2500 years of anthropogenic and climatic landscape transformation in the Stymphalia polje, Greece

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A B S T R A C T

Lacustrine sediments generally record landscape development in the lake’s catchment area controlled by palaeoclimatic and human induced changes. To improve our understanding on the anthropogenic and climatic influences on landscape development in Southern Greece for the last 2500 years, we report a 2 m-long, continuous high-resolution sedimentary record from shallow Lake Stymphalia (Peloponnese, Greece). Our proxies record climatically as well as anthropogenically induced landscape changes, influencing the lake area and lake depth.

The Classical-Hellenistic era reflects a moderate, stable Mediterranean climate with low sedimentation rates. The parallel existence of the highly populated, major ancient city of Stymphalos, on the contemporary lake edge, doesn’t seem to have caused lasting alterations in the record. The construction of the Hadrianic Aqueduct in the Roman era, ca. 130 AD, however causes an influential transformation in the lake development. It has a lasting effect on the lake hydrology as well as the vulnerability of this ecosystem. During Late Roman times, 5th to 6th century cal AD, the abandonment of the aqueduct combined with cooler climate conditions allows lake levels to recover. A phase of very high climatic instability was identified for the subsequent Early Byzantine (EB) period, during the 7th and 8th century cal AD. For this period, the later phase of the Late Antique Little Ice Age (LALIA), our proxies indicate further cooling and highly fluctuating water availability in a rather small lake area. The Middle Byzantine (MB) Period (9th-12th century AD) is characterized by an over fivefold increase in sedimentation rates. Since local population was still well below Classical levels, we explain this singular period through an interaction of modest increase in land use but marked by careless management of deforested areas, warm and wet climatic conditions during the Medieval Warm Period and long-term effects of vulnerability caused by the aqueduct construction. Probably during this phase, the lake level rose through unparalled sedimentary infill to flood and bury a significant part of the Lower Town of the abandoned ancient city. The Late Byzantine Period (13th and 14th century AD) sees core evidence for erosion of established, non-vegetated soils (high magnetic susceptibility), in a period of almost total depopulation. In the subsequent Ottoman era (late 15th — early 19th centuries AD) local settlement made only slight recovery, the climatic conditions seem less stable during the Little Ice Age (LIA) and the lake seasonally and later periodically starts to dry up, cumulating in a longer dry phase at the end of the 19th century AD,

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when agricultural activity on the polje floor was possible. The conclusion conforms with recent modelling of environmental change, critical of mono-causation, rather focussing on complex interactions of human and natural factors in the inception of landscape transformation.

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1. Introduction

The Late Holocene in Southern Greece is shaped by a strong interaction of climatic changes with natural and anthropogenic landscape transformations. Although there is an increasing number of studies demonstrating the complex interrelationship between climate and societies, it often remains challenging to decipher the influence of climatic change versus human activities in environmental records. Palaeoclimatologists have developed reconstructions of climate change in the Mediterranean region during the Holocene, covering cultural periods back to the Neolithic, when humans became sedentary and the interrelationship between climatic fluctuations and human activity grew in importance (Finné et al., 2011; Magny and Magny, 2013; Meriam et al., 2017; Palmisano et al., 2019, 2017; Roberts et al., 2016).

Recent studies have suggested that important climatic shifts in the Late Holocene coincide with major changes in Mediterranean cultural history (Butzer, 2012; Drake, 2012; Kaniewski et al., 2013; Langgut et al., 2013; Staubwasser and Weiss, 2006; Weninger et al., 2009). However, many archaeologists and historians have been critical of naïve use of climate change as a forcing factor in the socio-cultural development of the region due to the lack of both high-resolution terrestrial palaeoclimate data in a solid chronology framework and simple forcing-and-response mechanisms (Haldon et al., 2018). Hence, there is a strong need for closer interdisciplinary collaboration on research questions dealing with human-environmental interaction and societal response to climatic changes (Bintliff, 2012a, 2002; Casana, 2008; Izdebski et al., 2016; Knapp and Manning, 2016; Sadori et al., 2008).

Climate reconstructions from lake sediment archives in the Eastern Mediterranean are still relatively scarce and the climate patterns often seem less well constrained compared to the Western Mediterranean (Gogou et al., 2016; Luterbacher et al., 2012; McCormick et al., 2012). In particular, the last 2500 years have been studied less frequently or with lower resolution in palaeoenvironmental records although this time period is of major relevance for the development of Greek society (Finné et al., 2011; Sadori et al., 2016; Koplaki et al., 2016a). Recently, Büntgen et al. (2016) identified a cold phase in Eurasia lasting from 536 to 660 AD based on high-resolution tree ring records and named it Late Antique Little Ice Age (LALIA). This overlaps with the latter part of the European Migration Period (4th – 7th century AD; Moschen et al., 2011), an interval of widespread migration movements into the Roman Empire, which saw considerable societal changes, including the collapse of the Western Roman Empire, the transformation of the Eastern Roman Empire into the Byzantine state, the collapse of the Sasanian Empire, the expansion of Slavic-speaking peoples in central and eastern Europe and the Justinian Plague (Moschen et al., 2011). Due to these significant societal changes and its negative impacts on European civilisations, this wider period is also referred to as the “Dark Age[s]” (Brooke, 2014; Büntgen et al., 2016; Helama et al., 2017a; McCormick et al., 2012). While there is considerable archaeological information from the Greek Mainland, including the Peloponnese Peninsula, for human activities during the last two millennia (Bintliff, 2012b; Izdebski et al., 2016), high resolution palaeoclimate records for this period are rare (Atherden and Hall, 1994; Finné et al., 2011; Izdebski et al., 2016; Jahns, 1993). In a recent review of the currently available climate records from the Mediterranean for the last two millennia, Luterbacher et al. (2012) state that the existing climate proxies often express varying trends, even within the same region. All of this demonstrates the need for further interdisciplinary, high-resolution studies on landscape development in the Eastern Mediterranean.

With the intention of addressing this gap and limited dataset, we here provide a detailed palaeoenvironmental reconstruction of the last 2500 years from Lake Stymphalia, the only remaining natural perennial lake in the Peloponnese. We discuss the environmental changes in the catchment in relation to the human history known from the area in order to distinguish anthropogenically from climatic developments imprinted into the sedimentary record. The potential expression of the LALIA in Southern Greece is investigated in order to improve our understanding of the societal and environmental history of this area during this period of rapid climate fluctuations. Excavations at Ancient Stymphalos by the Canadian Institute in Greece since 1983 provide the archaeological groundwork to reconstruct human activity in the area (cf. section 3.6). As a karst polje without surficial outflow represents on the one hand a continuous sediment sink and on the other hand has always been considered as an important location for agriculture and farming in the Mediterranean area (Vött et al., 2009). Lake Stymphalia represents an excellent archive to study a combination of climatically as well as anthropogenically induced environmental changes. The differentiation between human and climate induced factors behind environmental changes, however, is not always trivial and several causes may provoke the same response in the sedimentary record. For example, reduction in the amount of water available in Lake Stymphalia may result from either: (1) a decrease in precipitation; (2) an increase in evaporation; (3) changes in the thawing period and variations in the discharge related to snowmelt; (4) inferred or recorded human channelling of the water from the source; (5) increased water usage of lake water for agricultural purposes. To get a better idea of the complete picture, we take into account several different palaeoenvironmental proxies, traditional and well-established ones as well as new and innovative proxies. As far as available, we included archaeological or historical evidence and when we can still not be certain of the process causing a signal in the record, we provide a selection of possible scenarios.

2. Study area

Lake Stymphalia (Λίμνη Στυμφαλίας) (37.85° N, 22.46° E), is a shallow karstic lake located in the north-eastern Peloponnese (Greece; Figs. 1 and 3-A). It is described in detail by Heymann et al. (2013). Sediment material is only received from surface runoff and torrential rivers originating from karst springs, which depend on the amount of precipitation that is brought mainly in winter and early spring (Fig. 2). On the polje floor, the karstified limestones are covered by argillaceous sediments of up to 160 m thickness (Morfis and Zojer, 1986). Presently, Lake Stymphalia is the largest remaining mountain lake in the Peloponnese, protected by the NATURA 2000 network (Heymann et al., 2013; Morfis and Zojer, 1986;
Modern climatic conditions are described in Heymann et al. (2013) and Morfis and Zoyer (1986). In a recent publication, Nanou and Zagana (2018) indicate a mean annual precipitation of 850 mm and ranges from 719 to 1656 mm for the time period 1975–2015, confirming high inter-annual variation. Based on daily precipitation data recorded between 1949 and 2011 at the meteorological station Driza-Stymphalia (37.8699° N, 22.4643° E, Greek Special Secretariat for Water, Ministry of Environment and Energy), we calculated the mean annual precipitation at 618 ± 201 mm over the respective period; this occurs mainly from October to February (Fig. 2). In April 2017, we installed a small datalogger (Tinytag Plus 2) close to the fountain house of ancient Stymphalos to measure daily temperatures and relative humidity, which provided the monthly temperature values shown in Fig. 2.

The lake’s surface area may have varied substantially throughout time and there is evidence for seasonal desiccation (Walsh et al., 2017). Since the 19th century, the lake occasionally dried out completely, which in the mid-20th century allowed it occasionally to function as a aircraft runway (hence the reason for its local nickname “aerodromo” (airport)). In recent times, Lake Stymphalia fell dry during the early 1990s and was used for agricultural purposes (Papastergiadou et al., 2007). For several reasons, we do not assume any extreme lake level rise at Lake Stymphalia, at least not during the last 2500 years, although local archaeological and historical records indicate significant variation in the height and extent of the lake since Classical times: (1) there is no evidence of rocky, barren beach deposits in Stymphalia comparable to those described by Knauß (1990) from the neighbouring Peneios polje, where an exceptionally high lake level was artificially induced by Ottoman troops during the Greek liberation battle in the 19th century; (2) Stymphalia has three discharge possibilities, the large natural sinkhole in the North (Morfis and Zoyer, 1986) and the Hadrianc Aqueduct built around 130 AD; (3) the Cistercian Zaraka Monastery, the best preserved Frankish monastic site in Greece (Campbell, 2018), was built in the first half of the 13th century AD on the relatively flat valley floor, about 2 m above and 1 km distant from the present day lake shore, with no sign of later flooding. However, a major part of the Lower Town of ancient Stymphalos city has been submerged and silted since the Early Roman era and currently lies under sediments (Williams, 2005), induced by a rise of the lake bottom of only few metres since the founding of that town.

### 3. Materials and methods

#### 3.1. Sediment cores

Field and initial laboratory work were mostly conducted in 2010 and 2011 and have been described in detail by Heymann et al. (2013). Three overlapping sediment core pairs of different lengths (STY-1, STY-2, and STY-3) were retrieved. The 16-m-long composite core STY-1 is the most complete and here, we discuss the upper 208 cm of it in detail (units 59–70b; Table 1), that cover approximately the last 2500 years based on the up-dated age-depth-model described below which records both natural and anthropogenic influences. The lower limit was set at the upper sedimentary boundary of unit 58. We use the following proxies measured and described by Heymann et al. (2013): lithology, sediment structure, Munsell color (Munsell, 2000), grain size distribution, total carbon (TC), total inorganic carbon (TIC), total nitrogen (TN), magnetic susceptibility (Nowaczyk, 2001; Nowaczyk et al., 2002), and X-ray fluorescence (XRF) measurement (see section 3.3 below).

#### 3.2. Dating technique

The age control of the sediment cores was based on accelerator mass spectrometry (AMS) radiocarbon (14C) measurements performed at four different laboratories. For radiocarbon dating, 24 core samples and 3 surface samples have been taken and, as visible organic remains were almost absent from the core, mainly bulk sediments were used for dating (Table 2). The combined dating results lead to a time scale substantially different from the one published by Heymann et al. (2013). We present the construction of the time scale in detail in the following section 4.2. Throughout the paper, the year 1950 AD is used as year 0 BP (Mook and Plicht, 1999).

#### 3.3. Elemental composition: X-ray fluorescence measurements

Non-destructive X-ray fluorescence (XRF) measurements using energy dispersive fluorescence radiation on split core surfaces were performed with an Avantech XRF Core Scanner, using a Rhodium X-ray source. The scanning parameters are the same as described by Heymann et al. (2013). The scan resolution of the upper 5 m of core STY-1A and overlapping intervals of core STY-1B was 1 mm with an exposure time of 16 s at 10 kV and 15 s at 30 kV, respectively. We selected 13 elements (10 kV: Al, Si, S, Cl, K, Ca, Ti, Mn, Fe; 30 kV: Zn, Rh, Sr, Zr) for a detailed analysis of their presence across the sediment sequence and their palaeo-environmental and -climatic significance (n = 4961). Elements with low intensities (<300 total counts) which are less reliable (Tjallingii et al., 2007) were excluded. The XRF scanning results represent element intensities in total counts per second (tcp) which mainly depend on element concentration, but also on matrix effects, physical properties, sample geometry, and hardware settings of the scanner (Tjallingii et al., 2007). We chose to plot the XRF scanning results as log-ratios that can be interpreted as changes in relative concentration of an element pair, to avoid statistical analysis of data sensitive to the closed-sum effect and asymmetric element ratios (Weltje and Tjallingii, 2008). As we were applying the R software (R Core Team, 2017) for plotting, natural logarithms with base e (log) were applied by default. To assess the normalized elemental data in a palaeo-environmental and -climatic context, we compare relative changes of one element to another, rather than using absolute changes in element concentration.

#### 3.4. Organic analysis: lipid extraction and GDGT analysis

The interval 152–191 cm has been sampled at an average resolution of 0.5 cm from the sediment core STY-1A. Generally, five mm-thick sediment slices were taken, but for some exceptions, the spacing was varied due to the lithology. The sediments were lyophilized for 24 h and ground to a fine powder using a solvent-cleaned agate pestle and mortar. Subsequently, an aliquot (3.6–8.1 g) of each homogenized sediment was extracted using an ASE 200 (Dionex, USA) at a temperature of 75 °C and a pressure of 5.0 × 109 Pa. Each sample was extracted for 20 min using a solvent mixture of dichloromethane (DMC)/methanol (MeOH) (9:1, v/v). The bulk of solvent was removed by rotary evaporation and the obtained total lipid extract (TLE) dried under a gentle stream of nitrogen. An aliquot (0.7–1.0 mg) of each TLE was separated into an apolar and a polar fraction using a small Pasteur pipette filled with activated aluminum oxide (3.5 cm) as stationary phase. The apolar fractions were eluted with 4 ml n-hexane/DCM (9:1, v/v) and the polar fractions with 4 ml 10 kV and 15 s at 30 kV, respectively. The polar fractions (containing isoprenoid and branched glycerol dialkyl glycerol tetaethers (GDGTs)) were dried under nitrogen, redissolved in n-hexane:2-propanol (99:1, v/v) to a concentration of...
2 mg/ml and passed through a 0.45 μm polycarbonate filter (Macherey-Nagel, Germany) prior to analysis.

GDGTs were measured using an Alliance 2695 HPLC system (Waters, UK) following the analytical protocol described by Hopmans et al. (2016), which allows the separation of 5- and 6-methyl branched GDGTs. The HPLC system was equipped with
two Waters BEH HILIC silica columns (2.1 × 150 mm; 1.7 μm particle size) and a guard column of the same material, which were all maintained at 30 °C. Target compounds were eluted with a flow rate of 0.2 ml/min starting isocratically with 82% eluent A (n-hexane) and 18% eluent B (n-hexane:2-propanol (9:1, v/v)) for 25 min. A linear gradient was set to 65% eluent A and 35% eluent B in 25 min, followed by a linear gradient to 0% eluent A and 100% eluent B in 30 min. Re-equilibration of the column to initial conditions with 82% eluent A and 18% eluent B was within the following 20 min. Detection of isoprenoid and branched GDGTs was achieved using a Micromass ZQ single quadrupole mass spectrometer (MS) equipped with an atmospheric pressure chemical ionization (APCI) interface operated in positive ion mode. MS conditions were as detailed in Weidenbach et al. (2017). The methylation index MBT$_{5Me}$, a proxy that was developed to reconstruct absolute temperatures, was calculated using only 5-methyl isomers according to De Jonge et al. (2014) with roman numerals corresponding to GDGT structures displayed in the supplementary online material (SOM 5).

$$\text{MBT}_{5\text{Me}} = \frac{(Ia + Ib + Ic)}{(Ia + Ib + Ic + IIa + IIb + IIc + IIIa)}$$  (1)

The branched-over-isoprenoid tetraether (BIT) index, indicating the relative input of terrestrial organic matter, was calculated as given in Hopmans et al. (2004) using the combined peak areas of the 5- and 6-methyl isomers of the branched GDGTs:

$$\text{BIT Index} = \frac{(Ia + IIa + IIa') + (Ia + IIa + IIIa + IIIa')}{(Ia + IIa + IIa' + IIIa + IIIa' + IV)}$$  (2)

3.5. Statistical data processing

We applied statistical approaches such as correlations and multivariate analyses, including principal component analyses (PCA) using the R software (R Version 3.4.2; R Core Team, 2017) to investigate the covariance of the different chemical elements of the sediment core.

For the geochemical data, cleaning of the dataset, i.e. the removal of explicit outliers and filling of missing values by spline interpolation was done manually prior to statistical processing. Correlation coefficients of elemental log-ratios can give an insight into the coupling/decoupling of elements over time. Hence, the relationships between different elemental ratios were explored calculating Pearson correlation coefficients, if normal distribution of the data existed (tested with the Shapiro-Wilk-test), or alternatively, Spearman rank-based correlation was applied. Furthermore, we applied PCA to the original XRF elemental dataset to objectively describe similarities and differences between the elements and to identify the main environmental processes that influence the composition of the lake sediment. The aim of the PCA is to reduce a high dimensional dataset to a very limited amount of meaningful and uncorrelated variables, so called components or factors, that still explain most of the variance in the data set (Filzmoser et al., 2009). Here, the loadings indicate the contribution of each element to the respective principle component (PC). Not all element records in our dataset are normally distributed, and some show a pronounced skewness. As PCA requires a Gaussian distribution of the data, the dataset was standardized, i.e. z-normalized to a mean of zero ($m = 0$) and a standard deviation of one ($s = 1$) for each parameter. In this way, we also avoid overestimating elements with extremely high counts (mainly calcium and iron) in order to equally weight the different parameters. Subsequently, PCA based on the correlation matrix was applied using the function prcomp from the R stats package. This approach also includes an orthogonal rotation of the components, which may facilitate the interpretation of the scores and loadings. We abstained from the application of intensive smoothing of the dataset to avoid any further approximation of the data.

3.6. Archaeological data

Regional surveys in the area started in 1982. From 1983 to 2012,
Table 1
List of radiocarbon samples taken from Lake Stymphalia parallel cores STY-1A and STY-1B. Lab-Codes: KIA — Kiel; VERA — Vienna; Poz — Poznan; BETA — Beta Analytics. The sample numbers refer to the sampling depth before adjusting the field-based correlations between individual core sections in the laboratory to a master depth scale.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Analysis no.</th>
<th>Sample material</th>
<th>Sample fraction</th>
<th>C weight¹ [mg]</th>
<th>C content in this fraction² [%]</th>
<th>δ¹⁴C [‰]</th>
<th>δ¹⁴C age ± 1σ [BP]</th>
<th>IntCal13 [cal BP]³</th>
<th>Depth [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSR-01</td>
<td>KIA42322</td>
<td>Reed</td>
<td>Alkali residue</td>
<td>&gt;1950</td>
<td>0⁺</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1/0</td>
<td>KIA44002</td>
<td>Green Algae</td>
<td>Alkali residue</td>
<td>280±20</td>
<td>299–421 0⁺</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-res-03</td>
<td>VERA-6256</td>
<td>Ranunculus aquatilis</td>
<td>ABA</td>
<td>-25.2 ± 1.1</td>
<td>657 ± 29 565–664 0⁺</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1/32</td>
<td>KIA44003</td>
<td>Bulk sediment</td>
<td>Alkali residue</td>
<td>1.58 ± 0.2</td>
<td>3174 ± 29 3730–4433 32⁺</td>
<td>-22.74 ± 0.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/050</td>
<td>VERA-6380_1</td>
<td>Bulk sediment</td>
<td>TOC</td>
<td>2.50 ± 0.9</td>
<td>1557 ± 38 1406–1521 50</td>
<td>-20.4 ± 0.16 2171 ± 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/050</td>
<td>VERA-6380_2</td>
<td>Bulk sediment</td>
<td>TOC</td>
<td>2.38 ± 0.8</td>
<td>1568 ± 37 1413–1521 50</td>
<td>-21.3 ± 0.8 1575 ± 38</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>STY-1/92.5</td>
<td>VERA-6380_1</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.35 ± 0.3</td>
<td>2935 ± 25 3045–3157 107</td>
<td>-21.77 ± 0.17 2935 ± 25</td>
<td></td>
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</tr>
<tr>
<td>STY-1A/100</td>
<td>VERA-6382_1</td>
<td>Bulk sediment</td>
<td>TOC</td>
<td>2.62 ± 0.8</td>
<td>1419 ± 36 1298–1342 114</td>
<td>-25.3 ± 0.8 1444 ± 36</td>
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<tr>
<td>STY-1A/100</td>
<td>VERA-6382_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.62 ± 0.8</td>
<td>1419 ± 36 1297–1342 114</td>
<td>-23.9 ± 0.8 1419 ± 36</td>
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<tr>
<td>STY-1A/149.5</td>
<td>VERA-6383_3</td>
<td>Bulk sediment</td>
<td>TOC</td>
<td>2.89 ± 0.2</td>
<td>2174 ± 37 2124–2303 193</td>
<td>-24.94 ± 0.21 3285 ± 30</td>
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<tr>
<td>STY-1A/150</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.21 ± 0.6</td>
<td>1355 ± 23 1281–1298 164</td>
<td>-27.22 ± 0.19 1327 ± 35</td>
<td></td>
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<tr>
<td>STY-1A/180</td>
<td>VERA-6383_5</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.35 ± 0.6</td>
<td>1516 ± 36 1350–1515 161</td>
<td>-26.8 ± 0.6 1553 ± 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/207</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.34 ± 0.8</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-28.8 ± 0.8 1516 ± 36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/210</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.4 ± 0.9</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-27.22 ± 0.19 1327 ± 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/220</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.4 ± 0.9</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-26.8 ± 0.6 1553 ± 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/248</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.4 ± 0.9</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-27.22 ± 0.19 1327 ± 35</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/265</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.4 ± 0.9</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-26.8 ± 0.6 1553 ± 35</td>
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<tr>
<td>STY-1A/280</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.4 ± 0.9</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-27.22 ± 0.19 1327 ± 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STY-1A/300</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.4 ± 0.9</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-26.8 ± 0.6 1553 ± 35</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>STY-1A/300</td>
<td>VERA-6383_2</td>
<td>Bulk sediment</td>
<td>Humic acids</td>
<td>2.4 ± 0.9</td>
<td>1441 ± 35 1304–1354 161</td>
<td>-27.22 ± 0.19 1327 ± 35</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: ¹) calculated from CO₂ pressure; ²) Fraction of sample material after respective pre-treatment; ³) calibrated 1σ-age ranges without reservoir correction.

a Dates excluded from age-depth modelling.

the site of Ancient Stymphalos was excavated under the auspices of the Canadian Institute in Greece, however the publication of the finds has still not been completed. For the present study, no further excavation or archaeological data collection have been conducted, as the focus was on the palaeoenvironmental investigation. Instead, already existing, published data have been gathered (Bintliff, 2012a, b; Brown and Walsh, 2017; Iolos, 1997; Panagiotopoulos, 1985; Philippson, 1892; Schaus, 2014; Walsh et al., 2017; Williams, 1996, 1984a; 1984b, 1983; 2005, 2003; Williams et al., 2002, 1998; 1997; and consulted for information on human activity in the Stymphalia Polje.)
As empirical data collections from archaeological and palaeoenvironmental archives are traditionally very different, juxtaposition of these different kinds of (quantitative) proxies can be challenging (Palmisano et al., 2017) and only a small number of studies try to bring them together (Palmisano et al., 2019; Weiberg et al., 2016). Weiberg et al. (2016) provide continuous quantitative data on settlements from archaeological information during the last 8000 years on the Peloponnese Peninsula. As it is the only quantitative proxy currently available, we use it as indication of settlement intensity, also in the Stymphalia polje, and refined it from local archaeological information.

4. Results

4.1. Lithology

Building upon the stratigraphy presented by Heymann et al. (2013), the uppermost 208 cm of core STY-1 are subdivided into 20 stratigraphic units (No. 59–70b, Table 1, Fig. 4) based on sedimentological properties (e.g. colour, texture, macro remains). None of the units is laminated nor are there visual, sedimentological indicators of short-term cyclic beddings. The sediment sequence has a fine texture and is generally composed of a varying mixture of clay (mean = 27%) and silt (mean = 70%), containing 0–4% sand with the exception of units 63 and 70a, in which 7.5% and 17% of sand were recorded (SOM 3).

Munsell (2000) colours in the upper 161 cm of the core range from olive to greyish brown and are generally brighter than in the lower part, which is also evident in the distance of the respective RGB colours to each other (Fig. 4, Table 1). Organic debris and roots are generally small and scarce. Below 164 cm, darker greyish colours dominate and shell fragments of Bythinia sp. (Fig. 3-D) and Vulpava sp. gastropods are more frequent. A distinct black layer (unit 62), ranging from 164 to 161 cm, separates the upper brownish units from the lower more greyish units.

TIC values range between 0.8 and 8.0 wt% and correlate well with Ca counts (Fig. 4, Figure SOM 2). The TOC content varies from 1.2 to 6.4 wt% and is 3.0 wt% in the black layer (Fig. 4, SOM 2). While TIC values are lower in units 59 and 60 compared to the upper part, the TOC content does not show any obvious differences between these two. The blackish unit 62 exhibits a singularly high magnetic susceptibility (MS) peak (SI = 3000). For the rest of the depicted core sequence, MS constantly fluctuates around a median of 70.27 (mean = 103.68). The upper brownish units 68 and 69 dispose of persistently higher MS values.

4.2. Core chronology

4.2.1. Radiocarbon dates

From the uppermost 324 cm of the parallel cores STY-1A and STY-1B (units 48–70), 24 samples for radiocarbon dating have been taken. Although our focus is on the uppermost 208 cm recording anthropogenic influences, the age model was calculated for a longer interval in order to construct a solid model and avoid boundary effects (Fig. 5). The sedimentological analysis of the core sequence gave no indications for any hiatus or erosional discontinuities; hence, a continuous, even if sometimes very low sedimentation is assumed (Fig. 6).

To determine the time at which specific layers in a sediment core were deposited, we need to isolate organic material from the time of sedimentation that is either terrestrial or has a known reservoir age. The challenge in dating sediments is that they contain a small fraction of old carbon, eroded and transported with the mineral fraction, in addition to limnic and terrestrial material from the time of deposition. Furthermore, sediments are open systems, so dissolved and colloidal carbon may be introduced at a later point in time. The standard Acid-Alkali-Acid (AAA) chemical pretreatment, commonly used in radiocarbon dating, aims to remove potentially mobile contaminating acid and alkali soluble organic compounds. If no recognizable macrofossils can be found, dating the remaining insoluble fraction (humin fraction) is the best candidate to provide a useful sedimentation age in organic rich sediments (organic content of the residue >1%) (Grootes et al., 2004). A check on the age inhomogeneity of organic carbon in the sediment can be obtained by dating not only the insoluble residue, but also the organic material removed by alkali extraction. Acidification of this alkali extract precipitates the humic acid fraction. This fraction often dates younger than the insoluble residue since it may contain contaminating younger compounds and is less likely to receive a contribution from recalcitrant reworked carbon
compounds. In case of an age difference between the humic acids and the humin, the humins are most likely to indicate the approximate time of sedimentation for organic rich sediments. For organic poor sediments the fraction of old reworked carbon, which is often around 0.1%, is no longer negligible and can lead to measured humin ages that may be thousands of years too old (Grootes et al., 2004). In the eastern Mediterranean, it has been observed in a number of cases that humic acids extracted from samples appear not to offer appreciably different $^{14}$C ages and so likely derive from the sample in question or contemporaneous material (Wild et al., 2013).

In total, 45 radiocarbon measurements were made on these 26 samples (Table 2). Alkali residue, humic acids, shell carbonates, and repeats of some fractions were measured at four different AMS-$^{14}$C facilities, the Leibniz-Laboratory for Radiometric Dating and Isotope Research at Kiel University (KIA), the Beta Analytic Radiocarbon Dating Laboratory Miami (BETA), the VERA Laboratory at Vienna University, and the Poznań Radiocarbon Laboratory at Adam Mickiewicz University (POZ).

Due to the limestone rich environment containing a high amount of "old" carbon, a large hard water effect may be expected for limnic organics. Together with an influx of fresh and reworked old terrestrial organics this makes radiocarbon dating of the sediment challenging (Finne et al., 2011).

Table 2 shows sometimes large differences between results from different fractions and laboratories. Carbonate of the Bythinia gastropod shells at 141 cm dates at least 700 years older than organic samples above and below it indicating the expected large hard water effect. A *Ranunculus aquatilis* specimen, which grows subaqueously and was sampled live in 2015, provides an apparent age of $657\pm29$ years (PMC 92.15 or F$^{14}$C 0.92146; VERA-6256, Table 2) that after comparison with the Jungfraujoch atmospheric $^{14}$C record (Hammer and Levin, 2017) yields a reservoir age of $810\pm30$ $^{14}$C years. This is in good agreement with the carbonate result at 141 cm and slightly higher than the reservoir age of $600\pm10$ years applied by Heymann et al. (2013). The ten KIA results for the alkali residue give, as expected considering the low organic carbon content of 0.19–0.83% of this fraction, unreasonably old ages and should not be used in the time scale construction. Recognizable terrestrial plant remains are largely absent from the core, except for one single *Crataegus* seed, which was found at 165 cm depth (masterscale) in core STY-1A, yielding an age of $1237\pm35$ $^{14}$C years (690–870 cal AD; VERA-6258; Fig. 3-B). The humic acid result for KIA42912 of $1355\pm23$ yr BP at 164 cm is only 118 years older. This small difference indicates that the humic acid fraction is largely of terrestrial origin as opposed to the limnic material with 800-year reservoir effect. Ages obtained on the humic acid fractions may thus better indicate the time of deposition with a reservoir effect in the range 100–200 years. This reservoir effect will however vary with the balance between limnic and terrestrial organics supplied to the lake and there is no reason to assume that it was constant in the past. Hence, this is an inherently problematic issue and we can only employ the current situation as a guide and try to estimate the recent reservoir age (as we do below).
4.2.2. Bayesian age model

The Crataegus seed and a ceramic fragment (Fig. 3-C) – the latter was found at 205 cm depth (masterscale) in core STY-3B and was identified as non-Attic, late or sub-Archaic and dated approximately to 500 BC ± 50 years (ceramic classification: Bernhard Schmaltz, Christian-Albrechts-Universität Kiel, personal communication) – serve as “golden spikes” in the age-depth-model. For the ceramic shard, ca. 500 BC is considered a terminus post quem, the earliest possible date when the shard may have found its way into the lake; most likely it continued to exist as part of a decorative bowl for a while before it broke apart and then at some later point in time was deposited in the lake. A piece of charred organic matter from 324 cm depth, dated at 7708 ± 35 14C yr BP (KIA42913) and with a combustion yield of 32.5% carbon, which proves its high organic matter content, sets the lower limit of the age-depth-model (ADM).

Bayesian age-depth-modelling was performed using the R package Rbacon (v.2.3; Blaauw and Christen, 2011) as well as the software OxCal 4.2 (Bronk Ramsey, 2009; Bronk Ramsey and Lee, 2013; Ramsey, 2008), both using IntCal13 as the terrestrial calibration curve (Reimer et al., 2013).

The final age-depth-model (STY_25) was constructed with Rbacon in an iterative process based on several key assumptions and offers a best plausible interpretation: (1) The age of the core top is set at 2010 cal AD, the year of coring. The age determinations for the Crataegus sp. seed and the ceramic shard serve as reliable, solid anchor points. The charcoal sample at 324 cm likewise gives a reliable result for the bottom of the model. (2) If there are multiple dates for one depth derived from the same carbon fraction, they have been combined to one value using the R_combine function in OxCal. Otherwise, the fact of having a higher quantity of datings for a certain depth would have influenced the modelling by assuming a higher credibility for these samples. (3) As the Bythinia sp. shell samples (VERA-6381_30, VERA-6381_50) delivered different ages, depending on the degree of etching, they were excluded from the age-model (Fig. 5 marked in light blue). (4) Based on the assessment of alkali residue ages versus humic acid ages outlined above, the generally younger humic acid ages were regarded as more plausible and the considerably older KIA alkali residue ages were excluded from modelling (Fig. 5 marked in red). (5) As outlined in section 4.2.1, the reservoir correction was set to 200 ± 100 years for all bulk sediment samples because of the age difference between the Crataegus seed (1237 ± 35 14C years) and the adjacent KIA42912 humic acid sample (1355 ± 23 14C years). To take the uncertainty of varying reservoir effects into account, we assigned a relatively high standard deviation of ±100 years to the reservoir correction (the table can be found in SOM 1). (6) Finally, the construction of the Hadrianic Aqueduct, a cultural event that took place around 130 AD (Lolos, 1997), indicated in the sediment core among others by a strong and abrupt increase in the Fe content due to oxidation processes (see section 5.3.2), was taken into account in the modelling process. In the following, all proxies are plotted against the mean calendar age estimates of model STY_25. Calibrated years are denoted as cal BC/AD, due to the focus of this paper on cultural and climatic aspects of the last 2500 years (Mook and Plicht, 1999). The applied cultural chronology (Table 3) is based on Bintliff.
Based on the age-depth-model, we calculated the sedimentation rate in the lower part to be approx. 0.2 mm/yr. It rises slightly to 0.4 mm/yr at 195 cm and strongly increases to more than 2 mm/yr at 165 cm. For the uppermost 50 cm, a lowering of the sedimentation rate to 0.7 mm/yr was calculated (Fig. 6). This pattern of sedimentation largely resembles that of carbonate content and Ca (Fig. 4) and hence supports the age-depth-model.

Note that the age-depth-model published by Heymann et al. (2013), which was based on fewer radiocarbon dates for the respective core sequence, is outdated. The discovery of the Cra- tagus seed (VERA-6258) and the improved modelling approach presented here require a substantial shift – to more recent ages – in the dates and associations compared with the published data of Heymann et al. (2013).

4.3. Geochemical proxies

Our palaeoclimate record consists of continuous XRF core-log measurements of 13 chemical elements, augmented with discrete measurements of grain size, TOC, TIC, and TN contents as well as isoprenoid and branched GDGT distributions.

The sediment is dominated by calcium (Ca, 67.3% of all considered total counts), caused by autochthonous calcium carbonate precipitation in the lake and allochthonous limestone weathering in the catchment. Iron (Fe, 14.7%) and silicon (Si, 8.6%) were the elements with the second and third most abundant counts, respectively. The elements Rb, K, Zr, Ti, Si, and Al all show extremely high correlations (rhoSp > 0.9) throughout the sequence due to their common allochthonous origin from siliciclastic rocks in the catchment such as schists and breccias (Fig. 4).

Gastropod shells in core STY-1B1 in the depth interval 84.4–105.4 cm made it difficult to obtain the smooth, planar core surface needed for reliable XRF analysis (Bloemsma et al., 2018; Tjallingii, 2006; Tjallingii et al., 2007). As a result some element counts deviated from those in the other core sections, showing larger oscillation and leading to artefacts at the section boundaries (Fig. 7).

Four element ratios were determined that show trends which can be interpreted as suitable palaeoenvironmental proxies (cf. section 5.1). The generally negative log (Rb/Sr) ratios (Fig. 7) in our record (varying between −0.18 and −3.29) indicate the dominance of carbonates compared to siliciclastic material in the lake’s catchment, which is dominated by limestone karst. Relatively higher values of the Rb/Sr ratio occur in units with low carbonate content.

As stated by Heymann et al. (2013), we use the log (Zr/Rb) ratio as a grain size proxy; higher values are linked to the coarser, silt-sized fraction, while low values refer to fine, clayey mineral input. The mean is 0.44 and the median is 0.41. There is a considerable shift in the data around 700 cal AD and afterwards the variability in the ratio is considerably larger than in the first half of the sequence (Fig. 7). The log (Mn/Fe) ratio fluctuates between −5.0 and −3.0 and highest variation can be seen for the period 500–1000 cal AD. As Fe show a high correlation with other terrestrial elements (rhoSp for Fe and Ti = 0.92), it is mainly related to allochthonous input and hence the potential use of the Fe/Mn ratio as an indicator of redox conditions in the water column needs to be applied with caution. The log (Sr/Ca) ratio (Fig. 7) is consistently negative and varies between −4.6 and −2.8. Between 350 and 700 cal AD, we see the highest variation.

We additionally applied a principal component analysis (PCA) to the dataset of the 13 selected geochemical elements in order to reduce the dimensions and summarize the data structure. The screen test suggests using the first three factors, as the first (PC1), second (PC2) and third principal component (PC3) account for about 79% of the variance in the dataset (SOM 4). We only apply PC1, taking into account 52.9% of the variance. The loadings provide information on the influence of the chemical elements on the respective component. While PC1 is tied to Ca and Sr at the negative end and to all the other elements at the positive end, PC2 is negatively related to Zr and Si, while the other elements show positive loadings (SOM 4). Consequently, PC1 can be interpreted as an axis that spans between carbonate rich samples (Ca, Sr) on the negative end and mineral rich assemblages indicated by positive values. These divergent elemental compositions are likewise reflected in the Rb/Sr ratio. A Spearman correlation between log (Rb/Sr) and PC1 hence leads to an extremely high correlation (rhoSp = −0.968, p < 0.05). This similarity is also apparent in the high degree of alignment between the curve progressions in Fig. 7, as they show the same temporal responses. It can thus be concluded that PC1 for the STY-1 XRF dataset represents a suitable summary proxy for chemical weathering. In addition, the results of the PC1 confirm the applicability of Rb/Sr as a palaeoenvironmental proxy, because it covers the most important fluctuations in the complete dataset.

4.4. GDGT distributions

Both isoprenoid and branched GDGTs were ubiquitously present in the investigated interval with the latter dominating the GDGT pool. This is also expressed in generally high BIT values varying between 0.95 and 0.98 (data not shown). Highest MBT$^\text{Sm}$ values of
Jin et al., 2006; Xu et al., 2010). Rb has an allochthonous source and from precipitation of SrCO₃, as substitute for Ca, within the lake can have an allochthonous or autochthonous origin and is thus enters the lake environment with silicates and K-rich minerals. Sr can replace potassium (K) in the crystal lattice of clay minerals. It warm climate conditions (Heymann et al., 2013). Hence, high Rb/Sr often happens during a lowering of the lake level due to dry and increases by evaporative concentration in lakes, a process which driven carbonate precipitation in the lake (Heymann et al., 2013; Cruz et al., 2007). Precipitation of SrCO₃ also in- phasess with less water availability and thus a smaller lake area, summers, while high Rb and high Rb/Sr values are present in indi- cate high water availability dissolving carbonates from the limestone bedrock and precipitating in the lake during warm summers, while high Rb and high Rb/Sr values are present in phases with less water availability and thus a smaller lake area, where terrestrial detritus is more easily eroded up to the depo- centre of the lake. The proxy does not indicate whether these processes occur naturally or are human induced.

For the strontium-calcium (Sr/Ca) ratio, some authors associate higher values in stalagmites with lower levels of recharge into the karstic aquifer during dry climate conditions (Cruz et al., 2007). Other authors explain higher Sr concentrations with enhanced biogenic carbonate precipitation compared to detrital carbonates, because the Sr partition coefficient (K_DSr) for biogenic carbonate is much greater than that for inorganic carbonates (Hodell et al., 2008). We here follow the interpretation of Hodell et al. (2008) and interpret higher Sr/Ca ratios as more biogenic carbonate precipitation in the lake and lower values as more inorganic, detrital carbonate input from the catchment.

Iron (Fe) and manganese (Mn) concentrations correspond among others to oxidation processes within the lake. The Mn/Fe ratio is often interpreted as an indicator for redox conditions (Davison, 1993; Heymann et al., 2013). In the water column, Fe²⁺ is less stable than Mn⁵⁺ and precipitates earlier. Thus, low (high) Mn/Fe values are considered to indicate anoxic (oxic) conditions, often visible by greyish-blue (brownish-red) sediments (Koinig et al., 2003; Unkel et al., 2014). Besides redox conditions, pH changes affect the ratio, as more Mn is mobilized when pH is decreasing. Hence, low (high) Mn/Fe values may also indicate acidic (alkaline) conditions. In periods of high productivity, intensive degradation of organic matter leads to oxygen depletion and acidic condition and may also be reflected in higher TOC values (Koinig et al., 2003). If the variability of Fe is closely related to allochthonous input, this suggests that Fe mainly originates from terrestrial sources and the use of the Mn/Fe ratio as an indicator of redox conditions in the water column may be limited (Naehrer et al., 2013). As Fe and inert Ti show a high correlation (Spear: 0.86) at Lake Stymphalia, we assume that Fe mainly originates from terrestrial sources and interpret the Mn/Fe proxy with caution only in phases when both elements show clear signals.

The ratio of allochthonous Rb versus zircon (Zr) is widely used as grain-size proxies, as Rb is associated with clay minerals, while Zr is mainly associated with coarser grain material (Chen et al., 2006; Cuven et al., 2010; Dypvik and Harris, 2001; Koinig et al., 2003; Kylander et al., 2011). In the Stymphalia record, Zr is linked to the silt-sized fraction and Rb is strongly linked to the clay mineral assemblage suggesting no K-feldspar source contribution (Heymann et al., 2013).

5. Discussion

5.1. Geochemical ratios

The geochemical elements obtained from XRF analysis are shown and interpreted as log-ratios to circumvent the closed-sum effect and to obtain a signal that is relatively easy to interpret for palaeoenvironmental variation (Lowemark et al., 2011; Weltje and Tjallingii, 2008). Selected element ratios are explained and discussed in the following.

The rubidium-strontium (Rb/Sr) ratio is commonly applied as a proxy for weathering intensity in the catchment (Chen et al., 1999; Jin et al., 2006; Xu et al., 2010). Rb has an allochthonous source and can replace potassium (K) in the crystal lattice of clay minerals. It enters the lake environment with silicates and K-rich minerals. Sr can have an allochthonous or autochthonous origin and is thus introduced either from carbonate weathering in the catchment or from precipitation of SrCO₃, as substitute for Ca, within the lake (Cohen, 2003; Koinig et al., 2003). Precipitation of SrCO₃ also increases by evaporative concentration in lakes, a process which often happens during a lowering of the lake level due to dry and warm climate conditions (Heymann et al., 2013). Hence, high Rb/Sr values in lake sediments may generally be interpreted as enhanced erosion of siliciclastic material under cooler and wetter climatic conditions and enhanced catchment precipitation, while low Rb/Sr values indicate warmer and drier conditions with evaporation-driven carbonate precipitation in the lake (Heymann et al., 2013; Unkel et al., 2014). As the period presented in this paper shows a strong imprint of human activity in the polje, the Rb/Sr ratio cannot unequivocally be linked to climatic variations and firstly reflects the balance between carbonates and clastic components. For the period presented here, the Rb/Sr ratio can instead be interpreted as proxy for water availability and lake size. High Sr and low Rb/Sr values indicate high water availability dissolving carbonates from the limestone bedrock and precipitating in the lake during warm summers, while high Rb and high Rb/Sr values are present in phases with less water availability and thus a smaller lake area, where terrestrial detritus is more easily eroded up to the depocentre of the lake. The proxy does not indicate whether these processes occur naturally or are human induced.

For the strontium-calcium (Sr/Ca) ratio, some authors associate higher values in stalagmites with lower levels of recharge into the karstic aquifer during dry climate conditions (Cruz et al., 2007). Other authors explain higher Sr concentrations with enhanced biogenic carbonate precipitation compared to detrital carbonates, because the Sr partition coefficient (K_DSr) for biogenic carbonate is much greater than that for inorganic carbonates (Hodell et al., 2008). We here follow the interpretation of Hodell et al. (2008) and interpret higher Sr/Ca ratios as more biogenic carbonate precipitation in the lake and lower values as more inorganic, detrital carbonate input from the catchment.

Table 3

<table>
<thead>
<tr>
<th>Time (BC/AD)</th>
<th>Period</th>
<th>Event</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD 1204</td>
<td>Byzantine and Frankish/Late Medieval</td>
<td>Start: Frankish conquest of Constantinople.</td>
<td>B-F</td>
</tr>
<tr>
<td>AD 900—1204</td>
<td>Middle Byzantine/Medieval</td>
<td>Start: Consolidation of the Roman (Byzantine) power in the southern Balkans.</td>
<td>MB</td>
</tr>
<tr>
<td>AD 641–842</td>
<td>Early Byzantine/Early Medieval</td>
<td>Start: Death of Emperor Heraclius and the collapse of the Late Roman political order.</td>
<td>EB</td>
</tr>
<tr>
<td>AD 300–641</td>
<td>Late Antiquity/Late Roman</td>
<td>Start: Founding of the city of Constantinople and the parting of ways between the Western and Eastern parts of the Roman Empire.</td>
<td>LR</td>
</tr>
<tr>
<td>31 BC—AD 300</td>
<td>Roman</td>
<td>Start: Destruction of Corinth and end of Achaian war.</td>
<td>R</td>
</tr>
<tr>
<td>323</td>
<td>Classical</td>
<td>Start: Death of Alexander</td>
<td>H</td>
</tr>
<tr>
<td>479–323 BC</td>
<td>Classical</td>
<td>Start: Greek victory over the Persians in the battle of Plataea; Persian invasion of Greece repelled.</td>
<td>C</td>
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The lack of lamination throughout the entire core sequence indicates that the water level has never been considerably higher than at present over any long time period as would be necessary to...
allow for water column stratification and repress complete mixing of the water column (Zolitschka et al., 2015). A generally low water level is also supported by the presence of *Bythinia* sp. (Fig. 3-D) and *Valvata* sp. shells or shell fragments throughout most of the sediment sequence (Fig. 4). Both organisms are gastropods living in well oxygenized, shallow waters and swamps, and are often found, e.g., in the reed belt of shallow lakes in the Balkans (Tom Wilke, personal communication 2015; Davies, 2008). Their presence in Lake Stymphalia thus indicates a generally molluscan favourable environment with well-mixed, oxygenized conditions in the bottom water. Sr/Ca explains the origin of the carbonates. Arrows to the right explain how to read the proxies. All proxies are plotted against age (cal BC/AD). Approximate depth scale (cm) is included for comparison. The upper boxes above the graph show the lithological units. The lower boxes and vertical red lines refer to the transitions between Greek cultural boundaries as specified in Weiberg et al. (2016; cf. Table 3). The blue vertical bar shades the approximate period of the functioning of the Hadrianic Aqueduct (130 – max 500 AD). Values in the grey shaded area (>1720 cal AD) need to be interpreted with caution due to strong anthropogenic alteration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 7. Selected elemental ratios depict paleoenvironmental changes at Lake Stymphalia for the last 2500 years. The log-normalized ratios plotted in grey are based on the Avaatech XRF counts per second measured on STY-1. Colored lines were calculated with a 5-point moving window. Dashed horizontal lines mark the respective mean values for the whole dataset. PC1 and Rb/Sr indicate changes in the material composition. Zr/Rb is used as a grain size proxy. Mn/Fe hints to redox conditions in the bottom water. Sr/Ca explains the origin of the carbonates. Arrows to the right explain how to read the proxies. All proxies are plotted against age (cal BC/AD). Approximate depth scale (cm) is included for comparison. The upper boxes above the graph show the lithological units. The lower boxes and vertical red lines refer to the transitions between Greek cultural boundaries as specified in Weiberg et al. (2016; cf. Table 3). The blue vertical bar shades the approximate period of the functioning of the Hadrianic Aqueduct (130 – max 500 AD). Values in the grey shaded area (>1720 cal AD) need to be interpreted with caution due to strong anthropogenic alteration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
varying depositional conditions. While the lower part of the core shows signs of low sedimentation under water-logged conditions, the brownish colours of the upper part indicate increased erosion, a higher input of terrigenous material and short periods of desiccation, e.g. during summer (Fig. 4).

The grain size distribution in lake sediments provides information on the erosion, transport and accumulation mechanisms of material from the source to the lake. The compact, fine-grained silty clay and clayey silt units in this sequence point to a dominance of chemical weathering in the catchment. In a water balance calculated by Morfis and Zojer (1986), more than half of the water discharge volume is ascribed to underground inflow,
suggesting the importance of mineral transport in dissolution, mainly concerning the carbonates.

Four main sedimentation phases can be distinguished over the last 2500 years (Fig. 6). During Classical-Hellenistic times, the sedimentation rate is approx. 0.2 mm/yr. It slightly increases to about 0.4 mm/yr during the Roman Period. Interestingly, this is on a comparable scale to the sedimentation rates calculated from colluvia in the neighbouring Philous basin (Fuchs et al., 2004). Around 800 cal AD, we see a strong increase in the sedimentation to >2 mm/yr lasting for approximately 300 years and then gradually decreasing to the top; and for the last 500 years it is calculated at 0.7 mm/yr (Fig. 6). Walsh et al. (2017) report a mean accumulation rate of 1.7 mm/yr for their Stymphalian sediment cores recovered from the lakeshore.

The MBT$_{5Me}$ proxy provides a means to quantify temperature variations over time (De Jonge et al., 2014). As no regional lake temperature calibration for the MBT$_{5Me}$ is currently available and the only other calibrations available for tropical East African lakes (Russel et al., 2018) and alkaline Chinese lakes (Dang et al., 2018) yield temperature estimates for Lake Stymphalia that are much higher than the 20th century data from the meteorological station at Driza-Stymphalia, and are thus highly unrealistic, we prefer to discuss relative temperature trends instead of reporting absolute temperatures (Fig. 8). Additionally, we do not address the question of variation between autochthonous and allochthonous sources in the sediment composition, which likely affects the palaeo-thermometer. As lipid biomarker analysis in Greece is still at an early stage (Gogou et al., 2016; Katsantiotis et al., 2018; Norström et al., 2018), we assume the full potential of this method is not yet achieved, and only provide a first tentative interpretation. However, we included this dataset with the aim to contribute to the further development of this method.

5.3. The socio-environmental history

5.3.1. Classical-Hellenistic and early Roman Periods (479 BC – 130 AD; unit 59)

Archaeological investigations and palaeoecological findings postulate agricultural activity in the Stymphalia catchment from the Early Neolithic onwards (Walsh et al., 2017; Williams, 2005). Thus, variations in the analysed sediment sequence most likely reflect both natural as well as anthropogenic changes in the landscape.

During Archaic to Middle Hellenistic times (600—250 BC), the city of Stymphalos was flourishing, accommodating ca. 2500 people plus potentially another 500 people in the rural surroundings (Williams, 2005, 2003; Karambinis personal communication). Williams (2005, 2003) describes a large, fortified wealthy city for the 5th to 3rd century BC; the florescence of the city was associated with the maximum regional population and land use unrepeated until the later 20th century AD. Excavations in the Lower Town by Williams, a large part of which lies in the lake flats, have revealed that the archaeology is covered by at least 1 m of fine-grained colluvial sediments deposited into a shallow freshwater environment overlaying the abandoned buildings, while the house foundations extend below the modern water level. Clearly, the lake during this urban phase must have been further out into the current lake bed, and at a significantly lower level.

The geochemical records for this urban period (lithological unit 59) are all very stable (Fig. 7). The absence of major fluctuations points to a phase of rather stable environmental conditions. Greyish clayey silt with a slightly black tilltelled appearance and a high content of shell fragments suggests that the sediments were continuously water-logged at that time.

The finding of a larger ceramic shard at 205 cm in core STY-3B (Fig. 3-C) as well as a small amount of tiny ceramic particles in STY-1B prove human presence at this depth, during the 6th to 5th century BC. The shard was embedded in a fine matrix, indicating slow, regular and constant accumulation excluding any extreme event such as a debris flow or strong erosion induced by land-use management which would have required a coarser matrix, whilst the Zr/Rb ratio shows consistently fine sediment. The low sedimentation rate (~0.2 mm/yr) for this period further confirms this assumption (Fig. 6). On that basis, we assume that the ceramic was deposited under regular, stable sedimentation conditions and it was thus also considered a terminus post quem for the surrounding sediment. It is striking, that despite high levels of local population and inferred maximal land use in the surroundings of the lake, unparalleled until the late 19th century AD, no larger disturbances can be found in the sediment core. Clearly, on the one hand, farming and pastoralism were practised in ways that protected the landscape from significant erosion, and on the other hand, reconstructions of contemporary climate in Classical-Hellenistic Greece suggest stable climate conditions unlikely to destabilize the land surface (Finne et al., 2011).

In later Hellenistic into Early Roman times (locally 250 BC — 100 AD) the city shrank and then lost its city status, becoming a far smaller settlement which by Middle Roman times (200–400 AD) may have been little more than a village (Williams, 2003). This demographic decline in Stymphalia is in agreement with decreasing settlement activity from the Peloponnese (cf. Fig. 8-1; Weiberg et al., 2016).

Around the beginning of the Roman period, we observe a slight shift in the grain size of the sediment core towards even finer silty clay. This matches the archaeological data indicating that land use was more restricted. During this period, land use will have declined on a massive scale and natural vegetation cover may have spread again, stabilizing the soils, limiting surface weathering, and leading to less detrital input. The sedimentation rate is lowest around 0–100 cal AD which suggests a largely abandoned land use and a recolonization of the landscape by stabilizing natural vegetation such as scrub and woodland that hinders the soils from eroding. However, the TOC/TN values for this period are incomplete and pollen is not well-enough preserved in the sediments to support this indication.

It can be considered that during Classical, Hellenistic and the first two centuries of the Early Roman period, inhabitants of the Stymphalia polis practised sustainable agro-pastoralism that didn’t cause a lasting imprint in the lake. For this period, the lake seems to have been steady in size and the ecosystem seems to have been resilient and in equilibrium as no large disturbances have been recorded.

5.3.2. Later early to Late Roman Period (ca. 130–641 AD; unit 60)

From approximately the first two centuries of Early Roman times onwards, only a very small settlement is known in the catchment of Stymphalia and the impact on the landscape is assumed to have been small (Williams, 2003). A slight increase in population might be recorded for Late Roman times (400–650 AD), indicated among others by the finding of graves dated to the late 4th and 5th century (Williams, 2003; Williams et al., 2002); but in the former city and in the wider region it will have been a fraction of the population development seen in the climax era of Archaic to Middle Hellenistic times. For the Peloponnese, a higher settlement activity is also reported by Weiberg et al. (2016) for the time span 350–700 AD (Fig. 8-4).

All geochemical elements measured from the sediment core show an abrupt change in the measured counts at 189 cm (140 cal AD). While the carbonates Ca, Sr as well as the TIC content drop considerably, the terrigenous elements (Rh, Zr, Al, Ti, K, Si) increase...
sharply and stay constant at higher level for several centuries, with the exception of a small dip at 180 cm (360 cal AD). This very sudden shift at 189 cm, clearly seen in Mn and Fe counts (Fig. 4) is interpreted as a direct consequence of the building of the imperial, Hadrianic aqueduct. Around 130 AD the Hadrianic aqueduct was built over a distance of 84 km from the spring of Driza to the ancient city of Corinth in order to extend the latter city’s water supply (Lolos, 1997; Unkel et al., 2011). In the natural state, underground discharge from the Stymphalia catchment would drain first into the lake, mainly being fed by two sources, and then by subterranean sinkholes into the Gulf of Argos to the SE (Morris and Zojer, 1986), but with the help of tunnels and bridges, the engineers of the time redirected the bulk of the water to the NE. Ancient Corinth, as the capital of the Roman province of southern Greece, was flourishing at that time, and although water supply in the city was generally sufficient for the basic needs of the citizens, it is assumed that the Corinthians wanted the additional water source for elaborate water infrastructure features such as fountains and bath complexes (Lolos, 1997). The construction of the aqueduct meant a huge impact for the Stymphalia lake system. As response to the water being diverted directly from the spring of Driza to the aqueduct, the lake area shrank drastically and the lake level became lower. This explains the sudden shift in the geochemical elements at 189 cm (Figs. 4 and 7).

The sedimentation rate was at a minimum at the beginning of the aqueduct construction project and reached a small local maximum of approximately 0.5 mm/yr between 200 and 300 cal AD (Fig. 6), contemporaneous with the zenith of the aqueduct. We assume that the increase in sedimentation rate can best be explained by the diminishing lake area; the coring spot in the depocentre of the lake would have been closer to the shores and thus more terrigenous material would reach its position. Throughout the existence of the aqueduct during the Roman and Late Roman Period, carbonate content in the system is considerably lower and we hardly find any gastropod and shell fragments here, while detrital input of terrigenous elements is highest, indicating that material input was dominantly allochthonous.

Additionally, a strong increase in Fe is visible over the running time of the aqueduct, peaking at 178.9 cm and 176.8 cm (ca. 380–440 cal AD). Here, we find a coarser grained, oxidized, orange layer, clearly visible in the high Fe content as well as in the RGB colour together with a peak in Zr/Rb (Figs. 4 and 7). Sedimentologically, the orange colour and the high Fe content point towards oxidation and precipitation of Fe-hydroxide. It seems plausible that the lake area continuously shrank over time and by the end of the 4th century AD, the lake seasonally or periodically dried up allowing for oxidation to take place. Several proxies point towards a very small lake, desiccating and oxidizing conditions around 400 cal AD, which can be ascribed to the draw off of water discharges for the aqueduct. When we compare the Stymphalia dataset to other archives for the Eastern Mediterranean, e.g. the δ18O and δ13C stable isotope data from Kapsia Cave, Peloponnese (Finné et al., 2014), Soreq Cave, Israel (Orland et al., 2009), and Sofular Cave, Turkey respectively (Fleitmann et al., 2009; Göktürk et al., 2011), we do not see a consistent picture, but rather regionally diverse expressions (Luterbacher et al., 2012; Manning, 2013; Roberts et al., 2012). Around 400 AD however, most proxies tend to indicate slightly drier conditions (Fig. 8-C,D,E) and it is thus possible that the dry conditions in Lake Stymphalia at that time may have additionally been influenced by a climatic factor.

Conditions change during the 5th century AD, when relatively more Sr is precipitated within the lake and additionally the Mn/Fe ratio points towards more anoxic conditions suggesting that the lake was continuously waterlogged again. Historical information indicate that during the 3rd to 4th century AD maintenance was carried out to keep the aqueduct working, while during the 5th century AD, the Hadrianic Aqueduct was abandoned and partially collapsed, associated with a significant decline in the size and prosperity of Corinth (Hammond, 2015; Lolos, 1997). The beginning of the long-term abandonment of the aqueduct — which was actually not re-activated until the 1880s (Morris and Zojer, 1986) — coincides with the changes in the sediment geochemistry. After the collapse of the aqueduct, more water stayed in the basin and the lake was refilling. The Fe content is continuously decreasing again and it seems as if the lake system that had been disturbed and unbalanced by the construction of the aqueduct was trying to retrieve its equilibrium state. The Rb/Sr ratio, which was relatively constant since the construction of the aqueduct, starts to decrease around 540 cal AD, parallel to when Mn/Fe reaches its minimum. Temporally, this coincides with two large volcanic eruptions in 536 AD and probably in 540 AD, which caused atmospheric dimming and contributed to a cold spell in the Northern Hemisphere. A climatic connection, concomitant with cooler conditions at Lake Stymphalia, seems possible and could be consistent with the age-depth-modelling for this phase.

The period 500–650 cal AD, depicting high Sr/Ca values and low Mn/Fe ratios, emphasises constantly waterlogged conditions. As the Mn/Fe ratio during this period shifts to more anoxic conditions, we conclude that Lake Stymphalia was probably (slightly) deeper and less well ventilated. One possible explanation could be that wind intensity during this phase was lower causing less frequent mixing of the whole water body and the sediment surface. Another scenario would be that the target surface for the wind might have been lower due to protection by vegetation cover, e.g. like a pronounced reed belt as it can be found around the lake today. Sr/Ca shows its highest peak in the record here, pointing to an increased supply of biogenic carbonate material. This is supported by a high amount of shells and shell fragments. The gastropods must have developed under constant water conditions. It can thus be concluded that during the 6th and early 7th century cal AD considerably higher amounts of water reached the Stymphalia polje enabling the extension of the lake area. As the aqueduct was not working anymore and human influence in the area is very low at that time, the water supply can be primarily associated with the reintroduction of water from the lake’s main source, the Driza spring. Additional effects of changes in precipitation and temperature may have influenced this turn; reconstructions from the Eastern Mediterranean however do not show a homogeneous pattern. The Sofular Cave proxies show considerably higher precipitation at this time (Fleitmann et al., 2009; Göktürk et al., 2011), while data from Soreq Cave is interpreted as showing a decrease in precipitation for the 2nd to 7th century AD (Göktürk et al., 2011; Luterbacher et al., 2012). In their review of climatic changes during and after the Roman Empire 100 BC – 800 AD, McCormick et al. (2012) state that precipitation in France and central Europe became exceptionally variable between 250 and 650 AD. They see a warming trend in the 4th century AD, while the 6th century is characterized by generally cooler conditions, crop failures and the Justinian Plague (541 AD onwards), a devastating epidemic outbreak in the Mediterranean, as well as droughts and heat events, a high number of famines and cold winters in the Middle East (600–724 AD) (McCormick et al., 2012).

During the Roman Period, we initially see crucial human influence on the lake ecosystem with the building of the aqueduct, followed by a period, when the proxies seem to respond to climatic influences again, however more sensitively than before, which may be ascribed to the unbalancing caused by natural rebound of the hydrographic system once the aqueduct ceased to function.
5.3.3. The Early Byzantine Period (641–842 AD; units 61–65)

During the Early Byzantine and the early part of the Middle Byzantine very low population and very limited land use are expected for the Stymphalia basin in the context of generally low settlement activity in the Peloponnese and Greece generally (Bintliff, 2012a; Weiberg et al., 2016, Fig. 8-I). The plague in the Eastern Mediterranean began in 541 AD and recurved several times until ca. 800 AD (Benovitz, 2014; Izdebski et al., 2016; Little, 2007), causing major depopulation for the Stymphalia area. The Migration Period in Greece is most prominent in the 8th century AD, when Slavic colonisation spread to the Peloponnese, taking in some of the land emptied by the lost local population. Although recognition of Slavic sites is highly problematic (just two cemeteries have been excavated in the Peloponnese), and surviving Greek populations in the countryside are hard to detect since much of their material culture continues Late Roman forms, the evidence overall points to a demographic low point in Greek rural landscapes (Bintliff, 2012b). Dated churches confirm the delay in population recovery until the 10th century AD (Sigalos, 2004).

For the 7th and early 8th century cal AD (156.5–167.5 cm, unit 61–64) we see high variability in the sediment core and all geochemical proxies (Fig. 4). As human activity is considered to be low, the outlined above, it can be assumed during this period that fluctuations in the sediment are primarily attributed to natural climatic and environmental changes rather than to anthropogenic influence. Four very thin but lithologically different units (unit 61–64) have been identified in this phase. As gastropods are present throughout all phases, we assume the constant existence of a lake, however with varying extent. The short but intense fluctuations indicate that after the vast disruption from building the aqueduct, the lake system had not fully recovered and regained its balance, but was highly vulnerable and new environmental changes led to significant repercussions in the ecosystem.

Unit 61, dating to the second half of the 7th century, contains light olive grey material with a higher amount of coarse material and only few shell fragments (Table 1). It contains a sharp Ca peak, higher than in the units below but lower than in unit 65 and above. High Zr counts indicate coarser grain size most likely due to more intense erosion or strong precipitation events in the lake’s catchment. Vegetation cover or a potential reed belt around the lake must have been low or absent, allowing the coarser material to reach the coring spot. Unit 62 again is rather fine grained, has a high amount of terrigenous elements and the lowest Ca counts of the analysed core sequence. The Cretaceus seed, dated to ca. 780 AD, was found within this unit (modelled to 690 cal AD). The most characteristic features of this unit are its black colour and the high magnetic susceptibility values (>30x higher than the median). The blackish colour may indicate organic matter and anoxic conditions, supported by a very low Mn/Fe ratio. Unit 63, is also black, but consists of considerably coarser material, a high amount of intact shells and shell fragments and shows a strong Fe peak. What can clearly be observed here is a sudden, strong increase in the sedimentation rate to over 2 mm/yr that continues with a slightly decreasing trend for the following centuries. The variable and rapidly changing Zr/Rb proxy, reflecting grain size fluctuations, implies a vulnerable environment with quick changes in water availability. The intensity of variation of the geochemical proxies in units 61–64 is unparalleled through the entire sequence at Lake Stymphalia, even stronger than during the Pleistocene/Holocene transition (Heymann et al., 2013).

The period between, approximately 100 to 750 cal AD was specifically investigated using the distribution of branched GDGTs MBTs to gain information on relative temperature fluctuations, because it is known as a period of significant temperature variations (Büntgen et al., 2016). The relative ΔMAAT variation (Fig. 8-B) based on the MBT5Me lipids suggests relatively warm conditions in Stymphalia during the 2nd to 3rd century cal AD followed by a strong cooling trend at the beginning of the Late Roman period and coldest temperatures around 400 and again later around 700 cal AD. This first cold phase is parallel to the decrease in rainfall described from the Middle East (Göktürk et al., 2011; Orland et al., 2009), and also aligns with δ18O inferred drier conditions observed in the Kapsia Cave (Finné et al., 2014) and the Soreq Cave (Bar-Matthews et al., 1999). Within the error margin of the age-depth model, the MBT5Me-reconstructed relative MAAT variation is also largely in agreement with a previously reported cooling in the 6th and 7th century AD based on dendrochronological data from the French Alps and the Russian Altai described by Büntgen et al. (2016) and referred to as the "Late Antique Little Ice Age" (LALIA, Fig. 8-G). As possible triggers, Büntgen et al. (2016) suggest high volcanic activity and low solar forcing. In a recent review paper, Helama et al. (2017) describe a longer period of cold conditions between 400 and 765 AD termed “Dark Ages Cold Period” (DACP). However, we here follow the terminology of Büntgen et al. (2016) and abstain from using the term DACP (Büntgen et al., 2017; Helama et al., 2017b), as the latter is not only culturally pejorative, but it can also easily be confused with the Greek Dark Ages at the Bronze Age/Iron Age boundary (Drake, 2012), which for the same cultural reasons are more frequently referred to as the Early Iron Ages (Proto-) Geometric and Archaic Period (Bintliff, 2012b; Weiberg et al., 2016). For the temporal extension of the cold LALIA period as reflected in our Stymphalia record, we would however rather follow Helama et al. (2017), as our brGDGT-inferred relative temperature record shows continuously colder temperatures until the beginning of the 8th century as compared to the 2nd century cal AD. Izdebski et al. (2016) also report colder climate conditions during the Late Antiquity for Anatolia and the Levant and add that the coldest decade most probably covered the time of the devastating pandemic known as the “Justian plague” (541 AD). Büntgen et al. (2016) also consider the LALIA as one influential factor on “crop failure, famine and plague, as well as a possible trigger for political, societal and economic turmoil”. During this period, described as the “rural agrarian system of Antiquity” (Izdebski et al., 2016), the people in the Eastern Mediterranean were strongly depending on cereal cultivation, viticulture and arboriculture, activities that are generally vulnerable to climatic fluctuations. The rapid drop in temperatures may have strongly increased their vulnerability, made them more resilient and more fragile to social crises. More pertinent, as occurred in the early years of the 17th century during the LIA, closely spaced and even contiguous severe drought years may have caused historically significant unrest/collapse of normal agrarian adaptive systems (Manning, 2018; White, 2013).

The situation in the eastern Roman Empire during the 6th and 7th centuries AD is described as showing “signs of hydroclimatic difficulties” and drier conditions that seemed to have prevailed until the 8th century AD (Manning, 2013; McCormick et al., 2012). The onset of the Late Antique cooling in the 7th and 8th century AD is described by McCormick et al. (2012) as a period of “deep transformations”. This phase of high climatic instability in the Eastern Mediterranean is contemporaneous to the period of high instability and very varying conditions seen in Lake Stymphalia.

The core sequence reflecting the second half of the Early Byzantine Period, unit 65, comprises bright clayey silt containing some sand and a considerable amount of gastropod shells. Ca content is highest compared to the lower core sequence and the Sr/Ca ratio indicates mainly detrital input due to enhanced limestone weathering intensity. Strong chemical weathering may be explained by episodes of warm and wet climate conditions (Jin et al., 2001). Strong precipitation events may account for the
influx of coarser material in unit 62, together with chemical changes. The continuing effects of the LALIA climatic fluctuation may be responsible, given the very low human impact. The notable rise in sedimentation after 780 cal AD and on till the 14th century AD begins in what Büntgen et al. (2011) as well as Bradley et al. (2016) term “Medieval Quiet Period”, a period of reduced climate variability between 700 and 1000 AD. With the exception of the Mn/Fe ratio, which points towards decreasing oxic conditions and thus less intense mixing conditions, our proxies also show comparatively few fluctuations within that period, but that may also be explained by low human activity in a more stable land-cover. Although evidence for population changes in the Stymphalos polje are so far not studied for the entire Early Byzantine period, wider evidence from the Peloponnese and other parts of Greece suggest low population and levels of land use throughout the era. The onset of increased sedimentation seem to mark the earliest phase of the Early Medieval Warm era, but this in itself would not seem sufficient to account for the increased influx of erosion products, which is lacking in the Greco-Roman eras under similar climatic conditions.

5.3.4. Middle Byzantine period (842–1204 AD; units 66–67)

In the 9th century AD, southern Greece is re-integrated into the Byzantine Empire (Xoplaki et al., 2016a). From Middle Byzantine (MB) times onwards, we see a gradual rise in population and a revival of agricultural use across the study region, reaching its climax after 1150 cal AD (Fig. 8-I; Bintliff, 2012b; Williams, 2005; Xoplaki et al., 2016b). Xoplaki et al. (2016) define the 12th century AD as a "most prosperous period for southern Greece, with high agricultural productivity" and a relatively resilient society. The steady increase in terrigenous elements (Fig. 4), consequently an increase in Rb/Sr (Fig. 7) and the sustained high sedimentation rate (Fig. 6) from the 11th century until approximately 1400 cal AD would fit increasing human impact. While the Zr/Rb ratio showed only minor fluctuations before ca. 700 cal AD, the ratio strongly oscillates within this period starting in the mid-8th century, which could suggest enhanced human activity, land use, and erosion of soils with varying grain sizes. The silt content increases from 63% in unit 64—79% in unit 68 (SOM 3). The coarsening of the particles could potentially be linked to more intensified land use, such as herding, agricultural activity or deforestation loosening the soil and destabilizing the slopes, although the archaeologists believe that during this period the area was largely covered by forest (Campbell, 2018). Contrary to the Late Roman period, we do not consider that the lake area was small during the MB time, allowing more coarse-grained material to reach the depocentre, because we see high carbonate content here, which demands chemical weathering due to the presence of water and a rather large lake surface for summer evaporation to be more effective. Additionally, more allochthonous organic matter is washed in and pre-large lake surface for summer evaporation to be more effective. The uppermost part of sedimentary unit 67 and the lower part of 68 cover the era of Crusader occupation and parallel Byzantine control of different parts of the Peloponnese, before the Ottoman conquest of the mid-15th century. Since the 13th to early 14th centuries show dramatic contrasts both in the archaeological and historical record, as in the core evidence, to the period of the late 14th into mid-15th centuries, we shall discuss these separately.

For the 13th century the high sedimentation rate which had commenced already in Middle Byzantine times is maintained, but with a visible slowing down. The continued increase in Rb/Sr points to more terrigenous influence and Mn/Fe suggests that the lake continued to become shallower and/or well mixed, reaching its most oxic state in the first half of the 13th century, which coincides with societal changes in the catchment.

5.3.5. Late Byzantine-Frankish period (1204–1460 AD; units 67–68)

The uppermost part of sedimentary unit 67 and the lower part of 68 cover the era of Crusader occupation and parallel Byzantine control of different parts of the Peloponnese, before the Ottoman conquest of the mid-15th century. Since the 13th to early 14th centuries show dramatic contrasts both in the archaeological and historical record, as in the core evidence, to the period of the late 14th into mid-15th centuries, we shall discuss these separately.

In the second half of the Late Byzantine-Frankish (B-F) era, there is strong societal transformation. The collapse of Frankish power leaves the Peloponnese in Byzantine control, and the monastery at Stymphalos is abandoned. Furthermore, in the mid-14th century, the Black Death produces a massive reduction in European populations, while a period of colder climatic conditions lasting into
the 15th century, a first phase of the Little Ice Age, was reconstructed from the Alps (Büntgen et al., 2011). Although this climatic period is associated with increased precipitation in temperate Europe, the effects in the southern parts of Europe may have been temperature and rainfall decline (Magny et al., 2007).

The latter part of the B–F period is covered by sedimentary unit 68, which shows a more brownish colour and considerably high magnetic susceptibility (MS) values suddenly increasing by a factor of 4 around 1400 cal AD and this continues into the first part of the early Post–Medieval period (Fig. 4). High magnetic susceptibility indicates that these sections contain a higher amount of terrigenous material that may be magnetized, especially ferromagnetic elements such as magnetite or maghemite (Lucke and Sprafke, 2015). Fe counts are elevated but not as high as during the Late Roman period (Fig. 4). Contrary to the material eroded in early centuries, it seems likely that the sediments eroded at this period were stored locally as colluviums or on terraces before, where processes of soil formation took place before they were finally deposited in the lake. This would likewise explain the strong rise in the magnetic susceptibility followed by a declining trend; upper layers with most intensive development of soil formation and highest MS values eroded first. The loss of soil from abandoned fields following the phase of the Black Death is also described from Macedonia (Gogou et al., 2016).

Throughout Greece, the 14th to early 15th centuries is a period of large-scale depopulation in the countryside, associated with a devastating plague, prolonged episodes of warfare between Franks, Byzantine and the expanding power of the Ottoman Turks, and colder climatic conditions (Bintliff, 2012b; Finnie et al., 2011). After the abandonment of the Zaraka monastery in the mid-14th century, we have only minor archaeological traces of human settlement in the region at the ancient city site and the former monastery until archival records from 1700 AD (Campbell, 2018; Williams, 2003). In agreement with better-documented trends elsewhere in Greece (Bintliff, 2012b), we expect very low populations and widespread abandonment of cultivated land in the 14th to early 15th centuries, coinciding with the core trends just discussed. Hence, the highly magnetized sediments eroding into the lake probably mark the erosion of deserted, non-vegetated fields during an unstable and generally colder climate, perhaps with shorter but more powerful precipitation events.

5.3.6. Ottoman to modern times (1460–2010 AD; units 68–70)

With the Ottoman conquest of the Peloponnese in mid-15th century, we enter a new phase of local settlement history, so we shall first discuss the relevant evidence up until the end of the 18th century AD, associated with the upper three-quarters of sediment unit 68. The age-depth-model for the uppermost 50 cm of the core has high uncertainties and the calculated ages are probably slightly too old. Thus, we rather combine the geochemical signals with known historical dates.

The Ottoman authorities were proactive in Greece in encouraging the resettlement of abandoned fields and villages (Bintliff, 2012b; Kiel, 1997, 1987), in particular inviting Albanian farmers and pastoralists to recolonise the Greek regions, including the Stymphalos district, where the modern villages mostly take their origin from this population movement. In Central Greece, repopulation began in the late 14th century and led to settlement growth into the late 16th century. The later inception of repopulation in the Peloponnese occurred within the late 15th into 16th century. This era falls within the generally colder and locally potentially drier Little Ice Age period and posed problems to the population for prosperous land use (White, 2013). The rate of sediment deposition into the lake continues to decrease up to the 16th century and stays at a rather constant level of ca. 0.7 mm/yr until the core top.

Throughout unit 68, this is accompanied by a parallel fall-off in magnetized material, indicating that less soil material is eroded. Additionally, a refinement of the material is observed as shown by the Zr/Rb ratio. We suggest this marks stabilisation of an almost empty landscape by vegetation, scrub or emerging young woodland and only minor human impact.

Central Greek populations were to collapse dramatically from the late 16th into the 18th century. The demographic recovery which had begun much later in the Peloponnese, would also have been reversed at this time. The failure of central government, the peak of the Little Ice Age, and devastating warfare between the Ottomans and Venice were the major factors (Bintliff, 2012b). As a result, the first census figures for villages in the Stymphalos district ca. 1700 AD show very low levels, with 50 or less inhabitants per village for almost all settlements in the Stymphalos district (the successor to the ancient city and medieval monastery, the village of Stymphalia, has 52, Panagiotopoulos, 1985).

Brown and Walsh (2017) see a drastic decrease in clastic sedimentation (Cu, Zn, Fe, Ti) and an increase in Ca in the upper 72 cm of their sediment cores taken from the lake shore, which they interpret as a lake level becoming constantly shallower and drying out repeatedly. However, their chronology needs to be regarded with caution, as it is not well anchored in the uppermost part. To contrast to these results, we see the opposite elemental trend in our sediment record, a constant increase in terrigenous elements (Rb, Zr, Al, Ti, K, Si) for the upper 156.5 cm (with the exception of unit 69–70) and a decreasing carbonate content (Ca and Sr). TOC and TOC/TN values for this period are low, indicating, as the Mn/Fe ratio implies strongly oxic conditions, that organic matter input in this section was strongly decomposed and not preserved. Unit 68 contains shell fragments of *Bythina* sp. proving that a lake, however shallow, existed at that time. In addition, the sediment in unit 68 is orange mottled with iron oxides hinting oxygen supply and desiccation. This leads to the conclusion that a small, shallow lake existed for most of the year and periodically dried out in summer. Thus, although the geochemical argumentation is different, we come to a similar conclusion as Brown and Walsh (2017) that the lake bottom became shallower over time and since approximately 1500 AD may have periodically dried out.

The uppermost units 69 and 70, covering the Early Modern era of the 18th to 20th century cal AD, need to be regarded with caution. We see very strong, abrupt changes and we assume that the material was altered post-hoc; for example due to desiccation, some material might have been eroded or due to agricultural activity on the lake bottom, it may have been anthropogenically reworked and first soil formation processes may have set in. According to Walsh et al. (2017) the lake dried up completely over several years in the recent and was even used as alanding strip. This is known from historical sources and brought the lake its nickname "aerodromio", airport (Walsh et al., 2017). The desiccation, compaction and anthropogenic drainage can also be seen in the sedimentological record; unit 69 (dated to ca. 1720–1860 cal AD) is very dense and compact and contains a sudden, abrupt increase in terrigenous elements, especially in Rb and K, typical clay elements; this increase in clay can also be seen in the Mastersizer data. Zr/Rb firstly indicates a shift to coarser material and then a refining within the unit. The TOC content in this section is low, only increasing in unit 70 above, indicating that enough oxygen was present in this section to decompose the organic matter. An increase in Mn, Fe and MS suggests first soil formation processes; gastropods are absent here. All these proxies indicate that in the 19th century the lake has repeatedly fallen dry. Furthermore, there is historical evidence that the authorities in the Corinth region reactivated the aqueduct in the 1880s to irrigate their local farmland (Morfas and Zojer, 1986), giving one explanation why less water...
reached the lake. Although the sinkhole at the southern shore has been isolated from regular outflow since the 19th century (Walsh et al., 2017), no larger flooding events are visible in the core apart from the more coarse grained unit 70a (at 9 cm, dated to ca. 1880 cal AD). During the late 19th and early 20th century, agricultural production in the polje strongly expanded. The population of this district, as over the rest of the Peloponnese, grew exponentially; Philippson (1892) lists village sizes in the Stymphalos district that are 10–15 times those of the same communities two hundred years earlier (Stymphalos has now 808 inhabitants). This did not simply mean sustainable subsistence and minor commercial agriculture as during Classical-Hellenistic times (cf. section 5.3.1), but rather industrialized primary production for the global market with the help of farming machines (Kourelis, 2018), which would also explain the strong compaction of the soil. The shift from the colder LIA climate to a more typical Mediterranean climate over this same period, starting in the 19th century AD based on SSTs in M2 (Fig. 8–F; Gogou et al., 2016), was highly positive for the observed agricultural take-off.

The thin unit 70a, characterized by a high amount of sand particles probably indicates a stronger precipitation event with surface run-off refilling the lake and feeding in coarser grained material into the centre of the lake that accumulated in the plain during the dry period; reed vegetation holding back the material was probably absent by then. Unit 70b may be characteristic for today’s conditions; high TOC, average TIC and Ca counts as well as moderate terrigenous input. The lake is perennial, but depending on the season it can vary considerably in size. The polje is intensively used for agricultural purposes. For the second half of the 20th century, land use has also been analysed by Papastergiadou et al. (2007); wet meadows and open water areas declined considerably while reed beds and irrigated agricultural land spread out. The use of fertilizers reinforces the reed growth and most likely affects the faunal populations.

6. Conclusion

The geochemical and sedimentological analyses of the Stymphalia lake sequence show a complex interlinking of natural variability and anthropogenic influence on the lake over the last 2500 years. Water supply to the lake was not constant over time and the land cover in the catchment must have changed substantially in relation to climate fluctuations, intensity of land-use and human occupation phases that influenced the sedimentary conditions. The lake level and particularly the lake area have fluctuated considerably over the last 2500 years including shorter periods of desiccation, more frequently occurring in the younger phase. No evidence for a very high lake level comparable with the neighbouring Pheneos polje has been found in the sediment sequence; we are continuously dealing with a shallow lake system here.

Stable climatic conditions and sustainable agro-pastoralism prevailed during Classical Hellenistic times. Major alteration in the lake's hydrological cycle occurred with the construction of the Early Roman Hadrianic Aqueduct around 130 AD, which increased the vulnerability of the ecosystem and, even after its failure, probably had a long-lasting impact on ecosystem reactions to climatic changes during the following centuries. We interpret this event as a trigger for the highly sensitive reaction to climatic variations during the LALIA period in the 6th to 8th century AD. The Lake Stymphalia data indicate that the Late Roman to Early Byzantine Period in southern Greece is associated with a shift to several cold periods of varying durations, strong variation in water availability and a generally more unstable climatic context. Although anthropogenic influence was chronologically limited, it represents a significant element in understanding long-term reactions in the sediment core that were mainly linked to water availability. For the period 9th to 17th century, the age-depth-model implies higher uncertainties; however, we see a phase of higher sedimentation and carbonate precipitation during warm and wet conditions within the Medieval Warm Period roughly until the 15th century and indications for colder conditions during the Little Ice Age. The last 200 years are strongly shaped by desiccation and human activity.

Land use intensity and vegetation cover were in a fluctuating dialectic with temperature and precipitation changes in the degree and nature of surface erosion. These conclusions agree with recent modelling of environmental change, critical of mono-causation, rather focussing on complex interactions of human and natural factors in the inception of landscape transformation (Bintliff, 2002; Casana, 2008). Pollen analysis would lead to an additional value, supporting our hypotheses or further classifying the land use activities, however pollen preservation in the core sequence was inadequate for any detailed analysis. The close interdisciplinary collaboration between natural scientists and archaeologists in this research field was highly beneficial and offers a more holistic interpretative approach. In the near future, independent sedimetary records from other sedimentary archives in adjacent valleys shall offer additional insights on the reconstruction of climatic changes and associated human impact interaction in the NE Peloponnese.

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Appendix A. Supplementary data

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References
