Chapter

"Geo-archives of a Coastal Lacustrine Eco-system": Lake Bafa (Mediterranean Sea)

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Abstract

A hypothetical novel, which aims to summarize the whole geological history of the coastal area surrounding the Mediterranean Sea, probably contains a sum of intensive and impressive topics, such as tsunamis, storms, earthquakes, volcanic activities, human-nature interactions, and their products. These abrupt geo-event changes (e.g., water chemistry fluctuations) remark a dynamic nature of this unique coastal area. Paleolimnological studies of a coastal lacustrine archive (i.e., Lake Bafa, Turkey), associated with syngenetic deposits accumulated in neighboring geological settings (i.e., swamp, deltaic, lagoon, marine), has allowed us to reconstruct the local geological history. Following this hypothesis, we aimed at investigating the paleoenvironmental establishment of the Lake Bafa and surrounding coastal area. Lithologic and geochemical investigations of the lacustrine ("BAF37:4.2 m) core and surrounding swamp ("BS":12 m) sediments supplied us an excellent geo-archive, continuously accumulated during the last 4.5 ky. Following conclusions are provided concerning the main depositional stages: Recent swamp-lacustrine separated stage (S-I: last 0.8 ky), lagoon stage (S-II.: 0.8–1.75 ky BP), marine-river interaction stage (S-III: 1.75–2.7 ky BP), and marine-dominated stage (S-IV: 2.7–4.5 ky BP). Our observations indicate that ecosystem characteristics of the basin have been mainly controlled by the hydroclimate and geotectonic processes.

Keywords: Lake Bafa, coastal lake, Holocene environment, sediment geochemistry, isotope geochemistry, Mediterranean Sea

1. Introduction

The marine and terrestrial geological settings influence each other in the coastal areas [1, 2]. The Aegean Sea and its onshore areas have raised a substantial interest of the geologists and geomorphologists, since this region is under a north–south tectonic extension, with the formation of hosts and grabens and occurrence of high seismic activity [3]. These very active tectonics, together with postglacial sea level rise, modified the geomorphological evolution of the Aegean coastal area, driving intensive sediment transport along the main river systems (e.g., Büyük Menderes), high amount of sediment accumulation with delta formations, and progradational deltaic processes [4, 5]. Accordingly, the late Quaternary geomorphological development of the eastern coast of the sea witnessed the formation of various inland or transitional basins.

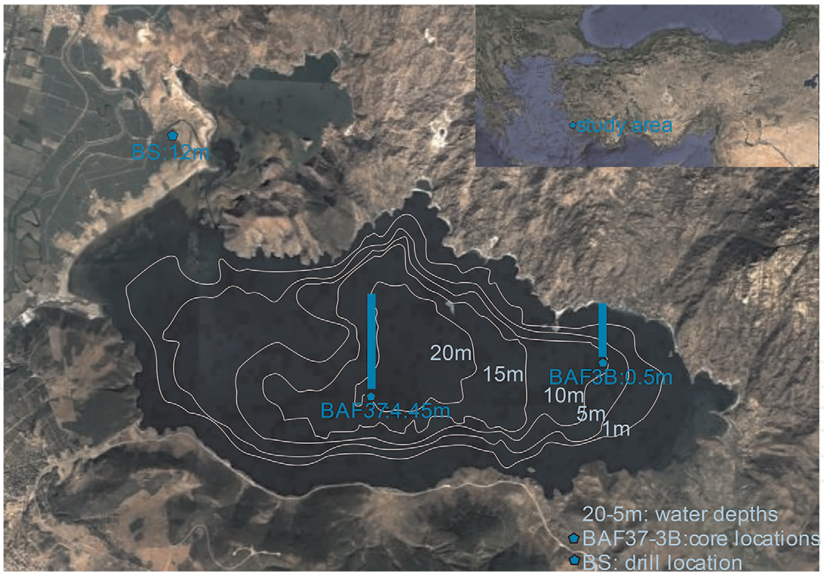


Figure 1.
Lake Bafa bathymetric map showing the piston core and drill core locations.

As a Middle to Late Holocene age coastal lacustrine basin formed in this specific geological area, Lake Bafa shows a complicated paleoenvironmental and paleoecological history [6, 7] (**Figure 1**). The lake evolved by the progradation of the Büyük Menderes River (Maiandros, Maeander) delta and the closure of the former Latmian Gulf during the late glacial-Holocene transgression [6]. It was subjected to ecological changes from a coastal marine inlet to a lagoon and finally to a completely isolated lake [6, 8, 9]. From this point of view, Lake Bafa provides an important sedimentary archive of these ecosystem changes and associated physical–chemical shifts, which are the main objectives of this study. To achieve these objectives, we carried out lithological descriptions and sedimentological and geochemical analyses of various sediment cores from the lake. The use of specific element concentrations and their ratios and organic geochemical analyses allowed us to reconstruct the past organic matter productivity-preservation rates, the water column chemistry, and the clastic material supply signals [10–12].

2. Samples and methods

An 11.9-m-long borehole (BS) was drilled on a swamp area, near the northwestern boundary of Lake Bafa, during a field survey in December 2012 (**Figure 1**). Subsequently, cores BAF-3B (0.5 m) and BAF37 (4.1 m) were retrieved from the central and eastern parts of the lake, using hammer and Kajak coring methods, respectively. The borehole section and sediment cores were lithologically described, systematically subsampled, and dried by using the freeze-drying method. Prepared mixtures of the selected 34 subsamples were analyzed as $LiBO_2/Li_2B_4O_7$ flux by ICP-MS in ACME laboratories, Canada. AMS 14C age determinations of selected *Cerastoderma glaucum* shells (**Table 1**) were analyzed in Beta Analytical Laboratories [8, 9, 13]. Calibration of the samples was calculated in Beta Analytical Laboratories, using one of the databases associated with the 2013 INTCAL program, using the reservoir age correction of 400 years [14, 15]. However, we realize that the reservoir age for samples representing the isolated stage of Lake Bafa (e.g., sample BAF 37/2, 72–73) may be different and that this deserves further investigation. Therefore, we submitted here the carbon dating data either in measured values and calibrated data (**Table 1**). Total organic carbon (TOC) analysis and Rock Eval

Submitter Nr.	Material pretreatment	Measured age	13C/ 12C	Conventional age	2 Sigma calibration
BAF37/2 72–73cm	(Shell): acid etch	1220 +/− 30 BP	−3.9 o/oo	1570 +/− 30 BP (1457 ± 70 adjusted for local reservoir correction)	Cal AD 780 to 1065 (Cal BP 170 to 885)
BAF37/P3–96	(Shell): acid etch	2250+/− 30 BP	−1.6	2345 BP+/− 30 BP	Cal BC 360 (Cal BP 2310)
BAF37/4 19–20cm	(Shell): acid etch	1980 +/− 30 BP	−3.6 o/oo	2330 +/− 30 BP (2217 ± 70 adjusted for local reservoir correction)	Cal BC 30 to AD 295 (Cal BP 1980 to 1655)
BS-FM/9 K-BS 14–7 cm	(Shell): acid etch	2710	−3.1	3070 +/− 30 BP (2957 ± 70 adjusted for local reservoir correction)	Cal BC 910 to 655 (Cal BP 2860 to 2605)
BS-9 K- 65–67 cm	(Shell): acid etch	2450+/− 30 BP	−4.7	2780 +/− 30 BP (2667 ± 70 adjusted for local reservoir correction)	Cal BC 645 to 230 (Cal BP 2595 to 2180)

Table 1.
AMS radiocarbon ages, calibrated ages, and description of the related sediment samples.

Pyrolysis VI measurements are performed in Turkish Petroleum Cooperation Laboratories.

3. Geological setting and limnology

From a geologic point of view, Western Anatolia and the Aegean Regions represent a broad extensional zone [16], stretching from Bulgaria to the north to the Hellenic arc to the south [17]. The Western Anatolian region is characterized by several approximately E-W trending, subparallel, normal fault zones, bordering a set of grabens and intervening horst blocks. The Lake Bafa is located on the Büyük Menderes Graben zone [18], which is a seismically active depositional basin [19]. The graben was opened in the Paleozoic–Mesozoic rocks of the Menderes Massif and Lycian Nappes during the Early Miocene [19–21]. The catchment mainly consists of metamorphic bedrocks belonging to the Menderes Massif. The basin-fill deposits, partly Early Miocene lacustrine limestones and the overlying units of Pliocene and Quaternary clastics, overlie the bedrocks [19]. The Lake Bafa formed as an alluvial set lake in the Western Anatolia because of the closure of the ancient Latmos Gulf, caused by the delta progradation of the Büyük Menderes River [6, 16]. The Holocene deposits of the Büyük Menderes River form an alluvial delta plain, separating the Lake Bafa from the Aegean Sea at around A.D. 1500 [6, 22]. The present- day lacustrine basin is currently at 2 m above sea level (masl) (**Figure 1**). The modern basin of the lake has a surface area of 315 km^2, a volume of 692 hm^3, and a maximum depth of 20 m. The lake is oligo-mesotrophic with annual average values of total nitrogen 0.45 mg/L, total phosphorus 1.3 mg/L, and total dissolved oxygen 7.49 mg/L [23, 24]. Additional to surface inflows, the main recharging inlet is Büyük Menderes River [22, 25].

4. Lithostratigraphy

Based on visual observations, such as lithology, color, water content, grain size distributions, and fossil content, sediment core and swamp section were subdivided into several lithostratigraphical units (BAF37, five litho-zones; BS, four litho-zones).

4.1 Lithology of the sediment–water interface core BAF-3B

The lithology of the sediment–water interface core "BAF-3B" from the north-eastern part of the lake predominantly contains fine-grained sediments, with averages of 18% sand, 34% silt, and 40% clay. The uppermost 0.15 m of the core contains gray and greenish-gray homogeneous sandy silty clays. Sediments from the lowermost parts were characterized by light to dark gray laminated sandy silty clay layers, enriched with small bivalve shell fragments [8].

4.2 Lithology of the core BAF37

The sedimentary section of core BAF37 consists of five main lithostratigraphic units (**Figure 2**). The uppermost 1.2 m of the sediment section is a greenish-olive gray homogeneous sandy, clayey silt. A 15 cm thick, black, banded, homogeneous clayey silt layer follows this unit downward. The third unit (UII:1.35–1.90 m) is a light bluish gray to yellow, laminated clayey silt. The following unit (UIV:1.90–3.56 m) consists of intercalations of bluish gray homogeneous sandy silty clay and olive-green clayey silt and clay. The lowermost unit below 3.56 m (UV) has variable lithological layers changing from homogeneous to laminated and from sands to clays, with beige and light gray to black colors. In detailed lithological observations including the grain size composition data (averages of 4% sand, 68% silt, and 28% clay), this unit is composed of predominantly fine-grained sediments [8, 9].

4.3 Lithology of the borehole (swamp) section (BS)

The swamp section is divided into four main lithological units. The uppermost 2.7 m of the sequence (Us I) is mainly characterized by brown sandy clay (**Figure 3**). Unit "Us I" includes a topsoil formation and is rich in plant residues in the uppermost part. Lowermost parts include a well-sorted sand layer and partly oxidized clay layers. The second unit (Us II; 2.7–7.2 m depth) contains laminated,

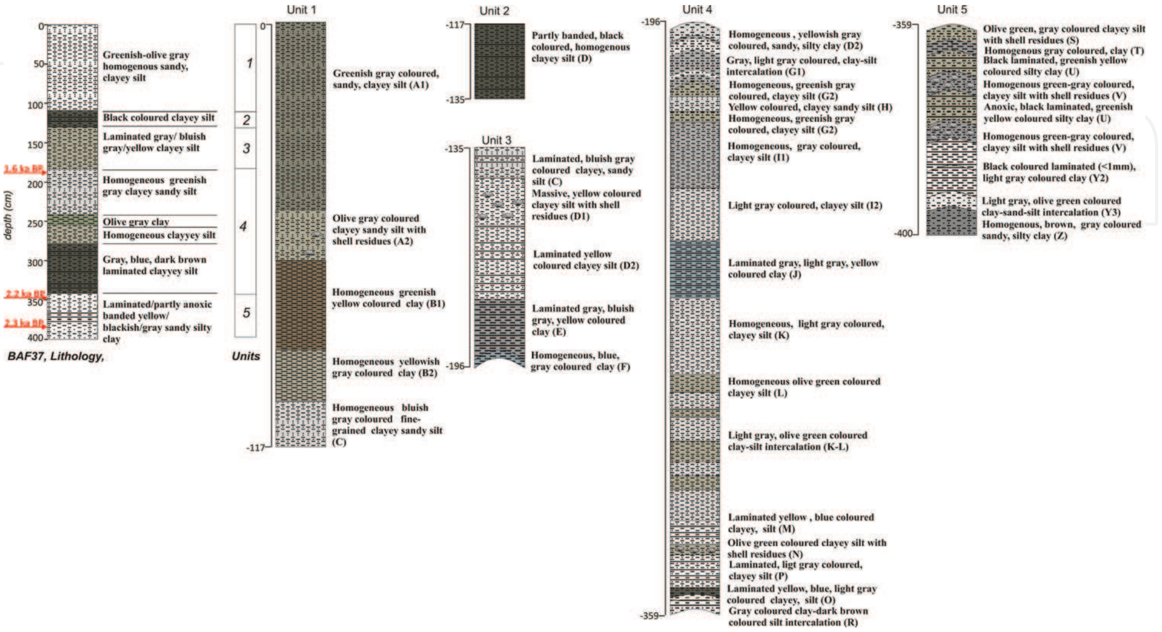


Figure 2.
Lithostratigraphic description of core BAF37.

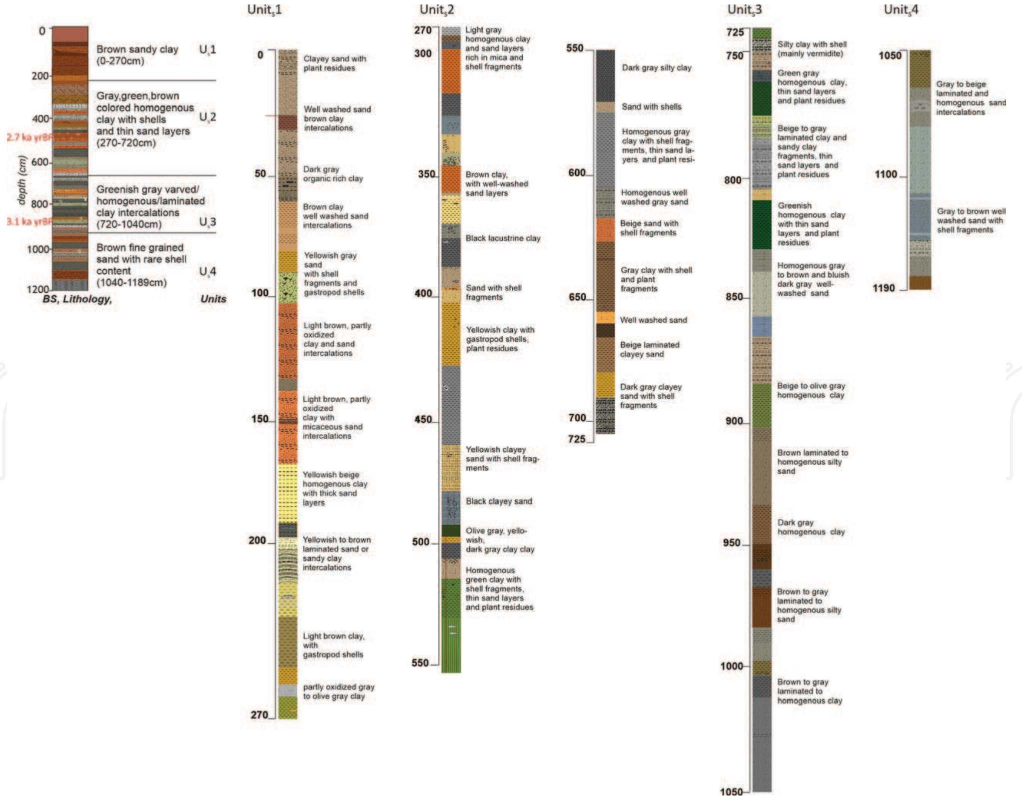


Figure 3.
Lithostratigraphic description of the swamp section (drill core BS).

partly organic-rich or oxidized clay layers, enriched in gastropod shells and shell fragments. The third unit (Us III; 7.2–8.7 m) is characterized mainly by a gray to brown, homogeneous clay, which is partly interrupted by either thin laminated clay layers or sandy, silty clay layers. It is enriched in Vermetidae or bivalve shell fragments. The lower parts of this unit (8.9–10.4 m) consist predominantly of homogeneous sand layers, containing abundant bivalve shells. The lowermost unit (Us IV; 10.4–11.9 m) is a gray, well-sorted homogeneous sand, with the abundant rock fragments and bivalve shells.

5. Chrono-stratigraphy

A total of five radiocarbon ages measured on mollusk shells were considered for the chronology (**Table 1**) [8, 9]. Three *Cerastoderma glaucum sp. shells* from three different depths in core BAF-37 were radiocarbon dated. A single valve of *Cerastoderma glaucum sp. from* 1.98 m depth provided a conventional age of 1570 (+/− 30) BP. Additional two AMS radiocarbon dates from single valves of *Cerastoderma glaucum sp. from* 3.38 m and 3.83 m core depths yielded 2250 (+/−30) and 2330 (+/−30) year BP. The 14C ages show a regular increase with depth. Furthermore, these age estimates indicate a low sedimentation rate during the deposition of lake sediments (0.24 cm/year); this rate is in agreement with the results of previous measurements [22]. Two AMS radiocarbon dates from single *Cerastoderma glaucum sp. shells* collected at the 4.81 m and 7.53 m depths of swamp section (BS) yielded conventional dates of 2780 (+/− 30) and 3070 (+/− 30) BP, respectively. According to the radiocarbon dates, together with visual observations, the swamp and lake sequences represent continuous sedimentary records of the last 4.5 and 2.5 cal. ka years, respectively.

6. Chemo-stratigraphy

Chemical characterization of the sediments (BAF-3B; BAF37; BS) investigated applying ICP-Ms analysis and revealed abundances of selected elements (Al, K, Ti, Zr, Rb, Fe, Mn, Ni, V, Cu, Pb, Zn, Mg, Ca, Na, P, Ba, Sr). A selected statistical method is also applied using geochemical data, namely, “factor analysis” (FA). Accordingly, eigenvalues of I and II factors were determined from 16 variables (**Table 2**). Congruent factor load values indicate either the same geological sources or element enrichment processes [26]. However, several element contents (Cu, V, Pb, Zn) were below the detection limits (*bdl*) in the sediment–water interface sediments (core: BAF-3B). These values were not applied for FA approaches.

6.1 Chemical composition of core BAF37

Unit I has relatively high Ca, Ni, Fe, and Zr concentrations; low contents of Si, K, Ti, Mn, and Rb; and low ratios of Mn/Fe, V/V + Ni, and Mg/Ca (**Figure 4**). Contrarily, a tendency through the increased Mn/Fe and Mg/Ca ratios suggested for the sediments belonging to units II to IV. Overall downcore characterization also reflects increasing values of Si, K, Ti, Fe, Ni, Zn, Ca, and Zr in units III and IV. These elements correlated oppositely with declining Ca values, indicating the carbonate dilution effect. Especially, the lowermost unit (Unit V) is characterized by the obvious fluctuations of the Ca, Fe, Si, K, Ti, Rb, and Fe. In addition to element concentrations, cross-correlations of V/Cr–U/Th, Ni/Co–U/Th, V/V + Ni–U/Th,

Cores	**BAF 3B**		**BAF37**		**BS**	
	factor 1	*factor 2*	*factor 1*	*factor 2*	*factor 1*	*factor 2*
Al	**−0.9**	−0.1	**−0.7**	0.6	**−0.7**	−0.6
Fe	**−0.9**	0.0	**−0.9**	0.3	**−1.0**	−0.2
Mg	**−1.0**	0.0	**−0.9**	0.5	**−0.8**	0.2
Ca	0.3	**0.9**	−0.2	**0.8**	**−0.7**	0.6
Na	0.7	−0.7	0.4	0.6	**0.9**	−0.4
K	**−0.9**	−0.2	**−0.9**	0.3	−0.7	−0.7
Ti	**−0.9**	−0.3	**−0.8**	0.6	**0.8**	−0.5
P	**0.7**	−0.2	0.0	**0.9**	**0.9**	−0.1
Mn	**−0.8**	0.5	−0.7	−0.2	**−0.9**	0.2
Ni	**−0.9**	−0.1	**−0.8**	−0.4	**−0.9**	0.2
Ba	**−0.9**	0.3	**−0.8**	−0.3	−0.5	**−0.7**
Sr	**0.8**	0.3	0.7	0.4	−0.5	0.6
V	*bdl*	*bdl*	**−0.8**	−0.4	**−0.9**	−0.3
Cu	*bdl*	*bdl*	−0.5	−0.5	**−0.9**	−0.1
Pb	*bdl*	*bdl*	0.4	−0.3	**−0.9**	0.0
Zn	*bdl*	*bdl*	−0.6	−0.6	**−0.9**	−0.3
Expl.Var	8.4	1.8	7.5	4.3	10.7	2.9
Prp.Totl	0.7	0.2	0.5	0.3	0.7	0.2

Table 2.
Factor loads of 16 selected elements (bold numbers indicate high positive and high negative factor loadings).

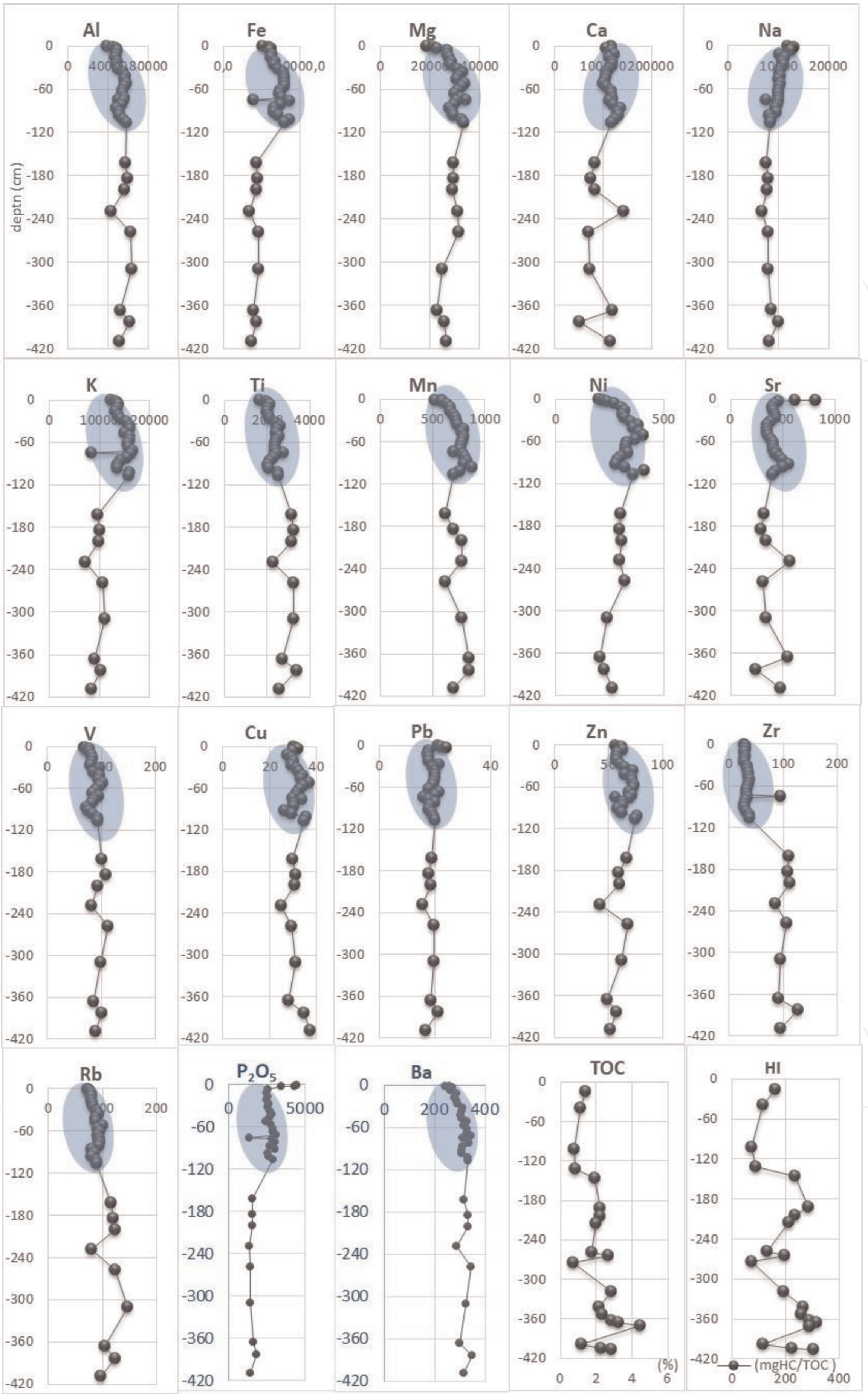


Figure 4.

Concentrations of selected element and element oxides (in ppm) in BAF37 core sediments (in ppm), TOC% contents, and HI values in BAF37 sediments (blue-colored area represents values measured for sediment–water interface phase and long core sediments, jointly).

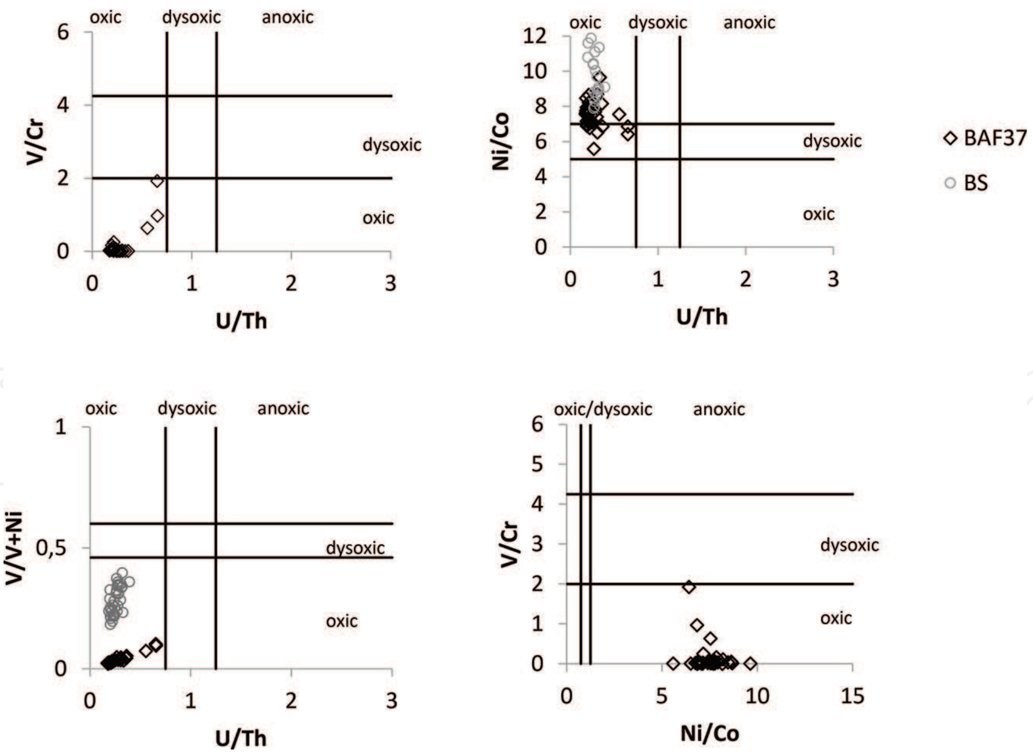


Figure 5.
Redox conditions of the lake bottom waters and the adjacent swamp environment.

and V/Cr–Ni/Co were applied for detailed investigations of the past lake water column properties (**Figure 5**).

6.2 Chemical composition of the borehole (swamp) section (BS)

Fluctuated values between average to higher values of Si, TiO_2, and Zr elements are observed in sediments retrieved from the swamp section. These elements exhibit similar patterns along this section. Contrarily, CaO, MnO, FeO, and Rb concentrations reflect average to relatively low concentrations. Uppermost two units (Us I and Us II) contain relatively high CaO, K_2O, and MnO contents but low to average concentrations of Si, Ti, Fe_2O_3, and Zr (**Figure 6**). The highest concentrations of Si, Zr, and TiO_2 are observed in unit Us III, which has overall relatively low concentrations of CaO, MnO, FeO, and K_2O. The lowermost unit (Us IV) also reflects a characteristic geochemical signature, with the uppermost part of this unit containing relatively high K_2O, CaO, MnO, FeO, Zn, and Rb and low Si, TiO_2, and Zr concentrations. The general downcore increasing tendency of Si, TiO_2, and Zr concentrations continues in this unit. The rapid variability of the redox-sensitive elements (Zn, V) and V/V + Ni was observed for 2.6–4.7 m interval. Lower values of these elements and element ratios were observed for the 7.9–9.7 and 11.3–12 m intervals and at 6.2 m depth (**Figure 6**). In accordance to V/Cr, U/Th, Ni/Co, and V/V + Ni cross-correlations, BS sediments are placed at the same specific area, which is also characteristic for the BAF37 sediments (**Figure 5**).

7. Discussion

A quantitative chemostratigraphic approach, together with sedimentological observations, has been used for a better understanding of the Late Holocene paleoecological history of the Lake Bafa and related aquatic environments. Furthermore, a sum of the selected paleo-ecosystem parameters (e.g., element concentrations and

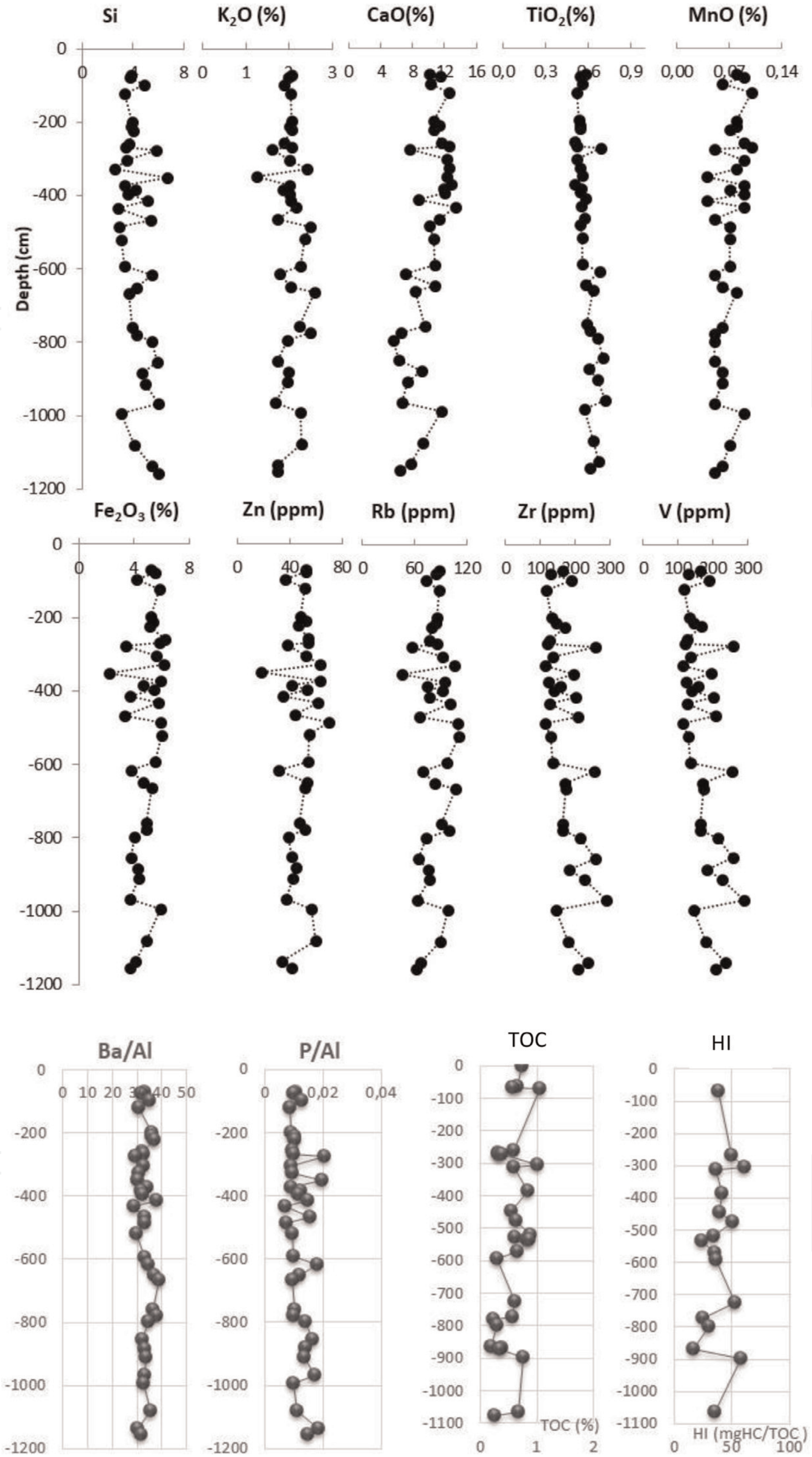


Figure 6.
Concentrations of selected elements and element oxides along the drill core BS, including TOC and HI data, and specific element ratios as a measure for organic matter accumulation rates.

element ratios) have been applied to identify the physical dynamics of the environment and the chemical characteristics of the water column, in terms of oxidation level and salinity. Furthermore, main environmental controls on Lake Bafa aquatic ecosystem were constructed using statistical approaches (FA) on geochemical data.

These controls include the external processes of terrigenous supply, leading to the enrichment of the siliciclastic elements, such as Si, Ti, and K and internal processes of biologic activity, which results in enrichment of Ca, Mg, Sr (in endogenic carbonate), TOC, and P. Herewith, high negative Factor I loads indicate similar geological sources for Al, K, Ti, Fe, Mg, Ni, Ba, and V enrichments for lacustrine sediments (cores BAF37 and BAF3B) (**Table 2**). Taking into consideration the Factors I and II loadings together, two main subgroups are suggested for these sediments. The first group is mainly a clastic-sourced element group (Al, Ti, Fe, Mg, K). The second group is related to the endogenic processes of carbonate deposition (Ca, Sr) and organic productivity (P) and water and sediment column redox processes (Ni, Co, V). The enrichment of these transition metals (Mn, Fe, Ni) is probably controlled by both detrital input and redox processes in the water and sediment columns. The factor load signature indicates that the swamp section reflects similar sources and modes of enrichment for most of these elements (**Table 2**). This suggests that the same geological processes prevailed also in the adjacent swamp area. However, there are also differences; Ba, Sr, and Ti enrichment pathways are different in the swamp sediments. Moreover, the nutrient elements (mainly P) and endogenic carbonate group elements (Ca and Sr) have similar factor (high Factor II and lower Factor I) loadings, suggesting a strong association with the organic productivity.

7.1 Detrital input and changes in hydrological conditions

The interpretation of the detrital sources and transport intensity of the detrital material allows us to determine the physical dynamics and energy conditions of the Lake Bafa Basin. Basically, elemental enrichment of Si, K, Ti, Zr, and Rb indicates the terrigenous material supply. Contrarily Sr, Ca, Mg, and Ba reflect biogenic sources [11, 27–29]. K, Si, and Ti element enrichments and enhanced average grain size distribution of the lake sediments (BAF37), "accumulated during the period of 2.5–2.2 ka year BP," indicate deposition under high energy conditions (**Figure 4**). This likely corresponds to a period when intensive freshwater input occurred during the earlier stages of separation of Lake Bafa from the Aegean Sea. However, this input was interrupted abruptly and followed by a short-term low energy conditions, indicated by the increasing clay size fraction and Ca (carbonate) contents of the sediments [8, 13, 31]. Average detrital input was low during the period of 1.95–0.8 cal. ka year BP, except for a brief period around 1.8 cal. ka year BP when relatively high energy conditions prevailed, which was likely caused by an abrupt hydrological change. After 0.8 cal. ka BP, the lake became completely isolated from the sea [8, 9] but continued to be influenced by the water and sediment inputs in its western part from the Büyük Menderes River. This river flooding events strongly influenced the Lake Bafa hydrology and caused abrupt water level fluctuations as well as rapid increases in the sedimentation rates during the Late Holocene [8, 9, 13, 30, 31]. The high variability of the river discharge was mainly controlled by the climate-driven rainfall pattern. During the enhanced discharge events, transported sediments could easily reach the lake since the streambed slopes have lower gradients. Therefore, we would suggest the climate-driven processes mainly controlled the variability of the hydrological conditions in the isolated lake during the last 800 or so years. Starting from the 1990s, a rubber dam was constructed. Since then, the lake level is currently artificially controlled.

7.2 Organic matter productivity

Relative variations of the biological production rates were determined, applying organic matter accumulation indicators (i.e., P concentrations, Ba enrichments, TOC concentrations). Phosphorus is known as the main nutrient marker, which would limit the biological productivity in any aquatic ecosystem [27, 32]. Ba enrichments are usually considered as a productivity proxy, being incorporated in the diatom frustules as micro-barite crystals [11, 27, 28]. However, these two elements would easily mobilize in anoxic conditions [33, 34]. Therefore, their signals may partly diminish from the sediments [33, 34]. Particularly, bulk organic carbon content (TOC) indicates changes in accumulation and/or preservation intensity under changing paleoecological conditions [10, 35–37]. Furthermore, hydrogen index (HI) values were applied to determine sedimentary organic matter sources [37, 38].

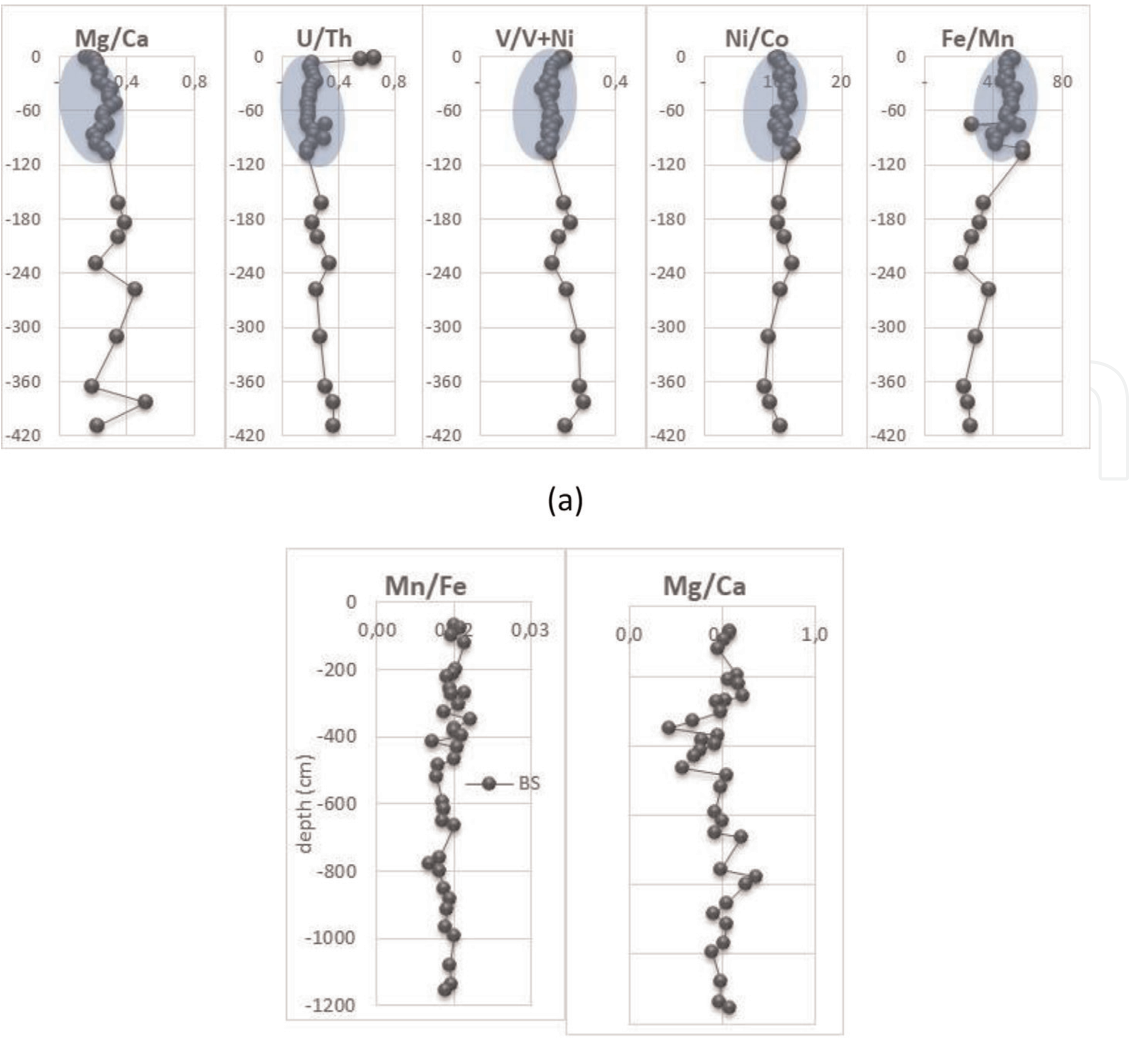
TOC content of lacustrine sediments is observed in a wide range between 0.7 and 4.4% (BAF37). TOC concentrations of swamp section sediments are quite low (≤1%) (**Figure 6**). Mean TOC content is 2.15% in the lake section and, however, 0.6% in swamp section. This obvious difference probably arises from overall distinct organic matter production processes, accumulation ranges, and preservation conditions. Main nutrient input parameter, P, is relatively low in the older lacustrine sediments (core BAF 37; >1.2 cal ka years). During the recent period, P availability was higher than the mean values. Therefore, P was probably not a limiting factor for organic matter productivity in Lake Bafa water column. Overall Ba trend which is similar to that of P, without obvious fluctuations, supports this conclusion (**Figure 4**).

Detailed investigations of lacustrine sediments supply additional information about time-dependent organic matter accumulation rate signs. Therefore, organic matter transportation and production ranges were probably intensive during the accumulation stages of the older sediments (Units III, IV, and V). During this stage, the organic matter type was probably controlled by a mixed contribution of the aquatic and terrestrial sources, reflected by the relatively higher HI values. Only exceptions are observed in two (2.74 and 3.98 cm) thin layers. These layers have lower HI values, mainly suggesting terrestrial organic matter sources. Similarly, organic matter accumulation of the recent lacustrine sediments (Units I–II; last 0.8-ka-year record) and the entire swamp section (BS) are also sourced by the terrestrial vegetation supply (**Figure 7**).

7.3 Water chemistry

Chemical properties of the water column are evaluated focusing on respective changes in salinity and redox conditions. Mg/Ca provides important evidence for the past salinity history of the water column. Basically, enhanced salinity (Mg/Ca) ratio favors the formation of aragonite, whereas low salinity (Mg/Ca) ratios promote calcite precipitation. This variation has important effects on the biota and the type of carbonate mineral accumulated in the sediments [29, 39]. Minerals containing Ti are conservative in geochemical reactions (e.g., redox conditions) [40]. Contrarily, changing redox conditions strongly affect iron (Fe) and manganese (Mn) cycles either in sediments or water column (trend toward lower pE). In particularly, Mn easily mobilizes in changing redox conditions than Fe [11, 41]. Accordantly, low Mn/Fe ratios reflect reducing conditions. Following the similar aspects V/Cr, U/Th, Ni/Co, U/Th, and V/V + Ni, cross-correlations were used to interpret past redox conditions [11, 12, 42, 43].

The Mg/Ca trend in Lake Bafa's sedimentary successions indicates an upward decrease, which suggests a decrease in salinity in time (**Figure 7**). Time-dependent decrease of the lake water column chemistry from past to recent terms is also supported by the diatom analysis results of the same sedimentary section (core BAF37), published by Bulkan et al. [8, 9].



(a)

(b)

Figure 7.
Element ratio indicator for water chemistry conditions. (a) represents specific element ratios for core BAF37 (blue-colored area represents values measured for sediment–water interface phase and long core sediments, jointly). (b) indicates drill core BS sediments.

Previous studies suggest that Cr, U, and V elements are rare in denitrifying conditions. Contrarily, enhanced Ni, Co, Cu, Zn, Cd, and Mo contributions are documented for organic-rich sediments, accumulated under sulfate-reducing bottom water conditions [11, 44–46]. Cross-correlations of V/Cr–U/Th, Ni/Co–U/Th, V/V + Ni–U/Th, and V/Cr–Ni/Co indicate that both the lake and the swamp sections deposited mainly under oxic conditions (**Figures 5** and **7**). Cr, U, and V element ratios in the Lake Bafa core and the swamp section indicate deposition under mainly oxic conditions. Despite most of the redox proxies showing the general oxic water column conditions, Ni/Co ratio points to somehow anoxic conditions. Furthermore, relatively low Mn/Fe ratio of the lake sediments (core BAF-37) indicates that the water column was probably partly oxygen depleted during 1.7–1.4 cal. ka year BP and during the isolated lake period, starting ca. 800 years ago.

7.4 Implications for Holocene age local environmental conditions

Both tectonics and sedimentological processes (N-S extension, graben, horst, erosion, delta progradation) and climate events (both orbital and abrupt changes) have played spectacular roles in modulating the ecological conditions in the Eastern Mediterranean Sea coastal areas. The ecological systems in this region include a variety of terrestrial aquatic ecosystems, ranging from fluvial, lacustrine, and lagoonal to coastal marine environments [6, 47–55]. Additional factors affecting the environmental conditions in such systems include abrupt geological events (e.g., storms, earthquakes, and tsunamis) and global fluctuations of sea level changes related to orbital climatic oscillations. We applied both sedimentological and geochemical proxies to unravel the time-dependent stages of landscape evolution in the coastal area of the Büyük Menderes Graben.

Several geological and geomorphological studies have been carried out in and around the Lake Bafa These studies have contributed to our knowledge of the coastal geomorphological history, sea level changes, tectonic processes driven erosion rates, climate and environmental induced changes (vegetation and faunal changes) and human impact [6, 8, 9, 48–57].

One study by Bruckner et al. [48] suggests that horst and graben tectonics in the Büyük and Küçük Menderes Grabens caused serious environmental and coastline changes. Mullenhoff et al. [6] concluded that the Lake Bafa was formed as a consequence of erosional processes in the adjacent mainland of Turkey, which have controlled the deltaic progradation and the filling of the Latmian Gulf. Particularly, in Miletus and the Büyük Menderes Graben, remarkable transformations have been revealed, with the metamorphosis of the marine gulf into residual lakes (e.g., lakes Azap and Bafa) [48]. The coastline of the Büyük Menderes Delta, located close to the southern graben area, progradaded seaward some 5 km [5] during the last 1.5 ka cal. year BP. Further progradation closed the entrance of the Latmian Gulf that resulted in the isolation of the Lake Bafa from the Aegean Sea at 0.8 cal. ka year BP. Lake Marmara in the Gediz Graben in the north, with a similar setting to that of the Lake Bafa, shows resembling environmental evolution [5, 7, 47], with the detrital input records reflecting synchronous changes within its catchment area. Similar to the Lake Bafa, Marmara witnessed a marked environmental change with a shift toward more oxic and freshwater conditions at 0.95 cal ka year BP and the increased effects of fluvial activity during the last 300 years. [47].

The strongest human impact has been detected at the time of the Greek period in the seventh- to first-century BC and especially during the Roman period in the first-century BC until the fourth-century AD, when sedimentation was about five times higher than that in the periods before and after [22]. These changes were accompanied by changes in the vegetation type. The palynological analyses have shown high amounts of Quercus type before the period of the strong human impact, which is also reflected by the element composition of the relatively recent sediments, water column samples, plant, and shells that have been analyzed for the pollution assessment studies [49–52].

A sum of local environmental conditions in the Lake Bafa and its catchment changed during the last 4.5 cal. ka years, but still several questions in this context remain to be answered. Basic questions are as follows: (I) Are the sediment accumulation rates different during the lacustrine, lagoon, or shallow water environmental phases and transitional stages? [53, 54], (II) how does the radiocarbon reservoir effect varies with changing environmental stages and time? [53, 54], (III) what is the temporal evolution of meandering delta progradation? and (IV) would it be possible to estimate the behavior and frequency of the river flood intensity from the lake's sedimentary record? These questions can be addressed by acquiring and analyzing additional long cores from different parts of the lake and from the delta. Furthermore, the same cores can be used to study rapid geological and climatic events such as tsunamis, volcanic explosions, and storms. Additional methods, including diatom analysis [8, 9], isotope analysis [8, 9], and lipid or amino acid biomarker analyses, would contribute further to our understanding of the ecological evolution of this unique basin.

8. Conclusions

Paleolimnological study of the Middle to Late Holocene lacustrine archive of Lake Bafa allowed us to reconstruct the geological history of the Büyük Menderes Graben's coastal area.

Lithological and geochemical analyses of the 4.2-m-long lacustrine core BAF37 and 12-m-long swamp drill core BS in the adjacent area provide a continuous archive of environmental changes during the last 2.5 and 4.5 cal. ka years, respectively. Geochemical and sedimentological proxy records from both cores show the following significant changes in the ecosystem of the area, from oldest to the present-day: stage IV, marine-dominated (4.5–2.7 cal. ka year BP); stage III, marine–river interaction (2.7–1.75 cal. ka year BP); stage II, lagoon (1.75–0.8 ka year BP); and stage I, the recent isolated swamp lake (last 0.8 cal. ka). This transition from marine stage to the recent lacustrine conditions was somewhat a gradual process, and the environmental conditions during the stage III were predominantly controlled by the tectonics and postglacial sea level rise, resulting in subsidence, erosion, sediment transport, and delta progradation.

The redox conditions were oxic before the isolation but became relatively reducing during the ensuing period. K, Si, and Ti concentrations and grain size distributions reflect a high energy environment interrupted by fluctuating short-term low energy conditions during 2.5–2.2 cal. ka year BP. Low energy conditions also prevailed during the 2.2–0.8 cal. ka yr. BP and particularly during the last 800 years.

Our observations indicate that ecosystem characteristics of the study are controlled by the combination of the hydroclimate and geotectonic processes. However, their effect of intensity is also reflecting changes from past to previous terms.

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