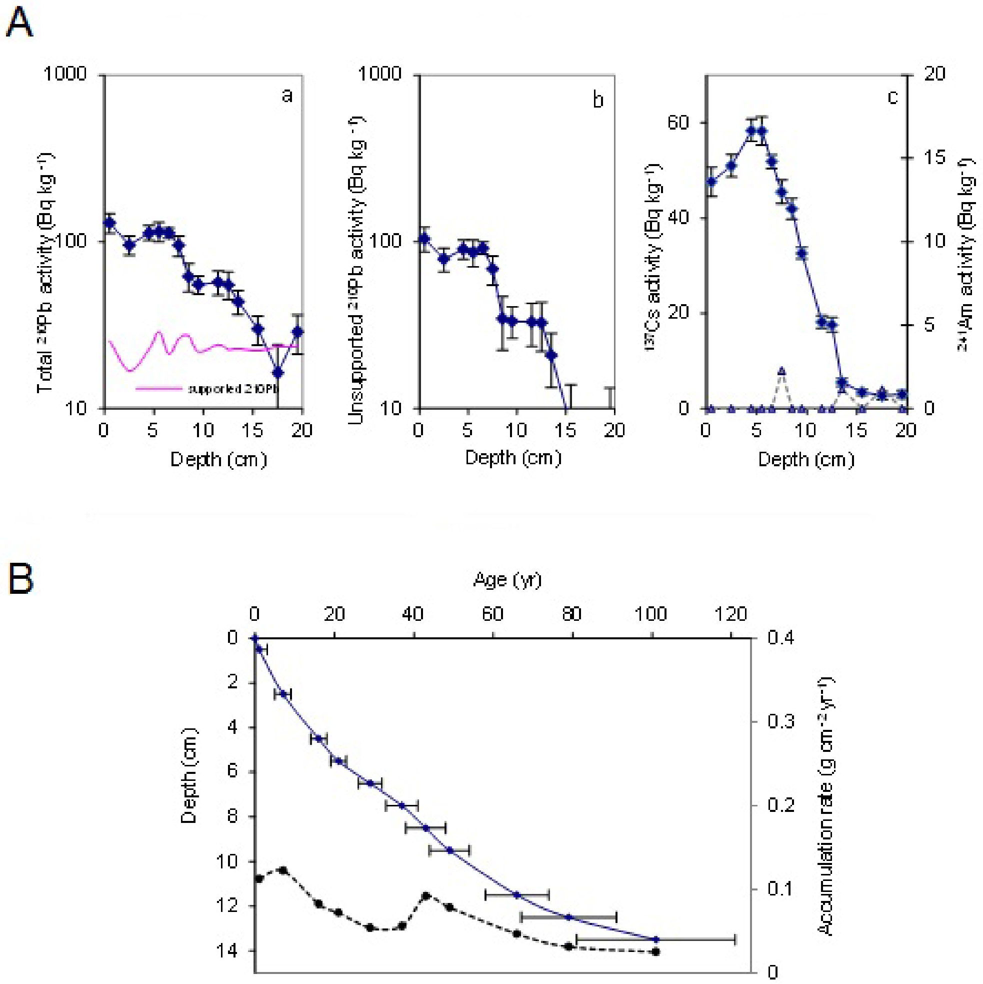

Figure 3. A) Fallout radionuclide concentrations in the Sarıkum Lagoon short core SSC1, showing (a) total 210Pb, (b) unsupported 210Pb, (c) 137Cs and 241Am concentrations versus depth. B) Radiometric chronology of the core SSC1, showing the CRS model 210Pb dates. The solid line indicates chronologies, while the dashed line shows sedimentation rates.

Table 2. ^{210}Pb chronology of the Sarıkum Lagoon short core 1 (SSC1).

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2007	0				
0.5	0.1294	2006	1	2	0.112	0.325	18
2.5	0.8624	2000	7	2	0.122	0.313	17.4
4.5	1.6906	1991	16	2	0.082	0.194	15.6
5.5	2.138	1986	21	2	0.072	0.161	20.4
6.5	2.5854	1978	29	3	0.054	0.121	14.4
7.5	3.0327	1970	37	4	0.056	0.126	24.3
8.5	3.4801	1964	43	5	0.092	0.19	38.6
9.5	3.9977	1958	49	5	0.078	0.152	28.2
11.5	5.0329	1941	66	8	0.047	0.091	39.4
12.5	5.5505	1928	79	12	0.031	0.056	49
13.5	6.1581	1906	101	20	0.025	0.042	71.2

4.3. Physical paleolimnological proxies (organic and carbonate carbon, dry weight, and magnetic mineralogical approach) and chlorophyll a concentrations

Total organic and carbonate carbon and chlorophyll a are measures of lake productivity that tend to be very consistent within individual lakes and lagoons. For this reason, they can be used for correlating multiple cores from a lake. When LOI is plotted against the sample depth, SLC1 and SSC1 cores can be correlated (Fig. 4). Magnetic susceptibility, mineral weight and dry weight percentages show similar trends in 10 - 30 cm sections of the sediments. Whereas chlorophyll a concentrations, organic matter and carbonate carbon percentages show opposite trends. From 30 to 27 cm of the cores (event layer) (Fig. 4), there is a relatively abrupt (occurring within ~ three decades) increase in mineral weight, dry weight and magnetic susceptibility, while sediment water content, organic matter and chlorophyll *a* values decrease rapidly. Sediment characteristic was also changed (from 70% to 100 % clay & silt composition (from 30% to 0 % sand composition) (Fig. 5) and from olive black to bluish black colour) (Fig. 4) during this time. Since the transition event, there is an abrupt increase and followed by a gradual decrease in magnetic susceptibility, mineral weight, and dry weight percentages (e.g. it increases 25 % during the event), and an abrupt decrease followed by gradual increase (above the event layer; in the uppermost sediments) in chlorophyll a concentrations and organic matter (lake productivity) in lacustrine sequence (Fig. 4).

4.4. Ostracods and other biological proxies

Two species were identified in the Sarıkum Lagoon sediment. They are: *Cyprideis torosa* (Jones, 1850) and *Neglecandona neglecta* (Sars, 1887) Krstić, 2006. Ostracod stratigraphy together with population structures of both *Cyprideis torosa* and *Neglecandona neglecta* species throughout the core are presented in Figures 5, 6 and 7, respectively. *Cyprideis torosa* is highly abundant in the sediments. It is cosmopolite, euryhaline species tolerating high salinity, up to 60‰ (Meisch 2000). Our assemblages have smooth valves (Fig. 8) and represent sexually reproduced population of *Cyprideis torosa* (Fig. 6). *Cyprideis torosa* and *Neglecandona neglecta* assemblages consist of both small and large instars of juveniles (the full range of instars were not presented, though) and mainly disarticulated valves of adults (Fig. 6 and 7). Their population structures reflect low-energy life assemblages (Boomer et al. 2003) indicating that these two species were living in the Sarıkum Lagoon sediments. In the coarse residue obtained after ostracod analysis, benthic foraminifera, marine bivalves, snails and Charaphyte oospores were also counted and plotted together with ostracod stratigraphy (Fig. 5). Based on the biological proxies preserved in the sediments, three zones are differentiated (Fig. 5). Zone 3 includes *C. torosa*, snails, bivalves, abundant Charaphyte oospores and a few *N. neglecta* valves. Zone 2 includes *C. torosa*, snails, bivalves, foraminifers, less abundant Charaphyte oospores and a few *N. neglecta* valves together with decreasing sand and increasing clay & silt ratios in the sediment record. Zone 1 includes a few bivalves, few snails, no foraminifers, abundant *C. torosa* and *N. neglecta* valves, less abundant Charaphyte oospores with very low sand but high clay & silt ratios in the sediment record (Fig. 5).

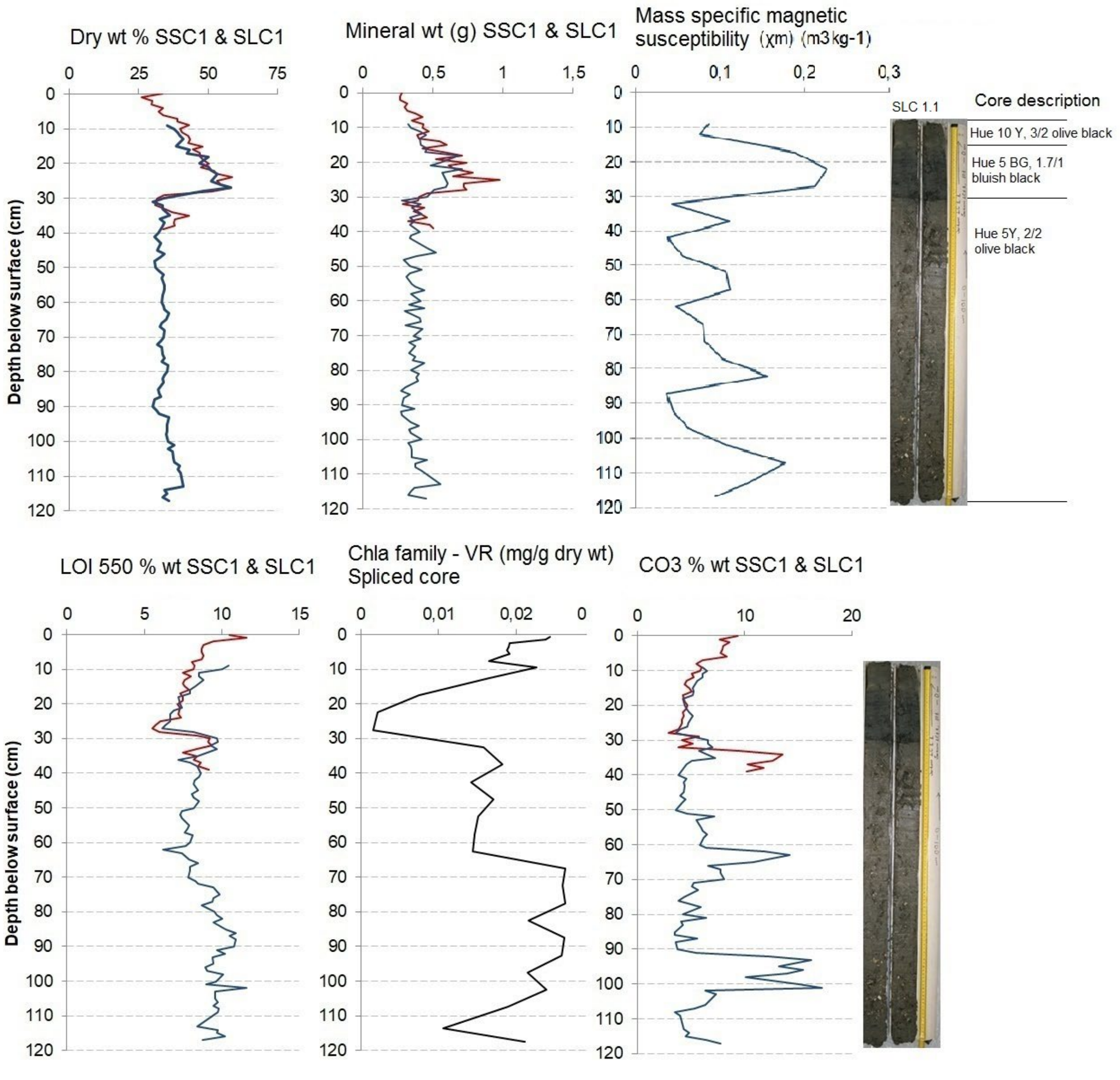

Figure 4. Dry weight, organic and inorganic carbon, mineral content, magnetic susceptibility and chlorophyll *a* in SSC1 (red curves) and SLC1 (blue curves) cores.

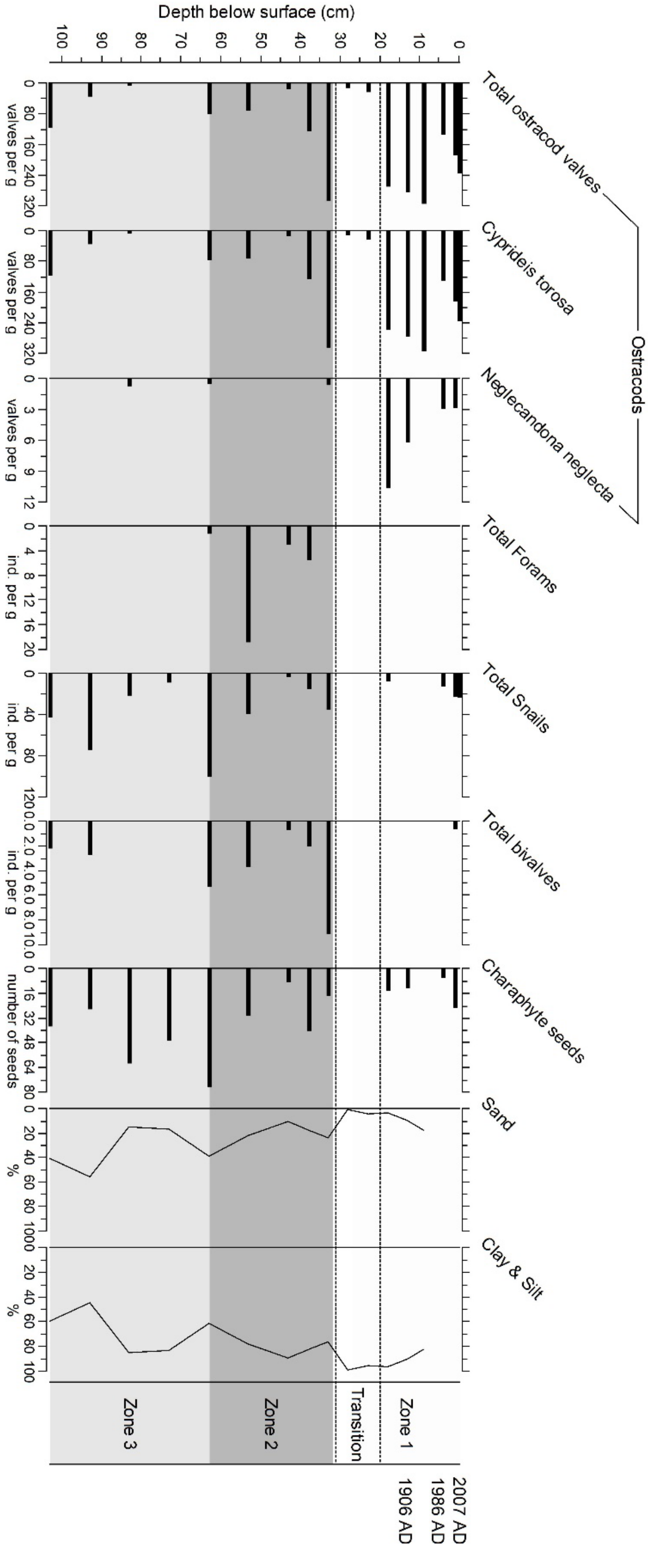

Figure 5. Ostracod stratigraphy, total forams, snails, bivalves, Charaphyte seeds, together with sand, clay & silt percentages in SLC1. In the ostracod stratigraphy, a carapace was counted as two valves in ostracod assemblages. Transition, revealed by physical proxies in the sediments (Fig. 4), is also represented here.

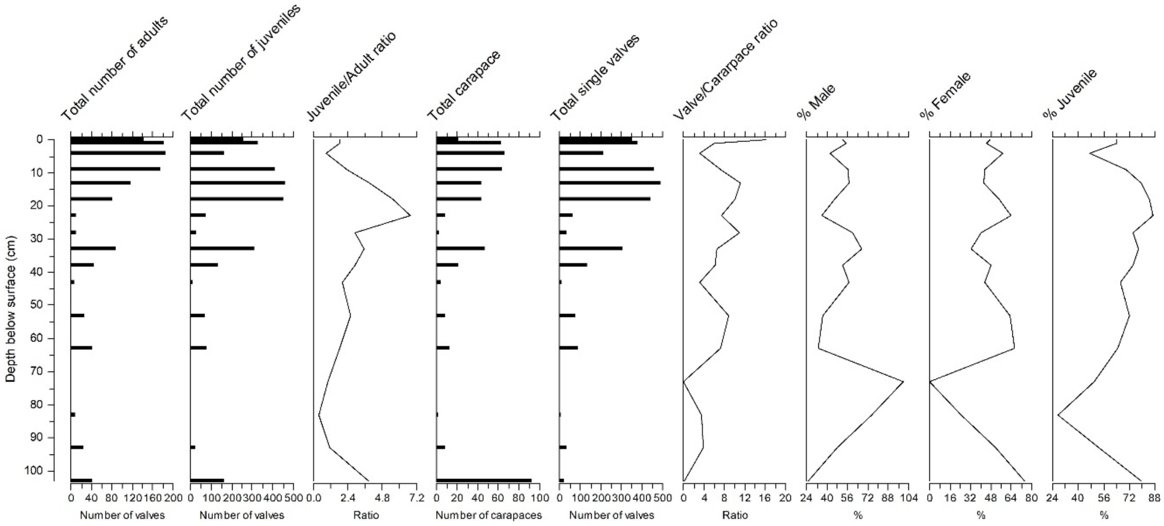

Figure 6. Population structure of *C. torosa* in SLC1.

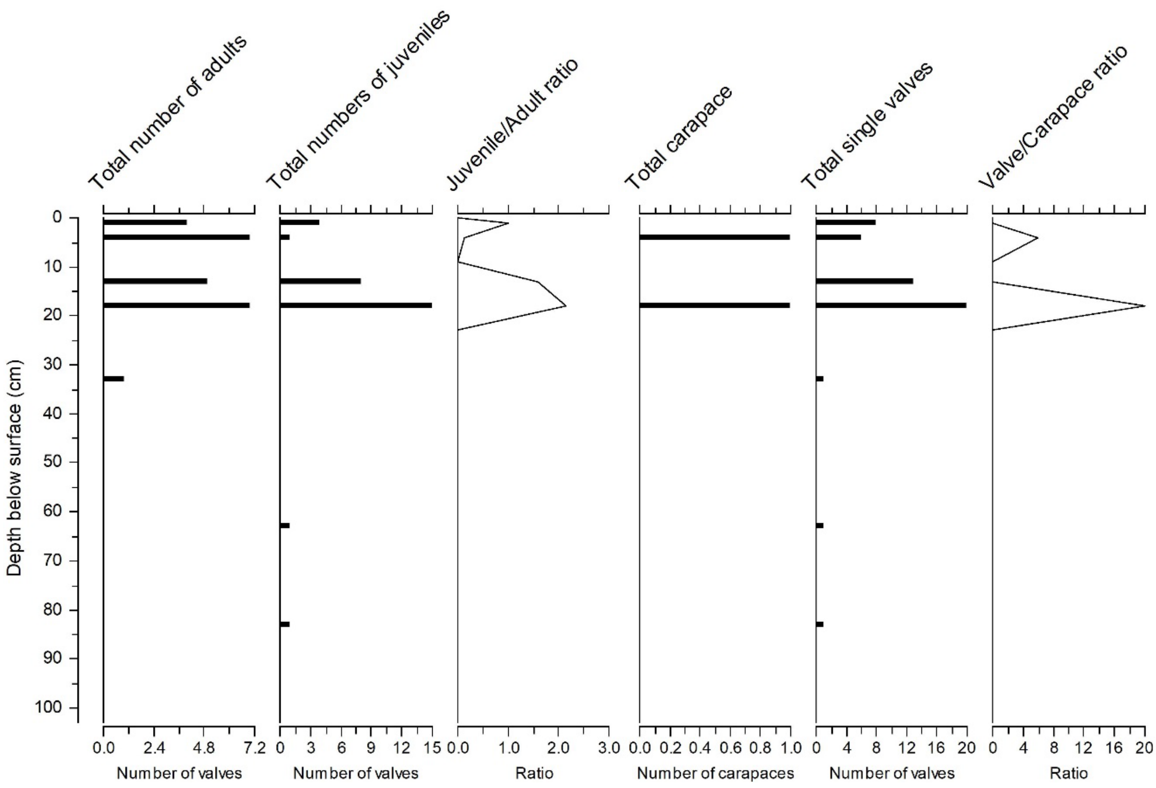

Figure 7. Population structure of *N. neglecta* in SLC1.

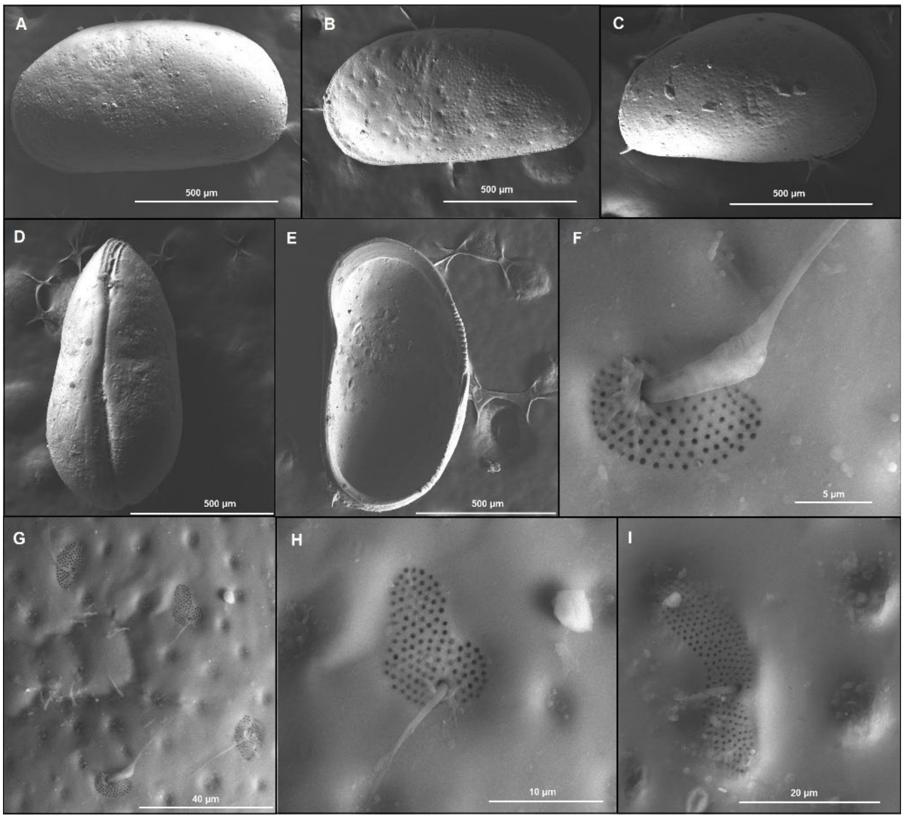

Figure 8 (Plate 1). Scanning Electron Microscopy (SEM) Photographs of *Cyprideis torosa* (Jones, 1857) from the surface sediment collected at site 2 (s2) in Fig. 2 and Table 1. A) Female LV (left valve) lateral view; B) Male LV lateral view; C) Juvenile RV (Right valve) lateral view; D) Female dorsal view; E) Female RV internal view; F-I) Sieve pores with different shapes.

5. Discussion

Paleolimnological approach is perhaps the only way to assess past environmental conditions for a lake with the lack of long-term (> 100 years) environmental monitoring data (Smol 2008; Smol 2019). With these tools, we can estimate background or reference conditions and natural variability which are crucial for the effective management of our aquatic resources (Smol 1992; Smol 2008). This may also help to understand and track hydrological dynamic changes in coastal environments.

Cyprideis torosa is the abundant ostracod species in Sarıkum Lagoon sediment. It comes with two forms: smooth and noded valves. Noding can be used as an environmental marker for low salinity and/or low calcium content (Keyser 2005). Noded and smooth forms may be found in a single population, depending on the local salinity range. It is Euryhaline cosmopolite species common in coastal regions (Meisch 2000). It needs permanent, shallow, warm, brackish water conditions to be able to colonize in athalassic water bodies (Pint et al. 2012). *C. torosa* can reproduce both sexually and asexually, ratios of males versus female and adults versus juveniles are used to infer the environment of deposition (Boomer et al. 2003). *C. torosa* population in Sarıkum Lagoon are composed of smooth forms of both males and females. Although *Neglecandona neglecta* (Sars, 1887) Krstić, 2006 can also tolerate wide range of environmental conditions, it is usually preferring cold waters (Meisch 2000). It is common in slightly salty inland or coastal waters (e.g 0.5-16 ‰) (Meisch 2000); however, it was also reported from springs, groundwater (Meisch 2000) and alpine freshwater lakes (Sekeryapan 2022).

At around 30 cm of the sediments, there are abrupt changes in both physical and biological paleolimnological proxies (Fig. 4 and Fig. 5), indicating a transition from marine/estuarine (or transitional water) to lacustrine conditions (e.g. abundant *C. torosa* and *N. neglecta* valves, no foraminifera and very few bivalves together with very low sand % in the sediment during Zone 1, in Fig. 5). When dry weight, mineral content and the magnetic susceptibility reach almost the highest values (Fig. 4), chlorophyll *a* is reaching minima at around the same depth (Fig. 4). At the same time the sediment was composed of very high ratios (~ 100%) clay & silt (Fig. 5). This transition event was an unfavorable period for algal growth (Fig. 4), benthic ostracods and Chara (Fig. 5). *Neglecandona neglecta* started to be present in the lake sediments after this transition (event layer) (Fig. 5). Those suggests severe/high freshwater inputs (freshwater flooding) to the lake basin (e.g. Lintern et al. 2016; Johanson et al. 2020). In Fig. 4, an event layer from 30 to 18 cm of the cores indicates sediment input from the lake catchment through freshwater flooding. This event first causes the decrease of total ostracods (mostly *C. torosa*), but then followed by increase in total ostracods (both *C. torosa* and *N. neglecta*) (Fig. 5). This ~ 12 cm long bluish black (Hue 5BY, 1.7/1 according to Oyama 1970) sediment (event layer) (Fig. 4) shows fine lamination and composed of 100-95 % clay & silt. The lagoon basin doesn't have steeply sloping shores. Below and above of that event layer aquatic environments change. That's why we think that the origin of that event was freshwater flooding instead of a turbidite. It can be fine laminated turbites. But, that also prove our freshwater flooding interpretations. Preserved abundant remains of benthic foraminifera, marine bivalves, and snails in the long core, together with Charaphyte oospores, are evidence of shallow lagoon and marine conditions in Zone 3 and 2 (Fig. 5). The sediment record suggests that the lake has been in lacustrine conditions (Zone 1 in Fig. 5) for the last ~ two and half centuries following that abrupt transition event (Fig. 4, Fig. 5). This information should be considered while making ecosystem management and conservation plans for today's coastal lagoon system.

According to dendroclimatic/dendrochrolonological data, 1751-1755 was one of the longest wet period (lasting 5 years) during the past 600 years in the Eastern Mediterranean (Touchan et al. 2005). This period includes part of the Little Ice Age (LIA) (Mann 2009). In Europe, Little Ice Age freezing event started at sixteenth or seventeenth century and ended somewhere between 1850 and 1890. Between 1768 and 1816, Europe endured 20 harsh winters, an almost continuously cold period (Yavuz et al. 2007), marking the maximum of the Little Ice Age in Europe (Grove 1990). Intense storm activity was seen in the lagoons of French coast of Mediterranean at around 17th century, during the latter half of Little Ice Age (Dezileau et al. 2011). Lagoons and wetlands on the southern coast of Caspian Sea were connected to the sea (Caspian high stand) due to high rainfall around its catchment during the latter half of Little Ice Age (Leroy et al. 2011). On the other hand, Sarıkum Lagoon on the southern coast of the Black Sea was isolated from the Black Sea during almost the same time (around two and half century ago) due to the similar climatic influence (high precipitation) in the region. High precipitation and/or humid conditions were also observed during the second half of the LIA, from other natural archives (e.g cave deposits, lake sediments) in Turkey (e.g. Jacobson et al. 2021; Roberts et al. 2012).

In Sarıkum Lagoon, the primary source of high organic matter (especially in Zone 2 and 3) might be submerged plant such as Chara, whose oospores were observed throughout the SLC1 core. Present conditions also imply a submerged plant-dominated shallow lagoon in Sarıkum Lagoon. Following the event at around 30 cm in Zone 1 (Fig. 5), Chara oospores decreased in Zone 1, and during the transition layer it was absent (Fig. 5). Charaphyte oospores observed in Sarıkum Lagoon sediments can refer its macrophyte dominated shallow water conditions. In shallow lakes, macrophytes are mostly responsible for primary productivity. Shallow lakes are usually characterized by abundant, submerged macrophytes, by clear water at relatively low nutrient concentrations, and by abundant phytoplankton and turbid water at higher nutrient concentrations (Blindow et al. 1993). At intermediate nutrient concentrations, shallow lakes are dominated by either submerged macrophytes or phytoplankton. However, it has been recognized that changes in nutrient loading to lakes are not the only reason for fluctuations in area coverage of submerged macrophytes. Water level change is another important factor creating oscillations of macrophyte density (Regmi et al., 2021). Van der Valk (2005) proposed that water level fluctuation can have both direct and indirect effects on establishment, growth, and survival of wetland plants. So, rapid changes in water level (the increased water level conditions due to flood) might be responsible for the decrease of Charaphyte oospores (macrophyte density) in our study site, during the onset of Zone 1.

6. Conclusion

At around 30 cm of the sediments there was an abrupt event. This can be explained by abrupt, catastrophic sediment input (probably via flooding due to high freshwater input to the lake basin, having an increasing trend up to around 20 cm) to the lake, through elaborating lake's biota during the transition. According to the faunal record (Fig. 5) the latest zone, just started after the transition event, is a represented lacustrine condition, suggesting the lake was hydrologically less connected with the Black Sea.

Lacustrine condition in Sarıkum Lagoon might have been created via intense/severe freshwater flooding at around two and half century ago (mid-18th century). This should be considered while making management and conservation plans for this lake basin (e.g. today's freshwater flooding shouldn't be considered as a disaster/disturbance for the lake ecosystem since it has already been created via such event). Also, geological/geomorphological changes in the basin due to extreme weather conditions should be considered while making management plans for this ecosystem, especially when we consider the impact of current climate crisis, in the near future.

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Author contributions

Ceran Sekeryapan's part of the PhD thesis. Ceran Sekeryapan carried out field work in 2007. Ceran Sekeryapan and Lisa Doner carried out field work in 2008. Ceran Sekeryapan conducted ostracod, LOI, chlorophyll *a*, magnetic susceptibility analyses and interpreted data. Handong Young conducted ^{210}Pb and ^{137}Cs analyses and interpreted the data. Ceran Sekeryapan wrote the manuscript.

Declarations

Conflict of interest: The authors declare that they have no known competing interests.

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