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The evolution of Lake Bafa (Western Turkey) – Sedimentological, microfaunal and palynological results

Marc Müllenhoff[1], Mathias Handl[1], Maria Knipping[2] & Helmut Brückner[1]

[1] Department of Geography, Philipps-University Marburg, Germany
[2] Institute of Botany, University of Hohenheim, Germany

Abstract

During the last six or so millennia, the former marine embayment of the Latmian Gulf has been silted up by the progradation of the Büyük Menderes (Maeander) delta. Long-term human impact together with the ecologically unstable natural environment of the Mediterranean region has led to strong erosion in the hinterland resulting in the progradation of the delta and the gradual infill of the embayment. Due to these processes, Lake Bafa has been created as a brackish residual lake in the southern part of the former embayment. We present results of sedimentological, microfaunal and palynological analyses of two sediment cores out of the lake, which provide insights into the palaeogeographic evolution of the Latmian Gulf as a whole and its vicinities in the Holocene.
Open deciduous oak forests represent the climax vegetation of the area. When human impact increased in the so-called "Beyşehir Occupation Phase" in the late 2nd millennium BC, degradation to the secondary formations of maquis and phrygana took place. Whilst grain-growing was important only during Antiquity, strong evidence of pasturing and the cultivation of fruit (mostly olive) trees in the area around the lake could be found until recent times. Full marine conditions in the embayment prevailed until the Hellenistic period. Owing to the delta progradation of the northern branch of the Maeander and the development of the "Milesian Lake", the milieu became stagnant and gradually turned brackish. A freshwater impulse can be deciphered in the 1st half of the 2nd millennium AD, when Lake Bafa as such was created.

1 Introduction

The "Bafa Gölü" east of the ancient city of Miletus is one of the largest coastal lakes in Turkey. Having a maximum depth of roughly 20 metres, its surface covers an area of approx. 7000 ha (Kasparek 1988; Figure 1).

Although various studies of landscape and vegetation history have been carried out on the sediments of nearly every lake in southwestern Turkey, an indepth study has not yet been published for Lake Bafa. This may be due to its polygenetic origin. The lake developed as a result of the delta progradation of the Büyük Menderes (Maeander) river. In the past six or so millennia, the river sediments have gradually infilled nearly the whole marine embayment of the so-called Latimian Gulf, thereby separating its southeastern part from the open sea. The palaeogeographic evolution of the area has been reconstructed by the indepth study of numerous geological corings in the alluvial and delta plain of the Maeander (Figure 1; cf. Brückner 1996, 1998, 2003, Brückner et al. 2001, 2002, 2003, 2004, Müllenhoff 2004, Müllenhoff et al. 2003).

Ongoing from the marine phase until recent times, Lake Bafa has acted as a sediment trap, storing most of the material produced and supplied by erosion and denudation in its vicinity. In order to decipher the palaeogeographic information stored in this excellent geo-archive, two sediment cores were retrieved out of the lake by means of a floating raft. The first one (Baf S1, water depth 10.50 m, length of the core 3.50 m) was taken from the eastern part of the lake near the ancient city of Herakleia, the second one (Baf S6, water depth 20.15 m, length of the core 9.75 m) from the profundal in its midwestern part. Both cores have been analysed with sedimentological, micro-faunistical and palynological methods. Radiocarbon dates render the chronostratigraphic framework. This study presents the results of the investigations to date (see also Müllenhoff 2004).

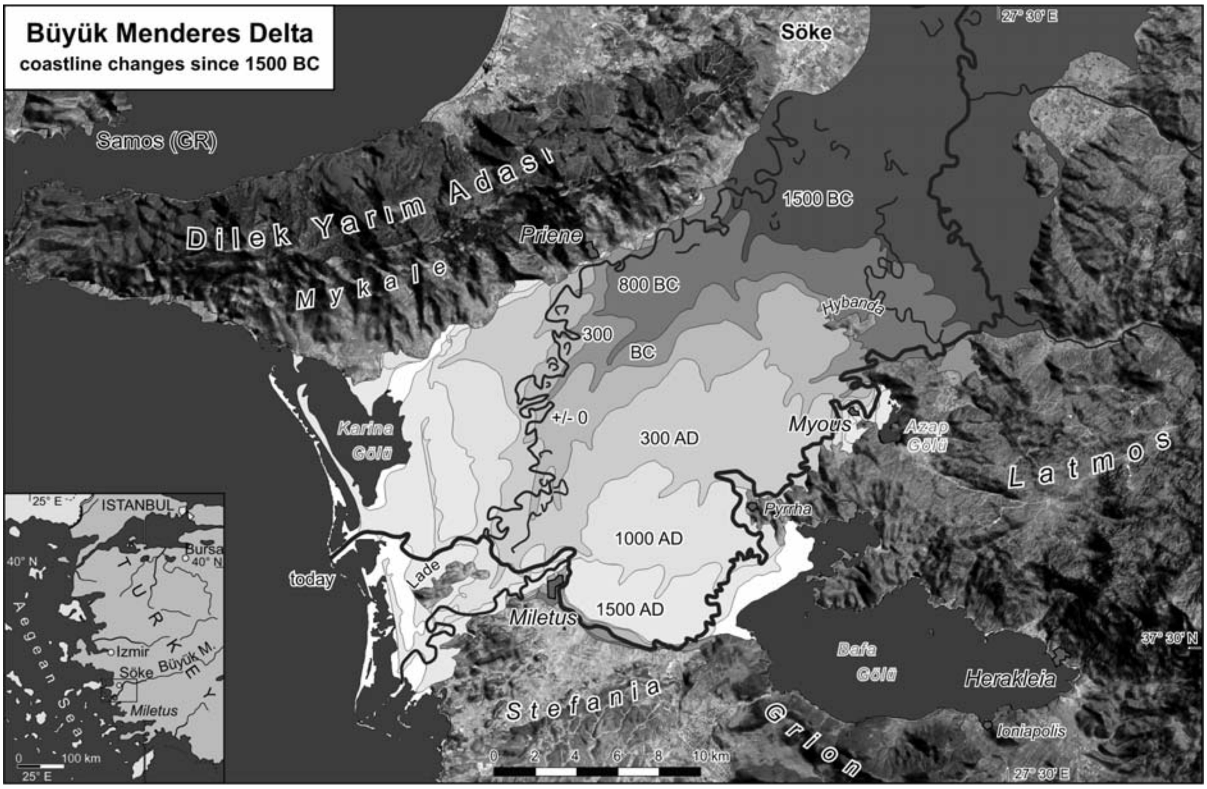


Fig. 1: Scenario for the progradation of the Büyük Menderes Delta in historical times. Source: Müllenhoff (2004), slightly modified.

2 Sedimentological results

2.1 Core Baf S1

Core Baf S1 (Figure 2) shows a bipartite stratigraphy. Coarse torrential river sediments are found below 1.40 m b.l.b. (= below lake bottom). In the upper part, these sediments are transformed by marine influence. Upwards decreasing amount of coarse pebbles and single marine microfossils (*Xestoleberis* cf. *fuscomaculata*, ostracod, and *Triloculina* sp., foraminifer) indicate a gradual increase in water depth due to the postglacial transgression. The position of this material in more than 10.50 m b.s.l. (= below present sea level) points to a time of accumulation older than 4000 BC, when local sea level was at a significantly lower level than today (cf. Müllenhoff 2004).

The following strata is silty sand, gradually changing into clayey silt with a high content of organic matter (up to 9.1 % loss on ignition, LOI). Micro and macrofaunal analyses reveal full marine conditions. Between 0.95-0.85 m b.l.b., intercalated coarse sand void of fossil remains is found. It represents increased terrestrial input from the adjacent slopes. An articulated specimen of *Cerastoderma edule* dates the beginning of this layer to 1240-1126 BC (Baf S1/6D; Table 1). Above 0.85 m b.l.b. more clayey silt is found. Microfaunal analysis shows increasing influence of freshwater, whilst a rich macrofaunal assemblage proves full marine conditions again at least until 710-558 BC (*Cerastoderma edule*, Baf S1/3D; Table 1).

The top layer is clayey to finesandy silt. The microfauna mainly consists of *Cyprideis torosa* (ostracod) and *Haynesina* sp. (foraminifer), indicating the final turnabout to definitely brackish conditions.

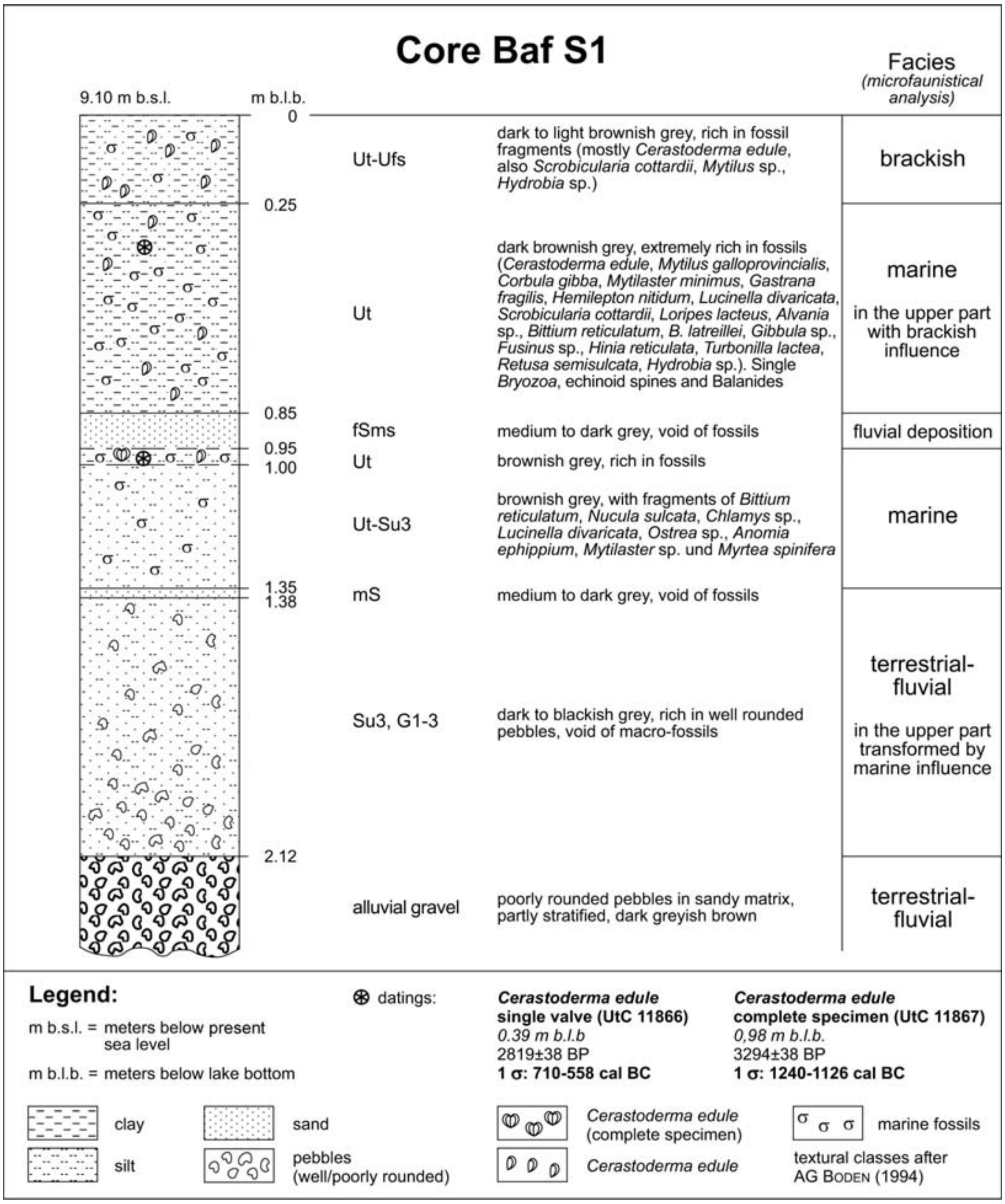
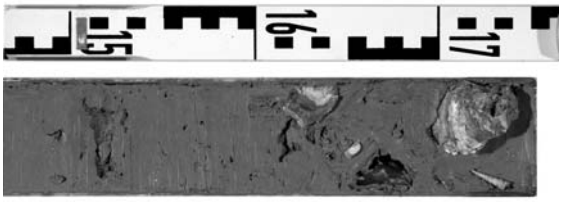


Fig. 2: Stratigraphy of coring Baf S1 out of Lake Bafa

2.2 Core Baf S6

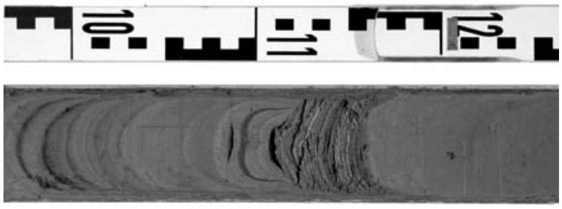
The stratigraphy of core Baf S6 shows three subsections. Beneath 9.16 m b.l.b. it reaches homogeneous clayey silts with a high content of organic matter (more than 8 % LOI). A rich microfaunal assemblage and numerous marine macrofossils (e.g. *Ostrea* sp., *Venus casina*, *Lucinella divaricata*, *Corbula gibba*, *Myrtea spinifera*, *Mytilus galloprovincialis*, *Nucula sulcata*, *Tellina donacina*, *Acanthocardia paucicostata*, *Turritella communis*, *Turbonilla lactea*, *Irus irus*, *Vermetus* sp., *Dentalium* sp.) prove oxygenated full marine conditions and a well developed benthic fauna at the sea bottom (Photo 1). One specimen of *Acanthocardia* cf. *echinata* dates the lower part of the sediments to 451-366 BC (Baf S6/6 D2, Table 1).

Between 9.16-9.11 m b.l.b., the character of sedimentation changes to a thin laminated bedding of at least 17 units of dark and light-coloured layers (Photo 2). Furthermore, microfaunal analysis indicates a total breakdown of population. Thin sections show annual layers (varves) of pure calcite (due to biogenous epilimnic decalcification during the summer; cf. Schwoerbel 1971, Kelts & Hsü 1978) and polymineralic composition (terrestrial clastic input during the winter). Both layers are rich in framboidic pyrite. In contrast to the sedimentological appearance, laboratory analyses evidence no major changes in all parameters. Thus, the varves indicate no modification of sedimentation circumstances, but a total ecological collapse owing to the loss of oxygen in the profundal zone of the embayment. Due to the absence of benthic fauna no bioturbation and subsequent deletion of the laminae occurred.



Baf S6/6 (9.46-9.75 m b.l.b.)

Photo 1: Marine sediments from the lower part of subsection 1 (core Baf S6).



Baf S6/6 (8.96-9.26 m b.l.b.)

Photo 2: Thin laminated bedding (varves) at the boundary between subsections 1 and 2 (core Baf S6).

Those modified circumstances were the result of the beginning separation of Lake Bafa from the open sea due to prograding Maeander delta and floodplain. The inflow of oxygen-rich seawater was then retarded; increasing freshwater supply by the Maeander caused a thermohaline stratification of the water body. Density distinctions prevented the mixing between the epilimnion and the hypolimnion, where oxygen rapidly diminished. Hence, holomixis was no longer possible and the profundal zone turned anoxic. According to the results of Müllenhoff (2004), the $2^{nd}/1^{st}$ century BC is considered to be the earliest date for this ecological change.

Subsection 2 spans 9.11-3.86 m b.l.b. It is characterized by 190 layers of differing thickness showing graded bedding. Grain size varies from slight to strong clayey silt. The single layers often end with blackish colour due to high contents of iron-sulphide, revealing once again anoxic conditions (Photo 3). The graded layers represent allochthonous input from the surrounding slopes during single events of high precipitation and/or floods, which may have spread as undercurrents or turbidity currents into the embayment (cf. Hupfer & Schneider 2001). The high sediment supply caused an attenuation of the autochthonously produced organic matter. Therefore, the LOI value is significantly lower than in section 1 (mean value: 5.7 %). Eutrophication seems to have started due to increased input of nutrients associated with the sediment load. This led to a high consumption of oxygen by biological activities, which preserved anaerobic conditions in the profundal zone. As a result of the strong sedimentation as well as the lack of oxygen, the material is almost completely void of fauna. Single specimens of the foraminifer *Haynesina* sp. prove unfavourable brackish conditions.

Baf S6/3 (4.98-5.37 m b.l.b.)

Photo 3: Graded bedding and black layers from subsection 2 (core Baf S6).

Baf S6/3 (3.45-3.75 m b.l.b.)

Photo 4: Stratified sediments with sporadic calcitic layers from subsection 3 (core Baf S6).

The top section of core Baf S6 is vaguely stratified clayey silt with a high content of organic matter (LOI approx. 12 %) and sporadic calcitic layers (Photo 4). Ecologically improved conditions with the possibility of biogenous precipitation of calcium carbonate are also documented by mostly brackish macrofossils (*Cerastoderma edule*, *Lentidium mediterraneum*, *Mytilaster* sp., *Hydrobia* sp.) and ostracods. Two specimens of *Cerastoderma edule* from the lower part of the sediments date from 438-528 and 628-654 AD, respectively (Baf S6/2 D2 and D1, Table 1).

Sample	Laboratory Sample Code	Depth (m b.l.b./ m b.s.l.)	Material	$\delta^{13}C$ (‰)	^{14}C Age	Calibrated Age (range ± 1σ)
Baf S1/3D	UtC 11866	0.39/ 9.49	*Cerastoderma edule*, single valve	-2.3	2819±38 BP	710-558 BC
Baf S1/6D	UtC 11867	0.98/ 10.08	*Cerastoderma edule*, articulated specimen	-3.4	3294±38 BP	1240-1126 BC
Baf S6/2 D1	UtC 12125	2.96/ 21.71	*Cerastoderma edule*, articulated specimen	-3.7	1755±35	628-654 AD
Baf S6/2 D2	UtC 12126	3.32/ 22.07	*Cerastoderma edule*, articulated specimen	-4.8	1925±41	483-528 AD
Baf S6/6 D2	UtC 12269	9.68/ 28.43	*Acanthocardia* cf. *echinata*, single valve	1.7	2681±38	451-366 BC

Tab. 1: Radiocarbon dates of the corings out of Lake Bafa. Radiocarbon age determination by Dr. K. van der Borg, R.J. Van de Graaff Laboratorium, University of Utrecht (AMS-technique). Calibrated ages according to the radiocarbon calibration program Calib4 (Stuiver & Reimer 1993; Stuiver, Reimer & Reimer 2003); for marine carbonate a reservoir correction of 402 years was applied (m b.l.b. = metres below lake bottom; m b.s.l. = metres below present sea level).

2.3 Chronostratigraphy and sedimentation rates

Allowing for the described stratigraphic results and the radiocarbon dates, calculation of sedimentation rates renders possible the chronological classification of the ecologic changes delivered by core Baf S6. Subsection 1, representing a full marine milieu, accumulated after 451-366 BC. The rich faunal assemblage proves at least episodic aerobic conditions in the profundal zone. The following varved section indicates the beginning separation of the embayment and the development of an anoxic profundal. Within 5 cm, 17 units consisting of both calcitic summer and clastic winter laminae have been deposited. The outcome of this is a mean accumulation rate of 0.29 cm/a. Presuming the 2nd century BC as the earliest date for the environmental change, a sedimentation rate of 22 cm/100 a can be calculated for the overall period between ca. 400-150 BC.

Subsection 3 yields two radiocarbon dates at a depth of 3.32 resp. 2.96 m b.l.b. The age difference of about 160 years leads to a mean accumulation of 22.5 cm/100 a. Allowing for this rate, the boundary between the subsections 2 and 3 dates to approx. 240 AD.

Thus, deposition of subsection 2 must have occurred between ca. 150 BC and 240 AD. From this it follows that the sedimentation rate in the late Hellenistic and Roman eras was accelerated by 6 times (135 cm/100 a) as compared to the timespan before and after. The reason for the enormous increase in sediment supply is ecologically unwise land use, particularly in Roman times. Deforestation of the hinterland led to strong erosion in the vicinities of the Latmian Gulf. This process did not decrease until post-Antiquity due to the loss of economic and strategic significance – the former seaport city of Herakleia lost its direct access to the sea – and the following depopulation of the region (see also Brückner 2003, Müllenhoff 2004).

3 Palynological results

Besides the sedimentological and palaeoecological examination, palynological analyses were carried out to shed new light on the vegetation history of the vicinities of the Latmian Gulf in the past millennia. Core Baf S1 documents the older stage until the Hellenistic epoch, whereas Baf S6 covers the period from Classical to recent times.

3.1 Core Baf S1

The pollen-diagram of core Baf S1 (Figure 3) can be divided into four subsections. The first one in the lowermost part of the core represents the marine transformed coarse-grained fluvial sediments. It is characterised by large amounts of deciduous oak (*Quercus pubescens* type, 27.6 %) and *Pinus* (14.6 %) as well as *Isoetes histrix* type, the latter most probably originating from flat depression areas close to the coast, where the rising sea-level caused an ascending groundwater table and the development of seasonally (e.g. in winter) flooded areas, the favoured habitat of this plant (Davis 1984-1988). Pollen types showing a direct anthropogene impact on the vegetation could not be identified. Only the relatively low values of *Plantago lanceolata* type may be a hint to the first influence of grazing. Based on the age determination (more than 4000 BC, Chapter 2.1), this pollen assemblage probably represents the climax vegetation around the Latmian Gulf, consisting predominantly of deciduous oak forests. This open woodland was affected by human activities only little by little, starting in this area in the 7th/6th millenium BC (Peschlow-Bindokat 1996, Lohmann in prep.). Altogether, the results agree with the findings of Wille (1995) for the Lion Harbour of Miletus, also postulating a once greater extension of deciduous forests. Hence, earlier studies concerning the climax vegetation of the eastern Mediterranean (e.g. Van Zeist & Bottema 1991, Jahns 1993, Rossignol-Strick 1999) are confirmed by the results of this investigation.

The second zone shows decreasing values of deciduous oak and pine, but an increasing amount of maquis elements like *Phillyrea*, *Cistus* and *Ericaceae* (Jahns 1993) as well as fruit trees (*Olea*, *Castanea*) and indicators of farming (*Plantago lanceolata* type, *Juniperus* type; Eastwood et al. 1999, Bottema & Woldring 1990, Behre 1990). As confirmed by the radiocarbon dating of sample Baf S1/6D, the changes represent the so-called “Beyşehir Occupation Phase”, starting in different profiles in south-western Turkey in the late 2nd/early 1st millenium BC (Bottema & Woldring 1990). This settlement phase resulted in a degradation of the natural vegetation and in increased soil erosion, evidenced by the massive input of terrestrial material from the adjacent slopes (see Chapter 2.1). The supply of eroded soil material from the hinterland is also proved by the noticeable content of carbonated plant remains (probably from woodland clearance by slashing and burning) and high values of indeterminable and especially resistant pollen types (*Asteraceae, Cichoriaceae*).

Subsection 3 is characterised by predominantly decreasing values of potential indicators of human impact. A slightly reduced rate of *Olea* and the increasing amount of *Pistacia* indicate a reduction of olive cultivation and a spread of *Pistacia* maquis on the abandoned ground (cf. Jahns 1993). Higher values of Pine and evergreen oak exemplify a gradual stabilization of the ecosystem (spreading of *Quercus coccifera* in the less used maquis and *Pinus brutia* on formerly stubbed areas). Hence, soil erosion and resulting sediment supply was reduced. This is proven by the decrescence of *Asteraceae*, *Cichoriaceae* and Indeterminata.

Subsection 4 again shows decreasing values of *Pinus* and increasing values of *Olea* as well as *Chenopodiaceae* (up to 6 %), *Artemisia*, *Rumex* type and *Plantago lanceolata* type, which are considered to indicate open vegetation (i.e. non forested/steppic areas) or pasture (Behre 1990, Bottema & Woldring 1990). The *Cerealia* type reaches maximum values of 3.3 %. Furthermore, for the first time rye (*Secale*) could be proven. This points to an accentuated cultivation of cereals. The vegetation changes represent the effects of the increased cultivation from Archaic to Hellenistic-Roman times, which is supported by the radiocarbon age of sample Baf S1/3D.

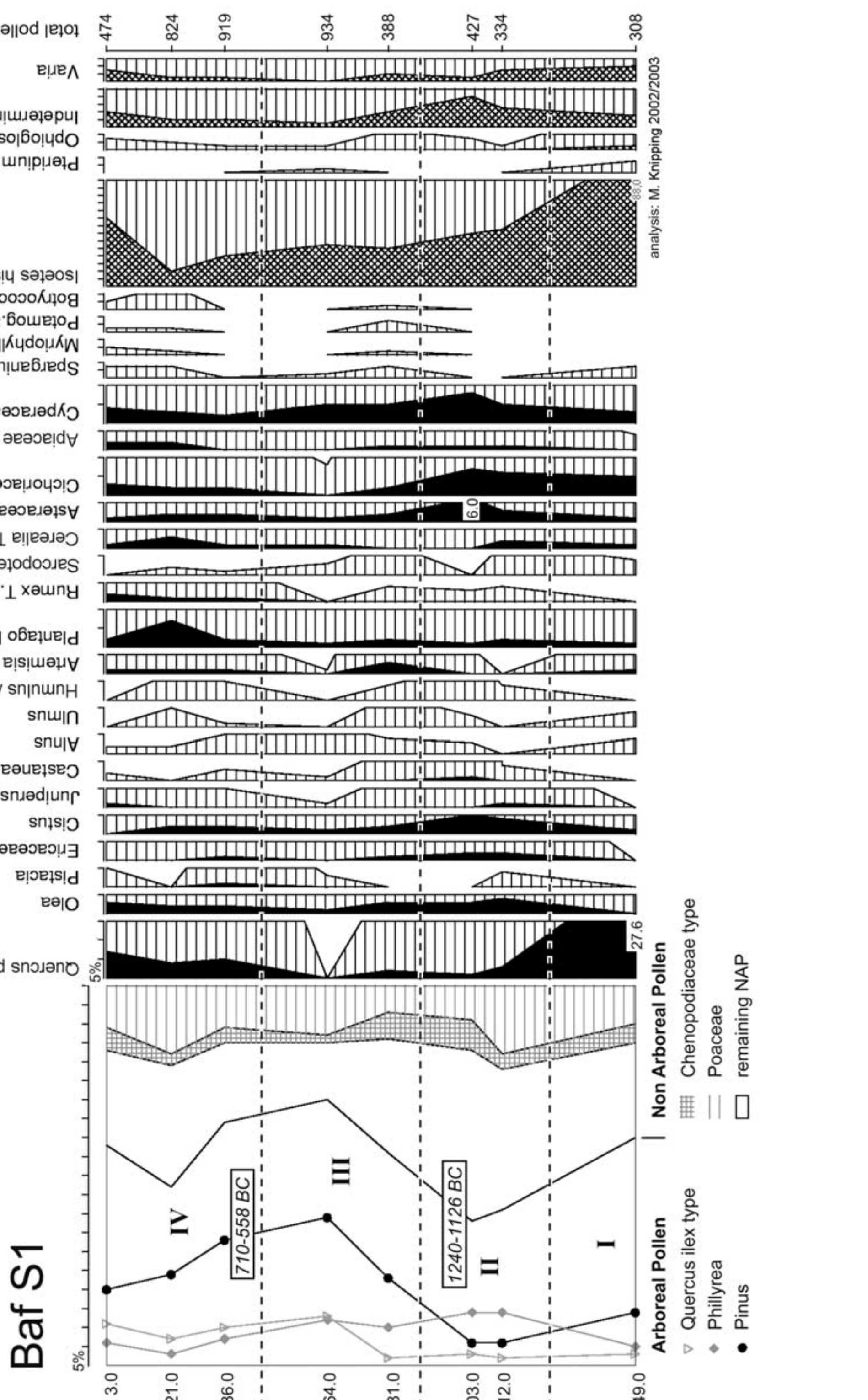


Fig. 3: Percentage pollen diagram of sediment core Baf S1. Basic sum = terrestrial elements excluding Varia and Indeterminata.

3.2 Core Baf S6

Palynological analysis confirms the subsections of core Baf S6, based on sedimentological criteria (Figure 4). The lowest part, representing the Classical and early Hellenistic periods (cf. Chapter. 2.2), is already disturbed by human impact. It shows large amounts of *Pinus* as well as maquis-type trees and shrubs (e.g. *Phillyrea*, *Quercus ilex* type, *Cistus*). High values of *Olea* confirm the cultivation of olive trees, evidenced also by historical tradition (Herodot 1,17-18). Furthermore, *Juniperus*, *Sarcopoterium* and *Plantago lanceolata* type indicate pasture.

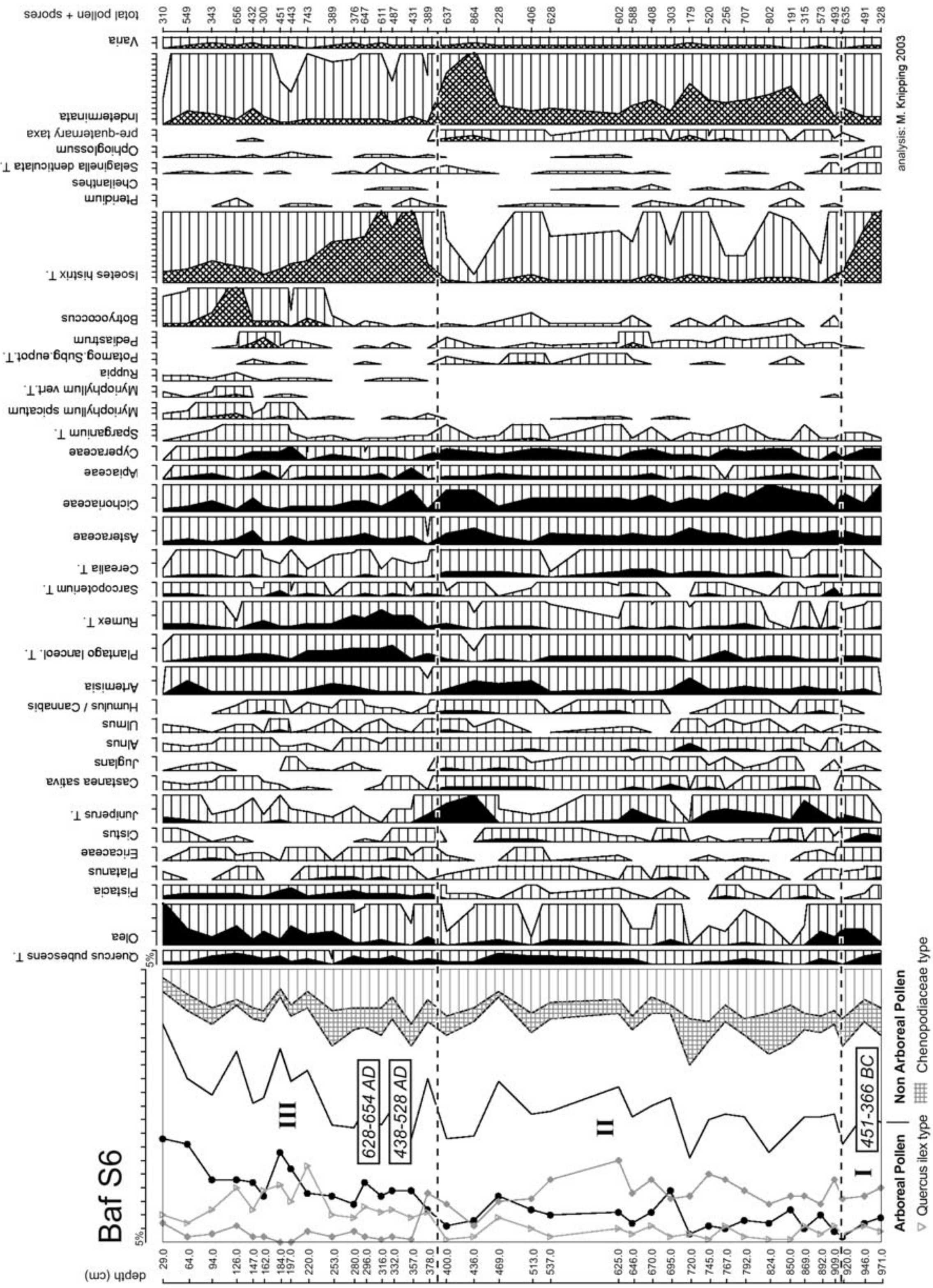


Fig. 4: Percentage pollen diagram of sediment core Baf S6. Basic sum = terrestrial elements excluding Varia and Indeterminata.

Subsection 2 is characterised by notably reduced pollen concentration and the content of reworked older pollen grains ("pre-Quaternary taxa") as well as a high amount of Indeterminata and resistant pollen types (*Asteraceae*, *Cichoriaceae*). This indicates enhanced supply of weathered sediment and older pollen material from the hinterland (cf. Chapter 2.2). The arboreal pollen is mainly dominated by *Phillyrea* and *Pinus*. *Olea* is decreasing, whilst *Juniperus* type reaches a maximum value of almost 9 %. Therefore, pasturing seems to have been preferred to the cultivation of olive trees. Agriculture is also conjecturable (*Cerealia* type up to 3.3 %). The high amount of *Artemisia* and *Chenopodiaceae* type may be the result of quarrying marble at the southern coast of the Latmian Gulf during Hellenistic and Roman times. Transport and on-board loading of marble columns for the temple of Apollon in Didyma (Peschlow-Bindokat 1996) created open surface areas near the coast, which may have been colonised by those halophytes.

Especially the upper part of subsection 2 shows extremely high contents of indeterminable pollen types and a different state of pollen preservation, due to a high supply of reworked pollen-bearing sediment. Considering the chronostratigraphical results of Chapter 2.3, this phase of high morphodynamic activity dates to the mid-3rd century AD. It is most likely associated with the devastations owing to the invasions of the Goths between 258-262 AD (cf. Peschlow-Bindokat 1996, Kasparek 1988). Thus, not only the quarries at the southern coast of the gulf were abandoned, but also the cultivated (perhaps terraced) farmland and olive groves. The subsequent decay triggered soil erosion and correlate accumulation in the adjacent embayment. Similar processes are described by Hess (1985) for the neighbouring delta of the Küçük Menderes at the time of the Seldjuk invasions (14./15. cent. AD).

Subsection 3, representing the post-Antiquity times (cf. Chapter 2.2), shows an increase in *Quercus ilex* type and *Pinus* and a decrease of *Phillyrea* (cf. Jahns 2003). Maquis and phrygana elements (*Pistacia*, *Ericaceae*, *Sarcopoterium* type) as well as indicators of grazing (*Plantago lanceolata* type, *Rumex* type) are increasing, too, whilst fruit trees (*Castanea sativa*, *Juglans*) and *Cerealia* type lose importance. This indicates a change in land use with decline in agriculture and increased importance of pasturing. The rising *Olea* curve (up to 17 %) gives evidence of major olive cultivation in younger history. Higher values of swamp and freshwater plants (*Sparganium* type, *Myriophyllum spicatum*, *Ruppia*, *Pediastrum*, *Botryococcus*) in the core section above 2 m b.l.b. point to the establishment of predominantly freshwater conditions owing to the definite separation of Lake Bafa from the open sea and the evolution of an independent brackish to freshwater environment. The palynological findings do, therefore, support the sedimentological and microfaunal results.

4 Conclusions

Sedimentological and microfaunal investigations on two sediment cores out of Lake Bafa (Bafa Gölü) shed new light on the development of this lake and its surrounding area in the last millennia. Baf S1 shows the transition from fluvial-terrestric to littoral-marine conditions in consequence of the post-glacial rise in sea level. Full marine conditions prevailed until the Hellenistic era. Due to the delta progradation of the Maeander and the subsequent separation of the remaining south-eastern part of the Latmian Gulf from the open sea, the milieu gradually turned brackish and stagnant. At the same time, sedimentation rate increased from 11 cm/100 a in the Geometric-Archaic periods (Baf S1) and 22 cm/100 a in the Classical-Hellenistic periods (Baf S6), respectively, to 135 cm/100 a in the Roman era as a result of increased deforestation and ecologically unwise land use. The destruction of a more or less well-regulated agrarian landscape as a result of the invasions of the Goths in the mid-3rd century AD caused accelerated soil erosion as well. Sedimentation rates only decreased as the re-gion's importance and population dwindled in post-Antiquity times.

Palynological analyses show high amounts of *Quercus pubescens* type before the times of stronger human impact. Therefore, former studies proving open deciduous oak forests as the climax vegetation of the coastal eastern Mediterranean (e.g. Van Zeist & Bottema 1991, Jahns 1993, Rossignol-Strick 1999) can be confirmed for the area around the Latmian Gulf. When human impact increased in the so-called "Beyşehir Occupation Phase" in the late 2nd millennium BC, degradation to the secondary vegetation formations of maquis and phrygana took place. Whilst grain-growing seems to have been important only during the Antiquity, strong evidence of pasturing and the cultivation of fruit (mostly olive) trees could be found from Antiquity until recent times. Tradition has it that the most important Milesian export good was wool, whereas cereals had to be imported from the Black Sea region (Kleiner 1968, Brückner 1996).

The sedimentological and palynological investigations presented here prove strong morphodynamic and palaeogeographic changes in times of high human impact on the natural ecosystems. Hence, the results of this study are in line with other investigations assigning man as the decisive agent for the shaping of the Mediterranean landscape since Antiquity. The friable natural predisposition of the Mediterranean ecosystems was a major reason why anthropogene interference was able to have such far-reaching effects.

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Adresse

Dipl.-Geogr. Marc Müllenhoff
Department of Geography
University of Marburg
Deutschhausstr. 10
D-35032 Marburg

E-mail: marcmuellenhoff@addcom.de
h.brueckner@staff.uni-marburg.de