Ephesus and the Ephesia –

palaeogeographical and geoarchaeological research about a famous city in Western Anatolia

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Contents

Abstract I

Kurzzusammenfassung III

Acknowledgements V

1. Introduction 1

1.1 Holocene coastline changes and settlement sites along the Mediterranean coasts 1
1.2 Objectives of this study 2
1.3 Research design and study outline 4
1.4 Study area 6
1.5 History of the Ephesia 8

2. The palaeogeographies of Ephesos (Turkey), its harbours, and the Artemision – a geoarchaeological reconstruction for the timespan 1500–300 BC 10

3. Life cycle of the Roman Harbour of Ephesus – multi-proxy analyses of the sediment record 45

4. Demise of a harbor: A geochemical chronicle from Ephesus 78

5. In search of the harbours: New evidence of Late Roman and Byzantine harbours of Ephesus 91

6. Neolithic settlement sites in Western Turkey – palaeogeographic studies at Çukuriçi Höyük and Arvalya Höyük 105

6.1 Introduction 106
6.2 Study area 107
6.3 Methods 110
6.4 Results and discussion 111
6.4.1 Drill cores at Çukuriçi Höyük 111
6.4.1.1 North-south cross section 111
6.4.1.2 West-east cross section 114
6.4.1.3 Interpretation of the cored strata at Çukuriçi Höyük 114

6.4.2 Arvalya Höyük 115
6.4.2.1 Geophysical investigations 115
6.4.2.2 Drill cores 117
6.4.2.3 Interpretation of drill cores of Arvalya Höyük 119
6.4.2.4 Archaeological analyses 119
6.4.3 Palynological analysis 121
6.5 Palaeoenvironmental reconstructions 123
6.6 Conclusion 124

7. Discussion 125
7.1 Delta progradation of the Küçük Menderes and Holocene sea-level changes during the Holocene 125
7.2 Investigation of different harbour sites of Ephesus 130
7.3 Human impact in the Ephesia 135
7.4 Landscape changes during the first time of settlement and vegetation history in Western Turkey 137
7.5 Preliminary results in the swamps of Belevi.... 139

8. Summary and conclusion 141

9. References 144

Paper Contributions 155

Erklärung 156

Curriculum Vitae 157

Abstract

Ephesus was one of the most important harbour cities of the Roman Empire. This dissertation deals with the environmental changes of Ephesus and the Ephesia, i.e., the area surrounding the city (the so-called *chora*), with particular focus on (i) the detection of Holocene coastline changes along the Küçük Menderes graben, (ii) the investigation of Ephesus' different harbours and settlement sites, and (iii) the reconstruction of the landscape evolution in the Ephesia especially under the aspect of human-environment interactions since Neolithic times. To achieve these goals, drill cores were retrieved from geo-bio-archives and analysed with sedimentological, geochemical, micro- and macrofaunistic, micromorphological, palynological and parasitological methods. Geophysical measurements and archaeobotanical investigations support these studies. The chronology is based on ^{14}C age estimates, archaeological evidence (e.g., diagnostic ceramics) and historical accounts.

The results prove that the postglacial sea-level rise had created a marine embayment, which reached c. 20 km inland during the middle of the 6th millennium BC. When the speed of this transgression decelerated considerably, the Küçük Menderes river started to prograde its delta. Two phases of delta advance can be distinguished: a slow progradation with low sedimentation rates between the 5th and the 1st millennia BC (up to 1 mm/y), and a much faster advance since then (c. 4–30 mm/y). The most likely reason for this considerable increase is human activities (mainly deforestation).

Settling in the Ephesia started during the Neolithic period. Two settlement sites in the floodplains of the Arvalya and Derbent valleys south of the Küçük Menderes graben, Arvalya Höyük and Çucuriçi Höyük, date to the 7th millennium BC. These settlement mounds are located c. 1.5–2 km south of the former coastline.

With the continued westward progradation of the deltas of the Küçük Menderes and its tributaries, the settlements and their harbours had to be shifted as well. The location of the so-called Sacred harbour near the Artemision, the famous Temple of Artemis, could be identified as a natural beach in a small embayment near the foot of Ayasoluk hill. It was in use from c. 1500 BC to max. 400 BC. With the ongoing siltation of the Sacred harbour, the Koressos harbour c. 1.5 km to the west came in use until this embayment was silted up as well. Thus, the city and its harbour were re-located further to the west in 289/288 BC by Lysimachos. This harbour was the predecessor of the hexagonal Roman–Byzantine harbour basin; it was intensively used from the 1st century BC to the 6th/7th centuries AD. While this site was most likely still accessible until the 13th century AD, the progressive siltation required the establishment of yet another harbour (Late Roman to Byzantine), located about 3.5 km to the west of the city and presumably in use until around AD 1000. Two more harbour sites can be detected even further to the west.

The harbours of Ephesus reveal the typical stratigraphy of a port in the Mediterranean: pre-harbour deposits at the base (i), overlain by harbour layers which were accumulated in a protected artificial basin and are characterised by increased sedimentation rates as well as a change in the microfossil assemblage (ii), and harbour abandonment layers on top (iii). In the Roman harbour and the harbour canal there are several indicators for dredging activities.

The following conclusions can be drawn regarding the vegetation changes. The presence of Cerealia-type pollen indicates agricultural activities as early as in the 7th millennium BC although by then the hills and hillslopes were still forested, i.e. covered by a natural vegetation community with an arboreal dominance of *Quercus robur*/*cerris*-type trees. Increased human activities are confirmed in the Roman harbour archive with eggs of intestinal parasites and roundworms, fruit tree pollen and heavy metal pollution; an intensive use is evident from the 1st century BC onwards. While high amounts of pine wood were used in Ephesus, low values of *Pinus* in the pollen profile seem to confirm deforestation activities in the vicinity of the city. Decreased human impact is reflected in the pollen record after the 6th/7th centuries AD with the decline of the city.

The swamps of Belevi in the hinterland of Ephesus are not only an excellent archive for the vegetation changes discussed above. They also archived an event layer: the Santorini ash of c. 1630 BC. It is the first find of this tephra in the environs of Ephesus.

Kurzzusammenfassung

Ephesos war eine der bedeutendsten Hafenstädte des Römischen Reiches. Diese Dissertation behandelt Umweltveränderungen in Ephesos und der Ephesia, d.h. in der Umgebung der Stadt (so genannte *chora*). Der Schwerpunkt der Untersuchungen liegt auf (i) holozänen Küstenveränderungen im Küçük Menderes-Graben, (ii) Ephesos' Häfen und Siedlungen, und (iii) einer Landschaftsrekonstruktion mit dem Schwerpunkt auf Mensch-Umwelt-Beziehungen seit der Erstbesiedlung im Neolithikum. Um diese Ziele zu erreichen, erfolgten Bohrungen in verschiedenen Geo-Bio-Archiven, die mit sedimentologischen, geochemischen, mikro- und makrofaunistischen, mikromorphologischen, palynologischen und parasitologischen Methoden analysiert wurden. Geophysikalische Untersuchungen und archäobotanische Analysen ergänzen diese Arbeit. Die Chronologie basiert auf ^{14}C Datierungen, archäologischen Befunden (z.B. diagnostische Keramik) und historischen Quellen.

Die Ergebnisse belegen, dass der postglaziale Meeresspiegelanstieg seit Mitte des 6. Jt. v. Chr. eine marine Bucht schuf, die ca. 20 km in das Landesinnere reichte. Einhergehend mit einer deutlichen Verlangsamung des Meeresspiegelanstiegs begann der Küçük Menderes sein Delta vorzubauen. Es lassen sich zwei Phasen des Deltavorbaus unterscheiden: ein langsamer Deltavorbau mit niedrigen Sedimentationsraten vom 5. bis 1. Jt. v. Chr. (bis 1 mm/Jahr), ein schnelleres Deltawachstum mit höheren Raten von dieser Zeit an (4–30 mm/Jahr). Die hohen Raten sind wahrscheinlich durch menschliche Aktivitäten hervorgerufen, vor allem durch Abholzung.

Die Erstbesiedlung der Ephesia begann im Neolithikum. Zwei Siedlungshügel in den Alluvialebenen von Arvalya und Derbent südlich des Küçük Menderes-Grabenbruchs, Arvalya Höyük and Çucuriçi Höyük, datieren auf das 7. Jt. v. Chr. Diese beiden Tells befinden sich ca. 1,5–2 km südlich der damaligen Küstenlinie.

Mit dem kontinuierlichen Deltavorbau sowohl des Küçük Menderes als auch seiner Zuflüsse in westliche Richtung mussten Siedlungen als auch ihre Häfen verlagert werden. Die Lage des Heiligen Hafens des Artemisions, des berühmten Tempels der Artemis, konnte als ein Strand identifiziert werden, der sich in einer kleinen Bucht in der Nähe des Hangfußes des Ayasoluk Hügels befand. Der Hafen wurde von ca. 1500 v. Chr. bis max. 400 v. Chr. genutzt. Mit der fortschreitenden Verlandung ging die Nutzung auf den Koressos-Hafen ca. 1,5 km westlich über, bis auch dieser verlandete. Als Folge des Deltavorbaus wurden die Stadt und ihr Hafen 289/288 v. Chr. weiter nach Westen verlegt. Dieser Hafen war der Vorgänger des hexagonalen römisch-byzantinischen Hafenbeckens, das intensiv vom 1. Jh. v. Chr. bis zum 6./7. Jh. n. Chr. genutzt wurde. Zwar war diese Anlegestelle wahrscheinlich noch bis zum 13. Jh. n. Chr. zu erreichen, aber infolge der fortschreitenden Verlandung wurde ein weiterer Hafen

(spätrömisch/byzantinisch) ca. 3,5 km westlich der Stadt errichtet, der bis höchstens 1000 n. Chr. betrieben wurde. Zwei weitere Häfen befinden sich noch weiter westlich.

Die beiden letztgenannten Häfen weisen eine typische Stratigraphie von Häfen im Mittelmeerraum auf: (i) an der Basis Sedimente aus der Zeit vor der Hafennutzung, (ii) darüber folgen Hafensedimente, die in einem künstlichen Becken mit einer erhöhten Sedimentationsrate und einer veränderten Mikrofauna abgelagert wurden, (iii) bis zur Geländeoberfläche sind Schichten nach der Aufgabe des Hafens zu finden. Im römischen Hafen und im Kanal sind mehrere Hinweise auf Ausbaggerungsarbeiten zu finden.

Für die Rekonstruktion der Vegetationsgeschichte können folgende Aussagen getroffen werden: obwohl Cerealia-Typ Pollen bereits auf landwirtschaftliche Aktivitäten im 7. Jt. v. Chr. hinweisen, waren die Hänge wahrscheinlich noch bewaldet und von einer natürlichen Vegetation mit *Quercus robur*/*cerris*-Typ geprägt. Der erste stärkere menschliche Einfluss lässt sich in den Geo-Bio-Archiven der Häfen mit Eiern von Darmparasiten und Spulwürmern, Pollen von Fruchtbäumen und Schwermetallbelastung ab dem 1. Jh. v. Chr. nachweisen. Während viel Pinienholz in Ephesos genutzt wurde, scheinen geringe Werte im Pollenprofil Abholzungen in der Umgebung der Stadt zu bestätigen. Ab dem 6./7. Jh. n. Chr. lässt der anthropogene Einfluss nach, was einhergeht mit dem Niedergang der Stadt.

Die Sümpfe von Belevi im Hinterland von Ephesus stellen nicht nur ausgezeichnete Archive für die Rekonstruktion der Vegetationsgeschichte dar (s.o.). Dort wurde auch die Santorin Asche von ca. 1630 v. Chr. nachgewiesen. Sie stellt den ersten Fund der Tephra in der Nähe von Ephesus dar.

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1. Introduction

1.1 Holocene coastline changes and settlement sites along the Mediterranean coasts

During the Holocene, severe coastline changes took place along the Mediterranean coasts. The rising sea level after the end of the last glaciation created large marine embayments in graben structures and lowlands (Kayan, 1995b; Perissoratis and Conispoliatis, 2003). Intensive and rapid coastline changes during the Holocene have been reported especially from deltas of large rivers such as the Nile (Marriner et al., 2012b) or the Rhône (Vella et al., 2005), and from deltas in large valleys, e.g. the Karamenderes plain (Kraft et al., 2003). In the graben systems in Western Turkey, the sea transgressed up to 60 km into the Büyük Menderes (Müllenhoff, 2005) and up to 20 km into the Küçük Menderes (Brückner, 2005; Kraft et al., 2011) grabens. Since the 5th/4th millennia BC, the sea-level rise has decelerated considerably. This caused delta progradation and floodplain evolution (Kayan, 1999). Meanwhile, the former marine embayments have nearly entirely silted up (e.g. Kayan, 1995a; Brückner et al., 2005).

At the same time, human occupation along the Mediterranean coasts has strongly influenced the environment since the first colonisation (Kaniewski et al., 2013; Anthony et al., 2014). However, until the 1990s, only scattered interdisciplinary research between humanities and earth sciences has been conducted (Marriner et al., 2010). Since then, geoarchaeologists have intensively investigated the Holocene landscape of settlement sites and their environments in order to better understand the interplay between natural and human-induced environmental changes. Prominent case studies are Troy (Kraft et al., 2003) and Miletus (Müllenhoff, 2005; Brückner et al., 2002, 2006, 2014). Harbour sites of ancient settlements, in particular, have increasingly become a focus in the ongoing research during the last years (Marriner et al., 2006a, 2010; Marriner and Morhange, 2007; Morhange and Marriner, 2010). Examples are the harbours of Yenikapı (Algan et al., 2011), Marseille (Morhange et al., 2003; Le Roux et al., 2005), Miletus (Brückner et al., 2014, in press), Elaia (Seeliger et al., 2013; Pint et al., 2014), Portus (Mazzini et al., 2011; Salomon et al., 2012; Delile et al., 2014a, b) and Tyre (Marriner and Morhange, 2006b).

The ancient city of Ephesus had to deal with strong coastline changes and the siltation of the marine embayment as well. During the 1st millennium BC, this resulted in a relocation of the major settlement site and its harbours, following the retreating coastline (e.g. Kraft et al., 2000; Steskal, in press). Although many geoarchaeological studies have been conducted about Ephesus' palaeogeography and its harbours since the 1990s (Kayan, 1995a; Kraft et al., 1999, 2000, 2001, 2005, 2007, 2011; Brückner, 1997, 2005; Brückner et al., 2005, 2008), still several research questions about the detailed palaeogeographical evolution, the spatio-temporal human-environment interactions, and the marine extension remained open.

1.2 Objectives of this study

Among the ancient cities on the Western Turkish coastline, Ephesus is well suited for studying major coastline and environmental changes during the Holocene. As stated above, numerous publications exist about the palaeogeography of Ephesus and the Ephesia, i.e. its environs, as well as the delta advance of the Küçük Menderes (Kayan, 1995a; Brückner, 1997, 2005; Brückner et al., 2008; Kraft et al., 1999, 2000, 2001, 2005, 2007, 2011). In order to extend and complete previous research, the Austrian Archaeological Institute (ÖAI) at Vienna initiated a project about the palaeogeography and geoarchaeology of the Ephesia in cooperation with Prof. Dr. Helmut Brückner, University of Cologne. It is under this umbrella that the dissertation at hand was written. It focuses on open questions related to landscape reconstruction, coastline changes, the relocation of settlements with special regard to harbour sites in the Ephesia and on human-environment interactions during the last 8000 years. Four main working hypotheses are subdivided into research goals.

Working hypothesis 1: The Holocene transgression of the sea created a marine embayment which reached far inland. This embayment was later entirely filled in by fluvial sediments.

Goal 1: Detection of the spatial and temporal shifts in the coastline during the Holocene

Although Kraft et al. (2000) and Brückner (2005) have already carried out pioneering research in the southern part of the Küçük Menderes graben, the maximum extension of the marine transgression and the subsequent coastline development still require further research in particular regarding the chronology of the delta advance.

Goal 2: Reconstruction of a sea-level curve for the Küçük Menderes graben

While numerous studies have dealt with the coastline retreat in the Küçük Menderes graben (Kayan, 1995a; Brückner, 1997, 2005; Brückner et al., 2008; Kraft et al., 1999, 2000, 2001, 2007, 2011), a Holocene sea-level curve for this area does not yet exist. The ensemble of reliable (palaeo-) sea-level indicators will help to reconstruct the sea-level history.

Working hypothesis 2: Ephesus' harbours are excellent geo-bio-archives.

Goal: Investigation of Ephesus' different harbour sites with regard to with special regard to their stratigraphy

The tripartite goal here is (i) to locate the different harbours, (ii) to study their stratigraphy and identify dredging traces, and (iii) to understand the role played by different sedimentation processes. The advantages and limits of the diverse methods traditionally applied to detect such kinds of palaeo-environmental shifts are also discussed. Finally, these geo-archives are compared and correlated to other Mediterranean harbour sites.

Working hypothesis 3: The sensitive environment of the Ephesia directly reacted to human and climate impacts during the Middle and Late Holocene.

Goal 1: Quantification of sedimentation rates

The research shall determine whether changes in sedimentation rate correlate with climatic variations and/or human impact.

Goal 2: Identification of the human impact in sediment archives

Considering the growing population of the Ephesia during the last millennia, it should be possible to identify distinctive traces of human impact in the geo-archives and to quantify them.

Working hypothesis 4: The Ephesia was suitable for settling already during Neolithic times.

Goal 1: Identification of and research about the spatial distribution of Neolithic settlements in the Ephesia

The knowledge about two Neolithic settlement sites in the vicinity of Ephesus is to be expanded with focus on the thickness, spatial extent, and age of the different cultural layers.

Goal 2: Reconstruction of the Early Holocene landscape

By synoptically viewing all of the available data, the Early Holocene landscape (local topography and vegetation etc.) shall be identified.

1.3 Research design and study outline

The geoarchaeological research in the Ephesia merges physical geography with archaeology (Rapp and Hill, 1998) in order to reconstruct the landscape of the last millennia and reveal human-environment interactions. This dissertation follows the research design of Brückner (2011) (see Fig. 1.1).

The analysis of topographic and ancient maps as well as satellite images helped in the identification of geo-archives. During several field campaigns selected geo-archives (delta plain, harbours, archaeological excavations, swamp, alluvial fans) as well as geo-bio-archives, suitable for palynological studies, were investigated with drill cores and geophysical methods. The coring positions were identified according to measurements with a DGPS.

In the first step, the resulting cores were analysed in the laboratory using sedimentological, micromorphological, geochemical, archaeobotanical, palynological, macro- and microfaunal as well as parasitological methods. The establishment of a chronostratigraphy relies on AMS-^{14}C age estimates and diagnostic ceramic finds. The results allowed for the interpretation and better differentiation of sedimentation environments (marine, lagoonal, littoral, limnic, fluvial, alluvial). In a next step, archaeological data (historical records and maps) and former publications were consulted and combined with the results of this study. The synopsis of all data led to the development of landscape scenarios for different epochs, with special regard to human-environment interactions.

The main part of this thesis (chapters 2–6) deals with the coastline evolution during the last 8000 years, especially during different settlement epochs after the first colonisation, and with the city's harbours. Research focused on the environs of the different settlement and harbour sites that had to be moved several times due to the shifts in the coastline.

Chapter 2 focuses on the evolution of the Artemision area from 1500–300 BC. Although several other geoarchaeological studies have been conducted during the last decades in the environs of the Artemision (Brückner et al. 2008; Kraft et al. 2000, 2001, 2007, 2011), still open questions remained. A more detailed analysis of the coastline development on the southern flank of the Küçük Menderes graben especially in the Derbent and Arvalya valleys, as well as in the environs of the Artemision is presented in this chapter. Drill cores have been analysed with geochemical, sedimentological and microfaunal methods in order to decipher the landscape evolution since 5000 BC, with special focus on the time slice 1500–300 BC. This information helped to understand historical records about potential landing sites. The analysis of the different sedimentation rates revealed the siltation process.

The case studies in chapters 3 and 4 deal with the development of the Roman-Byzantine harbour adjacent to Ephesus. In chapter 3, several drill cores from the Roman harbour basin and the harbour canal were investigated with geochemical, sedimentological, micromorphological, palynological, macro- and microfaunal, parasitological and archaeobotanical methods. The analyses yielded information about the harbour stratigraphy, as well as human impact. Moreover, ^{14}C ages provided a detailed chronology of the use and development of the harbour and its canal. Chapter 4 as adds to this information the Pb isotope compositions of one drill core in the Roman harbour. Lead and copper were the major pollutants found in the harbour archive. The identification of different sedimentation units was supported by statistical methods (PCA, principle component analysis).

Chapter 5 used sedimentological, geochemical and microfaunal methods in search for potential Late Roman and Byzantine harbour sites around the modern lake Çanakgöl and in the area of the lower Arvalya valley. The results revealed landscape and coastline changes, allowed for a better differentiation of sediment dynamics, and identified Çanakgöl as the remainder of a harbour.

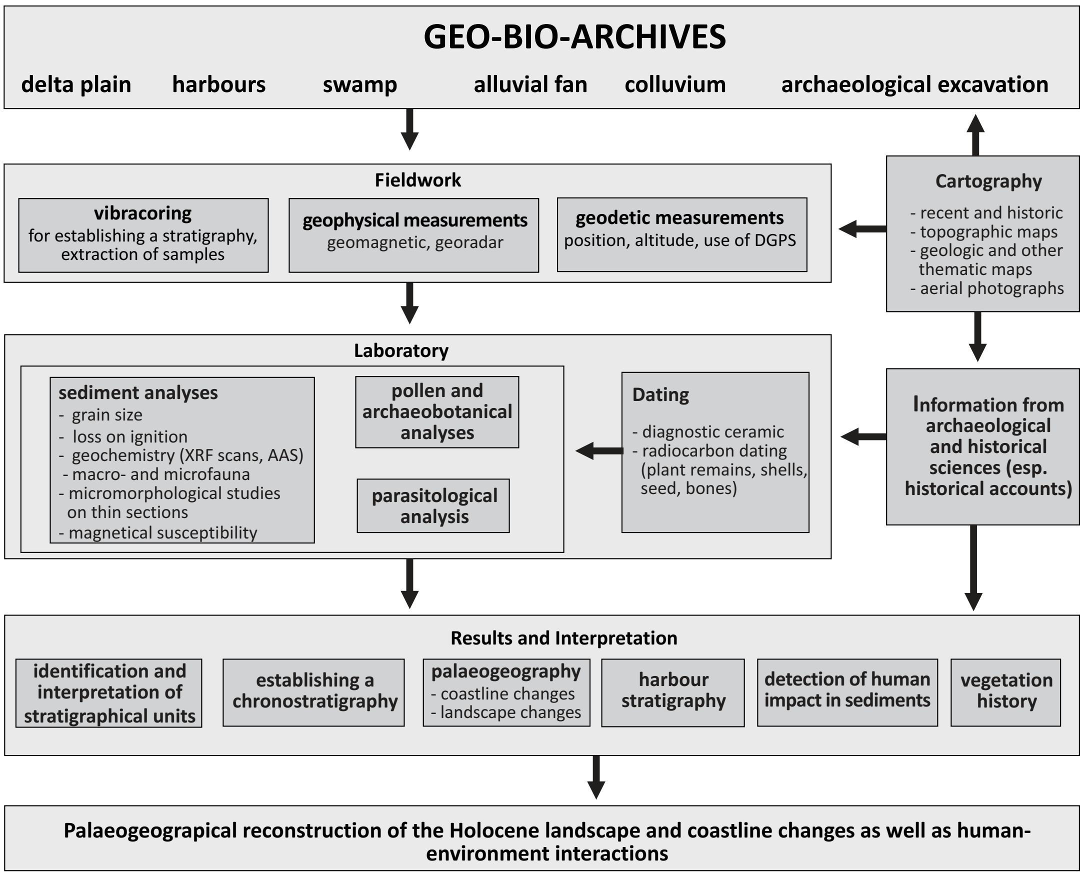

Fig. 1.1: The research design following Brückner (2011, modified).

While all of the chapters 2–5 deal with the environmental evolution since the 5th millennium BC, chapter 6 presents the first settlement sites of the Ephesia, the mounds Çukuriçi Höyük and Arvalya Höyük, which date from the 7th to the 3rd millennium BC. They were studied in order to determine their spatial extent as well as the thickness and the age of the cultural layers. Based on palynological studies, the vegetation history and the human impact on the landscape can be deciphered from Neolithic times on.

Chapter 7 discusses the presented research, with special regard to the working hypotheses proposed in chapter 1.3. Among others, the first draft of a locally valid sea-level curve is presented. The cumulative PhD thesis ends with summary and conclusion (chapter 8).

1.4 Study area

The Küçük Menderes graben in Western Turkey in which the study area is located is a subsidence area within the Aegean-Anatolian microplate. This subsidence related to an extensional regime is caused by the northward drift of the Arabian plate forcing the Aegean-Anatolian microplate to move in the southwestern direction (Polat et al., 2008). Since the Tertiary, several fault systems (e.g. North and East Anatolian fault systems) and active graben structures such as the Gediz, the Büyük Menderes and the Küçük Menderes consequently developed in Western Turkey (Taymaz et al., 2007). The Küçük Menderes graben has formed during the Neogene within the Palaeozoic Menderes massif (Bozkurt and Oberhänsli, 2001): it is subdivided into five subbasins and filled with Miocene-Quaternary sediments (Rojay et al., 2005). The investigated area lies in the Selçuk subbasin in the western part of the graben (Rojay et al., 2005). Dissecting the southern flank of the graben, the Arvalya and Derbent valleys are related to two parallel north-south striking fault systems.

Surrounding mountains of the Menderes Massif culminating at 700 m to the north (Bozdağ mountains) and south (Aydindağ mountains), and up to 500 m to the east (Philippson, 1918; Erol, 1983). They mainly consist of mica schist, marble, quartzite, limestone and phyllite (Philippson, 1912; Vetters, 1989; Çamakoğlu, 2007; Rantitsch and Prochaska, 2011; fig. 1.2). The western and northern part of the Selçuk subbasin (max. 360 m) consist of marble, dolomitic marble, mica schist and phyllite as well as outcrops of Miocene sediments (red breccia), while the eastern part is mostly composed of mica schist (Philippson, 1912; Çamakoğlu, 2007; Rantitsch and Prochaska, 2011). This area is tectonically active with earthquakes reaching up to 9 on the Mercalli scale (Vetters, 1998; Crouch, 2004). Strong earthquakes have been reported in 23, 29/30, 47 BC and 262, 266 and 467/468 AD (Karwiese, 1995).

The sea-level rise after the end of the last glaciation formed a marine embayment presumably extending about 20 km inland (Brückner, 2005; Kraft et al., 2000). During the last 6000 years, the delta progradation of the Küçük Menderes river has created a floodplain in the lower Küçük Menderes graben (chapter 1.1; Erinç, 1955; Kayan, 1999). In total, up to 30 m of Holocene sediments were deposited (Kraft et al., 2005). The former island Syrie (89 m) consisting of marble (Grund, 1906; Vetters, 1989) and two lakes (Akgöl und Gebekirse Gölü) are remnants of the marine embayment (Philippson, 1912; Brückner, 2005). Recent beach ridges developed close to the present coastline of the Aegean Sea (6 km to the west of Ephesus) (Eisma, 1962). Coastline changes have been studied intensively by Brückner (1997, 2005), Brückner et al. (2008) and Kraft et al. (1999, 2000, 2001, 2005, 2007, 2008, 2011).

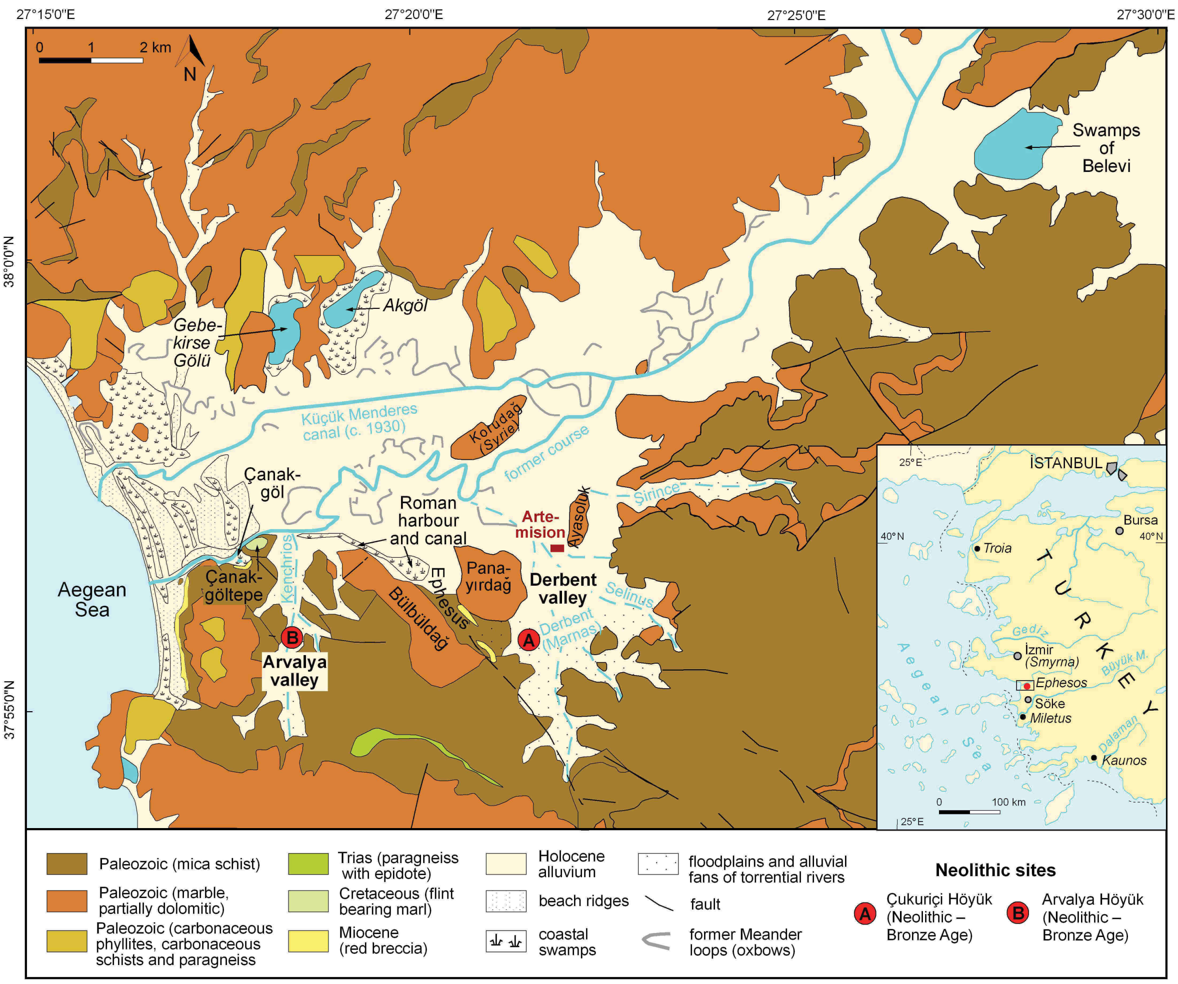

Fig. 1.2: Geological map of the study area. Based on Vetters (1989), Brückner (1997), Geological map of Turkey 1:25000 (General directorate of mineral research and exploration, Aydın – M 18-b1, Aydın – M 18-b2; 1981) and 1:100000 (General directorate of mineral research and exploration, Izmir – L 18; 1993).

The only perennial flowing river is the Küçük Menderes draining the graben and debouching into the Aegean Sea. Before its regulation in the 1930s (Eisma, 1978; Güldali, 1979), the main river channel was located in the southern part of the graben (Fig. 1.2). The Derbent and

Arvalya valleys are drained by the Kenchrios (in Arvalya valley), Derbent, Selinus and Şirince rivers (in Derbent valley).

The investigations took place in the southern part of the graben in the environs of the city of **Ephesus** which is located between the Panayırdağ (157 m) and Bülbüldağ mountains (356 m; both composed of marble; Fig. 1.2). The **Roman harbour and canal** lie westward of the city in a former embayment now located about 5 km to the east of the present coastline. Especially during winter characterised by heavy rainfall events, the former harbour basin and its canal are filled with water. During summer times, it is mainly fed by karstic springs (Somay et al., 2008; Somay and Gemici, 2009). The settlement sites **Arvalya Höyük** and **Çukuriçi Höyük** are located in the valley floors of the Arvalya and Derbent valleys about 2 km south of the Küçük Menderes graben at elevations of 20–30 m a.s.l. The **Artemision** was constructed on an alluvial fan of Derbent valley. Ayasoluk hill (87 m, composed of marble), a former peninsula, lies northeast of the Artemision. Çanakgöl northwest of the Arvalya valley is a remnant lake which was connected to the Küçük Menderes river.

1.5 History of the Ephesia

The Ephesia was settled in prehistoric times from the Neolithic period (7th millennium BC) to the Bronze Age (3rd millennium BC; Scherrer, 2007; Horejs, 2012) (Tab. 1.1). From the middle of the 2nd millennium BC on, a settlement site is known to have existed on Ayasoluk hill (Fig. 1.2). A number of relocations of the settlement until the 3rd century BC were all related to the changing coastline and the availability of a natural harbour (Zabehlicky, 1995; Kraft et al., 1999).

Especially from the 1st millennium BC onwards, Ephesus (Greek name: Ephesos) gained importance with the temple of Artemis (Artemision), one of the seven wonders of the ancient world. Around 300 BC, Lysimachos re-established the city at the northern flank of Bülbüldağ and the western flank of Panayırdağ (Scherrer, 2007; Fig. 1.2). During the 1st century BC, Ephesus became capital of the province of Asia, which was to become one of the most prominent cities of the Eastern Roman Empire during the following centuries, with an estimated maximum population from up to 100 000 (Groh, 2012) to 200 000–300 000 (Scherrer, 2004). During its long history until the end of the 1st millennium AD, the inhabitants of Ephesus had to adapt to the ongoing coastline changes. Therefore, a harbour canal was built in order to maintain the connection to the sea. Several severe earthquakes damaged the city in the course of its history. In Byzantine times, especially from the 7th century AD onwards (Scherrer, 2007), the area of the city and its population declined. Destructions due to earthquakes and attacks by the Arabs led to the establishment of fortifications on Ayasoluk hill to where many Ephesians moved after the 7th century AD.

Epoch	**Time**	**Event**
Prehistory	7th–3rd mill. BC	Early farming settlements **Çukuriçi Höyük** and **Arvalya Höyük**
Mycenaean	After 1500 BC	Naming of country **Arzawa**, capital '**Apaşa**' (Ephesus?) Mycenaean grave on Ayasoluk
Geometric	11th c. BC 9th c. BC 8th c. BC	Ionian Greeks under Androcolos settle at **Koressos** (northwestern part of Panayırdağ) Beginning of continuous use of **Artemision** as a sanctuary Establishment of the village Smyrna close to Ephesus
Archaic	6th c. BC 2nd half of 6th c. BC	Relocation of the settlement (Ephesus) in the plain of the Artemision, construction of archaic Artemision, donated by Croesos Persian reign
Classic	466 BC 407 BC 356 BC	Ephesus joins Attic sea alliance Peloponnesian War, Admiral **Lysandros** from Sparta chooses Ephesus as head quarter, he expands the harbour (Koressos?) 'Herostrates fire', restoration of Artemision
Hellenistic	289/288 BC 281 BC	Re-foundation, **Lysimachos** establishes the city Arsinëoia (Ephesus) between Panayırdağ and Bülbüldağ, **construction of Hellenistic city wall** Death of Lysimachos
Roman	154–138 BC 133 BC Middle of 1st c. BC 1st century BC 29 BC 1st c. AD 1st half of 1st c. AD 43–47 AD 62 AD 64 AD 129 AD 146/147 AD 64, 129, c. 200 AD End of 2nd c. AD 262 AD 359–366 AD c. 400 AD	Construction of dam against siltation of Kaystros (Küçük Menderes) in Roman harbour Establishment of Roman province Asia Beginning of **city expansion** Ephesus **capital of Roman province Asia** Strabo visits Ephesus City's **most prosperous phase** Construction of harbour gate Destructions by several earthquakes Dredging of harbour entrance Start of construction works for Olympieion, Hadrian's emperor temple Construction of dam at Mantheites, regulation of Kaystros (?) **Edict** of Lucius Antius for **pollution control of harbour basin** M. Aurelis Daphnus donates 20,000 denar for **cleaning of harbour basin** Donation by Titus Flavius Damianus: artificial island for unloading ships **Destruction** of the Artemision and parts of the city by an earthquake, plundering by Goths Several earthquakes with severe destructions **Reconstruction** of city, adaption of harbour street as Arcadiane
Byzantine	From 391 AD 431 AD 467/468 AD 557 AD 7th c. AD	**Reduction of city area**, destruction of pagan buildings e.g. Olympieion 4th Ecumenical council in Ephesus Several earthquakes Earthquake, fortification of Ayasoluk hill Plundering by Arabs , retreat on Ayasoluk, **slowly decline** of the city
Seljuk	13th–14th c. AD	**Seljuk reign**
Ottoman	From 1424 on	Part of the **Ottoman empire**

Tab. 1.1: Overview of the history of the Ephesia. Compilation based on Brückner (1997), additionally Karwiese (1995), Ekschmitt (1991) and Scherrer (2000).

2. The palaeogeographies of Ephesos (Turkey), its harbours, and the Artemision – a geoarchaeological reconstruction for the timespan 1500–300 BC

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The palaeogeographies of Ephesos (Turkey), its harbours, and the Artemision – a geoarchaeological reconstruction for the timespan 1500–300 BC

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with 9 figures and 2 tables

Abstract. This geoarchaeological study deals with the coastline evolution around Ephesos (Western Turkey), as well as the related settlements and harbours from 1500 until 300 BC. It focuses on the vicinity of the Artemision (sanctuary of Artemis) site, with special regard to the sacred precinct (*temenos*) of the main sanctuary of the city. The results give new insights into (i) the farthest inland extension of the Holocene marine transgression, (ii) the sedimentation rates during the Holocene, and (iii) potential harbour sites adjacent to the Artemision. Vibracores up to a depth of 17 m were analyzed using geochemical and sedimentological as well as micro- and macrofaunal methods. In the area of the (later) Artemision the maximum marine transgression dates to the beginning of the 5th millennium BC. At that time, the sea had transgressed at least 18 km inland up to Belevi. The sedimentation rate was very low (0.4 mm/yr) until the 1st millennium BC; by the end of the 1st millennium AD it had accelerated, at times by up to a factor of ten. This was due to human impact, mainly deforestation, and resulted in a delta advance of the Derbent and Selinus rivers. The first temple of Artemis was built in the 7th century BC with a much smaller size and simpler ground plan than the subsequent large marble temples, the construction of which started in the 6th and 4th centuries BC, respectively. By then, the area of the Artemision had silted up, and the coastline had shifted to the north and west of the temple. Ancient authors mention two harbours at Ephesos in pre-Hellenistic times: the Koressian harbour and the 'sacred harbour'. The latter was most probably located in a small embayment between the Artemision and Ayasoluk hill 150 m to the north of the 6th century BC temple of Artemis. It silted up during the following two centuries and had completely disappeared by around 300 BC. We therefore presume that during the 5th to 4th centuries BC the Koressian harbour, located in a marine embayment on the northern side of Panayırdağ, gradually took over the function of the main harbour of Ephesos.

Zusammenfassung. In diesem Artikel werden die Ergebnisse der geoarchäologischen Forschungen zur Entwicklung der Küstenlinie sowie zu den Siedlungsplätzen und ihren Häfen in der Umgebung von Ephesos (Westtürkei) von 1500 bis 300 v. Chr. vorgestellt. Der Fokus liegt auf dem auf dem heiligen Bezirk (*temenos*) und der Umgebung des Artemisions, des Hauptheiligtums der antiken Stadt. Die Studien geben neue Erkenntnisse über (i) die weiteste landeinwärtige Ausdehnung der holozänen Meerestransgression, (ii) die holozänen Sedimentationsraten und (iii) mögliche Hafenplätze in der Nähe des Artemisions. Bohrkerne bis zu einer Tiefe von 17 m wurden sowohl mit geochemischen und sedimentologischen als auch mit mikro- und makrofaunistischen Methoden untersucht. Im Gebiet des (späteren) Artemisions datiert die maximale marine Transgression auf den Beginn des 5. Jt. v. Chr. Damals reichte das Meer mindestens 18 km landeinwärts bis Belevi. Mit 0,4 mm/Jahr war die Sedimentationsrate bis zum 1. Jt. v. Chr. sehr gering; sie beschleunigte sich bis zum Ende des 1. Jt. n. Chr. teilweise auf das Zehnfache. Als Hauptgrund wird der menschliche Einfluss vermutet (vor allem Abholzung und Ackerbau), der zu einem Vorbau des Deltas von Derbent und Selinus führte. Der erste Tempel der Artemis aus dem 7. Jh. v. Chr. war sehr viel kleiner als die Marmorbauten des 6. und 4. Jh. v. Chr. Im 7. Jh. v. Chr. war der zentrale Bereich des heiligen Bezirks (*temenos*) des Artemisions bereits verlandet und die Küstenlinie hatte sich in

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das Gebiet nördlich und westlich des Artemistempels verschoben. Antike Autoren erwähnen zwei Häfen in vorhellenistischer Zeit (bis zum Ende des 4. Jh. v. Chr.): den „Heiligen Hafen" und den Koressischen Hafen. Der erstgenannte kann vermutlich in einer kleinen Bucht zwischen Artemision und Ayasoluk-Hügel 150 m nördlich des Artemistempels aus dem 6. Jh. v. Chr. lokalisiert werden, der andere an der Nordseite des Panayırdağ. In der klassischen Epoche bis 300 v. Chr. verlandete die Bucht des „Heiligen Hafens" zusehends. Als Folge wird der Koressische Hafen ab dem 5./4. Jh. v. Chr. die Funktion als Haupthafen von Ephesos übernommen haben.

Keywords: Artemision, Ephesos, Turkey, Geoarchaeology, Coastline evolution, Sedimentation rates

1 *Introduction*

The Artemision was the main sanctuary of ancient Ephesos in Western Anatolia. In the second half of the 4th century BC a huge marble temple was erected for the city goddess Artemis, succeeding a predecessor of similar size and ground plan dating from the 6th to early 5th century BC. With a length of more than 100 m the two successive *dipteroi* (i.e. temple with a double row of outer columns) were some of the largest temples ever built in antiquity. The second *dipteros* was one of the Seven Wonders of the Ancient World (Ohnesorg 2012). The earliest temple of Artemis was erected in the second quarter of the 7th century BC (Kerschner & Prochaska 2011), but a cult can be traced back at the site to the Protogeometric period of the late 11th to 10th centuries BC (Kerschner 2003a).

The sanctuary was situated on an earlier shoreline of the delta floodplains formed by the Selinus and Derbent (presumed ancient name: Marnas) rivers (Bürchner 1905, Benndorf 1906, Keil 1922/24). Kraft et al. (2001, 2007) and Brückner et al. (2008) proved the presence of an earlier shoreline below the Archaic and Late Classical temples, thus demonstrating that in the Bronze Age the former shoreline was located under the middle part of the later temple of Artemis. By the Archaic period (7th/6th centuries BC), however, the shoreline had already shifted a hundred or so metres to the west and north of the temple (Brückner et al. 2008).

We herein present the results of our geoarchaeological and sedimentological investigations in the vicinity of the Artemision. Our goals were: (i) to define the ancient coastlines and geometries of the marine, fluvial and lacustrine areas as they reflect on the potential coastal harbour sites of Ephesos during the Late Bronze Age (LBA) and Early Iron Age (EIA), until the re-foundation of the city by King Lysimachus around 290 BC; (ii) to determine sedimentation rates for the vicinity of the Artemision; and (iii) to present possible sites for the 'sacred harbour' mentioned by the ancient historian Creophylus around 400 BC.

Brückner et al. (2008) and Kraft et al. (2001, 2007, 2011) already presented possible harbour sites for the sacred harbour. In the investigated area, however, no detailed research had been undertaken until now. Drill cores with ^{14}C age estimates northeast, south and southwest of the Artemision proved the position of the coastline, possible embayment areas and the siltation period. In addition, information from written sources was added. Thus, this paper supplements the results already presented by the authors mentioned above.

2 *Physical setting*

The regional geological framework of Western Turkey includes a succession of west-east orientated graben structures (Fig. 1). The study area is situated in the Pleistocene Küçük Menderes graben (Taymaz et al. 2007).

After the last glacial maximum (LGM) sea level rose from its regression maximum by about 120 m worldwide. When the rapid rise had slowed down around seven millennia ago, a marine embayment had formed in the Küçük Menderes graben, reaching inland for at least 18 km (Brückner 2005). Since this time, it has been infilled with alluvium from the Küçük Menderes (ancient Kaystros or Cayster) and its tributaries (Brückner 1997, 2005, Kayan 1999, Kraft et al. 1999, 2000, 2001, 2005, 2007, 2011, Brückner et al. 2008, Stock et al. 2013). The prograding deltas have caused a continued seaward retreat of the Aegean coastline.

Our study area includes a zone of about 2.5 km^2, centred around the Artemision sanctuary (Fig. 1a). It is located at the interface between the Küçük Menderes graben in the northeast, the Şirince river valley in the east and the valley of three small rivers in the southeast (Fig. 1b), which are – from north to south – the ancient Selinus (Pliny 5, 31), a second river that might have also been called Selinus (according to Benndorf 1906 and Keil 1922/24 on the basis of Pliny 5, 31) and the Derbent (presumably the ancient Marnas according to Benndorf (1906)). Adjacent mountains are Panayırdağ (elevation: 155 m) to the west and Ayasoluk hill (87 m) di-

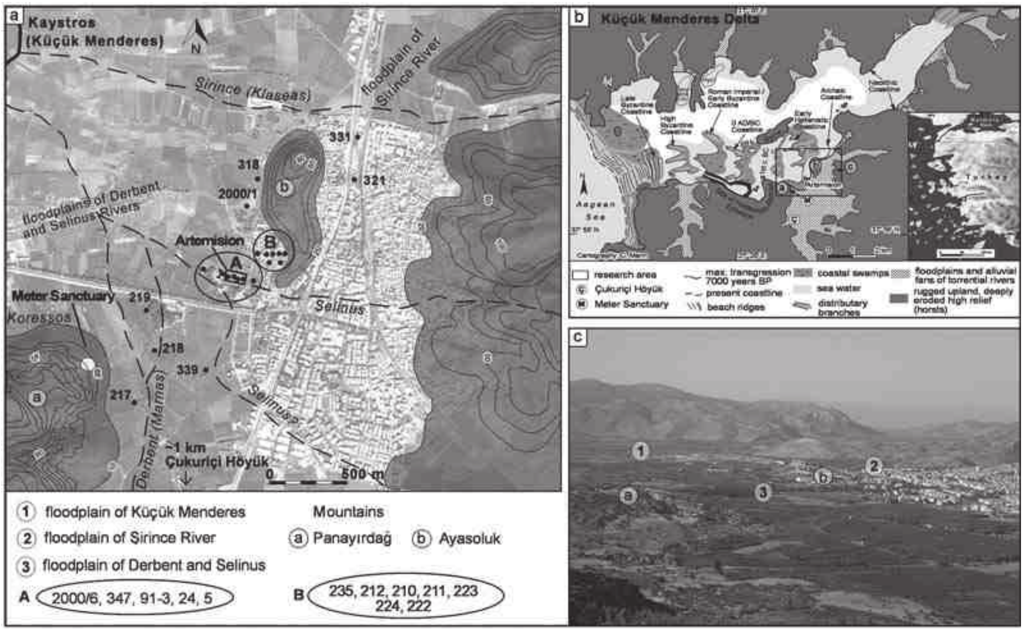

Fig. 1. Setting of the area of research. (a) It is located around the Artemision, bordered by Panayırdağ to the west (Quickbird 2 satellite image, modified). (b) Scenario of the coastline evolution since Neolithic times; the present coastline is about 6 km to the west of the working area (Brückner 2005, modified). (c) View of the floodplains of the rivers Derbent, Selinus, Şirince and Küçük Menderes (ancient Kaystros).

rectly to the northeast (Schindler 1897; see also Fig. 1). The bedrock within the study area is dominated by Palaeozoic formations, mostly micaschists and crystalline series; to the west, dolomitic marble outcrops at several places (Vetters 1989, Rantitsch & Prochaska 2011).

3 *The settlement and harbour history of Ephesos according to written sources*

The settlement pattern of Ephesos and its development through the centuries has been strongly affected by the seaward migration of the coastline. As trade was a key factor in the economy of the city, an operative harbour was a necessity. The marine regression forced the Ephesians to transfer their main harbour four times (Kraft et al. 2000, Groh 2006, Scherrer 2007, Kerschner et al. 2008, Steskal in press).

During c. 1500–700 BC the inner gulf of Ephesos reached and washed the western slope of Ayasoluk hill (Kraft et al. 2000). The subsequent delta progradation had already been reported by the Roman military commander and naturalist Pliny the Elder (23/4–79 AD) in the chapter on the geography of Ionia of his "*Naturalis historia*" (5, 115):

"Ab his multitudo limi est, qua terras propagat mediisque iam campis Syrien insulam adiecit" ("From these [rivers] comes a quantity of mud which advances the coastline and has now joined the island of Syrie on to the mainland by the flats interposed") (translation Rackham 1947).

Thus, in the Early Roman Imperial period, the Ephesians had to struggle against major shipping problems; they tried to clean and dredge their harbour (Kraft et al. 2000, Scherrer 2007, Steskal in press). The former island of Syrie (modern Kurutepe or Korudağ) had by then already been reached by the prograding delta of the Kaystros River and became part of the mainland (cf. Kraft et al. 2000, Scherrer 2007).

Obviously, the Roman author obtained his knowledge from an earlier source, possibly the local historian Creophylus of Ephesos. Creophylus' "*Annals of the Ephesians*" is the earliest book on the history of Ephesos of which we know. We have no information about his biography, but it can be inferred from the preserved fragments that he lived "at the earliest in the last third of the 5th, but perhaps not before the first [third] of the 4th century" (Jacoby 1955).

Only two short fragments of Creophylus' book were transmitted by later authors (Jacoby 1955). One of them relates to the foundation myth of Ephesos (transmitted by Athenaeus of Naucratis, *Deipnosophistai* ["The learned banqueters", written around 190/195 AD], 8, 361 c–e (62) = Jacoby 1950). In his narrative, Creophylus mentions an offshore island, where the newly arrived Greek settlers had lived before they finally founded Ephesos. The preserved passage does not contain the name of the island, but it is generally accepted that he refers to Syrie:

"*Creophylus (says) in his 'Annals of the Ephesians': The people who were trying to found Ephesus had a great deal of trouble, because they were unable to locate a site. Finally they sent to the god's oracle and asked where they should put their city, and he prophesied to them that they should found a city in a place a fish would show them and to which a wild boar would lead the way. The story goes, then, that some fishermen were having lunch in the spot where the so-called Hypelaeus spring and the sacred [harbour] are located today, and that one of their fish jumped out of the fire with an ember struck to it, and fell into some dry bush. This set fire to a thicket in which a wild boar happened to be; it was thrown into a panic by the fire and ran for a long distance along the mountain, which is known as Trecheia. After it was hit by a javelin, it collapsed in the spot where* *the temple of Athena is now located. The Ephesians crossed over from the island where they had been living for 20 years, and settled Trecheia and the area around Coressus for a second time; they also established a temple of Artemis in the marketplace and a temple of Pythian Apollo by the harbour*" (translation Olson 2008, modified by M. Kerschner).

This narrative is the longest and earliest preserved version of the foundation myth of Ephesus (cf. M. Steskal in Kerschner et al. 2008, with a comprehensive bibliography). The whole story of the discovery of the right place to settle with the fanciful involvement of a fish and a boar reveals characteristic traits of a legend (for a detailed discussion see: Kerschner et al. in review). Although the historicity of Creophylus' account is largely doubtful, it is still valuable with regard to the topography of pre-Hellenistic Ephesus. Since we may presume that the author wanted to be taken seriously by his contemporaries, his descriptions of places and monuments in his native city must have been plausible for an Ephesian of the $5^{th}/4^{th}$ centuries BC. Even if the story is not trustworthy, its setting is.

Creophylus is the only ancient author that mentions a "ὁ ἱερὸς λιμήν" at Ephesos, which has been translated by nearly all philologists with 'sacred harbour' (on another proposal by Olson 2008, see Kerschner et al. in review). The reason for using a specifying adjective is that at this time another harbour was also in use, the Koressian harbour (see below). In the preserved passages, Creophylus does not give a systematic description of his native city as a whole, but he mentions a few sites and indicates the approximate distance between them. Starting point of the narrative is "*the spot where the so-called Hypelaeus spring and the sacred [harbour] are located today*". Neither of them has been identified to date, although many proposals have been made (for a detailed discussion of the localisation see Kerschner et al. in review).

An important indication is given by Strabo (ca. 62 BC–after 23/24 AD) in his "Geographica" (14, 1, 4 [634]): "*The city was in ancient times round the Athenaeum, which is now outside the city near the Hypelaeus, as it is called*" (translation Jones 1960).

If the spring Hypelaeus was located outside the Roman city of Strabo's days, the 'sacred harbour', which was situated close-by, was also "*outside the city*", i.e. east of the northeastern corner of the city wall and northeast of the later buildings of the stadium and the Vedius gymnasium (Fig. 8). Since Creophylus says explicitly that the 'sacred harbour' existed in his days, we have to look along the coastline of the early 4^{th} century BC. Going east, the first bay suitable for a harbour is a wide embayment at the northern side of Panayırdağ (Kraft et al. 2000, Scherrer & Trinkl 2006). It had already convincingly been identified by Keil (1922/24) with the 'Koressian harbour', attested by several ancient sources (see below). Since this bay had been called 'Koressian harbour' at least from the mid-5^{th} century BC onwards and still bore this name in Creophylus' lifetime, it surely was not the sacred harbour. The latter must have been somewhere else, farther to the northeast. Creophylus saw a transition between two stages around 400 BC. It can be inferred from his narrative that the 'sacred harbour' was still in use, since he explicitly states: "*where the so-called Hypelaeus spring and the sacred [harbour] are located today*". But it was no longer the main harbour as is shown by the account of Herodotus on the Ionian Revolt. Since around 500 BC at the latest, the 'Koressian harbour' had taken over this function.

Herodotus (c. 484–425 BC) tells us in his "*Histories*" (5, 100) that the allied Ionian fleet assembled in the harbour of Koressos 498 BC:

"*The Ionians, having with this armament come to Ephesus, left their ships at Coressus in the Ephesian territory, and themselves marched inland with a great host, taking Ephesians to guide them on their way. Journeying beside the river Caystrus, and crossing thence over Tmolus, they came to Sardis and took it, none withstanding them*" (translation Godley 1998).

Since it is evident from the ancient literary and epigraphic sources that (at least) the northern part of Panayırdağ was called Koressos (M. Steskal in Kerschner et al. 2008 summarises the long and controverse discussion on Koressos in the light of recent research), the broad bay at the northern side of the mountain is the only suitable location for a large harbour that was able to accommodate a big fleet as in 498 BC (Fig. 8). It is this bay, where the Koressian harbour was probably located (Keil 1922/24, Scherrer & Trinkl 2006, Mohr 2007, Scherrer 2007, Kerschner et al. in review).

The 'Koressian harbour' was abandoned to the advantage of the Hellenistic harbour at the beginning of the 3rd century BC, transferred about half a kilometre to the west, where in the 2nd century AD the hexagonal basin of the Roman Imperial harbour was built. Connected by a canal with the open sea, it was in use until the Early Byzantine period, although outer harbours had been concomitantly used at least from the time of Augustus onwards (Strabo 14, 1, 20, cf. Kraft et al. 2000, Scherrer 2007, Steskal in press). In the Early Medieval period, presumably in the 7th century AD, the Roman harbour basin was finally abandoned and the outer harbours took over its function (Ladstätter 2011). In the same way as the harbour followed the regressing coastline, the city followed its harbour, on which it depended economically.

4 *Methodology*

Several drill cores up to a maximum depth of 17 m were recovered from the floodplains and the excavation area with a vibracorer (Cobra mk1, Atlas Copco Co.). They were measured with a DGPS (Topcon HiPer Pro) and referred to the present mean sea level (maximum vertical deviation 2 cm). In the field, the sediments were described in terms of colour (Munsell Soil Color Charts), grain size, and carbonate content (AG Boden 2005) as well as macrofauna, plant remains, and ceramic fragments.

In the laboratory, the samples were analysed with geochemical, sedimentological and palaeontological methods. Macrofauna as well as microfauna are good indicators for detecting the former environments of deposition (Frenzel & Boomer 2005, Bernasconi et al. 2006, 2010, Marriner & Morhange 2007, Stock et al. 2013). For the microfaunal analysis, 2 cm^3 samples were sieved with a 100 µm mesh size, and species were mainly identified according to Meisch (2000) for ostracods and Meriç (2004) for foraminifers. In total, 16 samples from marine, littoral and alluvial layers were selected. The alluvial layer was void of microfossils, also the high energy coastal environments and layers with fluvial influence. In general, microfossils are rare in the sediments. The palaeontological results were supplemented by measuring the following geochemical parameters: electrical conductivity (electrical conductivity meter), carbonate content (Scheibler apparatus), loss on ignition (LOI, measured 10 hours at 105 °C and after 4 hours in the muffle furnace at 550 °C), phosphate content (1 g sediment was digested with 25 ml HCl (37 %); mixed with potassium antimony (III)-oxide tartrate and the reaction solution of sulphuric acid, ammonium molybdate and ascorbic acid; measured in a spectrophotometer) as well as element concentrations (Ca, Mg, K, Fe) by AAS (Perkin Elmer A-Analyst 3000) (1 g sediment (< 2 mm) was digested with 25 ml HCl (37 %)). Thus, the identification of ancient environments and their resulting geomorphologies – i.e., shallow marine, coastal, lagoonal, fluvial, alluvial, and limnic – is based on the evidence from fauna as well as geochemistry. Electrical conductivity measures easy soluble salts which often characterize marine layers. To the top, the measured values rise due to evaporation (Vött et al. 2002, Müllenhoff 2005). Carbonate content results from bedrock or shell fragments (Vött et al. 2002). LOI usually correlates with the organic content; high values are often found in a low energy aquatic milieu with a lack of oxygen (e.g. swamps, lakes) (Barsch et al. 2000). High values of phosphate occur in terrestrial material (Vött et al. 2002), and in bones, excrements and dung which are indicators of anthropogenic influence (Herz & Garrison 1998, Rapp & Hill 2006). High element concentrations of Fe indicate a terrestrial milieu, whereas high Ca occurs in marine and limnic sediments, mostly due to shell fragments or the bedrock. Mg accumulates by dissolution of salt in marine sediments. In terrestrial layers, Mg may be higher as a result of the weathering of dolomite. K may be high in limnic layers when derived from terrestrial erosion or bedrock (Vött et al. 2002).

Findings of diagnostic ceramics and AMS-^{14}C dating of plant remains, charcoal, and marine bivalves were used to establish a chronostratigraphical framework. For further details concerning the geoarchaeological research design see Brückner (2005).

5 *The subsurface strata in the vicinity of the Artemision*

Drill cores Eph 210 and 218 represent the typical stratigraphy in the vicinity of the Artemision. In the following section, their sediments are described in detail. They were carried out in order to reconstruct the maximum inland transgression in this area and to detect a possible harbour site of the Artemision.

5.1 *Drill core Eph 210 – northeast of the Artemision*

Eph 210 (Figs. 2a–c), drilled 100 m west of Ayasoluk hill and 140 m northeast of the temple of Artemis (see Figs. 1, 2b), can be differentiated into six sedimentary units (Figs. 2a, c). Drilling reaches slope debris (unit 1, pieces of mica schist up to 5 cm) at 4.66–4.51 m below present sea level (b.s.l.), obviously originating from the adjacent Ayasoluk hill.

A yellowish red silty clay with angular and subangular clasts follows (4.51–3.21 m b.s.l.; unit 2). Geochemical analyses show very low contents of Ca, phosphate and organic matter. The high Fe/Ca ratio indicates terrestrial influence (Vött et al. 2002), the low Ca value may be typical of a slightly recalcified sediment. In several other drill cores in the environs of the Artemision, a red palaeosol has been formerly described which developed on this sediment (Kraft et al. 2001, Brückner et al. 2008).

Unit 3 is a transition unit, coarsening upwards from silty clay to clayey silt and silty fine sand (3.21–2.84 m b.s.l.). The greyish brown sand contains subangular limestone pebbles and the bivalve *Cerastoderma glaucum*. The microfauna is characterized by the lagoonal and estuarine foraminifer *Haynesina germanica* (Table 1). Probably, a terrestrial layer with remnants of a palaeosol developed on top of the bedrock. The higher Ca, phosphate, and LOI values as well as

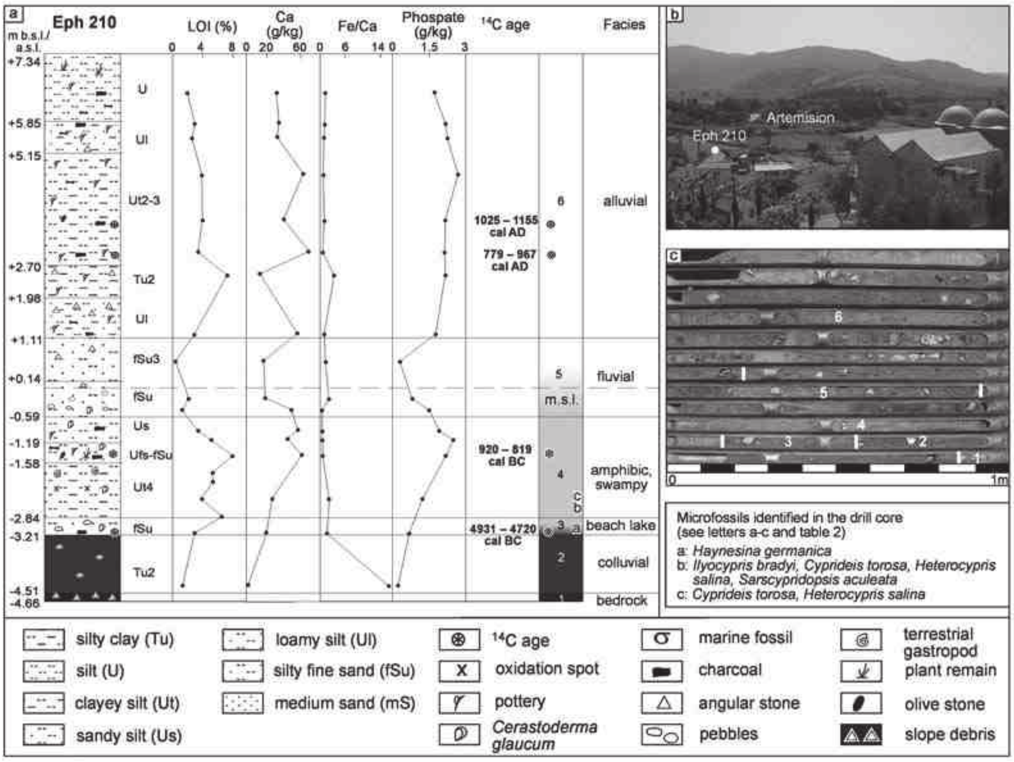

Fig. 2. Position and sediments of drill core Eph 210 (b.s.l. = below sea level; a.s.l. = above sea level). (a) Sediments, geochemical results, and microfossil analysis of sediment core Eph 210, 150 m northeast of the Artemision excavation. (b) Position of core Eph 210, drilled southwest of Ayasoluk. (c) Sediment core of Eph 210. Description of facies in the figure.

the low Fe/Ca ratio are indicators of a facies change. It is possible that a coastal lake developed behind a sand barrier 4931–4729 cal BC (^{14}C dated charcoal, Table 2).

Unit 4 consists of homogeneous grey clayey silt layers at 2.84–0.59 m b.s.l. The macrofauna is dominated by *C. glaucum* and the freshwater gastropod *Gyraulus* sp., the microfauna by the ostracods *Cyprideis torosa*, *Heterocypris salina* and *Sarscypridopsis aculeata*, typical of coastal ponds, and the halotolerant freshwater ostracod *Ilyocypris bradyi* (Table 1). The association indicates a brackish coastal lake environment. The geochemistry reflects the changing milieu with elevated Ca, phosphate, and organic contents, and a continuously declining Fe/Ca ratio. Bones, ceramic fragments (LBA to Archaic period), charcoal and an olive stone (920–819 cal BC) prove the presence of people. In this layer, the LOI value rises up to 8 %. The elevated phosphate content also hints at anthropogenic influence as it may originate from bones, excrements, and dung (Herz & Garrison 1998, Rapp & Hill 2006). The unit can be interpreted as a very low energy coastal lake which developed behind a sand bar, and which was connected to the sea occasionally, e.g. after severe storms. Temporarily, the coastal lake turned to freshwater, as evidenced by the occurrence of the gastropod *Gyraulus* sp. It is possible that an ephemeral swamp developed.

Table 1. Ostracods and foraminifers from several cores and their environments (b.s.l. = below sea level; a.s.l. = above sea level). Literature for palaeoenvironmental reconstructions: Frenzel & Boomer (2005), Bernasconi et al. (2006), Marriner & Morhange (2007), Stock et al. (2013).

Ostracoda	**Environment**	**Sample**	**Depth m b.s.l./a.s.l.**
Cyprideis torosa (Jones 1850)	lagoonal	Eph 210/21, 210/22	–2.41 m and –2.61 m
Heterocypris salina (Brady 1868)	coastal ponds	Eph 210/21, 210/22 223/13	210: –2.41 m, –2.61 m, 223: –2.72 m
Eucypris pigra (Fischer 1851)	freshwater	Eph 224/15II	–3.80 m
Ilyocypris bradyi Sars, 1890	freshwater, low salinity	Eph 210/22, 224/15II	210: –2.61 m, 224: –3.80 m
Sarscypridopsis aculeata (Costa 1847)	coastal ponds	Eph 210/22, 224/15II	210: –2.61 m, 224: –3.80 m
Foraminifera			
Haynesina germanica (Ehrenberg 1840)	lagoonal/estuarine	Eph 210/23	–3.16 m
Lobatula lobatula (Walker & Jacob 1798) s.l.	marine, coastal	Eph 223/4 I	+3.78 m
Challengerella bradyi Billman, Hottinger & Oesterle, 1980	marine	Eph 218/22, 218/23	–7.30 m, –7.40 m
Quinqueloculina disparilis d'Orbigny, 1926	marine	Eph 218/23	–7.40 m
Elphidium crispum (Linnaeus 1758)	marine	Eph 218/23	–7.40 m
Ammonia beccarii (Linnaeus 1758)	lagoonal	Eph 218/23	–7.40 m
Aubignyna perludica (Heron-Allen & Earland 1913)	lagoonal	Eph 218/23	–7.40 m

Table 2. Radiocarbon ages. The samples were dated at the Center for Applied Isotope Studies, University of Georgia, Athens (USA). b.s.l. below sea level, a.s.l. above sea level. All AMS-^{14}C ages were calibrated with Calib 6.0 (Reimer et al. 2009), and are given with a standard deviation of 2 sigma (probability of 95.5 %). The marine mollusk shell was corrected for a reservoir effect of 390 ± 85 years (valid for the Eastern Mediterranean region; cf. Siani et al. 2000). As for the other ^{14}C ages presented in the figures see Kraft et al. (2001, 2007) and Brückner et al. (2008). *presumably *Posidonia* sp.

Sample Code	Lab code (UGAMS)	Material	Depth (m) a.s.l./ b.s.l.	$\delta^{13}C$ (‰)	^{14}C age	Age cal BC/ cal AD (2 σ)
Eph 210/07	6026	Olive stone	+3.79 m	−19.9	950 ± 25	1025–1155 cal AD
Eph 210/08	6025	Charcoal	+2.94 m	−21.8	1160 ± 25	779–967 cal AD
Eph 210/18	6024	Olive stone	−1.46 m	−25.2	2730 ± 25	920–819 cal BC
Eph 210/23	6023	Charcoal	−3.16 m	−24.6	5950 ± 30	4931–4729 cal BC
Eph 212/08	6021	Charcoal	+1.45 m	−25.3	2470 ± 25	761–416 cal BC
Eph 212/18	6020	Marine shell	−2.66 m	+0.5	5980 ± 30	4515–4237 cal BC
Eph 218/09	6019	Charcoal	−0.26 m	−23.1	2460 ± 25	755–414 cal BC
Eph 218/26	6018	Seagrass*	−7.65 m	−14.9	5650 ± 25	4220–3882 cal BC
Eph 222/06	6017	Charcoal	+4.37 m	−23.7	1210 ± 25	716–889 cal AD
Eph 222/10	6016	Wood	+0.56 m	−23.1	2310 ± 25	407–259 cal BC
Eph 222/12I	6015	Charcoal	−0.5 m	−26.1	3040 ± 25	1394–1217 cal BC
Eph 339/40H	13061	Charcoal	−3.37 m	−27.3	3770 ± 25	2287–2061 cal BC

Unit 5 from 0.59 m b.s.l. to 1.11 m a.s.l. (above present sea level) testifies to a sharp contrast with high energy sedimentation with brown silty sands and subangular to rounded clasts up to 3 cm, most probably deposited by the advancing deltas of the Selinus and the Derbent (Marnas). As these rivers only have a small drainage basin in the surrounding mountains, most of the transported clasts are not rounded. The declining organic and phosphate contents can be explained by the higher depositional energy and a reduced human influence, but this trend may also be due to the coarser matrix. The change in colour to brown also underlines the facies change. The unit is void of macro- and microfossils.

Up to the present surface, the sediments are dominated by brown clayey silts and silty clays. Many ceramic and bone fragments, charcoal, food remains and a walking horizon prove the presence of people (unit 6, 1.11–7.34 m a.s.l.). Charcoal at 3.26 m a.s.l. dates to 779–967 cal AD. The higher phosphate values up to the present surface represent both human and terrestrial influence (Herz & Garrison 1998, Vött et al. 2002). Organic matter is mostly less than 4 %, Ca varies and phosphate content rises upwards. From 3.15 m a.s.l. onwards less pottery occurs. An olive stone at 3.79 m a.s.l. yielded a ^{14}C age of 1025–1155 cal AD. These alluvial sediments were deposited when the Küçük Menderes used to flood the area regularly during the winter season (Güldali 1979).

5.2 *The marine transgression in the lower Derbent valley – drill core Eph 218*

Drill core Eph 218, located in the lower Derbent valley 265 m east of Panayırdağ (see Fig. 1), reaching down to 7.75 m b.s.l., comprises five sedimentary units (Fig. 3; bedrock was not reached).

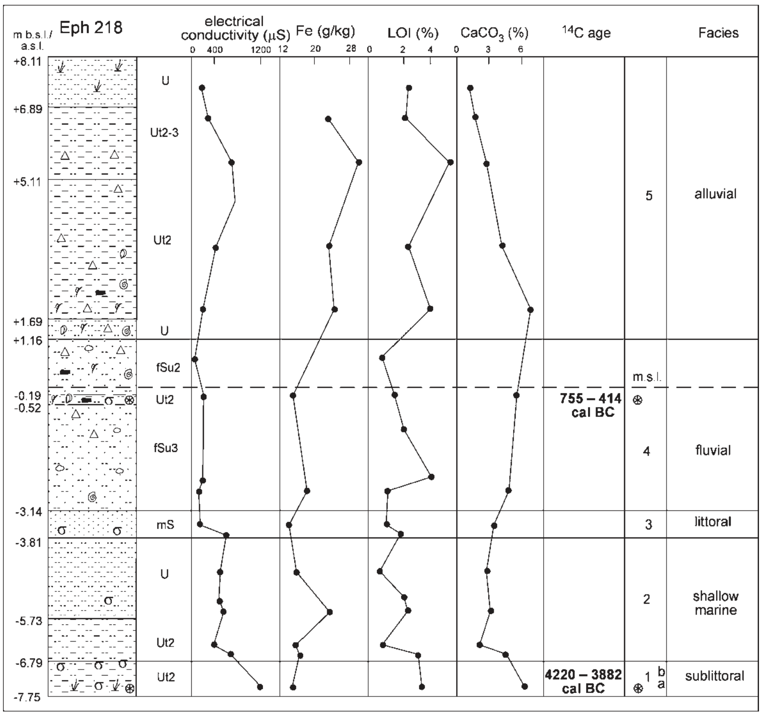

Fig. 3. Sediments and geochemical results of sediment core Eph 218, drilled in the lower Derbent floodplain. Legend in Fig. 2 (b.s.l. = below sea level; a.s.l. = above sea level). Foraminifers: a) *Challengerella bradyi,* b) *Aubignyna perludica*, *Ammonia beccarii* s.l., *Elphidium crispum*, *Quinqueloculina disparilis*.

At the base, Eph 218 contains dark grey clayey silts with marine macrofauna (*Corbula gibba*, *Nassarius incrassata*, Echinoidea) and marine to lagoonal foraminifers (marine: *Challengerella bradyi*, *Quinqueloculina disparilis*, *Elphidium*; coastal foraminifer: *Ammonia beccarii* s.l.; lagoonal foraminifer was probably redeposited: *Aubignyna perludica*) (see Table 1), plus an abundant occurrence of seagrass (*Posidonia* sp.). The stratum dates to 4220–3882 cal BC (unit 1, 7.75–6.79 m b.s.l.). High values of $CaCO_3$ (6.2 %) and electrical conductivity (700–1200 µS/cm) are typical of a marine environment close to the coast (Croudace et al. 2006). Low Fe values (14–16 g/kg) suggest little terrestrial input.

With a continuously rising water table, less seagrass and marine fauna were deposited (mainly silts; unit 2, 6.79–3.81 m b.s.l.). Compared to unit 1, the geochemistry changes with lower values of $CaCO_3$ (2.0–4.6 %) and electrical conductivity (500–713 µS/cm). Most probably, the stratum was deposited in a low energy shallow marine environment.

These sediments are overlain by sands including the marine shell *Nassarius incrassatus*. Electrical conductivity and LOI decline, suggesting a high-energy shoreface environment of the regression facies (unit 3, 3.81–3.14 m b.s.l.). $CaCO_3$ rises due to the presence of shell fragments. The regression is forced by the continued progradation of the Derbent (Marnas) and Selinus deltas.

Unit 4 follows with brown silty sands and subangular to rounded stones; it is void of macro- and mircofossils (3.14 m b.s.l. to 1.16 m a.s.l.; charcoal dates to 755–414 cal BC, 0.26 m b.s.l.). The low electrical conductivity (92–220 µS/cm), organic content and change in colour to brown are indicators for terrestrial influence (alluvium of the Küçük Menderes tributaries).

Unit 5, 1.16–8.11 m a.s.l., is composed of fine-grained sediments, mostly brown clayey silts and silty clays. These are floodplain deposits of the Küçük Menderes.

6 *Geological cross sections and supplementary drill cores*

In order to get a 2D image of the subsurface strata, the corings were assembled in cross sections. They supplement the already existing stratigraphy (Kraft et al. 2001, 2007, Brückner et al. 2008). Nine drill cores were sunken into the ground southwest of the Artemision in the lower Derbent/Marnas valley *via* the Artemision excavation site up to 400 m north of the Isa Bey Mosque (cross section 1, A in Fig. 1a; Fig. 4). Cross section 2 is composed of seven drill cores, located to the northeast of the Artemision along the western foot of Ayasoluk hill (B in Fig. 1a, Fig. 5). Two drill cores are situated to the east of Ayasoluk hill.

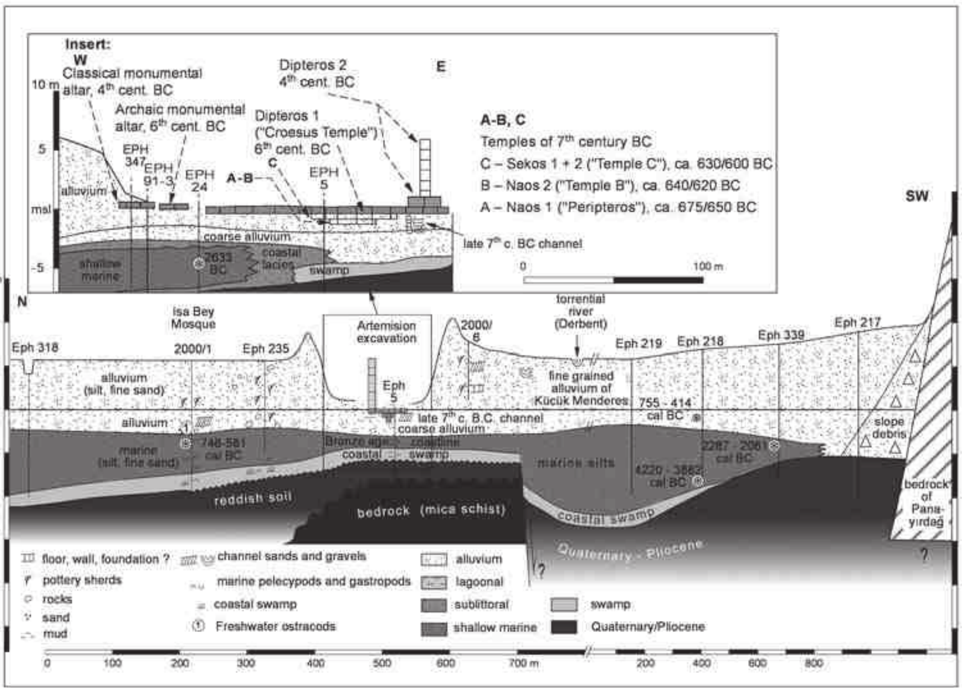

Fig. 4. Composition of drill cores ranging from the west of Ayasoluk hill south *via* the Artemision excavation into the lower Derbent floodplain. The cross section is based on Brückner et al. (2008), supplemented by further vibracorings. The insert shows the strata below the Artemis temple, and the constructions of different temples.

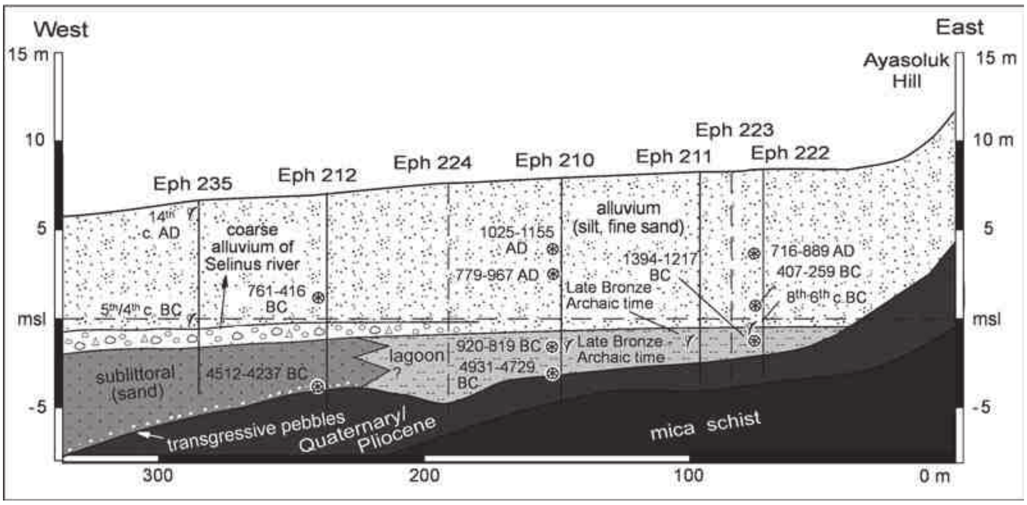

Fig. 5. Vibracorings in the area northeast of the Artemision. The sediments prove a former lake behind the coastline. Only the two westernmost drill cores show sublittoral sediments. Drill cores Eph 224 and 223, located 50 m to the south, are projected on the main transect and are therefore represented by dashed lines. For the position of the drill cores see Fig. 1. Facies and sedimentology are described in Fig. 4.

6.1 *The maximum marine transgression in the area of the Derbent/Marnas valley and the Artemision*

Despite the already existing geoarchaeological research in and around the Artemision (Kraft et al. 2001, 2007, Brückner et al. 2008), the position of the shoreline during the maximum marine transgression and its subsequent shifts were still open to debate. Therefore, nine new drill cores were carried out in the area north and west of the temple of Artemis and in the lower Derbent (Marnas) valley. This is all the more of high interest since the prehistoric site of Çukuriçi Höyük is situated in this valley 2.3 km to the south of the Artemision. Together with Arvalya Höyük this mound (*tell*) is the oldest settlement of the Ephesos region, dating back to the Late Neolithic period (Urz & Brückner accepted). What was the minimum distance between the sea and the *tell*, where, according to the finds, sea food was a common diet (Horejs et al. 2011)?

The important drillings to solve this problem are Eph 217, performed 150 m east of Panayırdağ close to the so-called Grotto of the Seven Sleepers, and Eph 339, 218 and 219, concentrated in the middle part of the lower Derbent (Marnas) valley (Figs. 1, 4).

The sediments of the 17 m deep drill core Eph 217, mostly composed of silts with angular and subangular clasts, were deposited in alluvial and colluvial environments. Since Eph 217 is only 150 m to the east of the mountain, influence by slope debris is likely. No marine macro- or microfauna was found. Thus, we conclude that the Eph 217 site has never been under marine influence. From hundreds of corings carried out around Ephesos and Miletos during the last two decades, we have learned that, if marine strata are not encountered at a depth of a few metres below the present sea level, then the site has never been inundated by the sea during the Holocene (e.g. Brückner et al. 2006, 2008, Kraft et al. 2007).

Drill cores Eph 218, 219 and 339, however, contain sediments with Echinoidea, *Nassarius incrassatus* and *Corbula gibba*, indicative of a shallow marine environment. At the southernmost site with signs of the marine transgression, the marine stratum was dated to 2287–2061 cal BC (sample Eph 339/40 H; Fig. 4).

In drill cores Eph 218 and 339, these deposits are topped by shoreface sands representing the regression facies. The association of brackish water bivalves (*C. glaucum*) and freshwater gastropods (*Gyraulus* sp.) in Eph 219, embedded in dark olive grey silty fine sands, indicates an amphibic environment with a nearby freshwater source (3.92–2.68 m b.s.l.). It can be assumed that the prograding Derbent deposited the gastropods in this area.

Eph 339, 218 and 219 show a transition layer composed of coarser sediments with pebbles and cobbles of fluvial origin. Alluvial sediments of the Derbent were deposited in Eph 218 (0.46 m b.s.l.) starting from 755–414 cal BC. Thus, the area may well have been infilled with sediments before the 8th–5th centuries BC.

The drill cores inside the Artemision sanctuary prove a former shoreline under the temples, dating from the 3rd millennium BC (drill core Eph 24, see insert in Fig. 4; Brückner et al. 2008). The maximum extent of the shoreline underlies the first limestone temple (Naos 1, *Peripteros*; insert in Fig. 4), constructed 675/650 BC (Kerschner & Prochaska 2011). The uppermost layer of the marine sediments 300 m to the north of the temple dates to 746–581 cal BC (core 2000/1; Fig. 4) (Brückner et al. 2008). By then, the area had not yet been silted up.

Drill core Eph 318 is located at the western foot of Ayasoluk (Fig. 4). At the base interbedded sands and silts suggest a narrow shoreline at the foot of the hill. While sea level was rising, grey silts with seagrass (*Posidonia* sp.) and shells, typical of a shallow marine embayment, were deposited. The marine strata in the lower part of the coring prove a formerly steep bedrock slope at the foot of Ayasoluk in the Early Holocene.

It can be concluded that the maximum marine transgression of the sea had reached into the lower part of the (later) Derbent valley between the drill cores Eph 217 and 339 (Figs. 1, 4) where the marine layers (shallow marine and shoreface sands) still have a maximum thickness of 2.5 m. Thus, it can be stated that once the sea had transgressed even a bit farther south.

6.2 *The area northeast of the Artemision*

To the northeast of the Artemis temple, seven drill cores were sunken into the ground at the foot of Ayasoluk hill in a small embayment in order to locate the maximum marine transgression. Eph 222 was drilled close to the slope of Ayasoluk, the other corings 20 to 50 m to the west, and the farthest (Eph 235) 320 m to the west (Figs. 1, area B, 5).

The base is mostly formed by Early Holocene/Late Pleistocene sediment, developed on Pleistocene strata. In drill core Eph 222 this contact is at 1.30 m b.s.l., in drill core Eph 212 at 3.60 m b.s.l., due to the pre-Holocene subsurface topography.

The sediments of cores Eph 222 to 224 are evidence of a low energy environment. Only a reduced spectrum of macrofauna was deposited (brackish water bivalve *C. glaucum* and freshwater gastropod *Gyraulus* sp.). Fragments of adult and juvenile ostracods (*C. torosa*, *Eucypris pigra*, *Sarscypridopsis aculeata*, *H. salina*) (Table 1) prove a former coastal lagoon or coastal lake; its transition to freshwater is evidenced by the high proportion of freshwater ostracods.

Another indicator for this ecological change is the disappearance of *C. torosa* in the upper part of the profile. This milieu of deposition dates to 4931–4729 cal BC (3.00 m b.s.l. in Eph 210). It persisted at least until the 9th century BC (Eph 210).

Eph 212 and 235, the two westernmost drill cores, are composed of greyish sandy silts with bivalve fragments deposited in a sublittoral environment 4515–4237 cal BC (Eph 212). The marine sediments are overlain by coarse alluvium from the Selinus river and colluvium from Ayasoluk hill. The cores are rich in artefacts, clearly indicating human impact during the Classical period at the latest. Ceramic finds in the alluvial layer date to the 5th/4th centuries BC in Eph 235 (0.98 m a.s.l.). A radiocarbon age estimate in drill core Eph 222 dates the alluvium to the 4th/3rd centuries BC. As in the area of the Artemision sanctuary, the marine embayment and the freshwater lake silted up after the 6th century BC, most probably at the end of the 4th century BC.

Winter floods of the Küçük Menderes deposited the silts and clays of the upper five meters. Hardly any traces of ceramics were found in this layer.

6.3 *Drill cores east of Ayasoluk hill*

Was there ever a marine embayment to the east of Ayasoluk hill, in the area of the modern city of Selçuk? Based on the present contour lines, Kraft et al. (2000, 2007) inferred a small bay east of the northern tip of Ayasoluk hill for the Neolithic period; however, geoscientific evidence was not available for this particular part of the original marine embayment at that time. Scherrer (2007) adopted this hypothesis for the 2nd millennium BC and proposed an even deeper inlet beneath the modern town of Selçuk. It would indeed have been an ideal harbour for the LBA settlement on Ayasoluk.

This problem could be solved with two drill cores (Fig. 1). Eph 321, located in the centre of Selçuk, reached down to 2.05 m b.s.l.; Eph 331 was drilled close to the northern end of Ayasoluk hill down to 3.39 m b.s.l. The western floodplain of Şirince River is located to the north of these drill cores. This is where – during antiquity – the Şirince River debouched into the sea. The base of both cores is a pre-Holocene reddish sediment, same as that described in chapter 5.1. It is covered by brownish silts, greyish coarse sands and pebbles of the Şirince River, and colluvium of the bordering mountains. There is no indication of any marine influence.

It is noteworthy that only a few ceramic fragments were encountered in these cores, which is in great contrast to the western side of Ayasoluk hill as well as the finds in the lower Selinus/Derbent valley where the cores are rich in artefacts. This suggests that there was no significant settlement activity in the area east of Ayasoluk.

7 *Palaeogeographies of the Artemision*

7.1 *Discussion of sedimentation rates*

Since many samples of organic material (charcoal, seagrass, olive stone, marine mollusk shell), taken from sedimentary contexts, were dated with AMS-^{14}C (Table 2), sedimentation rates can be calculated. In order to obtain good results, at least three age estimates are needed. In our case, drill cores Eph 210 and 222 were used for this kind of study (Fig. 6).

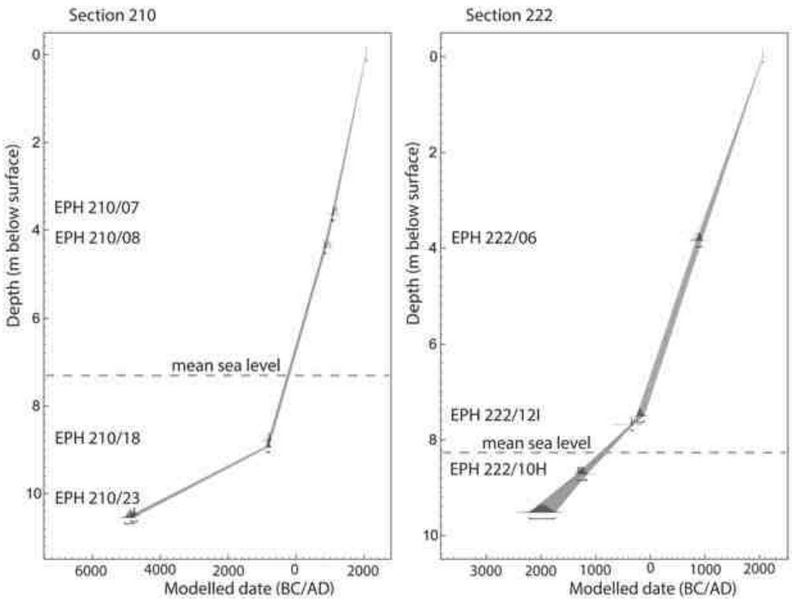

Fig. 6. An age-depth model for drill cores Eph 210 and 222. It was calculated using the OxCal 4.1 calibration software (Bronk Ramsey 2001, 2008).

The ^{14}C ages of both cores were calibrated with IntCal09 (Reimer et al. 2009). An age-depth model was calculated using the OxCal 4.1 calibration software (Fig. 6) (Bronk Ramsey 2001, 2008). This program combines the probability distributions of the calibrated radiocarbon ages with certain assumptions on sedimentary processes to obtain an age-depth curve with 2 σ (95.5 %) probability margins of the ^{14}C age estimates. We applied the *P_Sequence* model of OxCal to our data which assumes the deposition to be random, although with an approximate proportionality to depth (Bronk Ramsey 2008). We adopted a *k*-value of 150, which gives an estimate of the variation from a constant sedimentation rate equivalent to 7 mm calculation increments.

The analyses reveal sedimentation rates from 4800 BC until the present time for Eph 210 (Fig. 6a), and from 1300 BC until the present time for Eph 222 (Fig. 6b). Low sedimentation rates occur from the 5^{th} millennium BC to the Geometric period (up to 1 mm/year), in contrast to elevated ones from that time on (up to 3.9 mm/year).

The results of Eph 210 reveal a lower accumulation rate in the brackish/freshwater milieu (0.4 mm/year) than in the overlying floodplain sediments (2.4–3.9 mm/year) (Fig. 6a). For Eph 222, the same holds true (1 mm/year) (Fig. 6b). High sedimentation rates occurred from Geometric (second half of 11^{th}–8^{th} centuries BC) to Byzantine times (5^{th}–7^{th} centuries AD) (Eph 210: 2.4 mm/year; Eph 222: 3.3 mm/year). In the literature, a rapid delta progradation resulting from considerable hinterland erosion is postulated by Grove (2001) for the period 500 BC–200 AD, by Eisma (1978) for Hellenistic times from 300–100 BC, and by Kayan (1999) for the mid-Holocene. The intensive increase in human activities in terms of deforestation and agriculture is believed to be the main reason for the rapid increase in the aggradation and progradation rates in the delta floodplains during Hellenistic and Roman times (Eisma 1978, Brückner 1986, Kayan 1988).

Investigations performed elsewhere in the Eastern Mediterranean also prove higher erosion rates from Hellenistic to Late Roman times, thus confirming this assumption (Wilkinson 1999, 2005, Bintliff 2002, Butzer 2005, Beach & Luzzadder-Beach 2008, Casana 2008). For the Messenian delta plain, however, Engel et al. (2009) already revealed a higher accumulation rate for the Middle Helladic period associated with a first pronounced peak of regional population density. It is, however, noteworthy that the evidence from the just described drill cores indicates that the processes of increased erosion and correlated accumulation had already started considerably earlier, i.e. in the Geometric period (second half of 11th to 8th centuries BC). This may result from the fact that only four ^{14}C dates were used for the calculation of the age-depth model. More detailed results for the time after the 7th century AD are available for Eph 210 (9th–11th centuries AD) with 3.4 mm/year. The accumulation rates until the present time of 3.9 mm/year (Eph 210, Fig. 6a) and 3.1 mm/year (Eph 222, Fig. 6b), respectively, are similar. Since a Holocene sea level curve for the Küçük Menderes graben has not yet been reconstructed, the data still lack precision. Additional information is needed in order to provide a more detailed overview and to present the sedimentation rates at a higher resolution.

7.2 *Holocene landscape reconstructions*

Reconstructions of ancient landscapes show the siltation of the lower Selinus/Derbent valley, the area north and northeast of the Artemision, and to the east of Ayasoluk hill. These scenarios are based on geomorphological and sedimentological interpretations of corings described in chapters 5 and 6. Radiocarbon dates help to identify chronologies. Based on these data, ancient coastlines were reconstructed for the time span between the 5th millennium BC and the end of Hellenistic times (Figs. 7a–c).

According to Kayan (1999), the maximum landward position of the coastline during the Holocene was reached about 5000–4000 BC. During that time, the coastline extended up to Belevi, 18 km to the east in the Küçük Menderes graben (Brückner et al. 2008). The delta advance of the Küçük Menderes started at the end of the 6th millennium BC.

Fig. 7a shows the maximum landward ingression of the sea during the 5th millennium BC, which reached the area between Panayırdağ and the former island of Syrie around 5200 BC (Brückner 1997). The coastline stretched between the Eph 217 site with terrestrial layers only, and the Eph 339 site, where marine sediments were encountered. Seagrass in Eph 218 dates to 4000 BC (the base of the marine stratum was not reached). In the area of the temple of Artemis, the maximum coastline is below the earliest temple (Kraft et al. 2007, Brückner et al. 2008). With the rising sea level, coastal sands were deposited at the sites of Eph 212 and 235, while a coastal lake developed behind the coastline (Fig. 7a). To the east of Ayasoluk hill, however, only alluvial, colluvial and fluvial sediments accumulated, mostly by the Şirince River aggrading its floodplain. The sea has never transgressed into the area east of Ayasoluk during the Holocene.

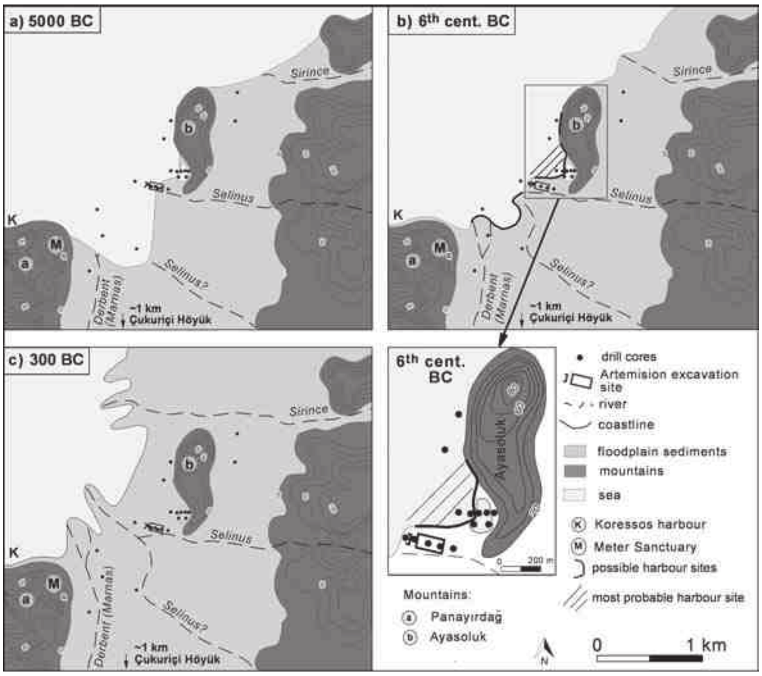

Fig. 7. Ancient landscapes in the vicinity of the Artemision for the time slices (a) 5000 BC, (b) the 6th century BC, with possible harbour sites in the vicinity of the Artemision, and (c) the Hellenistic period.

Until the end of the 3rd millennium BC, the floodplains of the Selinus and Derbent Rivers prograded northward. The deltas reached the Eph 339 site after 2100 BC. Around 1200 BC the shoreline was at the site of the later temple of Artemis (Kraft et al. 2007). Finds of pottery indicate the use of the area of the later sanctuary during this period, although its function remains unclear (see below). To the northeast of the Artemision, the coastal lake changed to a freshwater lake after the connection to the sea had ended. These palaeo-ecological conclusions are based on microfossil evidence as described above.

By the 6th century BC, the deltas of Selinus and Derbent had prograded farther north up to coring site Eph 218. Fig. 7b shows the most likely coastline for this period with the advancing deltas of Derbent and Selinus Rivers. Ceramic fragments dating to the 5th and 4th century BC were found in two trenches (excavated by J. Keil in 1929: Keil 1930, cf. I. Kowalleck in Kerschner et al. 2008) close to drill core Eph 219. These finds support the conclusion that this area was infilled with alluvium during that time and had already been silted up. In the Artemision, a huge marble temple of Artemis (*dipteros* 1 or 'Croesus temple', Fig. 4) was erected over the ruins of its predecessors during the 6th and early 5th century BC (Ohnesorg 2007). To the west of the temple, a monumental altar was built (Fig. 4), surrounded by a large paved area used for religious ceremonies (Kerschner & Prochaska 2011). The extension of this area to the west is as yet unknown. The freshwater lake behind the coastline northeast of the Artemision, wherein two diagnostic ceramic fragments date to the 8th–6th centuries BC (Eph 222, Fig. 5), still existed by then.

Ceramic sherds in Eph 235 date alluvium to the 5th/4th centuries BC. A radiocarbon age estimate 150 m to the north (drill core 2000/1, Fig. 4) indicates the persistence of marine strata until the 7th/6th centuries BC. As Creophylus tells us of the 'sacred harbour' at about 400 BC, the area must not have been completely silted up by then. Most probably, the sandbar between the freshwater lake and the coastline had enlarged. Finally, by the 3rd/early 2nd centuries BC the freshwater coastal lake was filled with alluvium and colluvium (Eph 222, 407–269 cal BC) as the coastline retreated farther to the west (Fig. 7c). By then, the shoreline was situated about 250 m to the west of the temple of Artemis (Kraft et al. 2007, Brückner et al. 2008). From the east, the advancing Küçük Menderes delta infilled the area of core Eph 318. Until the 1st century BC, the coastline retreated to the north of Panayırdağ. The drill cores in the study area only show alluvial sediments for that time.

A suitable harbour site until the 1st century BC is the embayment at Koressos to the north of Panayırdağ (as for the written sources on the Koressian harbour see chapter 3). Kraft et al. (1999) and our research of 2012 proved the presence of a large and deep embayment at the northern side of Panayırdağ, which was large enough to host a big fleet (~ 500 m west-east extension). Keil (1922/24) was the first to identify this bay with the so-called Koressian harbour that was used by the allied forces of the Ionian cities at the beginning of the Ionian Revolt in 498 BC (see chapter 8.1). The uppermost marine sediments in this bay date back to Late Hellenistic times.

The coastal retreat continued to the west, due to the rapid advance of the Küçük Menderes delta. Until the present time, 8 m of sediment have accumulated in the vicinity of the Artemision, and the coastline has shifted about 7 km to the west of the former sanctuary. Today, coastal erosion is dominant since the sediment budget has become negative due to the extraction of water for agricultural purposes, which has considerably diminished the sediment flux.

8 *The geoarchaeological approach*

8.1 *The early harbours of Ephesus according to written sources and the archaeological evidence combined with information from geosciences*

8.1.1 *The Late Bronze Age settlement and its harbour*

The settlement pattern of the area of Ephesos during the LBA can be deciphered on the basis of the distribution of contemporaneous finds and contexts (Fig. 8a) (cf. Kerschner et al. 2008). There is only one site, where archaeological evidence for settlement and burials of the second half of the 2nd millennium BC has been discovered: the hill of Ayasoluk (Gültekin & Baran 1964, Büyükkolanci 2007). This free-standing hill, 87 m in height, offered natural protection against would-be attackers through steep, partially rocky slopes to its west, north and east face. Its southern side, however, gradually slopes downwards in a long flank, thus being perfectly suited for a settlement.

After having discovered LBA pottery in his excavations on Ayasoluk hill from 1996 onwards, Büyükkolanci (2000) proposed to identify the site with Apaša, the capital of the Luwian kingdom of Arzawa in the LBA, which is mentioned in Hittite cuneiform texts. Nevertheless, it is evident that a capital and residence city like Apaša – if it actually was located there – must

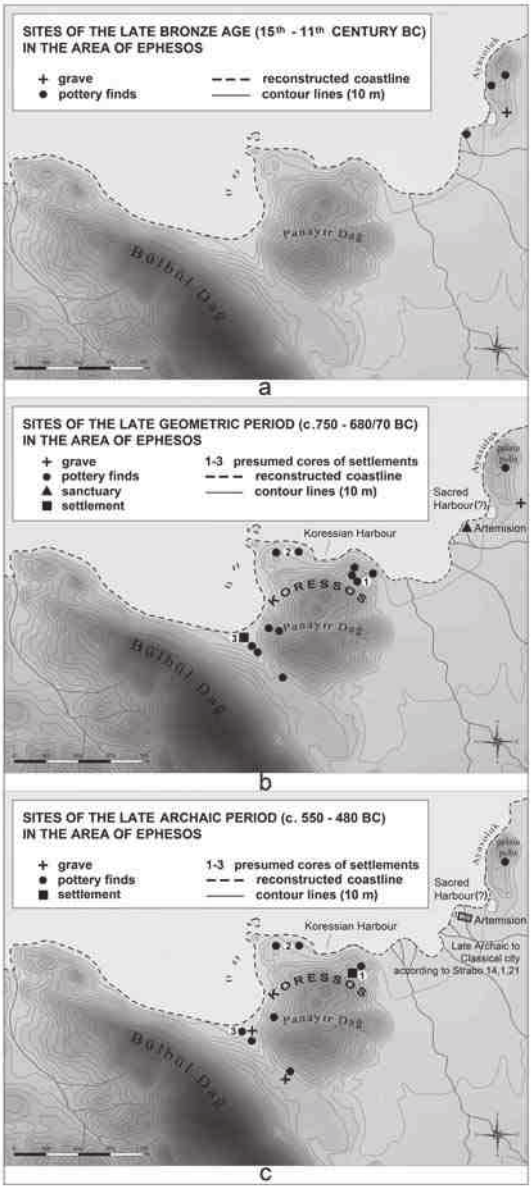

Fig. 8. Distribution of sites in the area of Ayasoluk, the Artemision and Panayırdağ. (a) Sites of the LBA (15th to 11th century BC). (b) Sites of the Late Geometric period (c. 750 – c. 680/70 BC). (c) Sites of the Late Archaic period (c. 550 – c. 480 BC).

have been larger than the area available on Ayasoluk hill. Therefore, Easton et al. (2002: 97) interpreted Ayasoluk hill as "the LBA citadel" and assumed a "lower town" extending at its foot. It is possible that the LBA pottery fragments found in the deepest excavated layers beneath the later temples of Artemis (Fig. 9) originate from such a lower town. Whatever the name and ex-

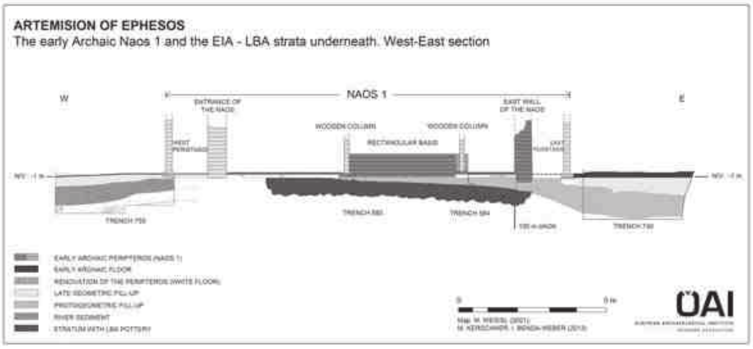

Fig. 9. Artemision of Ephesos. The Early Archaic Naos 1 and EIA–LBA strata below. West-east section.

tension of the LBA settlement on Ayasoluk hill, it was unquestionably equipped with a harbour. Along the western foot of Ayasoluk, deep water occurred, but the steep topography limits the possibility of a harbour site. Best suited for this purpose was the bay directly at the southwestern foot of the hill, which has been detected by the series of corings in 2009–2012 (Figs. 7a, b). This bay was immediately connected with the settlement, and it was protected by the hill against the northeast wind (Turkish 'poyraz'), which can be quite strong.

Therefore, it was significantly better suited for anchoring than the next bay to the south, where Scherrer (2007) assumed the harbour of the Geometric and Archaic city. Around 5000 BC, the marine embayment extended in the lower floodplains of the Derbent and Selinus rivers up to the location of core Eph 339 (Fig. 7a). In the first half of the 1st millennium BC, however, it had already considerably silted up due to the progradation of the three river mouths (Fig. 7b). This southern bay was not only farther away from the LBA settlement, but also exposed to the continuous aggradation of the torrents/rivers flowing in from the south and east; it was thus not very suitable for a permanent harbour (Figs. 7a, b). As mentioned above, Scherrer (2007) also assumed a marine bay east of the northern tip of Ayasoluk hill for the 2nd millennium BC, which indeed would have been an ideal anchoring site for the LBA settlement on Ayasoluk hill. In 2012, this hypothesis was tested by the drillings Eph 321 and 331 (chapter 6.3); the result was negative: a marine inlet at the northeastern side of Ayasoluk hill has never existed (Fig. 7).

As a result of our recent research we can therefore state that the most suitable harbour site for the city during the LBA and the EIA was the bay between the Artemision and Ayasoluk hill.

8.1.2 *The Early Iron Age settlement and its harbour*

The ancient tradition records an immigration of people from the Greek mainland in the course of the so-called Ionian migration in the 11th/10th century BC (Sakellariou 1958, Vanschoonwinkel 2006, Lemos 2007, Niemeier 2007, Crielaard 2009, Herda 2009). During the last decades, the critical analysis of the literary tradition has revealed that many of the myths of the Ionian migration are fictitious. While the historical events during the non-literate 'Dark Ages' cannot be reconstructed with any certainty from the literary tradition, some general facts can be discerned by analysing the archaeological evidence (Lemos 2007, Niemeier 2007). In the case of Ephesos, an alteration within the material culture can be noted, hitherto visible mainly in the pottery due to the lack of other evidence: in the late $11^{th}/10^{th}$ century BC, fine and coarse ware of Greek Protogeometric type superseded the western Anatolian classes that had prevailed during the LBA (Kerschner 2006). This observation, together with the change of the predominant language in the coastal region from Luwian to Greek, corroborates the tradition of an immigration of Greek settlers at the beginning of the EIA (Kerschner 2006, Lemos 2007, Niemeier 2007).

The distribution of the excavated EIA contexts dating to c. 1025/1000 – c. 750 BC in the area of Ephesos shows exactly the same pattern as that of the preceding LBA (Fig. 8a): Protogeometric to Middle Geometric deposits have been discovered only on Ayasoluk hill and at the Artemision (Kerschner 2006, Kerschner et al. 2008). At the Artemision, a rich Protogeometric deposit (Fig. 9) attests to the first use as a sanctuary in the late $11^{th}/10^{th}$ centuries BC at the latest, whereas the function of this area during the LBA is still unclear. At the beginning of the EIA, however, miniature vessels and terracotta figurines can be interpreted as votives, thus proving cultic activities.

The constancy of both the settlement pattern and the coastline along the west side of Ayasoluk during the LBA and the EIA (Figs. 7a, b, 8a, b) strongly suggests that the inhabitants of EIA Ephesos continued to use the small bay at the southwestern foot of Ayasoluk hill as their town harbour. Since it was immediately adjacent to the sanctuary of Artemis, it is likely that it can be identified with the 'sacred harbour' mentioned by Creophylus for the early period of Ionian Ephesos.

The adjective "ἱερὸς" (sacred) implies the proximity to a sanctuary. Therefore most scholars have assumed that this harbour was situated close to the main sanctuary, the Artemision (e.g. Bürchner 1905, Benndorf 1906, Keil 1922/24 who assumes the 'sacred harbour' south of the Artemision, Alzinger 1970, Brein 1976/77, Karwiese 1995, map 1, who assumes the 'sacred harbour' north of the Artemision, Knibbe 1998, Kraft et al. 2000, 2007, assume, following Keil, the 'sacred harbour' south of the Artemision, Scherrer & Trinkl 2006). Rejecting a connection between the 'sacred harbour' and the Artemision, Scherrer (2007) offered two alternative locations; both are, however, purely conjectural and do not find any corroboration in either the literary sources or in the archaeological record.

8.1.3 *The Late Geometric and Early Archaic settlements and their harbours*

A fundamental change in the settlement pattern can be observed during the Late Geometric period (c. 750 – c. 680/70 BC), when a number of new sites appeared along the seaside slopes of Panayırdağ (Fig. 8b; cf. Kerschner 2006, Kerschner et al. 2008). Our archaeological evidence from this period is still limited and scattered, so that the overall structure of the settlement(s) along the western and northern sides of Panayırdağ is not yet clear (Kerschner in press). According to the available data, it seems that three or four cores of settlements existed (Fig. 8b, nos. 1–3): (1) on the northeastern terrace of Panayırdağ (Kerschner in press), (2) on the northwestern spur of the same mountain in the area of the later buildings of the stadium and the Vedius bath-gymnasium (Keil 1926, Kerschner et al. 2008), and (3) in the bay between Panayırdağ and Bülbüldağ (excavation beneath the later Tetragonos Agora, cf. P. Scherrer in: Scherrer & Trinkl 2006, Scherrer 2007).

The settlement (1) on the northeastern terrace of Panayırdağ has to be seen in close connection with the adjacent Koressian harbour. While the site is naturally protected by steep rocky slopes in the east and north, a moderate incline connects the plateau on its northwestern side with the harbour bay. The earliest pottery finds from the northwestern spur of Panayırdağ (2) date to the mid-8th century BC and suggest that this area had been settled even earlier (Kerschner et al. 2008). Since this presumed settlement was situated immediately west of the Koressian harbour (Fig. 8b), the archaeological evidence suggests a systematic use of the bay on the north side of Panayırdağ as harbour from the second half of the 8th century BC onwards.

The settlement (3) beneath the later Tetragonos Agora was founded at the end of the Late Geometric period (Scherrer 2001, P. Scherrer in: Scherrer & Trinkl 2006, Scherrer 2007). The palaeogeographical investigations of the 1990s showed that the uncovered part of the settlement was situated adjacent to the coastline in the 7th/6th centuries BC (Fig. 8b, Kraft et al. 2000, Scherrer & Trinkl 2006, Scherrer 2007).

All three settlements, which were founded in the Late Geometric period, have one feature in common: they are situated close to marine bays that offer good anchorage. This is unlikely to be a pure accident, all the more, if we consider the fact that there is no evidence for settlements on the eastern and southern slopes of Panayırdağ which were further from the sea, but close to arable land. The search for new, good harbours seems to have been a decisive pull factor for the foundation of new settlements along the seaside slopes of Panayırdağ between c. 750 and c. 680/70 BC.

8.1.4 *The Late Archaic settlements and their harbours*

In the mid-6th century, another major change in the settlement pattern (Fig. 8c) can be inferred from Strabo (14, 21, 13–14 [640]), who states in the chapter on Ionia of his "Geographica":

"*Now Ephesus was thus inhabited until the time of Croesus, but later the people came down from the mountainside and abode round the present temple until the time of Alexander*" (translation Jones 1960).

Strabo does not explicitly name this ἱερόν (= holy place or temple), but it has been generally assumed that he means the main sanctuary, the Artemision, since this was the only one, where a more precise designation was not necessary. The new part of the city must have been situated in the alluvial plain south and southwest of the *temenos* of Artemis (Fig. 8c). This settlement was laid out in "*the time of Croesus*", whose reign can be determined within a time frame between c. 580 and c. 539 BC (Cahill & Kroll 2005, Stronach 2008, Kerschner & Prochaska 2011, with bibliography). The archaeological data for the recorded Late Archaic to Classical settlement are very scanty. Excavation in the alluvial plain is hampered by c. 5 m of sediments, by the ground water level, and by modern buildings as well as orchards (cf. Scherrer 2007).

We locate a littoral lake behind a narrow shoreline to the northeast of the Artemision, alternating into freshwater after the connection to the sea had terminated. A find of diagnostic pottery at the base of the first alluvial unit in drill core Eph 222 from the 6th century BC, and a ^{14}C date (4th/3rd century BC) prove that the lake was infilled by alluvium between the 6th and the 4th century BC; it had definitely silted up by the late 4th century BC. As the harbour must have been deep enough for ships with draughts up to 1 m, the former sea level has to be taken into account. Müllenhoff (2005) created a sea level curve for the Büyük Menderes graben where the same processes – delta progradation, siltation of the marine embayment – have occurred. This curve is critical due to possible compaction and tectonic subsidence in the graben. However, other sea level curves for the Mediterranean area also reveal a lower sea level of about 1 m or more for that time (Brückner et al. 2010). Müllenhoff's (2005) curve shows a sea level 1 m below the present one for the 6th century BC. By then, the littoral lake could not have been very deep, probably 0.50 m or a bit more depending on the sea level (olive stone in drill core Eph 210, 900–800 cal BC, 1.50 m b.s.l.). It was not connected to the sea. Thus, it is improbable that the littoral lake itself was used for regular anchoring, although this would have been possible for small ships after having been pulled over the sand bar. Most appropriate for a harbour was the bay immediately west of the lake, situated between the Artemision and the western slope of Ayasoluk. Presumably, the embayment was deeper than the mentioned lake and ships could anchor in direct vicinity to the Artemision, the settlement on Ayasoluk and southwest of it.

In 1994, an excavation beneath the eastern *sekos* wall of the Late Archaic temple of Artemis (*dipteros* 1) unearthed a river bed of the second half of the 7th century BC that was intentionally backfilled around 600 BC (Kerschner 1997, Kraft et al. 2001). It is possible that this river was the Selinus or one of its channels (Fig. 7). It was obviously deviated in order to protect the temple of Artemis from being flooded. The diversion of the river also prevented sedimentation from spreading into the basin of the presumed 'sacred harbor'. Thus, it was protected from being silted up by the Selinus and could have been used as a harbour until the end of the 4th century BC.

8.1.5 *The location of the lagoon Selinusia*

Strabo (14, 1, 26) mentions two lagoons that belonged to the Artemision. They were especially rich in fish and therefore an important source of income for the sanctuary:

"*After the outlet of the Cayster River comes a lake that runs inland from the sea, called Selinusia; and next comes another lake that is confluent with it, both affording great revenues. Of these revenues, though sacred, the kings deprived the goddess, but the Romans gave them back; and again the tax-gatherers forcibly converted the tolls to their own use; but when Artemidorus was sent on an embassy, as he says, he got the lakes back for the goddess, and he also won the decision over Heracleotis, which was in revolt, his case being decided in Rome; and in return for this the city erected in the temple a golden image of him*" (translation Jones 1960).

Scherrer (2007) proposed to localize these two connected lagoons between the Artemision and the island of Syrie. Theoretically this might be possible, since many lagoons must have been formed by the advancing Küçük Menderes' bird's-foot/Azmak delta until the lagoons turned to freshwater and finally silted up. There is, however, a contradiction in the chronology of the written account and the geoarchaeological data that excludes Scherrer's hypothesis. The account of Strabo refers to events that can be dated to the 2nd/1st century BC. The "kings [who] deprived the goddess" were presumably the Attalids of Pergamon, who ruled in Ephesos from 188 to 133 BC, possibly the preceding Ptolemaic or Seleucids kings (Radt 2009: 36). The geographer Artemidoros of Ephesos, who defended the claims of his mother city successfully, lived in the 1st century BC (Brodersen 1997). Therefore, the double lagoon Selinusia existed at least in the the 2nd/1st century BC according to Strabo. Our research, however, has shown the siltation of the area to the north and west of the Artemision already by the end of the 4th century BC (Fig. 7). During the 2nd/1st century BC, the period in question, the coastline was situated between Panayırdağ and Syrie (Brückner 1997). As the area had silted up completely and drill cores only show alluvial sediments of a floodplain to the north of the Artemision, we must assume that there was no lagoon between the Artemision and Syrie. As a consequence, the double lagoon Selinusia must be located farther to the west.

8.1.6 *The Koressian harbour replaces the 'sacred harbour'*

In 498 BC, when the large fleet of the allied Ionian poleis gathered at Ephesos on the eve of the so-called Ionian Revolt against the Persian rule of the Western coast of Asia Minor (cf. Tozzi 1978, Knibbe 1998), they already used the harbour of Koressos, as is related by Herodotus (c. 484–425 BC). The account of Herodotus shows that around 500 BC at the latest, the Koressian harbour, which was situated at the northern side of Panayırdağ (see above), became the second major harbour of Ephesus (Fig. 8). Although it can be inferred that the old 'sacred harbour' north of the Artemision was still in use a century later, at least for small boats and local transport, it was not apt to accommodate a large fleet. The Koressian harbour, however, was well suited for such a purpose. Our drill cores show that it had a width of about 500 m, whereas the 'sacred harbour' was smaller with a maximum width of about 250 m.

From the late 6th century BC onwards, the Koressian harbour must have gradually taken over the function of the main harbour of Ephesos, while the old 'sacred harbour' north of the Artemision was silted up completely at the end of the 4th century BC (Fig. 7c). This corresponds with the observation that the adjacent settlement on the northeastern terrace of Panayırdağ flourished during the second half of the 4th and the beginning of the 3rd century BC. This settlement was situated closer to the Koressian harbour than the other parts of the city; therefore, it seems likely that the economic situation of its inhabitants was also connected with it (Fig. 8c).

8.2 *The spatial relationship between the city of Ephesos, the Artemision and the harbours*

Artemis/Diana was the main goddess of Ephesos during the Greek and Roman periods, and her sanctuary was the most important one in the city. From the 7th century BC onwards, the Artemision increasingly gained supra-regional importance. An appropriate harbour nearby, such as the 'sacred harbour', facilitated the approach of cultists arriving from abroad. It was also advantageous for the transport of building material for the Archaic temples.

According to the religious belief of the ancient Greeks, an old-established, traditional sanctuary could not be moved, since it was bound to a specific cultic mark that was considered as a divine sign and thus sacred. As pointed out above, the city of Ephesos was moved several times during its history (Figs. 8a–c) – following its harbours, which, in turn, had to follow the prograding coastline. This particular development of the settlement entailed a complex and changing spatial relationship between the city and its main sanctuary. Originally, in the EIA, the *temenos* was situated in close vicinity to the town on Ayasoluk hill, the only settlement in the early

1st millennium BC. When new settlements were founded on the seaside slopes of Panayırdağ in the Late Geometric period (Fig. 8b), the Artemision was then located in between the old town on Ayasoluk hill and these new settlements, the latter being farther from the sanctuary, but still within a walking distance of approximately 20 to 40 minutes.

The next major change in the settlement pattern was the construction of habitation quarters "round the temple" (Strabo, 14, 21, 13–14) under the reign of the Lydian king Croesus in the second quarter/middle of the 6th century BC. This lower town presumably adjoined the *temenos* of Artemis on its southern and eastern sides (Fig. 8c). For about 250 years, the Artemision was an intra-urban sanctuary.

The situation changed again, when king Lysimachus re-founded the *polis* at the beginning of the 3rd century BC on the slopes of the valley between the city mountains Panayırdağ and Bülbüldağ, and on the alluvial plain west of it. The sanctuary of Artemis, the precise extension of which is unknown, was now more than 1 km away from the northeastern entrance to the new city (location of the nearest gate: Scherrer 2001, Groh 2006, M. Steskal in: Kerschner et al. 2008). The Artemision became an extramural sanctuary. Nevertheless the *temenos* was connected with the city, physically by a procession road, ritually by a procession (Knibbe & Langmann 1993, Groh 2006, Mohr 2007, Sokolicek 2009).

8.3 *The Artemision and the changing coastline*

There was an ancient tradition delivered by Callimachus and Pliny the Elder that the Artemision had originally been situated by the seashore.

Callimachus wrote in his 3rd hymn "*To Artemis*":

"*For thee, too, the Amazons, whose mind is set on war, in Ephesus beside the sea established an image beneath an oak trunk, and Hippo performed a holy rite for thee*" (translated by Mair 2000).

Callimachus of Cyrene (320/303 – after 246 BC) often narrates old myths, but sometimes modifies them and adds own parts in order to achieve a coherent picture (Petrovic 2007). The verse quoted above shows that there existed a tradition in the first half of the 3rd century BC, according to which the Artemision had originally been situated close to the seashore. A date is not given, but the legendary context of the Amazons shows that this was believed to have happened in the mythical past, earlier than the time of which written records had been preserved.

Our second source, Pliny the Elder in his "*Naturalis historia*" (2, 201), is more concrete:

"For lands are born not only through conveyance of soil by streams (as the Echinades Islands when heaped up from the river Achelous ...) or by the retirement of the sea as once took place at Circei; ... such a retirement is also recorded to have occurred ... at Ephesus, where once the sea used to wash up to the temple of Diana" (translation Rackham 1947).

Pliny explicitly states that he describes a situation, which existed long before his own lifetime and which he knew only from one or several older, unnamed sources. As a naturalist, Pliny was aware of the geological process of the marine regression ("*recessu maris*") at Ephesos. Concerning the Artemision, he states that the surf reached the temple ("*aedes*"). This, however, must have been a metaphoric exaggeration, since between the temple and the seashore, there was a contemporaneous monumental altar (Weissl 2002, Ohnesorg 2005, Kerschner & Prochaska 2011). It is not entirely clear, to which temple Pliny refers, but undoubtedly to one of the two *dipteroi*, on which he comments several times in the 36th book of his "*Naturalis historia*". In some of these text passages it remains unclear, if he means the Archaic *dipteros* 1 (the so-called 'Croesus temple') or the Classical *dipteros* 2 (Wesenberg 1983). His statement that "the sea used to wash up to the temple of Diana" could have been the case only for the Archaic *dipteros* 1, the construction of which was begun around 580/70 BC (Weissl 2002, Ohnesorg 2007, Kerschner & Prochaska 2011). If we take the metaphoric exaggeration into account that "aedes" does not mean the temple properly, but the central part of the sanctuary, this corresponds with the results of the recent core drillings (especially Eph 347) that have shown that the shoreline was still close to the temple in the 6th century BC (Fig. 4 insert, 7 b).

The westernmost limit of the excavated area coincides with the western edge of the Late Classical altar (this is the position of core Eph 347, cf. insert in Fig. 4). There, in some trenches excavated beneath the altar court, an earlier floor was discovered: a loose pavement of marlstone slabs with yellowish soil (so-called 'Kalkmergelboden' or 'gelber Boden'; Bammer et al. 1978 ['gelber Boden'], Weissl 2002 ['OGB = oberer gelber Boden'], Kerschner & Prochaska 2011). The finds from the fill below and between the slabs date to c. 580/560 BC, the same time, when the construction of the Archaic *dipteros* 1 started. Therefore, this Archaic floor must have been the paved space in front of the temple and the altar, where the worshippers gathered during the sacrifices for Artemis. Its extension to the west has not yet been explored. At present we can state that it reached at least as far west as to drill core Eph 347, presumably even farther. This provides an indication of the shoreline in the 6th century BC, which must have been situated west of it.

The area of the later Artemision was frequented at least since the second half of the 14th and the 13th centuries BC (cf. Niemeier 2002, Forstenpointner et al. 2008), although its function during the LBA is equivocal due to lack of evidence. The stratigraphy indicates a low hill at the site during the LBA and EIA (Fig. 9; Weissl 2002). Obviously this hill was the starting point of the cult, since it was there that the oldest votive objects were found. To the east, this hill was separated from the slope of the much larger and steeper Ayasoluk hill by a torrent (Fig. 7b), the bed of which was partly excavated in 1994 (Kerschner 1997). Due to this location, the early sanctuary of Artemis was vulnerable to inundation. Several severe floodings must have taken place between the 10th and 7th centuries BC, as indicated by sandy layers with only few or no finds at all (Kerschner 1997, 2003b).

Initially, during the EIA, the sanctuary of Artemis was small. From the 7th century BC onwards, however, the *temenos* expanded gradually. The importance of the sanctuary grew and it gained supra-regional attraction as is discernible in the range of votives, which rapidly increased in number, diversity and value (e.g. Klebinder-Gauss 2007, Pülz 2009). During the second quarter of the 7th century BC the first temple of Artemis, the 'Naos 1' (Fig. 9), was built of limestone slabs, quarried at Heybeli Tepe, which is situated some 6 km away at the south coast of the former inner gulf of Ephesos (Kerschner & Prochaska 2011, with bibliography). The building stones could have been transported by ships directly to the 'sacred harbour' close to the Artemision.

The first marble temple was built a century later, a huge *dipteros* with double outer colonnade (Ohnesorg 2007). It was later often called the 'Croesus temple', after its main donator, the

Lydian king Croesus. Its construction began around 580/70 BC (Weissl 2002, Ohnesorg 2007, Kerschner & Prochaska 2011). At that time, the 'sacred harbour' could still have been used for transporting building material to the construction site. The marble, which was quarried c. 12 km up the Kaystros river at Belevi (Kerschner & Prochaska 2011), was, however, transported (mainly) by land, if we rely on Vitruv (10, 2, 12).

9 *Conclusion*

This study presents a detailed analysis of the interdependent evolution of the coastline, the settlements and the main sanctuary at Ephesos. The alluvial plains surrounding the ancient sanctuary dedicated to Artemis were researched by means of drill cores. Their detailed analyses revealed the shifts in the shoreline from the time of the maximum marine transgression until Hellenistic times. Radiocarbon dates reveal a marine transgression to the southwest and northeast of the (later) Artemision around 5000 cal BC. Its maximum landward position is situated between cores Eph 339 in the area of the later temple of Artemis, and Eph 217 (Figs. 4, 7a), Eph 212 and 224 (Figs. 4, 5, 7a). To the north of Ayasoluk, the coast was located directly at the foot of this hill, while to the east of Ayasoluk, Holocene marine sediments are missing.

The continuously prograding deltas of the rivers Selinus, Derbent (Marnas) and Şirince slowly infilled the marine embayment. During that time the Küçük Menderes delta was still far to the northeast in the area of Belevi, several kilometres away from the (later) Artemision site. Then the construction of the first large marble temple of Artemis (so-called Croesus temple or *dipteros* 1) started in the 6^{th} century BC; the shoreline remained along the lower floodplain of the Selinus/Derbent valley and north of the Artemision. In a sediment core to the northeast, a ceramic fragment in alluvial sediments overlying the marine strata was dated to the $5^{th}/4^{th}$ centuries BC. ^{14}C ages are missing for this area. We presume that the embayment silted up until the end of the 4^{th} century BC. The initially brackish coastal lake behind the coastline northeast of the Artemision turned to freshwater, and finally silted up until the end of the 4^{th} century BC. The Selinus delta continuously prograded until the Hellenistic period when the coastline was located c. 200 m to the west of the temple. At the same time, the Küçük Menderes delta continued its advance from the east, so that the area north of Ayasoluk was infilled with sediments. In Late Hellenistic times, the shoreline was located along the northern foot of Panayırdağ, while the immediate environs of the Artemision turned into a floodplain.

In the search for a potential location of the 'sacred harbour', which had been mentioned by the Ephesian historian Creophylus around 400 BC, and which probably was the harbour of the EIA settlement on Ayasoluk hill, the entire area was investigated in detail. Since up to 8 m of sediments overlie the marine strata, an excavation was not possible; thus, we have no traces of harbour moles, jetties or dams. However, our studies clearly identify a bay immediately northeast of the Artemision, which was well suited for anchorage. We propose to identify this bay with the 'sacred harbour'. Creophylus' account that the 'sacred harbour' was still under marine influence in his lifetime, around 400 BC, fits with our results. Most probably, the area had silted up by the end of the 4^{th} century BC. The continued progradation of the Selinus and Derbent deltas bypassed the Artemision at the latest during the 4^{th} century BC. Thus, we can conclude that the harbour site for the Artemision and for the settlement on Ayasoluk was not in use beyond the end of the 4^{th} century BC (Fig. 7).

The Koressian harbour, an embayment located about 1.5 km to the west at the northern flank of Panayırdağ, was probably used as a harbour since the late 8th/7th centuries BC, based on ceramic findings. At the same time, three other settlement sites on the northwestern and northern side of Panayırdağ (in the area of the Hellenistic-Roman city), most probably in direct relation with the coastline, were established. The Koressian harbour became the main harbour of Ephesos about 500 BC when the fleet of the Ionian allies anchored there. It was larger and most probably also deeper than the 'sacred harbour'. At the beginning of the 3rd century BC, when Lysimachos relocated the city of Ephesos to the west and south of Panayırdağ, all marine traffic other than small riverine transport was focused on the harbour directly adjacent to the new city.

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3. Life cycle of the Roman Harbour of Ephesus – multi-proxy analyses of the sediment record

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Life cycle of the Roman Harbour of Ephesus – multi-proxy analyses of the sediment record

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Keywords: Ephesus, harbour basin, harbour canal, stratigraphy, geochemistry, human impact, palynology, geoarchaeology, parasites

Abstract

The Roman harbour of Ephesus was one of the most prominent harbours during antiquity. Due to the prograding Küçük Menderes delta Ephesus was in danger of losing its connection to the sea. Thus, in the 2nd century BC, a harbour mole was constructed and starting from the 1st century BC a canal was built. Meanwhile, both harbour basin and canal have nearly totally silted up. Therefore, they may serve as geobioarchives. To reveal their stratigraphy and assess the human response, several vibracorings were carried out. The sediments were analysed according to a multi-proxy approach.

In the eastern cores, the dominance of silts reveals a low-energy environment in a protected embayment, whereas in the western cores the dominance of sands is evidence of a high-energy marine environment. From the 2nd century BC to the 1st century AD a high

sedimentation rate and *Isoetes* spores indicate the proximity of the Küçük Menderes delta, probably deposited after a dam had been constructed. A stratified layer, rich in organic matter and in calcium, points to the installation of the protected harbour basin in the 1st century BC, the sudden change from mica-rich sands to silts to the installation of the canal during the same time. Heavy metal concentrations, fruit tree pollen and eggs of intestinal parasites reveal an intensive use of the harbour between the 2nd/1st centuries BC and the 6th/7th centuries AD. Macro-charcoal from the city area indicates a strong increase in human impact on the surrounding woodland, beginning in the 1st century BC and decreasing in the 3rd century AD. After the 6th/7th centuries AD, this evidence declines which reflects the decrease in population. Then a lagoon-like basin and a lake with epilimnic calcification evolved. Since the 14th century AD, the peat growth shows that the harbour had finally lost its function.

Introduction

Geoarchaeological studies on Mediterranean harbours have already been studied for a number of years, mainly looking at human–environment interactions (Algan et al., 2011; Bini et al., 2012; Brückner et al., 2006, 2014, in press; Delile et al., 2014a, b, c, accepted; Goiran et al., 2011; Kraft et al., 2000, 2003, 2011; Le Roux et al., 2005; Morhange et al., 2003; Salomon et al., 2012; Sarti et al., 2013; Seeliger et al., 2013; Stock et al., 2013), and the micro- and macrofaunal contents (Bernasconi et al., 2006, 2010; Flaux et al., 2013; Frenzel and Boomer, 2005; Morhange et al., 2003; Marriner et al., 2006, 2012; Marriner and Morhange, 2007; Mazzini et al., 2011; Sarti et al., 2013; Stock et al., 2013; Pint et al., 2014).

In Ephesus (Greek: Ephesos), geoarchaeological research has focused on coastal changes and siltation processes, landscape reconstruction in the city area of Ephesus, different harbour sites (Brückner, 1997, 2005; Kraft et al., 2000, 2001, 2005, 2007, 2011; Stock et al., 2013; Delile et al., 2015), and on the Artemision and its surroundings (Kraft et al., 1999, 2008; Brückner et al., 2008; Stock et al., 2014). Ephesus owed its prosperity mainly to the harbour, from which trade all over the Mediterranean took place (Zabehlicky, 1995). The continuous siltation strongly influenced the development and economy of Ephesus. A number of relocations of the harbours were all related to the changing coastline (Kraft et al., 1999; Zabehlicky, 1995).

In the Roman harbour basin, some drill cores have been retrieved in the 1990s. Together with historical sources, they were used for reconstructing the siltation process (Brückner, 1997, 2005; Kraft et al., 2000, 2005, 2011). However, no detailed study has yet been undertaken to probe the Roman harbour basin and its canal.

In this study, two sediment cores from the harbour basin and the canal are presented in detail. Several other cores complete this study. We used the multi-proxy approach by applying sedimentological, geochemical, palynological, parasitological, micro- and macrofaunal as well as archaeobotanical tools for a detailed knowledge about (i) the stratigraphy and evolution since pre-Hellenistic times; (ii) the landscape changes; and (iii) the intensity and direction of the human impact.

Study area

The study area is located on the Aegean coast of Turkey in the E–W striking Küçük Menderes graben. The still active graben has formed within the pre-Miocene basement during the Neogene, and contains a Miocene-Quaternary sediment fill (Rojay et al., 2005).

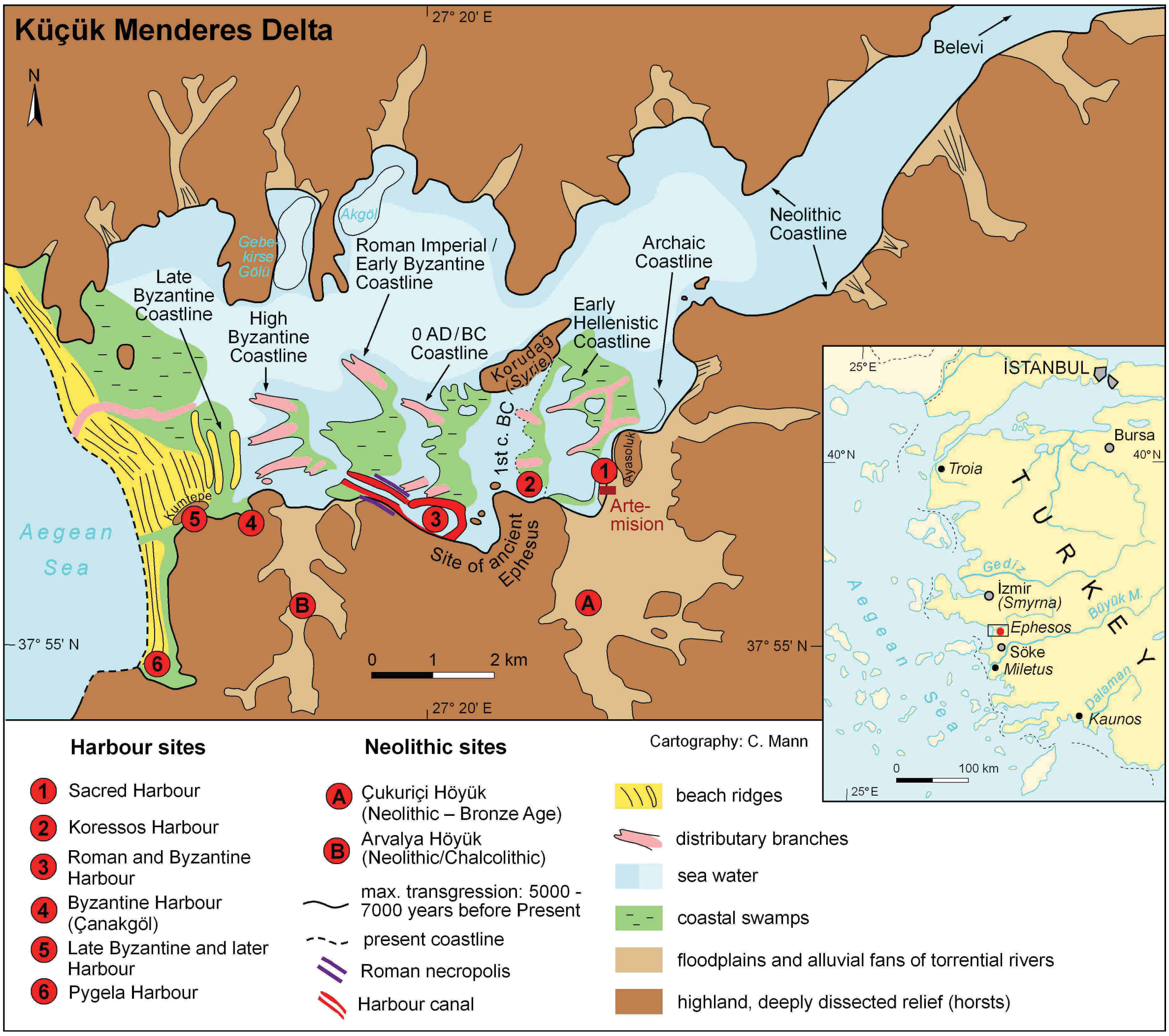

Fig. 1: Scenario of the progradation of the Küçük Menderes (Cayster) delta since Neolithic times (after Brückner 2005, modifed).

During the maximum ingression of the sea, a marine embayment had extended for about 20 km inland. Since 6000–5000 BC, an alluvial plain has formed due to the progradation of the deltas of the Küçük Menderes river and its tributaries, which has led to a continued regression of the shoreline towards the west (Brückner, 2005; Kraft et al., 2000). Many decametres of sediment have been deposited on top of the pre-Holocene strata (Kraft et al., 2005). Evidence of the former embayment are two remaining lakes at the northern side of the graben, and the fact that Korudağ had formerly been the island of Syrie (fig. 1).

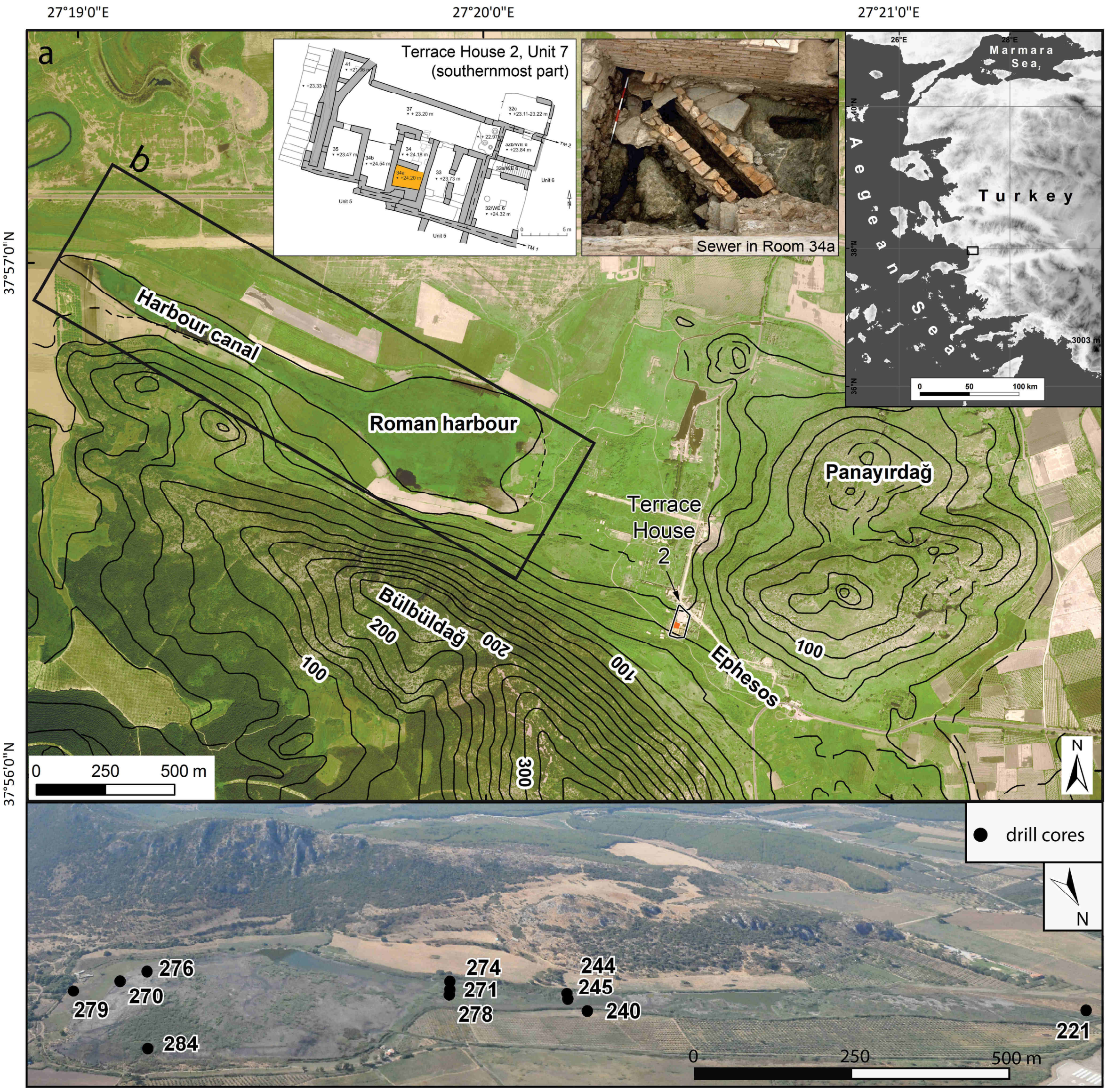

Fig. 2: (a) Study area within the city of Ephesus with the surrounding mountains of Bülbüldağ and Panayırdağ. The sewer is from Room 34a of Terrace House 2, a Roman agglomeration (*insula*) (stratigraphical units SE 1014 and 1024). Conversion of the aerial image from miscolour to natural colour. Sources: Austrian Archaeological Institute, University Vienna Institute of Photogrammetry and Remote Sensing, İstanbul Technical University Department of Photogrammetry, 1997, modified. (b) Location of drill cores in the Roman harbour basin and the harbour canal.

The Roman harbour of Ephesus is part of the Hellenistic–Roman city area. It is surrounded by the mountain ranges of Bülbüldağ to the south (356 m) and Panayırdağ to the east (157 m) which form the hanging wall of the graben and mostly consist of dolomitic marble, limestone, and phyllite (fig. 2a; Vetters, 1989; Çakmakoğlu, 2007; Rantitsch and Prochaska, 2011). The

Roman harbour is nowadays located 5 km east of the present coastline. During the summer it almost dries out (fig. 2b). It was constructed as a hexagonal harbour basin in the beginning of the 2nd century AD (Zabehlicky, 1995). Remains of the quay walls and of three jetties of the hexagonal basin persist in the south-western part of the former basin (Groh, 2006; Steskal, in press).

The Küçük Menderes follows the graben structure. Nowadays it debouches into the Aegean Sea 6 km to the west of Ephesus (fig. 1). At the end of the 19th century, Schindler (1897) had mapped two narrow connections between the harbour canal and the former course of the Küçük Menderes. In the 1930s, the course of the meandering river was regulated on the northern side of the graben (Güldali, 1979; fig. 1).

Methodology

Sediment cores up to a depth of 12 m and with diameters of 6 and 5 cm, respectively, were retrieved from the harbour basin and the canal using the percussion coring device Cobra mk1 of Atlas Copco. Coring position and elevation were levelled with a Topcon HiPer pro GPS (precision of 2 cm); they refer to the present mean sea level. During fieldwork, all open cores were documented for grain size, colour, carbonate content, macrofossils, and other parameters.

In the laboratory, magnetic susceptibility was measured with a Bartington MS2B sensor. Elemental analyses were conducted in 2 mm resolution using an energy-dispersive X-ray fluorescence (XRF) Itrax Core Scanner (Cox Analytical Systems, Sweden; Croudace et al., 2006) equipped with a 1.9 kW Cr X-ray tube set to a voltage and current of 30 kV and 30 mA, and an exposure time of 20 s. For core Eph 276, the measurement was done on the untreated core halves, whereas for Eph 244 23 dried samples were investigated.

For grain size analysis, the fractions <2 mm were measured with a laser diffraction particle sizer (Beckmann Coulter LS13320 Mikro); the results were statistically processed with GRADISTAT (Blott and Pye, 2001). Peat layers were excluded from grain size determination. Loss on ignition (LOI) was measured in a muffle furnace (c. 5 g of sediment heated for 12 hours at 105°C, and 4 hours at 550°C), $CaCO_3$ was determined with the Scheibler apparatus (0.5 g of sediment reacted with HCl (10 %).

Thin sections were carried out on samples from characteristic layers of Eph 276. The micromorphological interpretation is according to van der Meer and Menzies (2011).

A detailed microfaunal investigation was carried out for drill core Eph 276 (98 samples). About

4 cm³ of sediment were sieved with 100 µm mesh size, and determined following Meisch (2000) for ostracods and Meriç et al. (2004) for foraminifers.

For pollen analysis, samples (2–4 cm³) were treated as described in Eisele et al. (1994) and cleaned by ultrasonic sieving with a 7 µm mesh. For pollen and spore identification, the collection of recent pollen and spores at the Institute of Botany, University of Hohenheim was used together with Beug (2004), Moore et al. (1991) and Reille (1992). Calculation of the results and plotting of the pollen diagram were done using the software FAGUS (University of Innsbruck, Austria).

Sample Code	Lab code	Unit	Material	Depth (cm) b.s.	Depth (cm) b.s.l.	$\delta^{13}C$ (‰)	^{14}C age (BP)	Age cal BC/ cal AD (2σ)
Eph 270/12H	UGAMS 11910	3a	wood	3.77	-4.41	-26.5	1520±20	AD 439–602
Eph 270/14 Sg	UGAMS 13571	3a	echinoid spins	4.88	-5.52	1	2100±25	AD 172–366
Eph 276/186/113P	Lyon-9957 37622	6a	plant fragment	1.86	-2.32	-26.6	665±30	AD 1276–1392
Eph 276 362H	Lyon-9959 37624	4a	wood	3.62	-4.08	-30.8	1455±30	AD 555–650
Eph 276/460	Lyon-9960 37625	3a	seeds	4.6	-5.06	-31.3	2020±30	108 BC–AD 60
Eph 276 680-690	UGAMS 17652	2a	enriched pollen	6.85	-7.31	-27.8	2000±40	111 BC–AD 83
Eph 276 1080-1090	UGAMS 17352	1a	seeds	10.85	-11.31	-25.9	1990±25	43 BC–AD 62
Eph 276 1189pl.	Lyon-9962 37627	1a	plant fragment	11.89	-12.35	-31.9	2040±30	163 BC–AD 47
Eph 284/13H	UGAMS 11913	2a	plant fragment	4.6	-5.21	-28.9	2090±25	179–45 BC
Eph 284/21P	UGAMS 11912	2a	olive stone	9.4	-10.01	-26.3	1980±25	40 BC–AD 69
Eph 278/285	Lyon-9955 37620	8a	plant fragment	2.85	-3.52	-33.1	475±30	AD 1408–1455
Eph 278/660	Lyon-9958 37623	2a	shell fragment	10.5	-11.17	-6.2	3195±30	1172–932 BC
Eph 271/7	UGAMS 11909	1a	charcoal	0.9	-1.77	-24.5	390±20	AD 1445–1618
Eph 271/79Pf	UGAMS 11908	2a	plant fragment	9.87	-10.74	-22.9	2270±25	397–211 BC
Eph 271/95H	UGAMS 11906	2a	plant fragment	11.68	-12.55	-29.8	2020±25	92 BC–AD 53
Eph 244 B1 137-138	UGAMS 8222	2b	seagrass	1.37	-2.11	-29.0	650±35	AD 1279–1396
Eph 244 B5S 377	UGAMS 8223	5b	root	3.77	-4.51	-22.5	1700±25	AD 256–402
Eph 244 B8 575-577	UGAMS 8224	4b	seagrass	5.76	-6.5	-27.3	2120±25	334–53 BC
Eph 244 B12 859-860	UGAMS 8225	2b	seagrass	8.59	-9.33	-13.8	2520±25	792–545 BC
Eph 245 B4 77-78	UGAMS 8226	7b	plant fragment	1.27	-2.02	-29.5	1490±25	AD 539–637
Eph 245 B13H 738	UGAMS 8227	4b	charcoal	7.88	-8.63	-25.9	2270±25	399–212 BC
Eph 221/8H	UGAMS 6026	8b	charcoal	2.51	-1.01	-19.9	950±25	AD 1642–1950
Eph 221/16Cg	UGAMS 6025	5b	shell fragment	5.52	-4.02	-21.8	1160±25	130 BC–AD 55

Tab. 1: Radiocarbon data set. Samples were calibrated with Calib 6.0 (Reimer et al., 2009). Marine samples were corrected using the reservoir age for the Eastern Mediterranean region, i.e., 390±85 years (Siani et al., 2000). b.s. below surface, b.s.l. below sea level, a.s.l. above sea level. ^{14}C age estimates with 2 sigma standard deviation (95.5 % probability). The six radiocarbon ages from drill core Eph 276 have already been published in Delile et al. (2015).

Ancient parasite analysis was performed at the University of Cambridge, UK. Following disaggregation, 1 g samples were passed through sequential microsieves (300, 160 and 20 µm)

(Anastasiou and Mitchell, 2013a). Due to their size, intestinal parasite eggs are trapped on the 20 µm mesh; they were determined according to their shape, colour, dimensions and other characteristics (Garcia, 2009).

On-site macro-charcoal of Terrace House 2 was recovered from archaeobotanical flotation samples, dated by pottery and numismatic typologies. One sample (18.6 l) was taken from a secondary chalk pit filling (Room 32c, 2nd quarter of the 1st century AD; Ployer, in press), and three more (45 l in total) were recovered from the stratified filling of a sewer (Room 34, 2nd century BC – 3rd century AD) (Ployer, in press). Due to their precise numismatic dating the sewer layers in particular allowed for a high-resolution interpretation of the data. The material was floated and searched for plant macro-remains and charcoal (Heiss and Thanheiser, in press); this was carried out on a minimum of 50 randomly picked charcoal fragments per sample. Its identification is based on standard literature (Schweingruber, 1990; Heiss, 2000-2009; Heiss and Marinova, 2009).

In total, 23 AMS-^{14}C age estimates of organic material and enriched pollen plus fragments of diagnostic ceramics and coins constrain the chronostratigraphy (tab. 1).

Results

Overview of the stratigraphy in the harbour and the harbour canal

The study is based on 9 drill cores from the harbour basin and the harbour canal (fig. 3). Eph 276 represents the typical stratigraphy of the harbour basin, Eph 244 the one of the harbour canal, wherefore they are described in detail. The archived time span reaches from the end of the 2nd millennium BC to the 20th century AD.

In the harbour basin, Eph 276 reveals laminations of clayey silts at the base (unit 1 a). The drill cores from the harbour basin and the transition to the canal (Eph 279, 270, 276, 284, 278, 271) are characterized by silts with intercalations of fine sand from the base to c. 5 m b.s.l. (meter below sea level), dating from the end of the 2nd millennium BC to the 1st century AD (fig. 3, unit 2a). Different ages occur at the same level (e.g., 1172–932 cal BC and 43 cal BC – 62 cal AD at 11 m b.s.l.). This may be due to the fact that the harbour basin had once been dredged.

Unit 3a is a stratified silty layer of pale yellow to brown colour; it yielded ages between the 1st century BC to the 6th/7th centuries AD. The overlying greyish silts (units 4–5a) seem to have been deposited after the 7th century AD. Eph 271 and 279 are dominated by a brown layer rich in organic matter with angular stones, mortar and ceramic fragments spanning from Roman Imperial times to Late Antiquity.

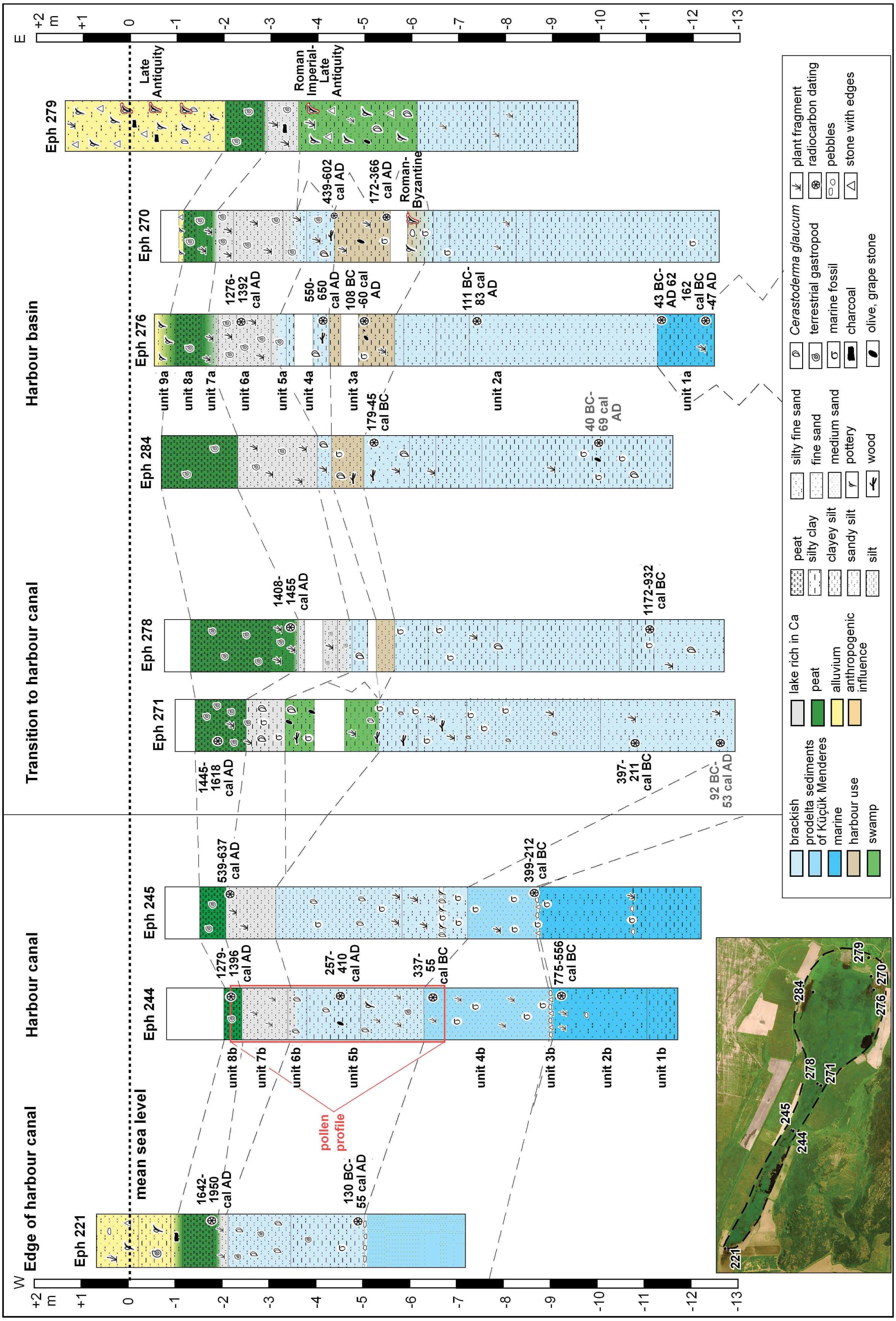

Fig. 3: Geological profiles and cross sections from the harbour basin to the edge of the harbour canal (see fig. 2b for core positions). Eph 271 and 284 reveal an age inversion. The improbable ages are shown in grey colour.

All drill cores reveal a silty to sandy pale yellow layer (unit 6a), deposited until the 14th century AD. Peat occurs after the 14th century AD (units 7–8a). Brown silts (unit 9a) with ceramic sherds (Late Antiquity) dominate Eph 279, 270 and 276 to the top. In the harbour canal (Eph 244, 245, 221), the base of Eph 244 and 245 is formed of sandy silts and overlain by mica-rich sands, deposited before the 8th–6th centuries BC (units 1–2b) and between the 4th and the 1st centuries BC (units 3–4b) (also Eph 221). A sharp contact separates the mica-rich sands from silts (unit 5b), dated between the 1st centuries BC/AD until at least the 5th century AD. Units 6b and 7b reveal the same silty to sandy pale yellow layer as units 5–7a, poorly dated with a ^{14}C age estimates of the 6th/7th centuries AD (Eph 245). On top follow peat (unit 8b, 13th–20th centuries AD), and in Eph 221 brown silts rich in ceramic fragments and edged stones.

Chronology and stratigraphy of the harbour basin

Master core Eph 276 (E 27°19'59.32", N 37°56'32.89") from the harbour basin can be differentiated into nine units (figs. 2, 4a, 5).

Unit 1a (12.46–11.26 m b.s.l.) is composed of clayey silt with laminations of greyish and dark greyish brown colour (cf. thin section in fig. 4a); it shows low LOI values (3–9 %), variations of Ti and relatively high Sr/Ca ratios. In the upper part few specimens of ostracods (esp. *Cyprideis torosa*, *Darwinula stevensoni* and *Limnocythere inopinata*) and foraminifers (esp. *Ammonia tepida*) are present. Unit 1a was deposited between 162 cal BC and 62 cal AD.

Slightly coarser sediments build up unit 2a (11.26–5.56 m b.s.l.), which consists of homogeneous, grey to dark greyish silts (up to 75 %). Subsections rich in fine sand and void of microfossils show an increased magnetic susceptibility (MS). High Ti and low Ca values, low Sr/Ca ratios, frequent *Pinus* pollen and *Isoetes* spores (at 9.31 m b.s.l.) occur. In this unit, the ostracods *C. torosa*, *D. stevensoni*, and *Candona* sp. dominate whereas towards the top the foraminifer species *A. tepida* and *H. germanica* appear. Units 1a and 2a both reveal similar ages and were deposited with a high sedimentation rate of ~30 mm/y from the end of the 2nd century BC to the 1st century AD.

Unit 3a (5.56–4.22 m b.s.l.) is characterized by alternations of greyish brown silts and pale yellow silts with a lower amount of sand and increased values of Ca. The facies change is demonstrated by raised values of organic matter (up to 25 %), declined Sr/Ca ratios, low Ti values, and the highest Cu peaks in the core. Ostracod *C. torosa* as well as foraminifers *A. tepida* and *H. germanica* are frequent. The age of this unit is sandwiched between 104 cal BC – 57 cal AD and 555–650 cal AD.

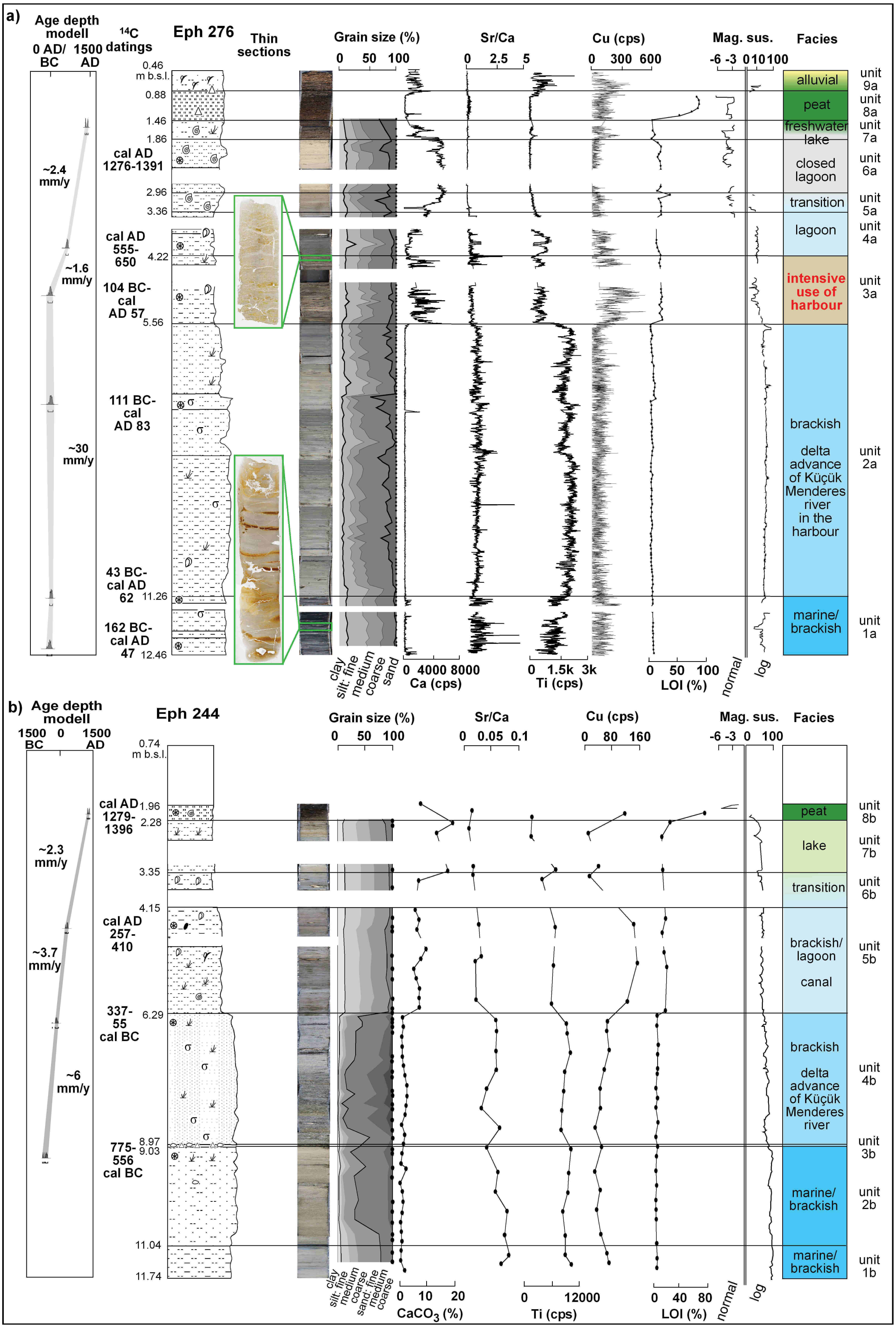
a)
Age depth modell
0 AD/ BC
1500 AD
14C datings
Eph 276
Thin sections
Grain size (%)
Sr/Ca
Cu (cps)
Mag. sus.
Facies
~2.4 mm/y
~1.6 mm/y
~30 mm/y
cal AD 1276-1391
cal AD 555-650
104 BC-cal AD 57
111 BC-cal AD 83
43 BC-cal AD 62
162 BC-cal AD 47
alluvial
peat
freshwater lake
closed lagoon
transition
lagoon
intensive use of harbour
brackish
delta advance of Küçük Menderes river in the harbour
marine/ brackish
unit 9a
unit 8a
unit 7a
unit 6a
unit 5a
unit 4a
unit 3a
unit 2a
unit 1a
clay
silt: fine
medium
coarse
sand
Ca (cps)
Ti (cps)
LOI (%)
normal
log
b)
Age depth modell
1500 BC
0
1500 AD
Eph 244
~2.3 mm/y
~3.7 mm/y
~6 mm/y
cal AD 1279-1396
cal AD 257-410
337-55 cal BC
775-556 cal BC
peat
lake
transition
brackish/ lagoon
canal
brackish
delta advance of Küçük Menderes river
marine/ brackish
unit 8b
unit 7b
unit 6b
unit 5b
unit 4b
unit 3b
unit 2b
unit 1b
clay
silt: fine
medium
coarse
sand: fine
medium
coarse
CaCO3 (%)
Ti (cps)
LOI (%)
normal
log

Fig. 4: Stratigraphy of vibracores Eph 276 in the Roman harbour basin (a), and Eph 244 in the harbour canal (b), together with age/depth model, ^{14}C ages, granulometry (except for peat), geochemical data (Ca and $CaCO_3$, respectively, Sr/Ca, Ti, Cu), LOI, magnetic susceptibility (Mag. sus.), and facies interpretation. Position of cores in fig. 2b, legend for the granulometry and fauna content in fig. 3. Photographs of thin sections reveal the detailed stratification at two important sections of the core. cps = counts per second, Magnetic susceptibility in normal and logarithmic scales.

Unit 4a (4.22–3.36 m b.s.l.) consists of homogeneous, very dark greyish clayey silts. Geochemical values are similar as for unit 2a. The layer contains shell fragments of the bivalve *Cerastoderma glaucum*, abundant specimens of the foraminifers *A*. *tepida* and *H*. *germanica* as well as the ostracod *C*. *torosa*. The sedimentation rate significantly decreases to 1.6 mm/y from the 1st–7th centuries AD (555–650 cal AD).

Unit 5a (3.36–2.96 m b.s.l.) is composed of sandy silts, with an increased amount of sand, lower Cu values and Sr/Ca ratios, and Ti values decreasing upwards. No foraminifers are present anymore, however a rich ostracod fauna.

Unit 6a (2.96–1.86 m b.s.l.), a silty layer of very pale brown colour, contains laminae rich in sand towards the top of the unit, as plant remains (LOI up to 25 %), and the highest Ca values of the core. The gastropods *Gyraulus* sp. and *Radix* sp., as well as the ostracods such as *C. torosa*, *Candona* sp. and *D*. *stevensoni* are present. The sedimentation rate rises to 2.4 mm/y.

Unit 7a (1.86–1.46 m b.s.l.) starts with a sharp contact to the underlying stratum. It is characterized by dark brown silts, low Ca content, the dominance of *Gyraulus* sp. and the same ostracods as for unit 6a. Moreover, *Pseudocandona* sp. and *Cyclocypris laevis* occur.

Unit 8a (1.46–0.88 m b.s.l.) consists of peat (LOI rises up to 87 %) and a strong decrease of microfossils. The stratigraphy is terminated by unit 9a (0.88–0.46 m b.s.l.), brown sandy silts with ceramic fragments.

Chronology and stratigraphy of the harbour canal

Master core Eph 244 (E 27° 19’29.372”, N 37° 56’47.795”) from the harbour canal comprises eight units (figs. 2, 4b). Unit 1b (11.74–11.04 m b.s.l.) is dominated by olive to dark olive grey sandy silts with intercalations of sandy laminae of up to 1 cm thickness. The sedimentary unit is void of plant remains and shell fragments. LOI and $CaCO_3$ show low, Sr/Ca, Ti and MS high values.

Unit 2b (11.04–9.03 m b.s.l.), a homogeneous sand-dominated deposit, contains a few remains of plants and mollusc shells. While MS exhibits the highest values of the whole core, the values

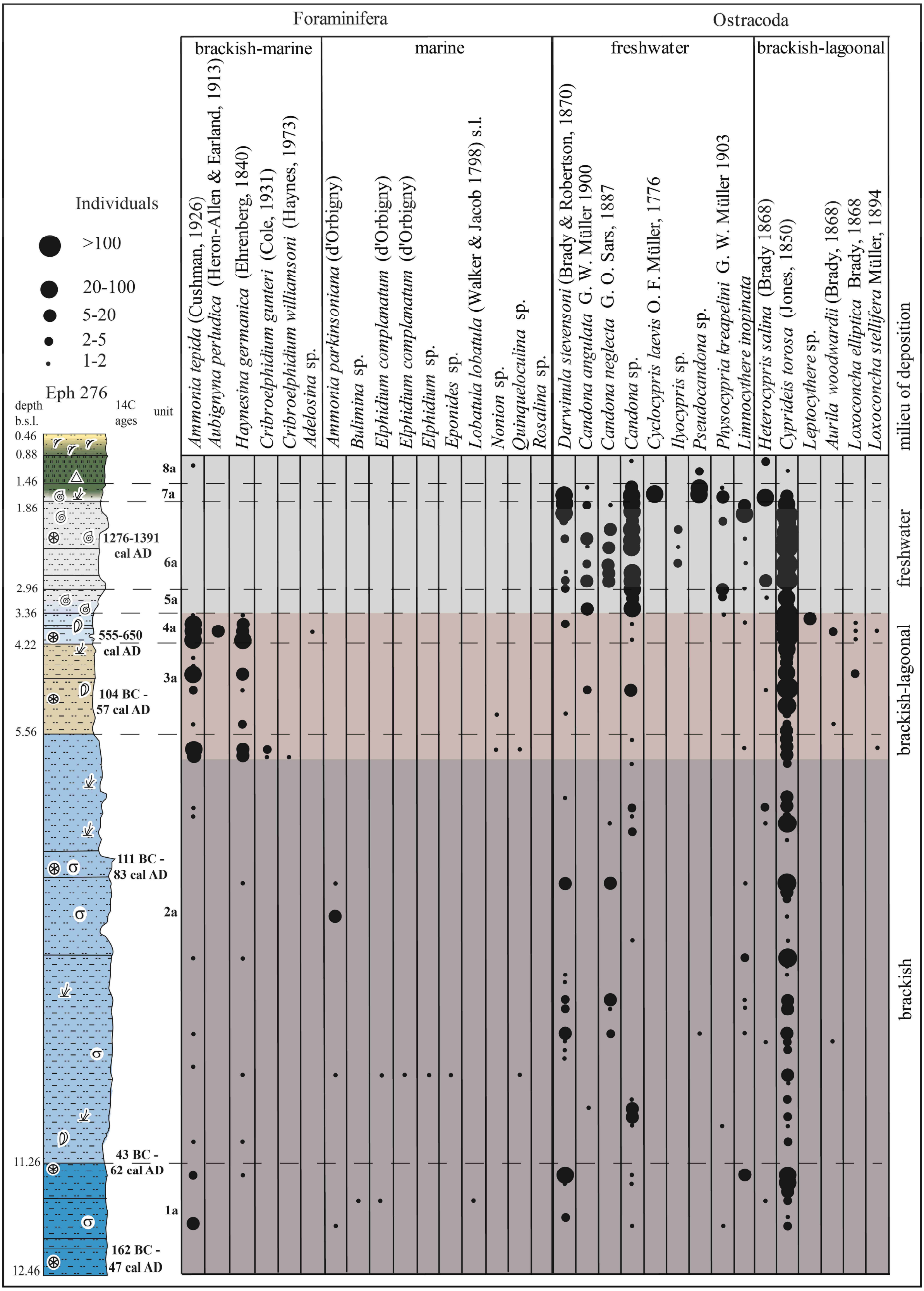

Fig. 5: Microfossil analysis of foraminifera and ostracoda (with frequencies) of drill core Eph 276 from the Roman harbour basin, with stratigraphic units and depositional environments. Four different habitats were detected which may overlap to some degree: marine, brackish-marine, brackish-lagoonal, and freshwater. The dashed line represents units 1a-8a.

of other geochemical parameters are low. Seagrass (*Posidonia* sp.) at a depth of 9.34 m b.s.l. dates to 775–556 cal BC.

Unit 3b is a 6 cm layer of stones (quartz and mica schist, mostly angular), sandwiched with sharp contrast between units 2b and 4b.

Unit 4b (8.97–6.29 m b.s.l.) is mostly composed of olive grey fine and medium mica-rich sands, with seagrass, fragments of mollusc shells and barnacles. The geochemistry shows minor changes, with low Sr/Ca ratios and Ti values. The MS peaks correlate with horizons of increased grain size. This unit was deposited between the 8th/6th and the 4th/1st centuries BC.

The boundary to unit 5b is marked by a sharp contact at 6.29 m b.s.l. Up to 4.15 m b.s.l. the sediments consist of silts with many mollusc shell fragments (including *C. glaucum*) and a pottery sherd. The geochemistry reveals an environmental change, with raised values of $CaCO_3$ and LOI (up to 20 %), the highest amounts of Cu of the core, decreased values of Ti, MS and Sr/Ca. A grape seed at 4.51 m b.s.l. dates to 257–410 cal AD.

A transition stratum (unit 6b, 4.15–3.35 m b.s.l.) consists of similar sediments as before, with *C. glaucum* and declined Cu values. The overlying unit 7b (3.35–2.28 m b.s.l.) is composed of homogeneous dark olive grey silts with intercalations of organic-rich layers, high $CaCO_3$ values and low Sr/Ca ratios; it was deposited after the 3rd/5th centuries AD. The top part is enriched in organic matter (up to 25 %). The uppermost part of the core (unit 8b) consists of peat (organic matter up to 80 %). Macrofossils are represented by the freshwater gastropod *Gyraulus* sp. One date of the compacted unit dates to the 13th/14th centuries AD).

Palynological and parasitological studies

The master core Eph 244

The master core of the harbour canal Eph 244 war also used for palynological studies. In total, five pollen assemblage zones were differentiated (fig. 6a, see figs. 3, 4b for depths in Eph 244).

PAZ 1, 6.71–6.35 m b.s.l., contains a high level of indeterminate pollen, *Isoetes* spores and burnt plant remains. The quantity of deciduous oak (*Quercus*) remains low and declines towards the top of the unit, while *Olea* pollen increases. Cerealia-type, *Plantago lanceolata*-type, *Cannabis* and a high amount of Fabaceae are present.

PAZ 2, 6.29–5.32 m b.s.l., is characterized by a sudden change in the pollen spectrum: discontinuation of *Isoetes* spores and a rapid decline of indeterminates. Typical of this unit are high amounts of *Sarcopoterium*-type and Brassicaceae (crucifers) -partly occurring in clusters

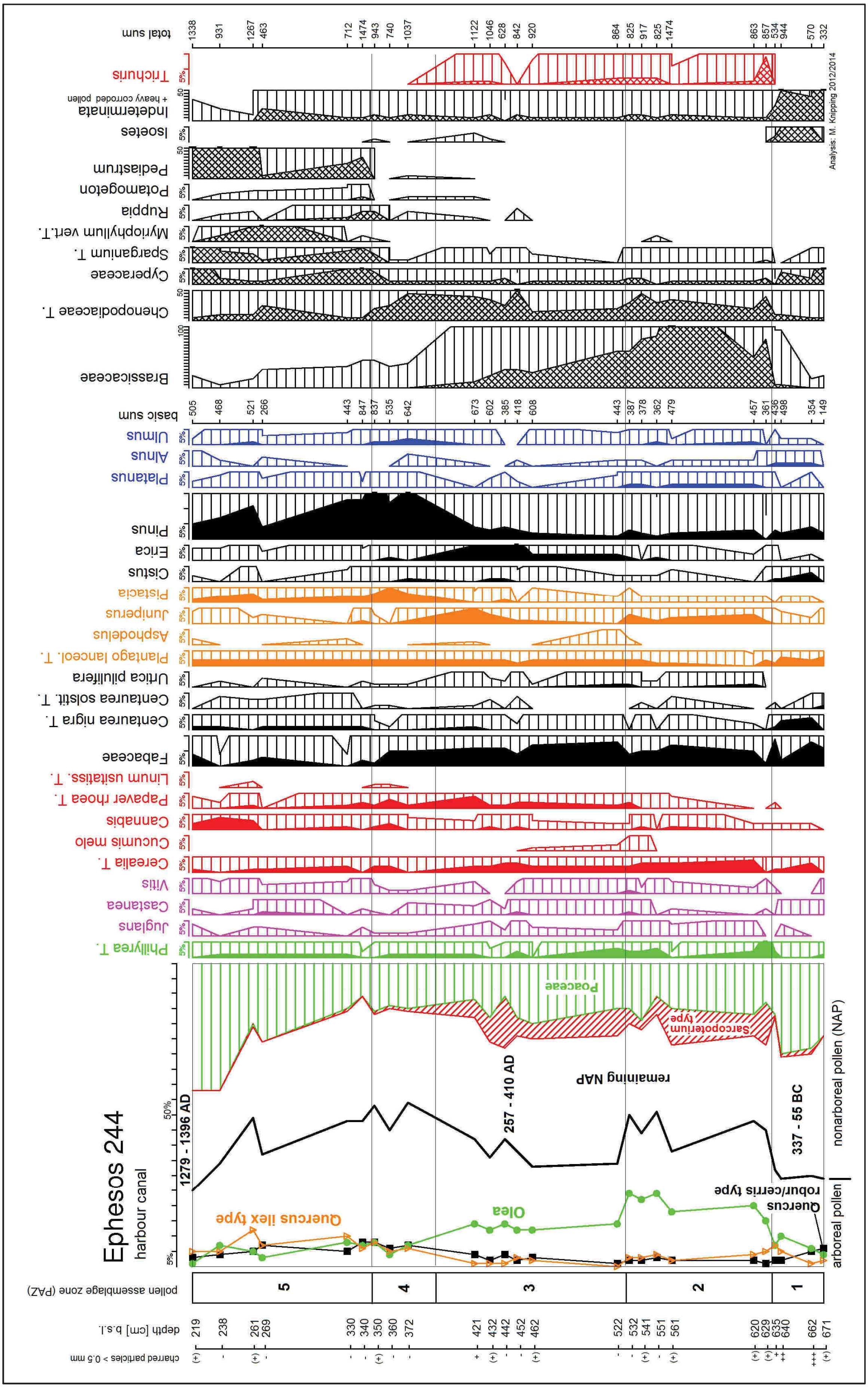
Ephesos 244
harbour canal
pollen assemblage zone (PAZ)
depth [cm] b.s.l.
charred particles > 0.5 mm
arboreal pollen
nonarboreal pollen (NAP)
Quercus robur/cerris type
Quercus ilex type
Olea
remaining NAP
Sarcopoterium type
Poaceae
1279 - 1396 AD
257 - 410 AD
337 - 55 BC
Phillyrea T.
Juglans
Castanea
Vitis
Cerealia T.
Cucumis melo
Cannabis
Papaver rhoea T.
Linum usitatiss. T.
Fabaceae
Centaurea nigra T.
Centaurea solstit. T.
Urtica pilulifera
Plantago lanceol. T.
Asphodelus
Juniperus
Pistacia
Cistus
Erica
Pinus
Platanus
Alnus
Ulmus
basic sum
Brassicaceae
Chenopodiaceae T.
Cyperaceae
Sparganium T.
Myriophyllum vert. T.
Ruppia
Potamogeton
Pediastrum
Isoetes
Indeterminata
+ heavy corroded pollen
Trichuris
total sum
Analysis: M. Knipping 2012/2014

Fig. 6a: Pollen diagram of sediment core Eph 244 from the harbour canal. The input of pollen in the sediment derives from different sources. Therefore, the preservation of pollen grains is extremely variable, which was accounted for by clustering them into different preservation groups during counting. All terrestrial taxa are included in the basic sum, whereas *Brassicaceae* and *Chenopodiaceae* (as possibly overrepresented elements), pollen clumps and anther remains, wetland plants (Cperaceae, *Sparganium*-type, *Typha latifolia*-type, *Lythrum*), indeterminable and heavily corroded grains as well as spores and algae are excluded. The scale is always 5 % with a magnification of 10. Only the most frequent taxa are shown in the pollen diagram. In total, 22,468 palynomorphs and algae were counted from 25 samples from drill core Eph 244.

Fig. 6b: Egg of the intestinal parasite *Trichuris* sp. (scale bar: 20 µm).

and anthers. A further differentiation between Brassicaceae in wild plants or crops is not possible. *Sarcopoterium*-type pollen appears as thorny burnet (*Sarcopoterium spinosum*) and/or small burnet (*Sanguisorba minor*), which cannot be distinguished accurately. Characteristic for PAZ 2 are pollen grains of fruit trees (*Olea*, *Juglans*, *Castanea*, *Vitis*), Cerealia-type, *Cannabis*, Fabaceae, eggs of the intestinal parasites whipworm (*Trichuris* sp.; cf. fig. 6b) and roundworm (*Ascaris* sp.), as well as *Cucumis melo* (muskmelon) (cf. Beug 2004) towards the top.

PAZ 3, 5.22–4.21 m b.s.l. still reveals *Cucumis melo*, *Trichuris* sp. and *Ascaris* sp. parasite eggs and *Papaver rhoeas*-type pollen (poppy) during the 3rd–5th centuries AD. Whipworm eggs were much more common than roundworm in all of the analyzed samples. The distinction between opium poppy and wild species is not possible. More burnt plant remains occur towards the top. In PAZ 4, 3.72–3.50 m b.s.l., the amount of *Pinus* pollen increases, *Olea* decreases while *Quercus ilex*-type and *Pistacia* rise. Eggs of *Trichuris* sp. and *Ascaris* sp. are lacking in this zone. More aquatic algae occur. Flax pollen (*Linum usitatissimum*-type) is still present. PAZ 5, 3.40–2.19 m b.s.l., is characterized by abundant aquatic and swamp plants during the 13th–14th centuries.

Comparison of pollen data with finds of plant macro-remains in Terrace House 2

Several of the pollen grains and especially the intestinal parasite eggs originate from the city area; they were washed into the Roman harbour and the canal. Therefore, it is interesting to study the source area of these sediments. In the following section, the plant macro-remains in Terrace House 2, a Roman agglomeration (*insula*) built upon Hellenistic structures, and spanning the 1st until the 3rd centuries AD, are described (fig. 7, tab. 2).

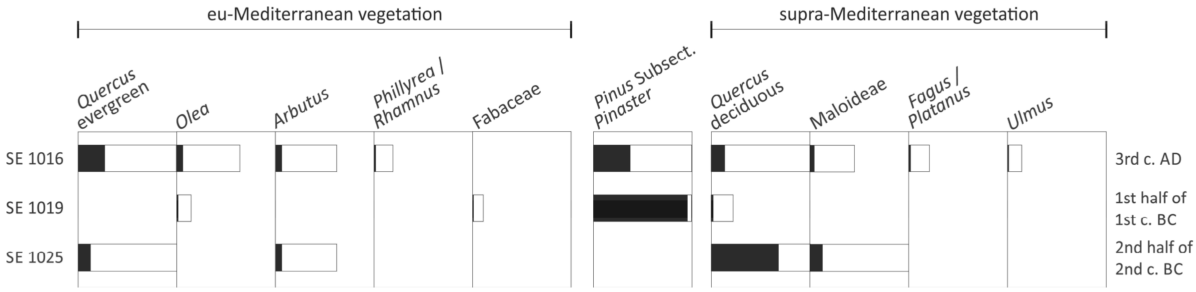

Fig. 7: Charcoal percentages by weight from the sewer in Room 34a (cf. fig. 2a).

Context	Room 34a, sewage canal layers						Room 32c, chalk pit filling	
Layer/Sample	SE 1025		SE 1019		SE 1016		99/640	
Period	2nd half of 2nd century BC		1st half of 1st century BC		3rd century AD		mid-1st century AD	
Volume [l]	10		10		15		18.6	
Total charcoal content [g]	6.22		10.53		37.16		17.6	
Identified charcoal	68%		53%		42%		26%	
	number	weight [g]	number	weight [g]	number	weight [g]	number	weight [g]
eu-Mediterranean vegetation								
Arbutus sp.	2	0.26	-	-	3	0.90	-	-
Fabaceae	-	-	1	0.05	-	-	-	-
Olea europaea s.l.	-	-	1	0.09	3	0.40	-	-
cf. *Olea europaea* s.l.	-	-	-	-	1	0.60	-	-
Phillyrea sp. / *Rhamnus* sp.	-	-	-	-	2	0.30	-	-
Quercus sp. evergreen	8	0.54	-	-	14	4.20	3	0.23
anthropogenic woodland								
Pinus subsect. *Pinaster*	-	-	31	5.31	17	5.80	15	1.71
supra-Mediterranean vegetation								
Fagus sp. / *Platanus* sp.	-	-	-	-	1	0.30	-	-
Fraxinus sp.	-	-	-	-	-	-	9	0.67
Maloideae	4	0.54	-	-	2	0.70	-	-
Quercus sp. deciduous	16	2.87	2	0.10	6	2.10	4	0.37
Ulmus minor	-	-	-	-	1	0.20	-	-
traded timber								
Abies sp. / *Cedrus* sp.	-	-	-	-	-	-	14	1.33
Tilia sp.	-	-	-	-	-	-	5	0.22
TOTAL	30	4.21	35	5.55	50	15.50	50	4.53

Table 2: Anthracological data from Terrace House 2, Unit 7 (cf. fig. 2a).

Samples were processed from Dwelling Unit 1 (Popovtschak, 2010), Dwelling Unit 2 (Thanheiser, 2010), and from the Rooms 32c and 34a in Dwelling Unit 7. There, a large amount of mineralized and some charred plant remains were recovered (Heiss and Thanheiser, in press) (tab. 2). The mineralized finds are dominated by c. 20,000 fig pips (*Ficus carica*) and nine muskmelon seeds in the canal (SE 1016) of Dwelling Unit 7; they are dated to the 3rd century AD. The musk melon deserves special notice; the latter species is now documented both by pollen in the harbour canal sediments and by macro-remains in a dwelling. Grapevine (*Vitis vinifera* ssp. *vinifera*), one of the most significant cultivated woody plants in antiquity (also documented in the pollen profile), is present in mineralized form throughout the sewage layers from the 1st century BC to the 3rd century AD. The presence and use of olive (*Olea europaea*) is proven by charred olive stones in all previously analysed Dwelling Units (Popovtschak, 2010; Thanheiser, 2010; Heiss and Thanheiser, in press). In the pollen profile olive also seems to be the major factor in the arboreal pollen sum; it declines after the 3rd century AD (fig. 6a).

But in contrast, in the charcoal record (fig. 7), *Olea* only appears in the upper layers beginning with the 1st century BC, which indicates that this species was also used for its wood, not only its fruits (see for instance older evidence of this kind from Sicily: Stika et al., 2008; Mercuri et al., 2013; Sadori et al., 2013). The charcoal spectrum is dominated by oak (*Quercus*, mainly deciduous taxa) and some species from the cluster pine group (*Pinus* subsect. *Pinaster*), to varying extents. Woody plants representative of a maquis shrubland, and high-altitude woodland from elevated altitudes are found in minor quantities.

Discussion

Interpretation of the stratigraphy of the harbour basin (with special regard to Eph 276)

The base of Eph 276 is formed of laminations, probably varves, deposited in a non-bioturbated marine embayment at a water depth of c. 10 m from the 2nd century BC to the 1st century AD (fig. 4a). Ostracods represent changing environments: brackish-lagoonal (*C. torosa*), freshwater to a slightly salinity (*D. stevensoni* and *L. inopinata*), and brackish-marine (*A. tepida*) ones. While variations of Ti may be linked to the beginning of detrital input from catchment erosion due to fluvial activity (Haug et al., 2001; Yancheva et al., 2007; Panizzo et al., 2008), the increased Sr/Ca ratio may indicate a strong salinity (Wünnemann et al., 2006). Therefore, the basal sediments were deposited in a very low-energy environment, probably under marine-brackish conditions with seasonal input of freshwater.

Unit 2a, also encountered in Eph 279, 270, 284, 271 and 278 (fig. 3), seems to reflect a very fast sedimentation of silts (~30 mm/y), with some thin sand intercalations, from the 2nd century BC to the 1st century AD; these are probably harbour muds (Marriner and Morhange, 2006a). Despite the very high sedimentation rate, a natural deposition is likely since the sediments at the base reveal stratifications under natural conditions (see thin section in fig. 4a). A high sedimentation rate has also been described by Marriner and Morhange (2006a) for the ancient harbour of Marseille (20 mm/y). In Eph 278 and 271, the silts were deposited earlier, between 1172–932 cal BC and 397–211 cal BC. Obviously, they represent the natural deposition before the harbour and canal construction. The age inversions in Eph 284 and 271 may derive from dredging activities (see chapter below). The presence of *Isoetes* spores in the lower part of unit 2b is typical of fluvial transport, as proven in the Büyük Menderes graben (Knipping et al., 2008). They indicate the proximity of the river delta which has also been described by Strabo (1924: 14, 1, 24) and Livius (37, 14–15) for this time (see also Kraft et al., 2000, 2011; Zabehlicky, 1995). Moreover, it is supported by the brackish-lagoonal ostracod *C. torosa*, and few freshwater ostracods (*D. stevensoni*, *Candona* sp.). Low Sr/Ca ratios are characteristic for a brackish water environment with low salinity. MS detects variations in the ferrimagnetic mineral content of sediments (Mn and Fe-oxides, hydroxides and oxyhydroxides) (Dearing, 1999). Thus, high MS values in the sandy intercalation reflect the terrigenous flux derived from fluvial input, as proven in Portus, the harbour of Ostia (Salomon et al., 2012). On top of the unit, the occurrence of the brackish-marine foraminifer species *A. tepida* and *H. germanica* indicate a facies change to a brackish-lagoonal milieu.

A sharp contact separates unit 2a from unit 3a, also encountered in Eph 270, 284 and 278 (fig. 3). The 0.40–2 m thick alternations of greyish brown and pale yellow silts may have been caused by seasonal variations in the hydrological conditions in a protected harbour basin (as for similar examples see Marriner et al., 2006, 2010; Algan et al., 2011; Salomon et al., 2012; Sarti et al., 2013): the pale yellow layer may result from epilimnic calcification during summer, with terrestrial clastic input occurring during the rainy winter season. Similar laminations composed of detrital sediments and evaporate minerals have been described, e.g., for the Black Sea (Garber et al., 1987), Saudi Arabia (Ginau et al., 2012) and Nar Gölü in Turkey (Dean et al., in press). In this section Cu attains the highest values in the core, most probably due to human impact (Sakan et al., 2013). A significantly decreasing sedimentation rate to 1.6 mm/y may indicate a decreased fluvial input, also proven by low Ti values. Declining Sr/Ca ratios towards the top of the unit reveal a low salinity and increased biogenic production; microfossils suggest once more a lagoonal environment with brackish ostracod *C. torosa* and brackish-marine foraminifers *A. tepida* and *H. germanica*. In core Eph 279 unit 2a is overlain by swampy material during Roman Imperial times which is evidence of siltation in the eastern part of the basin. Eph 271 reveals a similar environment on the southern side. According to historical sources of the 2nd century AD the deposition of waste and debris in the basin was prohibited since it contributed to siltation (Zabehlicky, 1995; Kraft et al., 2000).

Unit 4a (Eph 276, 270, 284, 278) reveals a decreasing grain size, similar to unit 1a. The layer was deposited in a low-energy environment with declining human impact (less Cu) and a more natural sedimentation in a lagoon-like environment with abundant brackish-marine foraminifers *A*. *Tepida* and *H*. *germanica* and the brackish-lagoonal ostracod *C*. *torosa*. It was deposited from the $6^{th}/7^{th}$ centuries AD onwards; the top is poorly dated.

Decreasing Ti values towards the top of the core indicate the recession of fluvial and marine input (unit 5a). The high Ca values and lower Sr/Ca ratios in units 5a and 6a (Eph 279, 270, 276, 284, 278, 271) can be explained by a higher biogenic calcite production (Bayon et al., 2007). Missing greyish brown silts may be a result of reduced cultivation on surrounding slopes leading to a recovery of the natural vegetation. While brackish-marine foraminifers disappear, abundant freshwater gastropods (*Gyraulus* sp. and *Radix* sp.), brackish and freshwater ostracods (brackish: *C. torosa*; freshwater: *Candona* sp., *D*. *stevensoni*) indicate the ecology of a permanent lacustrine system. Only one sample yielded an age of the $13^{th}/14^{th}$ centuries AD.

The organic rich layer in all drill cores (units 7a and 8a) with a thickness of 0.50–2.50 m together with low Ca contents and the dominance of freshwater fauna (gastropod: *Gyraulus* sp.; ostracods: *Pseudocandona sp.*, *Candona* sp.) indicate a swampy environment and the gradually siltation of the area. ^{14}C age estimates prove the peat development after the 14^{th} century. The uppermost part of Eph 276 and 279 represent the final siltation of the area (unit 9a).

Interpretation of the stratigraphy of the harbour canal

Facies interpretation

In contrast to Eph 276, the base of Eph 244 and 245 (units 1b, 2b) is dominated by high-energy conditions until the 8^{th}–6^{th} centuries BC, probably even until the 4^{th}–3^{rd} centuries BC (^{14}C age at the base of unit 4b, Eph 245). The time difference may derive from a slow sedimentation rate. High values of Sr/Ca are typical of a high salinity, Ti and MS to the top of unit 2b characteristic of detrital input from the environs. The sediments are interpreted to be deposited in a marine environment. The overlying layer of stones (unit 3b) may derive from slope debris, deposited during a catastrophic event.

The mica-rich sand (3–4 m thick) on top is evidence of the advancing river delta from the 4^{th} to the 1^{st} centuries BC, in Eph 221 until the 1^{st} century AD (unit 4b in Eph 244, 245, 221). The mica derives from deeply weathered mica schists of the catchment area (Brückner, 1997). Lower Sr/Ca ratios and decreased Ti values prove a lower salinity and increased erosion in the catchment area. The MS peaks correlate with horizons of increased grain size; they are interpreted as fluvial input of the Küçük Menderes in the marine embayment.

A sudden change to a low-energy environment with silts in all three drill cores represents sediments of the canal (unit 5b); its time of operation is dated from the 1st century BC onwards. The decreased Sr/Ca ratio towards the top indicates brackish waters, lower Ti and MS values a continued decline of fluvial input. In this unit, Cu shows the highest amounts of the drill core; it declines after the 5th century AD (unit 6b). It indicates human influence in the sediments as it is not linked to a changing grain size.

In unit 7b, high $CaCO_3$ values and low Sr/Ca ratios reveal biogenic production in a lacustrine environment and a change to freshwater conditions without marine influence (see unit 6a). The peat in the uppermost part of the drill core (unit 8b) represents the final phase of the canal from the 13th century AD onwards.

Interpretation of palynological and parasitological analyses

At the base (PAZ 1), the pollen diagram reveals many indeterminates and *Isoetes* spores, probably transported by the Küçük Menderes river in Hellenistic times. This zone is characterized by a strong anthropogenic influence (*Olea*, Cerealia-type, *Plantago lanceolata*-type, *Cannabis*, high amount of Fabaceae).

From Late Hellenistic to Early Byzantine period, PAZ 2 and 3 represent the canal sediments with a discontinuation of *Isoetes* spores and a rapid decline of indeterminates. *Sarcopoterium spinosum* hints at a higher grazing pressure whereas *Sanguisorba minor* is more likely to have been used as lettuce. With the appearance of eggs of the intestinal parasites whipworm (*Trichuris* sp.) and roundworm (*Ascaris* sp.), typical for latrines (Mitchell et al., 2008; Anastasiou and Mitchell, 2013b), *Cucumis melo*, also found in Portus (Pepe et al., 2013; Sadori et al., 2014), and pollen grains of fruit trees, the anthropogenic impact rises, most likely due to a rising population of Ephesus. *Papaver rhoeas*-type pollen as a predictor of poppy use is abundant. The high amounts of Brassicaceae during this period also point to the use of some species of this family as vegetable like cabbage or radish (cf. Russo Ermolli et al., 2014). Between the 3rd and the 5th centuries AD, the amount of eggs of the intestinal parasite *Trichuris* sp. decreases. This may be linked to a crisis at Ephesus in the 3rd to early 5th centuries AD. Several severe earthquakes occurred during that time.

In the overlying zone PAZ 4, the increasing amount of *Pinus* indicates fallow land with pines as pioneer trees. The decreasing indicators for human impact (less *Olea*, discontinuation of intestinal parasites) may reflect the declining population in Ephesus after the 7th century AD. However, settlement activities still continue (e.g. flax pollen *Linum usitatissimum*-type). It also persists during the 13th–14th centuries AD (PAZ 5). Abundant aquatic and swamp plants indicate the beginning siltation of the canal.

Palaeoenvironmental changes and their consequences on the harbour's life cycle

The Ephesia from the end of the 2nd millennium BC to the 2nd century BC

From the beginning of the 2nd millennium to the middle of the 1st millennium BC, sandy layers in the western cores reveal a dynamic marine environment with detrital input from the environs. This confirms, once again, that many parts of the later city of Ephesus were built over formerly marine strata (Kraft et al., 2005).

From the 4th–3rd centuries BC onwards, longshore drift and the influence of the Küçük Menderes became dominant in the marine embayment in the western part, represented by a mica-rich unit in the canal. Peaks in MS correspond to a coarse-grained fluvial material. Fluvial transport is also corroborated by many indeterminate pollen grains which show signs of decay during transport, and by *Isoetes* spores which derive from the hinterland. The sedimentation rate of ~6 mm/y (Eph 244) until the 1st century BC can be explained by an increased erosion rate in the drainage basin, triggering a faster advance of the Küçük Menderes delta. This has also been described by Grove (2001) and Eisma (1978). Human influence is apparent with Fabaceae, *Cannabis*, Cerealia-type and *Plantago lanceolata*-type pollen.

The Ephesia under strong human influence (2nd century BC – 7th century AD)

Within the harbour basin, laminations at the base of core Eph 276 dating from the 2nd century BC to the 1st century AD were formed under low-energy marine conditions (unit 1a). The sudden change in Eph 276 from laminae to homogeneous silts and a particularly high sedimentation rate is evidence of harbour muds and the proximity of the delta front, also confirmed by the presence of *Isoetes* spores. From historical sources it is known that a mole on the northern side of the harbour was constructed between 159–138 BC in order to maintain the harbour's function for trade and communication and as a protection against the deposition of river sediments (Kraft et al., 2000, 2001; Zabehlicky, 1995, 1999; Steskal, in press; Strabo, 1924: 14.1.24).

A sudden change to low-energy conditions indicates the man made development of a canal around the end of the 1st century BC to the beginning of the 1st century AD. This is consistent with results from the necropolis area which was accessible from the 1st century AD onwards (Steskal, in press; ÖAI, 2011) and a ^{14}C age estimate (44 cal BC – cal AD 52) of the siltation layer of Eph 243 north of the canal (coordinates: E 27°19'30,696", N 37°56'52,346"). In the pollen spectrum the decrease in non-identified pollen grains and the absence of *Isoetes* hint at a protection from fluvial sediments. Eggs of intestinal parasites, muskmelon, *Cannabis* pollen, and fruit tree pollen as well as raised Cu values are indicative of strong human influence. Most of the material originated from the discharge of sewage and city waste into the harbour and the canal since the city's drainage system led into the basin (Ortloff and Crouch, 2001).

This is also visible in the harbour basin: the deposition of laminae between the 1st centuries BC/AD and to the 6th/7th centuries AD suggests an intensive use of the harbour which corresponds to the most prosperous phase of the city. Low-energy sedimentation as indicated by the deposition of silts and clays together with a changing geochemistry and sedimentology resulted from the construction of a protected harbour basin (Kraft et al., 2000); later the construction of the hexagonal harbour basin in the 2nd century AD (Zabehlicky, 1995). The appearance of brackish-marine foraminifers 30 cm below this sharp contact already reveals a declining freshwater influence. Microfossil assemblages of ostracods indicate shallow brackish water conditions. The base of the stratified layer reveals a water depth of c. 4.5–5 m below the former sea level (sea level in antiquity was at least 1 m lower than today). This matches observations made during excavations: Zabehlicky (1999) reconstructed a water depth of ~4 m derived from the margins of the port. Raised Cu values, the occurrence of Pb and fruit tree pollen confirm human impacts (Sarti et al., 2013; Delile et al., 2015) and an ongoing siltation in the eastern part of the basin and on the southern side of the canal. The decrease of eggs of intestinal parasites may be linked to a crisis at Ephesus in the 3rd to early 5th centuries AD.

Anthropogenic impact also left its mark in the on-site charcoal record from the city area. The most significant aspects of the charcoal spectrum in the stratified sewer contents are a massive decline of oak in the 1st century BC and its nearly complete replacement by *Pinus*. This development only reverts incompletely in the 3rd century AD layer, still leaving a significant amount of *Pinus* along with *Quercus* and other woodland plants. The role of cluster pines in the region is most likely that of an anthropogenic indicator: only two species from the group – *Pinus brutia* and *P*. *pinea* – are likely to have occurred in the region during antiquity, and both are fostered by anthropogenic action, either through degradation of natural forest as in the case of *P*. *brutia* (Axelrod, 1975; Knipping et al., 2008) or by planting as in *P*. *pinea* (Kislev, 1988). High quantities of *Pinus* in the charcoal record during the Roman period may result from the overuse of woodland resources in the vicinity (Heiss and Thanheiser, 2014). In the pollen profile, however, as opposed to the charcoal record, only the major decrease in arboreal pollen (mainly of *Olea*) is noticeable for the Roman period, while the massive increase in *Pinus* pollen begins later, i.e., after the 3rd century AD.

The charcoal record also reveals another aspect of woodland use: When all data from the Roman period are included (tab. 2), it becomes apparent that throughout there is a noticeable presence of plants from the supra-Mediterranean vegetation and thus from woodland in the

Ephesian hinterland: *Fraxinus* (ash), *Ulmus* (elm), and *Fagus*/*Platanus* (beech/plane) point to a considerable amount of wood gathering – be it for fuel, tool-making or construction timber. Two wood types may have been imported from even further away: *Abies*/*Cedrus* (fir/cedar), both missing from the pollen profile, were most probably imported from at least 150 km away (Davis, 1965–1988), either to the north (fir) or to the southeast (cedar). The finds of *Tilia* (linden) charcoal may also represent aspects of Roman trade routes. However, the latter species is present in older phases of the pollen profiles Eph 269 and 228 in minor quantities, and may therefore have still been present in the area during the Roman period.

Dredging activities

From ancient literature we know that the harbour and canal had been cleaned and dredged several times between the 1st to the 3rd centuries AD (Kraft et al., 2000, 2011; Zabehlicky, 1995). While Vitruvius only describes the technique as such, findings of a wreck of a dredging vessel in Marseille, in addition to dredging scars in Naples, provide strong evidence for dredging (Marriner and Morhange, 2007; Giampaola, 2009; Carsana et al., 2009; Morhange and Marriner, 2010; Pepe et al., 2013).

In the homogeneous sediment of the harbour basin, direct evidence of dredging activities is not visible – at least not in the sediment cores with a diameter of 6 cm). Nevertheless, an age inversion in Eph 284 and 271 (fig. 3) may be the result of dredging close to the assumed quay on the northern and southern side of the basin/canal. In Eph 276, the high sedimentation rate of ~30 mm/y (2nd century BC to the 1st century AD) may be explained by a dredging dump site. However, the laminations at the base of Eph 276 are evidence of a deposition under natural conditions (thin section, fig. 4a).

A sharp contact separates sandy layers from overlying silts and clays (units 2b to 3b in Eph 244, 245, 221, fig. 3). Angular stones (quartz, mica schist) and several ceramic fragments detected in Eph 244 and 245 must have been washed into the canal or dumped there intentionally. A water depth of 3.50–4.00 m is estimated for the canal close to the mole, while it is about 7 m for the centre of the basin (Langmann, 1990; Zabehlicky, 1999). Dredging of up to 6 m matches observations from cores Eph 244 and 245.

Further possible evidence of dredging are the marine ingressions noted in the microfaunal study of core Eph 276 from the Roman harbour (fig. 4a). After a successful dredging of the harbour and the canal, the sea could once again ingress into the area – until the ongoing siltation re-established brackish and finally even freshwater environments.

The dredged material may have been deposited at Kumtepe on the northern side of the channelled Küçük Menderes, about 4 km to the west of the city. On Schindler's map of 1897 it is located next to harbour installations (harbour site no. 5 in fig. 1; see Stock et al., 2013). According to coring Eph 324 (coordinates: E 27°17'8.47", N 37°56'49.59"; total depth: 7 m), this artificial hill consists of sand. It is not a remnant of a beach ridge, because it is too high (elevation up to 20 m), and it trends perpendicular to the coastline (ÖAI, 2012).

Development since the 7th century AD

Greyish silts of a natural sedimentation were deposited in the harbour basin in the 6th/7th centuries AD, probably in a lagoon-like environment. The harbour is thought to have been no longer navigable by ships with a deep draught (presumed water depth <3 m) (Scherrer, 2007); thus, following the retreating coastline new ports were established, e.g. at Çanakgöl and the Customs house in Pamucak 5 km to the west of Ephesus (Stock et al., 2013, Steskal, in press). Both in the port and in the canal, a Ca-rich layer with freshwater and brackish microfauna overlies the brackish sediments. Its deposition took place between the 7th and the 13th centuries AD. The microfossils indicate the development of a closed lagoon-like water body. In contrast to the stratified layer in the basin, the Ca-rich unit is void of clastic sediments from the surrounding area. Parasite eggs disappear while *Olea* decreases considerably, maybe related to a decreased number of olive groves. The most probable reason is the decline of the city after the middle of the 7th century AD. In addition, the rise in *Quercus ilex*-type and *Pistacia* point to the increased importance of pasture farming. The higher values of pine tree pollen support this hypothesis of more abandoned land. The reason for the declining human influence is most likely the shrinking population and, thus, a less intensive use of the harbour and the surroundings. According to the palynological analysis, marine/brackish algae disappeared; they were progressively replaced by aquatic and amphibious plants, indicating a siltation of the canal. Even though the canal was still connected to the Küçük Menderes river and hence the sea *via* two small channels (cf. Schindler's map, 1897), its further use is unlikely. Settlement activities, however, are still confirmed by anthropogenic indicators (fig. 6a). Peat with freshwater species have evolved since the 13th/14th centuries; at the end of the visible canal from the 17th century onwards.

Conclusion

Our research on the Roman harbour and the harbour canal of Ephesus has revealed the development of the area since the end of the 2nd millennium BC. Rapid sea-level rise until the middle of the Holocene created a large marine embayment, bordered by the flanks of Bülbüldağ and Panayırdağ Mts. At the end of the 1st millennium BC, prodelta sediments of the Küçük Menderes were deposited as evidenced by sediments rich in mica and by the transport of *Isoetes* spores from the hinterland. The proximity of the delta is underlined by the high sedimentation rate from the 2nd century BC to the 1st century AD.

A stratified layer rich in organic matter, Ca and brackish microfauna, attest to the development of a protected harbour basin. Strong human impact is proven for the period between the 1st century BC until the 7th century AD with elevated Cu values, high amounts of pollen from cultivated plants, the occurrence of muskmelon pollen plus the discovery of eggs of two species of intestinal parasites. This suggests that most of the material originates from the city's waste and sewage. From the 7th century AD onwards Cu values decrease, fruit tree pollen declines, and parasite eggs disappear. Although more *Pinus* occur in the pollen profile, it decreases in the charcoal record after the 3rd century AD, possibly consistent with decreasing exploitation of the woody vegetation.

After the 7th century AD, the abundance of brackish and freshwater ostracods proves the development of a closed lagoon-like water body, which finally turns to freshwater. Dredging operations of the harbour basin are known from the literature; possible sedimentary evidence may be the marine ingressions evidenced by the microfauna study. Later, the harbour was still connected to the former course of the Küçük Menderes and with it to the sea *via* two small channels. However, when new harbours were established westwards the area closer to the sea became the important one for trading and commerce. Peat growth in the harbour and the canal since the 14th century AD is evidence that at least by then the Roman harbour of Ephesus had lost its connection to the sea and, thus, its function.

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4. Demise of a harbor: A geochemical chronicle from Ephesus

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Demise of a harbor: a geochemical chronicle from Ephesus

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ABSTRACT

At the end of the first century BC, Ephesus became the Roman capital of Asia Minor and the most important commercial, religious, and cultural center of the region. In order to evaluate the status of anthropogenic fluxes in the port of Ephesus, a 12 m long sediment core drilled in the Roman basin was investigated to shed light on the paleo-environmental evolution of the harbor using grain size distribution analysis, ^{14}C ages, major and trace element geochemistry, and Pb isotope compositions. With the help of complementary sedimentological data and Principal Component Analysis, five distinct units were identified which, together, reflect the different stages of water history in the harbor. Among the major disruptive events affecting the port were earthquakes and military events, both of which were particularly effective at destroying the water distribution system.

Seasonal floods of the Cayster River (Küçük Menderes) were the major source of the silt that progressively infilled the harbor. Silting in was further enhanced by the westward migration of the river mouth. A single major disruptive event located at 550 cm core depth and heralding the development of anoxia in the harbor marks the end of the dynamic regime that otherwise controlled the harbor water throughout the Roman Empire period. This remarkable event may correspond to a major disruption of the aqueduct system or to a brutal avulsion of the Cayster River bed. It clearly represents a major disturbance in the history of life at Ephesus. It is poorly dated, but probably occurred during the reign of Augustus or shortly after. Lead isotope and trace metal evidence suggest that in the four bottom units pollution was subdued with respect to other Pb metal inputs, presumably those from aqueducts and natural karstic springs. Near the top of the core, which coincides with harbor abandonment and the more recent period, anthropogenic Pb contamination is clearly visible in both Pb abundances and isotopic compositions.

1. Introduction

Lead isotope studies have opened up a new, though somewhat controversial, perspective on the development of the manufacturing status of ancient cultures over the past several millennia (Hong et al., 1994). Isolated artifacts alone do not suffice to assess the broad and long-lasting aspects of antique trade routes. Lead isotopes constitute a complementary tool in that they play a critical role wherever their compositions can be ascribed to anthropogenic influence in the form of lead and heavy metal pollution of sediments accumulated in harbors, which are highly efficient traps for clays and suspensions. Anthropogenic impact using Pb isotopes as a tracer has so far been documented for the ancient harbors of Alexandria (Véron et al., 2006, 2013; Stanley et al., 2007), Sidon (Le Roux et al., 2003), Marseilles (Le Roux et al., 2005), and Rome (Delile et al., 2014a).

Applying similar methods to the Roman harbor of Ephesus is appealing because of the status of the Ephesus city port during Roman times as an exceptionally influential commercial and religious center of the ancient Mediterranean world. Ephesus was a major town of Asia Minor and has a long history that began in the 10th century BC. Its position at short distances from both the Dardanelles and the populated city states of southern Greece gave Ephesus a strategic role in all the wars affecting Asia Minor and the Aegean Sea since the Persian wars of the classical period. Its

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importance remained prominent during Hellenistic and Roman times and during the entire history of the Byzantine Empire, and only declined as a result of the Turkish conquest. Because sediments gradually filled in the inlet of the Cayster River (Küçük Menderes), the harbor of Ephesus repeatedly moved down river over the centuries (Kraft et al., 2000, 2011).

Here we use samples from a 12 m long sediment core taken in the Roman port of Ephesus to investigate the paleo-environmental and hydraulic evolution of the harbor using grain size distribution analysis, ^{14}C ages, major and trace element geochemistry, and Pb isotope compositions. We focus in particular on the relative abundances of Pb and other chalcophile elements in the harbor sediments and discuss the respective status of the anthropogenic and natural metal fluxes and their origins as deduced from the Pb isotope record.

2. Historical background

Literature on the history of Ephesus is abundant because of the wealth of ruins left by its different inhabiting cultures and its role in the history of this part of the world first as a major religious center dedicated to Artemis and later as one of the leading churches of the Mediterranean world. For a detailed historical context of the present work, the reader is referred to the well-documented textbook by Foss (1979) and to Scherrer (1995). Here we provide only a brief overview.

Different sites were inhabited in the immediate vicinity of classical Ephesus since the Neolithic culture and during the Bronze Age. The historical city (close to the Artemision) was founded in the 10th century BC by Ionians and became part of the Ionian League. The classic site (at the base of the western side of the Panayırdağ) was occupied around 300 BC under Lysimachus, one of Alexander's generals, but quickly passed under Seleucid and then Ptolemaic rules. After the Battle of Magnesia in 190 BC, Ephesus came under the domination of Pergamon, and finally became part of the Roman Republic in 133 BC. After the Mithridatic wars (ending in 63 BC), Augustus made Ephesus the capital of Asia Minor. At that stage, the surface area of the city, enclosed by the walls of Lysimachus, is thought to have extended over more than 2 km^2 and its population to have reached 50,000 inhabitants.

The city and its temple were destroyed by the Goths in 262 AD. But Ephesus was rebuilt and enlarged by Constantine and soon recaptured most of the importance it had held since Hellenistic times. A burst of seismic activity between 358 and 365 AD repeatedly destroyed major cities around the Aegean (Guidoboni, 1994), including Ephesus. In the 7th century AD, several additional disasters struck Ephesus, notably the major earthquake of 614 AD, as well as the repeated sacks by Arab, Frankish, and Turkish raiders. Western Turkey is well known for being subjected to frequent earthquakes of large magnitude (e.g., Vannucci et al., 2004). Although some dates are not well established, particularly severe earthquakes persistently ravaged the city in AD 17, 23, 47, 178, 194, 262, 275, 337, 358 to 365, and 614 (Guidoboni, 1994; Foss, 1979). In AD 1304, what was by then left of Ephesus fell into the hands of the Turks, and its population was either deported or massacred. These adverse troubles combined with the final stages of insilting of the harbor basin, which had incessantly plagued harbor activity since its early Hellenistic days (Strabo, XIV.1.24), precipitated the demise of the harbor and the city it served.

3. The study area

Ephesus' harbor lies on the Aegean coast of Turkey at the western extremity of the Küçük Menderes graben (KMG) (Fig. 1). The KMG corresponds to the catchment area of the Küçük Menderes (Cayster) river, which is divided into five sub-basins delimited by pre-Miocene geology (Rojay et al., 2005). The surrounding hills are composed of crystalline marble or partially dolomitic breccias of Mesozoic age (Vetters, 1989; Çakmakoğlu, 2007). The hills over which Ephesus aqueducts run also include Paleozoic crystalline rocks such as granites, gneisses, and micaschists. Water was brought to the city by up to seven aqueducts built between Archaic times and the Roman Empire and repaired during different periods, notably after major earthquakes. This point is particularly important since all the waters from the aqueducts terminated in the harbor where they were susceptible to mixing with Cayster river water, marine water, and waste waters of public (baths, fountains) and domestic usage, as well as with water from local workshops (Ortloff and Crouch, 2001).

The variation of relative sea level and the westward migration of the shoreline since Antiquity have been studied by Brückner (2005) and Pavlopoulos et al. (2012). Comparison of the apparent sea level changes with the values predicted by the regional model of Lambeck and Purcell (2005) indicates that subsidence of the coastline next to Ephesus since the classical period was of the order of 3–7 m. According to coring evidence and with respect to sea level index points it seems that, in addition to eustatic sea level rise, there are max. 2 m of rise caused by subsidence.

Geoarcheological research has been carried out at the Ephesus site and in the delta of the Cayster river since the 1990s (Brückner, 1997, 2005; Kraft et al., 1999, 2000, 2001, 2011; Stock et al., 2013, 2014, unpublished data). Besides reconstruction of the successive paleo-environments and the coastline as it has existed since 6000–5000 BC (Fig. 1), this work also has shown that delta progradation led to multiple westward resettlements of the harbor. The ceaseless fight against silting to maintain the harbor of Ephesus as a functioning port during the Hellenistic period is first and foremost reflected in the displacement of the city to the western side of mount Pion (Panayırdağ) by Lysimachus in ~290 BC (Scherrer, 1995).

4. Analytical techniques

A sediment core about 12 m long (EPH 276) was drilled in the hexagonal Roman harbor basin of Ephesus (Fig. 1). We sampled the core at high resolution by taking a total of 111 samples (one sample every 10 cm). The samples were analyzed for grain size distributions (see Stock et al., 2013, for details), major and trace element concentrations (Table S1; see Delile et al., 2014b, for details), and Pb isotope compositions (Table S2; see here below and Delile et al., 2014a, for details). Lead isotope compositions were obtained not on the bulk sediment, but, in order to isolate potential anthropogenic components, on HBr leachates. The leaching procedure consisted in first treating the samples with chloroform to remove most of the organic fraction, then, after rinsing the residues with clean water, leaching them with dilute HBr including ultrasonicating and heating steps. As shown for Portus (Delile et al., 2014a), this technique enhances the contrast between Pb held in surface contamination-prone coatings and detrital silicates. Carbonates also dissolve during the leaching process, but Pb contents of detrital carbonates are naturally low. As for carbonates precipitated within the harbor, they are of biogenic origin (cf. discussion of series D and E below) likely meaning that isotope information obtained on carbonate-rich samples is consistent with that derived from the leachates of the rest of the sample series. The HBr leach fraction was recovered for Pb separation by anion-exchange chromatography using HBr as eluent of the sample matrix and HCl as eluent of the Pb. Lead was also separated from the residues of 16 of the 111 EPH 276 samples. The amounts of Pb extracted from all samples were large (>1 μg) and orders of magnitude above the total procedural blank of ~20 pg. The purified Pb was analyzed for its isotopic composition by multiple-collector inductively coupled plasma mass spectrometry

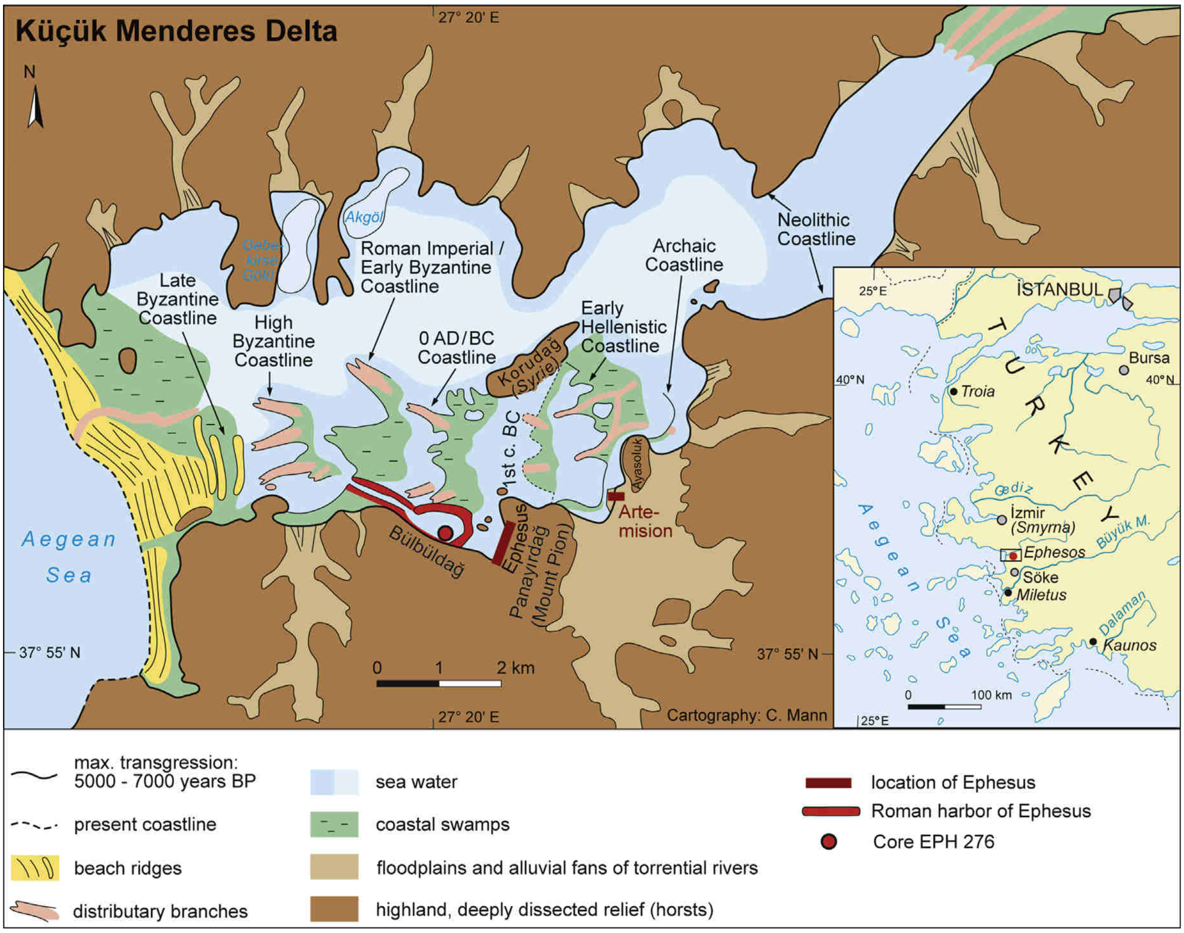

Fig. 1. Map of the Küçük Menderes graben located on the Aegean coast of Turkey (inset) with successive positions of the shorelines and site of core EPH 276 (from Brückner, 2005, modified by Stock et al., 2013 and this study).

(Nu Plasma 500 HR) at ENS Lyon using Tl for instrumental mass bias correction and bracketing the samples with the NIST 981 standard for which the values of Eisele et al. (2003) were used.

Six samples were AMS-^{14}C-dated (Table S3), complementing the chronostratigraphy of neighboring cores analyzed by Stock et al. (unpublished data). The Carbon-14 ages were obtained on fragments of wood, vegetal matter, seeds, and pollen, and are listed in Table S3 and shown in Figs. 2 and 3. Errors on raw radiocarbon ages BP are reported at the 95 percent confidence level (two sigma). The measured ^{14}C (BP) ages were converted into BC–AD dates relative to the continental and marine curves of Reimer et al. (2009) using the Clam software (Blaauw, 2010).

Interpretation of the analytical results rests on different methods of data processing. We applied Principal Component Analysis (PCA) and Factor Analysis to major and trace element concentration data, as well as loss-on-ignition (L.O.I.) (Fig. 2). In the very large data sets typical of those that modern geochemistry can now produce, observations are often correlated. A common case is that of the dilution of elements in sediments by detrital quartz. Such effects render the reading of the underlying causes of geochemical variation and their number difficult. PCA consists in rotating the data in their multidimensional space to convert them into uncorrelated variables known as principal components. Uncorrelated does not equate with independent, however, implying that small changes in rotation may affect all the principal components. PCA generally demonstrates that the variability of the observations can be accounted for by a very small (2–4) subset of variables that carry the bulk of the total variance. Principal components can be calculated from the covariance matrix or from the correlation matrix. Factor Analysis is a related technique that searches for the minimum variance for an arbitrary number of uncorrelated variables. It usually starts with PCA and implements different modes of rotation and weighing.

In addition to the PCA and Factor Analysis we also converted the Pb isotope compositions into their corresponding geochemically informed parameters, which are the model age T_{mod} and the $^{238}U/^{204}Pb$ (μ) and Th/U (κ) ratios (Table S2) using the equations given by Albarède et al. (2012), who also justified the advantages of this representation over those based on raw Pb isotope ratios. In short, T_{mod} is a proxy for the tectonic age of crystalline rocks and their associated ore deposits (or depositional age for sediments), while μ is the $^{238}U/^{204}Pb$ and κ the Th/U ratio of the province in which these rocks formed. T_{mod} closely maps the distribution of the Alpine, Hercynian, and early Paleozoic provinces of Europe, while μ delineates collision belts, and κ is a geochemical parameter with a remarkable regional consistency related to uplift and erosion. Maps of these parameters can be used to divide Europe into coherent regions (Delile et al., 2014a), which justify the use of T_{mod}, μ, and κ to determine provenance of archeological artifacts. T_{mod}, μ, and κ in turn provide a rapid characterization of the geological environment in which ores formed. A Matlab code is given in Appendix A and an Excel spreadsheet in which to calculate these parameters will be provided upon request. As mentioned above, T_{mod} represents the tectonic age of the geological province to which a given sample

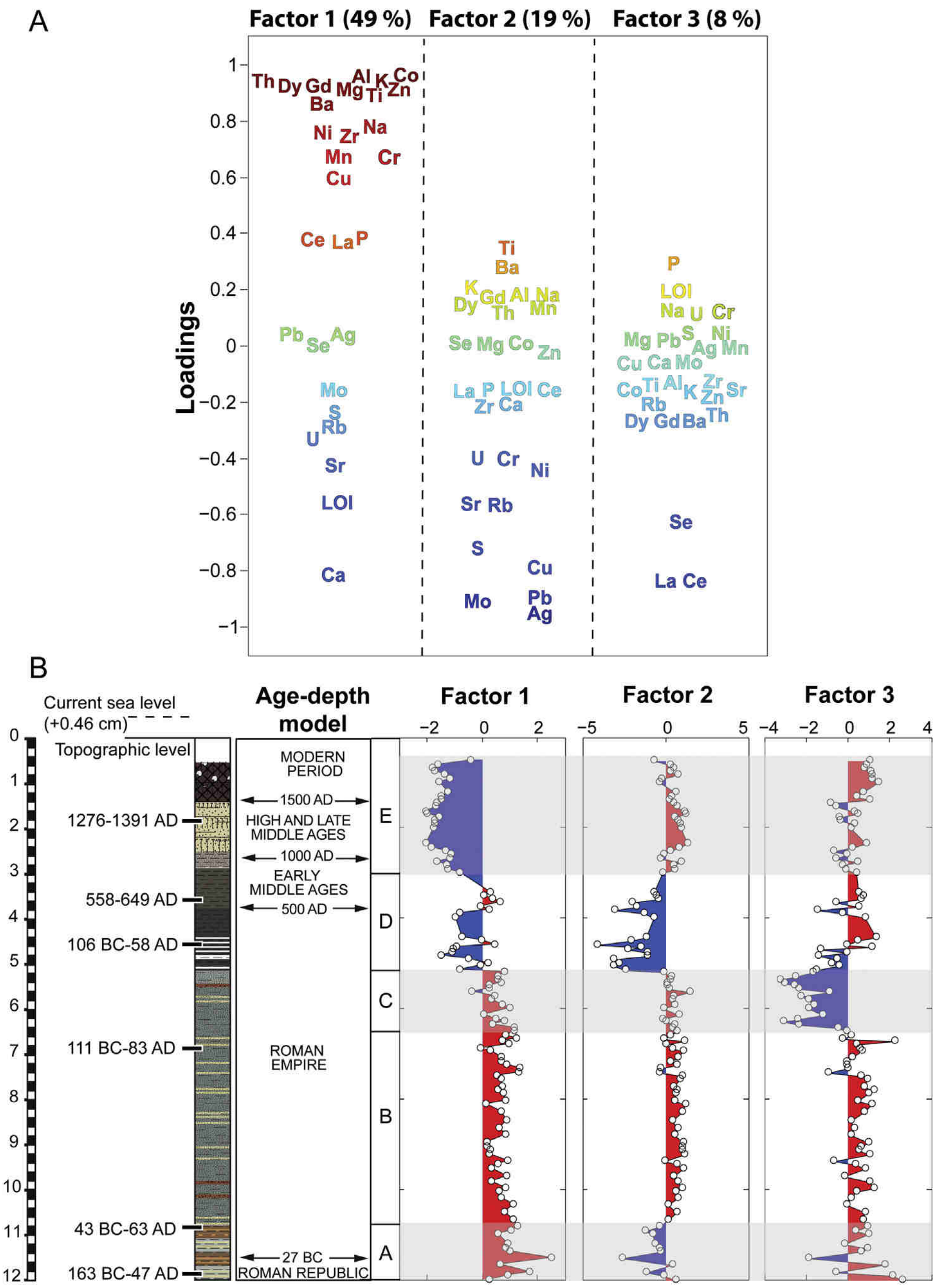

Fig. 2. Factor analysis of major and trace element concentrations. Based on Principal Component Analysis, the number of factors is limited to three. (A) Component loadings. The first factor F1 shows the trade-off between an (Al, Ti)-rich detrital component (F1 > 0) and a Ca-rich carbonate component (F1 < 0). The second factor F2 is dominated by metals (Ag, Pb, Cu, Mo) and sulfur and shows the effect of anoxia. The third factor F3 is dominated by the light rare-earth elements La and Ce and testifies to the presence of heavy minerals in sand. (B) Distribution of the different factors with depth in the column. The plots are compared with the sedimentary units and the age–depth model.

belongs, while μ is best perceived as an indicator of whether this province is a collision range or a tectonically stable area. The variable κ distinguishes upper crust with low κ values from middle and lower crust with higher κ values (Albarède et al., 2012). The precision and accuracy of T_{mod} is typically of a few tens of Ma, but, occasionally, the T_{mod}–μ–κ model fails when the underlying closed-system assumption breaks down due to U addition by recent weathering or hydrothermal activity.

5. Sedimentary units and the age–depth model

The core has been divided into five different units labeled A, B, C, D, and E on the basis of the sedimentological and geochemical traits described in Fig. 3A; they span the entire period of activity of the Hellenistic, Roman, and Byzantine harbor (Table 1).

Unit A (1200–1080 cm) exhibits alternating brown and gray varves composed of massive clayey silts with the presence of several beige to ocher fine layers. The C/M plot (Fig. 3B) indicates that the depositional processes are represented by mixed decantation and graded suspension. Units B and C (1080–515 cm) are characterized by gray to greenish massive sandy silts with the presence of several beige to ocher fine layers enriched in sand. These units were deposited as a graded suspension with embedded fine layers derived from mixed processes of graded and uniform suspension. Unit D (515–290 cm) consists of dark to greyish silts with variable clay (bottom) and sand (top) enrichments. From

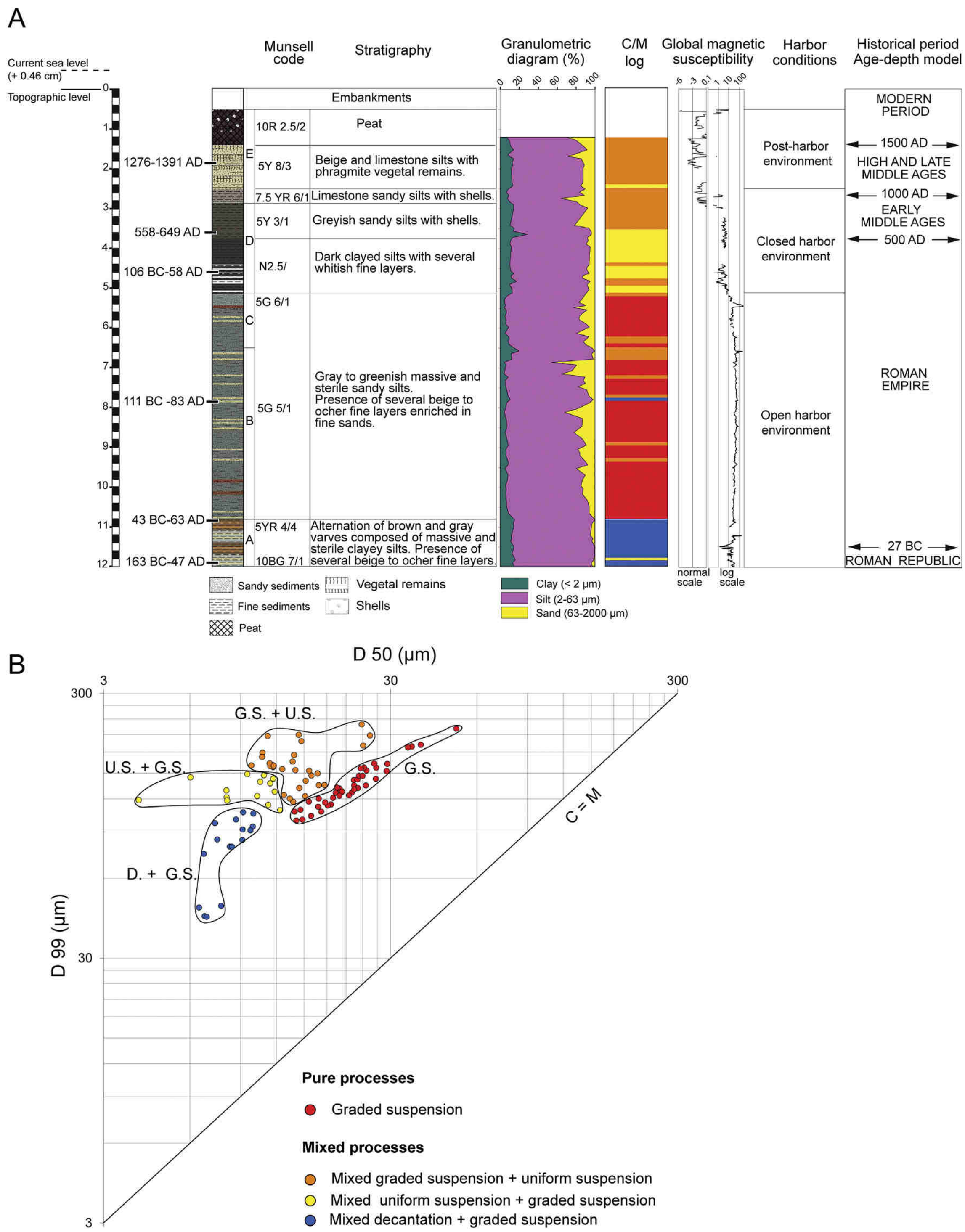

Fig. 3. (A) Stratigraphy and sedimentology of core EPH 276 showing grain size distribution and environmental facies. (B) Plot of the grain size 99 percentile (D 99) versus the median size (D 50) for the different samples analyzed. The different color groups correspond to different sedimentation regimes (see legend). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bottom to top, deposit processes evolve from mixed uniform and graded suspension to a blend with graded and uniform suspensions. Unit E (<290 cm) is composed of beige sandy silts with phragmite vegetal remains. The depositional processes point mostly to mixed graded and uniform suspensions.

The age–depth model is based on six ^{14}C ages (Fig. 4, Table S3). The four oldest ^{14}C ages fall within a narrow time interval and are statistically indistinguishable. An approximate seven meters of sediment were deposited in a few tens of years during the reign of Augustus or shortly after. Such an extraordinarily fast sedimentation rate is consistent with a periodogram analysis (e.g., Albarède, 1995) of the magnetic susceptibility record. The periodogram, which is the equivalent of a Fourier transform for unequally spaced data, identifies prominent periodic fluctuations in the targeted property, here the magnetic susceptibility. After removal of long-term variations (de-trending) by fitting a fourth-degree polynomial, the shortest

Table 1
Depth range of the sedimentary units and probable age assignment.

Unit	Depth (cm)	Probable age
A	1200–1070	Roman Republic
B	1070–650	Early Roman Empire
C	650–515	Late Roman Empire
D	515–300	Early Byzantine (4th–8th century)
E	300–0	Late Byzantine and Turkish

values with significance level $P > 0.95$ occur at 20 and 24 cm (Fig. 5). Longer wavelength peaks probably reflect climatic effects or are artifacts of de-trending. Assuming a seasonal cause for the observed susceptibility fluctuations therefore indicates a sedimentation rate of ~20 cm per year, equivalent, over the 7 m of sediment with the oldest ^{14}C ages, to ~35 years of sedimentary history. In contrast, the average sedimentation rate between the top three ^{14}C samples (early and late Byzantine) is only ~0.2 cm a^{-1}.

6. Results and discussion

6.1. Harbor hydraulics

In order to understand the hydraulic dynamics of the harbor, we first need to estimate its water capacity. The approximate dimensions taken from aerial photographs lead to a volume of (500 × 400 × 5) m^3 = 1.0 × 10^6 m^3 (see also Kirbihler, 2013; Stock et al., unpublished data). We assume that most of the sedimentary layers were deposited during short seasonal flood events of the Cayster River, whereas water running into the harbor came from different potential sources: seawater, runoff, karstic springs, and aqueducts. Seawater and water from springs and aqueducts must have been largely clear of sedimentary particles. Karstic springs are common in the area around the modern Lake Kocagöz (Somay et al., 2008; Somay and Gemici, 2009), which today exists on the site of the ancient harbor basin. A seawater component is present in the water from all the lakes, including Lake Kocagöz (Somay et al., 2008; Somay and Gemici, 2009). Such a component attests to a contribution from spring waters contaminated by marine intrusions into the karst. As for other water inputs, Kraft et al (2007)

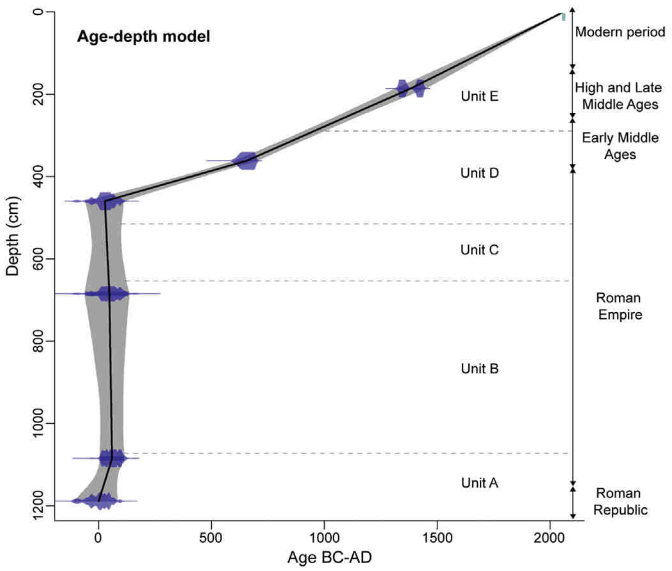

Fig. 4. Age–depth model for core EPH 276 deduced from the six ^{14}C dates with ranges calculated using the Clam software (Blaauw, 2010). The size of the data symbols reflects the confidence level.

pointed out that all the city sewage was diverted into the Great Harbor.

The up to seven aqueducts built during the existence of the Ephesus port carried substantial volumes of water into the harbor. Wiplinger (2013) quotes an estimate of 0.6 m^3 s^{-1} for the Derğirmendere aqueduct alone. Using the model by Ortloff and Crouch (2001), we surmise that the total water distribution to the city from the fully-functional aqueducts at the peak of city prosperity may have been over ~2 m^3 s^{-1}. This number is substantial with respect to the mean discharge of ~11.45 m^3 s^{-1} inferred for the river, not including flood events (Vliegenthart et al., 2007), indicating that if other inputs such as karstic springs and runoff are disregarded, water in the harbor was replaced by the aqueducts in merely six days. This estimate is of course an average estimate and during seasonal droughts the ingress of seawater attested to by the presence of brackish fauna also contributed to the harbor's overall water budget.

Water output is difficult to constrain independently. The harbor canal, whose construction may have started as early as during the first century BC when the shoreline swept past the harbor, was narrow at the harbor entrance (Kraft et al., 2007). Assuming a cross-section at the narrowest point of ~50 m^2 would imply that aqueduct-delivered water was leaving the canal at a rate of 145 m per hour, probably fast enough to limit water ingress from the sea under fair weather conditions. This velocity must have been reduced by the effect of draught and evaporation during the dry (hot) season, and increased by local springs during the wet (cold) season. The presence of brackish water ostracods and occasional occurrence of marine foraminifera (Stock et al., unpublished data) demonstrate that the flow could occasionally be reversed, presumably as a result of a low water table and reduced precipitation during the dry season. Over time, the harbor was nevertheless affected by westward delta progradation and proximity to the mouth of the Cayster river (Fig. 1): by the end of the 2nd century BC, the delta had advanced as far as the Great Harbor (Kraft et al., 2007) and the canal had to be constructed, thus limiting ingress of seawater into the harbor basin even further.

To summarize harbor hydrodynamics, the 'normal' situation is that of a basin steadily filled by polluted urban water initially brought to the harbor by aqueducts and local springs and quickly evacuated through a canal with little ingress from the sea. As long as the coastline is not too distant, some seawater may be admitted during the dry season, while floods of, in the present case, the Cayster River dominated the water balance during spells of heavy rain. Silting in of the harbor would have been caused only by floods, which today are known to carry up to 100–150 m^3 s^{-1} of water (Vliegenthart et al., 2007). The Romans went to great length to protect the harbor from river floods. Kraft et al. (2000, 2011) mention that, in the early 2nd century AD, Hadrian sought to divert the Cayster River with an 18 m high dam and also made multiple attempts to dredge the harbor.

6.2. Environmental conditions in the harbor basin

In order to assess the environmental conditions that prevailed during sedimentation, we plotted the concentrations of first-row transition elements (Ti–Zn) and other metallic elements (Ga, Pb, Mo, Bi, Cd, Ag, As, and Sb) normalized to the upper-crust concentrations of Rudnick and Gao (2003) (Fig. S1). Factor analysis of major and trace element abundances leads to the identification of three major components.

1. *The first factor* opposes elements indicative of the detrital load of the river (Al, Ti, Mg, etc.) to those distinctive of carbonate minerals (Ca, Sr) and L.O.I.
2. *The second factor* singles out chalcophile elements that, as attested to by the presence of sulfur in this group, precipitate as

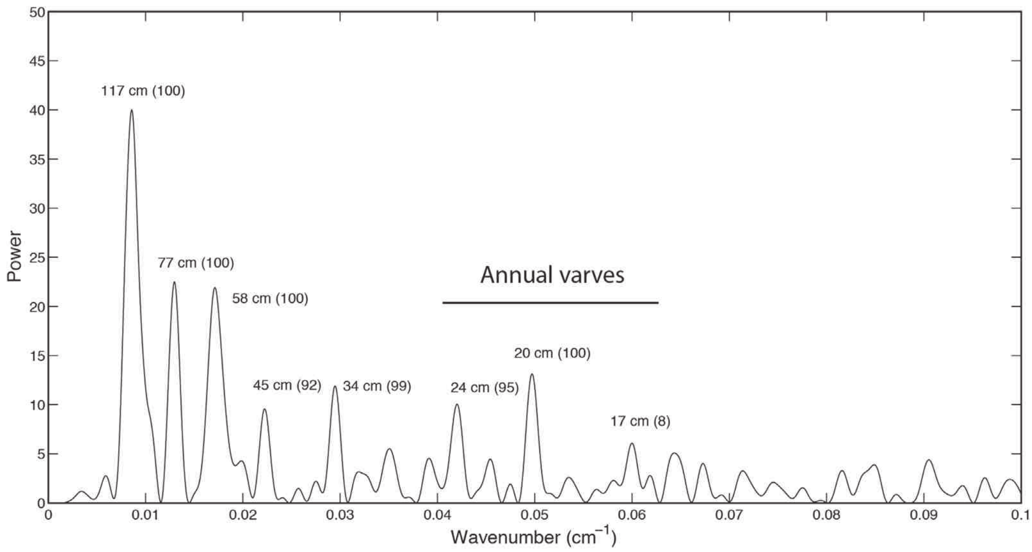

Fig. 5. Periodogram of magnetic susceptibility in core EPH 276 between 440 and 1100 cm. Mean sampling interval is generally ~1 cm. Four extreme values corresponding to discontinuities were removed from the data set. A fourth-order polynomial was then fitted to the data to remove the long-term trend. Peaks correspond to dominant periods, with confidence levels *P* in percent in parentheses. We consider that the shortest periods with $P \geq 95\%$ correspond to dominant annual varves, while longer periods correspond to climatic effects or to de-trending artifacts. The periodogram is interpreted as indicating an average sedimentation rate of 20 cm per year.

sulfide under anoxic conditions (Pb, Ag, Cu, Ni, Mo), or are particularly sensitive to redox conditions (U, Cr). When the elements embedded in this factor are normalized to Al (Fig. 6), as a means of accounting for the variable abundance of the detrital component, and plotted against depth in the core, a sharp increase is observed at 520 cm depth. The significance of this factor deserves some discussion because Pb, Ag, and Cu may also be seen as representing an anthropogenic component. Fig. 6 and S1 further show the striking consistency of these metals both among themselves and with respect to sulfur. Such regular behavior is not supportive of random contamination by a particular metal, such as Pb. The Mo–Pb correlation is very strong ($r = 0.90$ excluding the top five samples likely contaminated by gasoline Pb) as is the Ag–Pb correlation ($r = 0.95$). This factor therefore reflects more on changing redox conditions in the harbor than on anthropogenic pollution.

3. *The third factor* is dominated by La, Ce and, to a lesser extent, Se. Most other loadings are very small, except possibly P. The weak negative correlation between excess La and Ce on the one hand and P deficit on the other hand suggests the presence of non-phosphatic rare-earth minerals, such as allanite, notably in the coarse silts between 515 and 650 cm.

The accumulation of so much sediment in a matter of decades requires an explanation, especially since the thickness of the newly deposited layers exceeds the water depth usually assumed for the harbor (4–6 m), even next to the mole (Stock et al., unpublished data). One factor clearly is the westward progradation of the shoreline past the harbor at about the time of fast sedimentation. F. Stock (personal communication) obtained a ^{14}C age of 44 BC–AD 52 for the silting in of the harbor canal consistent with the present finding. The sharp geochemical discontinuities at 650 and 550 m

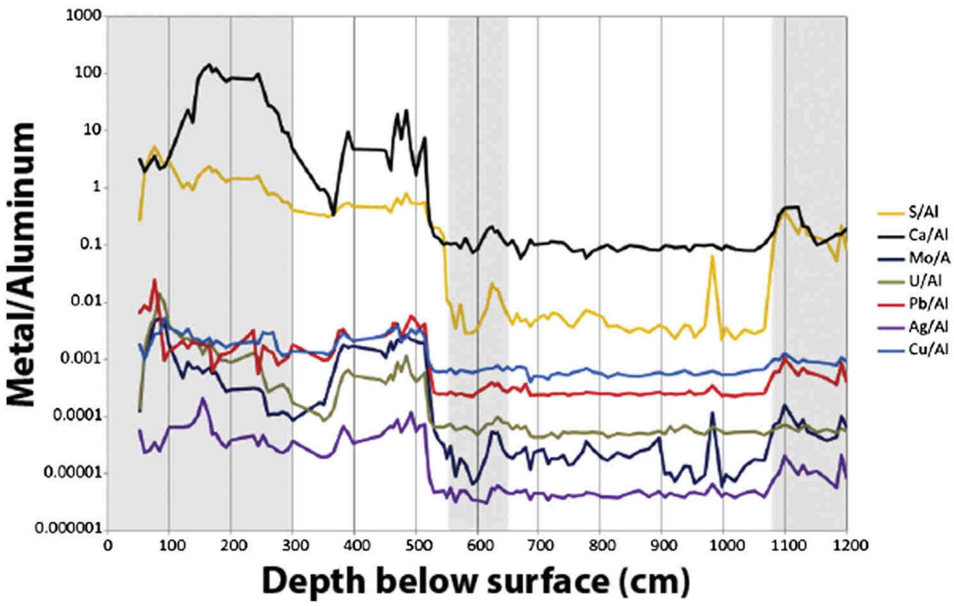

Fig. 6. Downcore variations of calcium and metal concentrations normalized to aluminum. White- and gray-shaded bands delineate the stratigraphic units A–E, with unit A being deepest and unit E shallowest. Note the discontinuities at ~1080 and ~550 cm depth, notably the increase in S and chalcophile elements at the latter.

are flagged by strong peaks of magnetic susceptibility (Fig. 3A). The efficiency of sediment confinement by the harbor prior to the three lowermost units is staggering, while the sudden drop in sedimentation rate and the short but intense episodes of high magnetic susceptibility require the intervention of a brutal event. A probable cause for this discontinuity is an abrupt jump of the Cayster River channel triggered by the abandonment of a meander (avulsions) or by exceptional floods (Brown, 1997). Co-seismic vertical movements (Pavlopoulos et al., 2012) associated with the major AD 17, 23, and 47 earthquakes may also have played a role.

The lowermost *unit A* (1200–1080 cm) was deposited during the Roman Republic. It is consistently dominated by silt (F1 > 0) with anoxic influence (F2 < 0). The anoxic conditions of the basin bottom as attested to by abundant S, Mo, and U (Fig. 2), small excesses of Mo and Ag (Fig. S1), and persistence of seasonal varves, indicate that the terrigenous flux into the early Roman harbor of Ephesus during the 1st century BC was not noticeably oxidized whether water input was freshwater or seawater. Grain size distribution (Fig. 3) reflects an environment where decantation is important (Bravard and Peiry, 1999; Bravard et al., 2014). Input of oxygenated freshwater into the harbor, regardless of its source, therefore was limited and whatever water was added by the aqueduct system must have been dominated by sewage.

Unit B (1080–650 cm) continues to show the prevalence of the detrital flux (F1 > 0), but now with evidence of oxygenation (F2 ≥ 0). The transition-element pattern typically is crustal in origin and no visible anomaly of Mo and Ag is observed (Fig. S1). Grain-size analysis indicates graded grain size distributions by turbulent waters, reflecting that, even at times of flood, water was being constantly evacuated from the harbor. Ephesus counted up to seven aqueducts implying that the early Roman harbor was saved from silting in as much by water from its many aqueducts continuously flushing the basin as by the Roman engineers. As shown by the return of some decantation events (Fig. 3), the aqueducts made silting depend on a fully functioning water distribution system. In this respect, the Menderes area is seismically active (Vannucci et al., 2004) and major earthquakes were particularly disruptive to the long and complex Ephesus aqueduct network (Passchier et al., 2013). Reduction of the water input by the seismic destruction of aqueducts translates into reduced water egress from the harbor basin and hence enhanced efficiency of its role as a sediment trap. Silting in of the harbor in the aftermath of major earthquakes therefore became collateral damage to the rest of the disasters caused by the seismic activity.

The transition to *unit C* (Fig. 2) (650–550 cm) is heralded by a peak of magnetic susceptibility (Fig. 3A). Highly negative values of factor 3, i.e., higher Se, La, and Ce contents, reflect lesser dilution of minor elements by quartz and carbonate. The variation patterns of transition elements and other metals are very similar to those of unit B. As already observed for rivers (Yang et al., 2002), a strong correlation exists between grain size and lanthanide concentrations (Zhang et al., 1998; Yang et al., 2002). This geochemical change is consistent with a sand fraction in unit C smaller than that in unit B. Unit C shows some transient geochemical features (Fig. 7), true harbingers of the major changes that would profoundly affect unit D, notably an increase in sulfur and heavy metal contents.

The transition (550–515 cm) between unit C and *unit D* (515–300 cm) also is announced by a strong peak of magnetic susceptibility (Fig. 3A), corresponding to a strong compositional shift with a surge of the biogenic component (F1 < 0) due to degraded ventilation of bottom waters by eutrophication (F2 < 0). Sulfide reduction and precipitation is attested to by a sudden two-order-of-magnitude increase in the S/Al ratio (Fig. 6). The surge in sulfur, Zn, Ni, and Co conspicuously follows the surge in Ca, Pb, Ag, Cu, Cd, Mo, and Cr by some 30 cm in the core. This delay, which may have been as short as a few years and possibly was only one or two years, is visible in the plot of Fig. 7 as a pronounced negative excursion of ratios such as Ca/S, Mo/S, and Pb/S between 520 and 550 cm depth. These characteristics together with high Sr abundance and the presence of fine calcareous layers (Kylander et al., 2011; Martín-Puertas et al., 2011) show that sulfide precipitation predated the development of eutrophic conditions manifested by the rise in Ca and was due to the sudden isolation of the harbor from ventilated waters. The trend of decreasing ratios of chalcophile elements relative to sulfur, which was perceptible already in

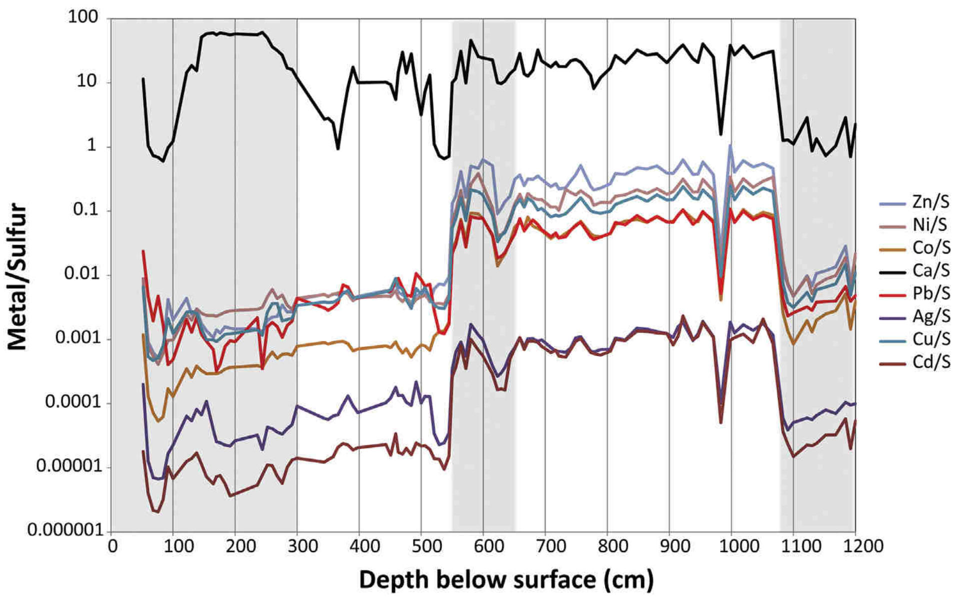

Fig. 7. Downcore variations of calcium and metal concentrations normalized to sulfur (see caption of Fig. 6 for details). Two major discontinuities are again observed at ~1080 and ~550 cm depth, which attest to sudden changes in sediment oxygenation. The 1080 cm discontinuity reflects the improved oxygenation of the harbor in the early 1st century AD. Most elements show a negative excursion between 550 and 520 cm indicating that the rise in sulfur precedes the rise in Ca and most other metals; exceptions are Zn and Co, which are in phase with S. Although a slow trend towards anoxia can be seen in sediments below the 550 cm level, the rate of ventilation is greatly reduced after this episode.

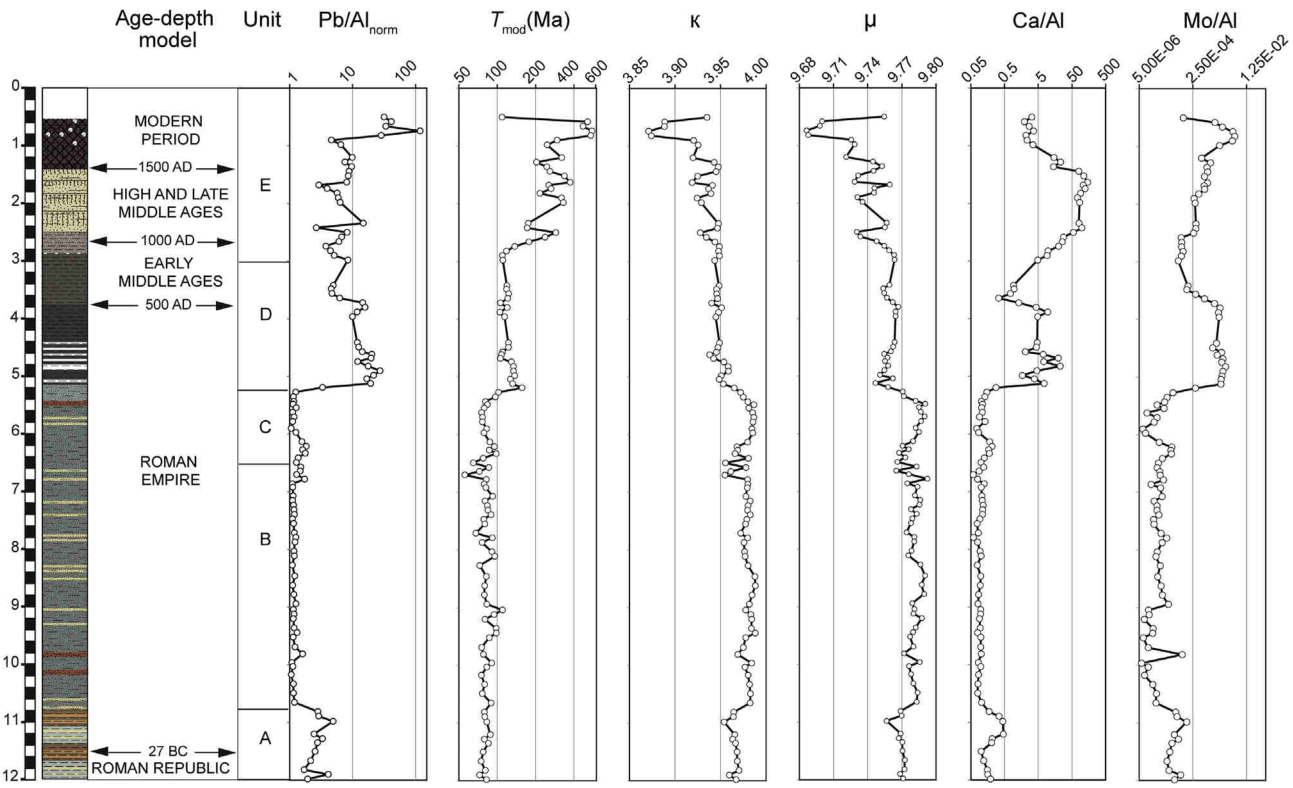

Fig. 8. Downcore variations of Pb/Al_{norm}, T_{mod}, μ ($^{238}U/^{204}Pb$), and κ (Th/U) compared with variations in Ca/Al and Mo/Al. Pb/Al is normalized to the upper continental crust average of McLennan (2001). Major T_{mod} discontinuities are observed between units C and D, and at the base of unit E. A major discontinuity in both μ and κ is observed between units A and B. The variability within unit E reflects an anthropogenic component of uncertain origin.

the early harbor, markedly changes at the C–D boundary, and the rate at which these ratios change significantly increases as well. Again, the correlation between Cr, Cu, Pb, Mo, and Ag (Figs. 6 and 7, S1) excesses is not in favor of selective pollution by metallurgical or any other industrial activities. The destruction of the aqueducts by the major earthquakes ravaging the city, such as the AD 17, 23, and 47 events (see discussion in Guidoboni, 1994), and the AD 64 AD cleaning credited to Barea Soranus by Tacitus (XVI,23) may have combined with the increasing silting of the harbor entrance upon westward progradation of the delta (Fig. 1) (Brückner, 2005) to modify the hydraulic regime of the harbor. The top of unit D records a short-lived return of better oxygenated conditions which, with the caution due the age–depth model, may correspond to the revival of the harbor by Justinian (early and mid- 6th century; Foss, 1979; Scherrer, 1995).

The age–depth model (Fig. 4) places the transition between units D and E (~300 cm) in the 9th century. Carbonate precipitation dominates unit E as it did the lower part of unit D (F1 < 0) indicating a negative water balance (Fig. 2B; Martín-Puertas et al., 2011; Delile et al., 2014b). Excesses of Cr, Cu, Mo, and Ag are still well correlated (Fig. 2A) and confirm the persistence of a sulfur-rich, oxygen-deficient eutrophic regime, but, as shown by the positive F2 values, with oxygen deficiency being less pronounced than in the underlying unit D. The water deficit caused conditions to evolve towards a peatland environment consistent with the considerable extension of the Cayster delta at this time (Fig. 1). The modern estuary of the Küçük Menderes is wetland dotted with alkaline lakes recharged from precipitation and local karstic springs. In late Byzantine times, the harbor may have been functional, but appears to have been increasingly cut off from the sea and the river (Kraft et al., 2011) (Fig. 1). Some of the shallow core samples show excess Pb of probable but uncertain anthropic origin (Fig. 8).

To sum up on environmental conditions, core EPH 276 holds the record of anoxic conditions prevailing at times in the harbor, likely compromising the control of harbor hydrodynamics by human activities. Lead isotopes are expected to shed light on the magnitude of anthropogenic contamination at the time of sediment deposition and this is what the next section will be addressing.

6.3. Interpretation of Pb abundance and isotopic signals

Here we focus on the Pb isotope compositions of the leached fractions only because this is where chances of observing anthropogenic input are maximum. Fig. 8 shows the Pb/Al ratio together with the Pb isotope data in the form of three geochemical parameters, T_{mod} (Ma = million years), μ, and κ. Based on these parameters and the enrichment factor of Pb as represented by Pb/Al and closely tracking F2, the chronostratigraphic evolution of these four curves shows remarkable discontinuities (Fig. 2). In agreement with what was discussed above for other metals, the transition between units A and B stands out clearly by a marked drop in Pb/Al. A subtle increase in μ and κ, while T_{mod} remains young (~80 Ma or Upper Cretaceous), is evidence of change in the sources of Pb. The next discontinuity takes place between units C and D. The increase in Pb/Al and Ca/Al is associated with older T_{mod} (~120 Ma or Early Cretaceous) and lower values of μ and κ. The Pb/Al ratio decreases steadily throughout unit D regardless of the changes in the major Ca/Al dip at 3.8 m depth that we assigned above to the 6th century. From unit D to E, most T_{mod} values exceed 240 Ma and the κ values decrease below the level of previous values. The samples at the top of the core seem to be largely influenced by a modern anthropogenic component.

The hydraulics of the harbor, notably its volume and output, may affect harbor oxygenation and thereby the metal contents of sediments. In contrast, changing Pb isotope compositions require changes in the relative contribution of all the sources of this metal. Lead isotopes reveal the nature and relative strengths of the following potential sources:

1. *Local natural sources*, which are multiple. Lead from the Cayster River comes during short-lived seasonal flood events. Seawater should be extremely poor in Pb, while brackish water from the estuary should be Pb-depleted by iron flocculation in the mixing zone. A contribution from the runoff and from karstic springs that discharge from marble-schists and marble-alluvium contacts (Somay et al., 2008; Somay and Gemici, 2009) should also be considered.
2. *Lead from the main water distribution system*. Such a component may come from the underground of the springs. It can also be acquired during transit from the aqueduct masonry, which includes mortar produced from local limestones. The laminated deposits observed in some aqueducts (Passchier et al., 2011, 2013) indicate hard water with excess alkalinity, which does not favor the idea that Pb was leached out of these conduits. The seemingly high concentrations of chalcophile elements in the sediments, first and foremost Pb but also Co and Mo, do not entail a pollution signal.
3. *The network of aqueducts*, which is unlikely to be a major Pb contributor. The secondary water distribution system at Ephesus is dominated by *terra cotta* pipes and only rarely involves small-diameter lead pipes or fistulae (Ortloff and Crouch, 2001).
4. *Anthropogenic Pb* from local workshops or ballast dropped by merchant ships. Zabehlicky (1995) writes that a lead anchor 14.2 cm long was found during excavations, as well as lead interpreted as ballast, which as much as hinting at a potential source of pollution, signals that the dissolution of Pb artifacts is an exceedingly slow process. The presence of an arsenal on the harbor site at the time of Augustus was noted by Strabo (XIV.1.24). There is no doubt that a city with the population of Ephesus at its best periods would have to rely on local metallurgy. In sediments, however, a geochemical signal of pollution is difficult to detect, and to which extent Pb artifacts attest to wholesale contamination of harbor sediments is not clear. The stability of Pb isotope compositions over long periods of time (decades, even centuries) does not bring to mind metal supply in troubled times. Even more conclusive is the observation that, except for unit E, Cr, Cu, Mo, Ag, and Cu coherently track Pb and Ca: although these elements are sensitive to redox conditions, they were not involved in Pb metallurgy. The Pb/Ag ratio remains remarkably stable, while the record of Ni and Co, for which extractive metallurgy was unknown at the time and which additionally are not found in the same ores as Pb, also follow the Pb record with depth. The lesser impact of anthropogenic Pb pollution at Ephesus relative to Portus (Delile et al., 2014a) directly reflects that the urban water distribution systems used different materials, *terra cotta* for the former (Ortloff and Crouch, 2001) and lead fistulæ for the latter.

The Cretaceous model ages of 80 Ma and 120 Ma observed in the lower part of the core are consistent with those of the carbonate hills surrounding Ephesus and may simply register Pb from the water distribution system (natural springs or conduits). This interpretation is supported by the similar Pb isotope compositions of leachate–residue pairs (Table S2). The residues of the samples with T_{mod} values >200 Ma have not been analyzed, but these ages are consistent with the age of the Paleozoic and Triassic crystalline basement of the Menderes Massif (Vetters, 1989; Bozkurt, 2007; Çakmakoğlu, 2007; Gürer et al., 2009) (see maps in the supplementary material of Delile et al., 2014a).

The appearance of old T_{mod} values shortly after the beginning of unit E, which have not been observed at earlier times, coincides with the onset of carbonate sedimentation (up to 45 wt.% CaO). Runoff and karstic springs more or less contaminated by seawater (Somay et al., 2008; Somay and Gemici, 2009) are therefore left as the main steady sources of water in the ancient port, which since has become the modern Lake Kocagöz. Two competing interpretations are left: (1) while ancient aqueducts were bringing in Cretaceous Pb, runoff and karstic springs now bring in Paleozoic Pb; or (2) old T_{mod} values reflect some anthropic influence of poorly constrained origin. The younger samples with T_{mod} values >200 Ma may represent sources in the Menderes region, but Pb from Thrace, or even from western Europe, cannot be excluded.

Historical evidence in favor of Ephesus hosting significant industrial activity in the 11th and 12th centuries (Foss, 1979, pp. 120–123), however, is faint. Foss (1979, p. 113) further argues that from the 8th century onwards the harbor district was literally abandoned. The center of town moved to the hill of Ayasuluk, while new ports, such as Scalanova (ancient Phygela) built on the site of modern Kuşadası, gradually took over the silted in harbor of Ephesus.

Nevertheless, from the middle of the 9th to the 10th century, the victories of the Byzantines against the Arabs in Asia Minor enabled Ephesus to regain a preeminent position in the Empire (Foss, 1979). A phase of economic development would be consistent with the influx of Hercynian Pb into the most recent harbor deposits. The 10th century medieval economic revolution in Europe favored the development of trade between Europe and the Orient. West or north European sources of Pb cannot be excluded for that period.

7. Concluding remarks

Major changes in the lithology, grain-size distribution, major and trace element chemistry, and Pb isotope compositions of the harbor sediments at Ephesus reflect the history of the water distribution system of this port, notably in response to the increasing and declining needs of a population inhabiting a city that at several points in history was one of the largest of the Eastern Mediterranean. Throughout its history, the Ephesus port was affected by major disruptive events in the form of earthquakes and invasions, both of which were particularly effective at destroying aqueducts.

Progressive silting in of the harbor responded to the westward migration of the coastline and to human maintenance aimed at keeping the harbor functional. A single major disruptive event located at 550 cm core depth and heralding a two-order-of-magnitude drop in sedimentation rate and the development of anoxia in the harbor is clearly visible in the major and trace element record. Although this event may have unidentified military or seismic causes, we favor a durable displacement of the river course, which starved the harbor from further silt input. Overall, despite the presence of metallic artifacts in the harbor, the record of metal concentrations, in particular the Pb isotope record, suggests that pollution of the harbor was subdued relative to other inputs, notably those of aqueducts, except near the time of harbor abandonment (unit E).

Dating and identifying the seemingly key event located in the present sediment core at 550 cm depth, as well as in other cores from the same basin, is a new and major challenge. This event conspicuously marks the end of the dynamic regime controlling the harbor water during all of the Roman Empire and clearly represents a major disturbance in the history of life in Ephesus.

Acknowledgments

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Appendix A. Matlab code for T_{mod}, μ, and κ calculations

The input data should be provided as an Excel file input.xlsx made of three columns,holding $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$.

```
% Matlab code for model age calculations (Francis Albarede)
%
A=xlsread('input.xlsx',1);
m=size(A,1); % find m the number of samples


% decay constants
l8=0.155125;l5=0.98485;l2=0.049475;
% common Pb parameters from Albarede and Juteau (1984)
xstar=18.7500;ystar=15.63;zstar=38.83; kappastar=3.90;mustar=9.66;
% Initialize
FF=zeros(m,1);mu=zeros(m,1);dmu=zeros(m,1);kappa=zeros(m,1);dkappa=zeros(m,1);Tmod=zeros(m,1);Tinit=
1;
T0=3.8; % Beginning stage 2 (Ga), see Stacey and Kramers (1975)
options=optimset('Display','off');
for i=1:m % loop through all samples
   x=A(i,1); y=A(i,2); z=A(i,3);
   myf=@(T)TmPb(T,T0,x,y);
   [Tmod(i),FF(i),exitflag(i,1)]=fsolve(myf,Tinit,options); % use Matlab fsolve with function TmPb
   T1=Tmod(i);
   dmu(i)=(x-xstar+mustar*(exp(l8*T1)-1))/(exp(l8*T0)-exp(l8*T1));
   mu(i)=mustar+dmu(i);
   dkappa(i)=(z-zstar+mustar*kappastar*(exp(l2*T1)-1)-kappastar*dmu(i)*(exp(l2*T0)-
exp(l2*T1)))/(exp(l2*T0)-exp(l2*T1))/mu(i);
   kappa(i)=kappastar+dkappa(i);
end
B=[A,1000*Tmod,mu,kappa,FF,exitflag]
% B holds columnwise the original ratios (A), the model age (in Ma), mu, kappa, the
% exit value of the function to solve (should be less than 1e-9) and an
% exit parameter (1 expected)

function F = TmPb(T,T0,x,y)
      mustar=9.66;
      xstar=18.7500;ystar=15.63; %AJ
      l8=0.155125;l5=0.98485;
      p0=(exp(l5*T0)-exp(l5*T))/(exp(l8*T0)-exp(l8*T))/137.8;
      p1=(exp(l5*T)-1)/(exp(l8*T)-1)/137.8;
      %
      if x~=xstar % Eq. 12 in Albarede et al. (2012)
         F=(y-ystar)/(x-xstar)-p0-mustar*(exp(l8*T)-1)*(p0-p1)/(x-xstar);
      else
         F=(y-ystar)-mustar*(exp(l8*T)-1)*(p0-p1);
      end
   end
```

Appendix. BSupplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.10.002.

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5. In search of the harbours: New evidence of Late Roman and Byzantine harbours of Ephesus

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In search of the harbours: New evidence of Late Roman and Byzantine harbours of Ephesus

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ABSTRACT

Ephesus (Greek name: Ephesos) in Western Turkey was an important harbour city during Antiquity. The progradation of the Küçük Menderes delta has continuously shifted the coastline westwards. Thus, along with the delta progradation, new harbour sites had to be established in a western direction. Historical sources refer to different harbours. While much is known about the Roman and older ones, the exact location of the ports and the coastline in late Roman and Byzantine times is still an open question.

This article presents the results of geoarchaeological research in the area located along the southern flank of the Küçük Menderes graben near Ephesus. Sediments from cores were examined with geochemical, sedimentological, and microfaunal analyses. These data were combined with the study of ancient maps and satellite images. The chronological framework was rendered by AMS-^{14}C ages and diagnostic ceramics. The farthermost inland shoreline dates from 5000 BC; since then, delta progradation has continuously shifted the shoreline westwards. Çanakgöl, today a little lake to the west of the city of Ephesus is identified as the harbour site in late Roman and Byzantine times. This harbour persisted at least until the 16th century AD. Further, a landing site with a pier was discovered west of Çanakgöl, presumably dating to the late Byzantine–Ottoman times.

1. Introduction

The Aegean coastal zone of Anatolia has a long settlement history. In particular, within the fertile alluvial plains and deltas of rivers, often situated in tectonic grabens, such as the Büyük Menderes, Gediz and Küçük Menderes, were favourable settlement areas (Kayan, 1999). Situated approximately 70 km south of Izmir, Ephesus is located on the southern flank of the Küçük Menderes graben (Fig. 1). During the last six millennia, the surroundings of the ancient city experienced major palaeogeographical changes. These were caused by the progradation of the Küçük Menderes (ancient name: Kaystros) delta and the resulting shoreline changes which fundamentally affected the development of the city of Ephesus and in particular of its harbour (Kraft et al., 2000). The advancing delta progressively silted the harbour areas. Thereafter, new harbours were built further to the west. Although literary sources mention "Panormos" and "Pygela" (Fig. 1) as late Roman and Byzantine harbours to the west of the city (Foss, 1979; Hess, 1985; Meriç, 1985; Kraft et al., 2000; Steskal, in press), their exact locations remained unknown. The research presented herein investigated the areas along the foot of the southern flank of the Küçük Menderes graben, and thus identified the ever changing ancient harbour sites. Methods encompassed satellite image interpretation, physiography, vibracoring, sedimentological, geochemical, and microfaunal (foraminifers, ostracods) analyses, as well as AMS-^{14}C and diagnostic ceramic dating.

2. Description of the study area

2.1. Physical setting

Stretching in a west–east direction of about 80 km, the Küçük Menderes graben ends in the Aegean Sea approximately 70 km south of Izmir (Fig. 1). It is surrounded by the Menderes Massif, a 300 km by 200 km mountain range with elevations up to 2000 m. The mountains around the Selçuk plain at the western end of the graben reach up to 700 m (Bozdağ mountains to the north and Aydındağ mountains to the south) (Philippson, 1918; Güldali, 1979; Erol, 1983; Bozkurt and Satir, 2000; Bozkurt, 2001).

Within the regional setting, the graben system of the Küçük Menderes is part of the Aegean–Anatolian microplate. Due to the northward drift of the Arabian plate, it was pushed into a southwestern direction (Polat et al., 2008). During the Pleistocene,

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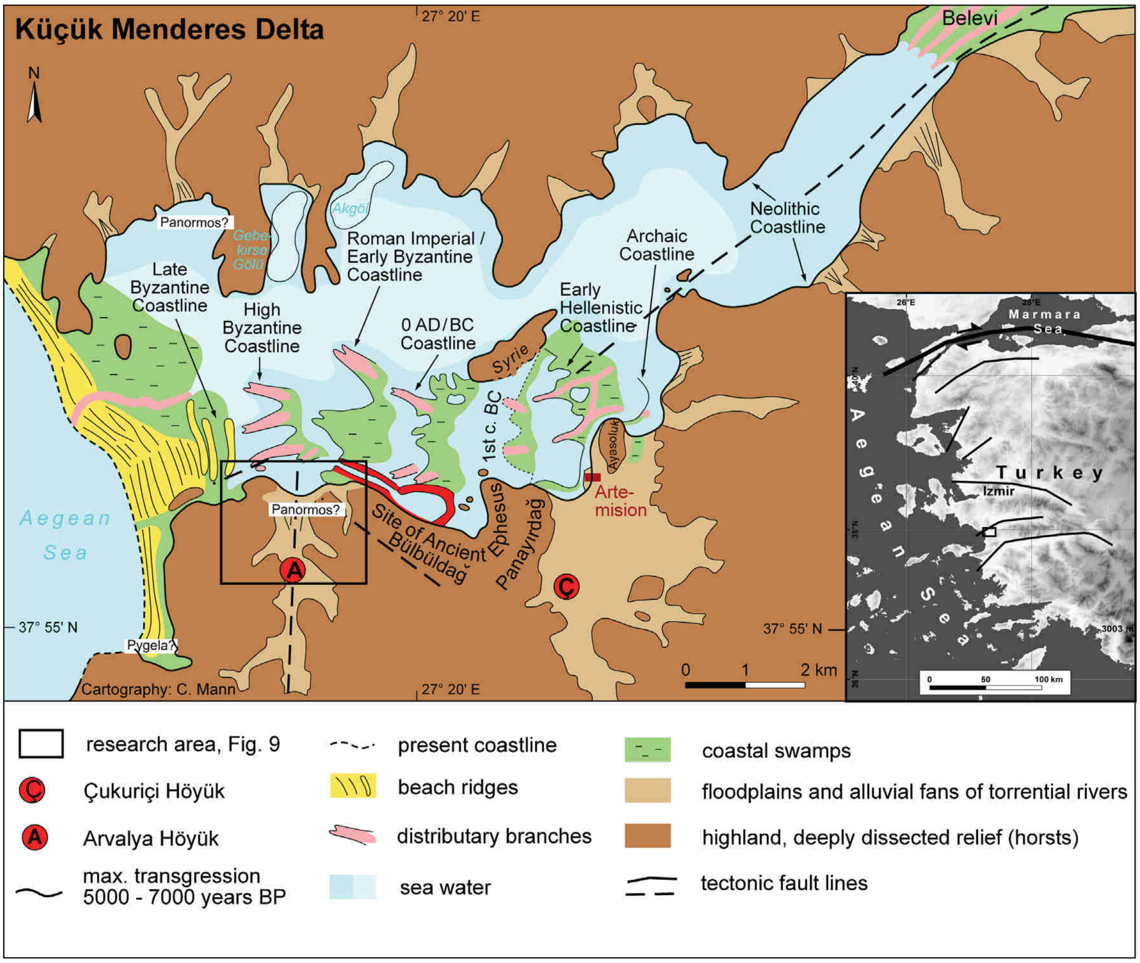

Fig. 1. Geographical setting of the research area and scenario of the delta progradation since Neolithic times. The scenario is based on historical sources and geoarchaeological research (Brückner, 2005, modified). The presumed harbour sites of "Panormos" and "Pygela", discussed in literature, are indicated. The research area is consistent with Fig. 9. The tectonic fault lines are based on Brückner et al. (2010).

the tensions led to the development of the fault system striking SW–NE (Doutsos and Kokkalas, 2000; Hütteroth and Höhfeld, 2002; Taymaz et al., 2007). The river Küçük Menderes follows this faulted structure and flows through the Selçuk plain into the Aegean Sea (Gulf of Kuşadası). Nowadays the floodplain of the Küçük Menderes, situated at the western end of the graben, has a west–east length of about 11 km and a width varying between 2 and 5 km (Fig. 1) (Güldali, 1979). Due to the presence of secondary N–S oriented faults, drained tributary valleys (Derbent, Selinus, Klaseas and Kenchrios) cut the southern flank of the graben (Derbent and Arvalya valleys) (Güldali, 1979; Crouch, 2004). The bedrock bordering the alluvial plain is dominated by marble, mica schist, carbonaceous schist, quartzitic schist, quartzitic paragneiss, quartzite and gneiss of the Menderes Massif (Philippson, 1912; Vetters, 1989).

During the Flandrian transgression, the sea level rose rapidly by about 120 m (Stanley and Warne, 1994) until the middle of the Holocene (Erinç, 1954; Kayan, 1999). A large marine embayment extended into the Küçük Menderes graben as far east as the area of Belevi, today some 18 km inland (Fig. 1) (Brückner et al., 2008). When sea level rise decelerated, the delta of the Küçük Menderes started to form around Belevi and then continuously prograded westwards. As a consequence, the formation of alluvial fans took place in the transition zone between the graben flanks and the developing floodplain (Erinç, 1954; Brückner, 1997) (Fig. 1). The floodplain is currently dominated by the former islands of Syrie and the former Ayasoluk peninsula (Philippson, 1912; Kraft et al., 2007).

The Küçük Menderes river was freely meandering until its regulation in 1934 (Eisma, 1962; Güldali, 1979). Since then, the Menderes debouches into the sea further north and a new delta was formed. However, little sediment has accumulated because of the building of barrages and the influence of the marine longshore drift (Eisma, 1978; Güldali, 1979). Former meander loops and oxbow lakes have persisted until today, as did the lakes Gebekirse Gölü and Akgöl (Fig. 1).

The ~9 km^2 research area is located at the confluence of the Kenchrios and the Küçük Menderes rivers. The valley floors are filled with Holocene alluvium, colluvium, and Pleistocene slope debris whereas the bordering mountains are mainly composed of mica schist and marble on the eastern side and Miocene sediments (red breccia) on the western side (Vetters, 1989; Brückner, 1997).

2.2. Location of the successive harbours of Ephesus: A historical perspective

Archaeological work in the Ephesus area started in 1863 with the British engineer J. T. Wood. He searched for the ruins of the Artemision temple that he finally unearthed in 1869 (Wiplinger and Wlach, 1996). Systematic research has been carried out in Ephesus since 1895 by the Austrian Archaeological Institute (Knibbe, 1998) and it has always been accompanied by geographical and geological investigations (Grund, 1906; Philippson, 1912, 1918, 1920; Darkot and Erinç, 1954; Erinç, 1954, 1978; Eisma, 1962, 1978; Vetters, 1985, 1989). Since the 1990s, numerous geoarchaeological studies have been carried out in the vicinity of Ephesus (Brückner, 1997, 2005; Kraft et al., 1999, 2000, 2001, 2005, 2007, 2011; Brückner et al., 2005, 2008).

Throughout its settlement history, the city had different centres and associated harbour sites. During the Archaic period, one settlement was situated on top of the Panayırdağ (Kerschner et al., 2008). The respective harbour site was possibly located on the northern side of the hill in a natural embayment. Palaeogeographic research (Kraft et al., 1999) as well as our field investigations carried out in 2012 in this area proved the existence of a marine embayment at that time. Many ceramic findings embedded in marine sediments date back to this Archaic period. The most important and most well-known settlement was situated between the mountains Bülbüldağ (northern side) and Panayırdağ (western side), directly next to the sea.

Ephesus was founded by Lysimachos around 300 BC and persisted for more than 1000 years as the main settlement site (Wiplinger and Wlach, 1996). During Hellenistic time, the harbour was situated at the foot of the Bülbüldağ and Panayırdağ. Ephesus became the most important city of the Roman province of Asia; in 133 BC the city was declared its capital. As a consequence of the ongoing siltation process during Roman time, the Roman harbour basin was created to the west of the city (Scherrer, 1995; Zimmermann and Ladstätter, 2011).

Already by the end of the 2nd century BC, prodelta silts were deposited in the harbour (Kraft et al., 2011). As the shoreline continued to advance into western direction, the harbour basin was infilled with sediments. It had to be dredged several times and a harbour canal had to be constructed in order to maintain the connection to the sea. From the 2nd century AD on, only small ships could enter the canal. When the Roman harbour basin and canal silted up, Ephesus had lost direct access to the sea, although anchorage sites to the west of the city were still utilised (Foss, 1979). It is not known how long the harbour basin was still in use, and when additional outer ports were constructed. Undoubtedly Ephesus could be reached by smaller boats until the medieval ages, at latest until the 14th century AD. In literature, different later ports are mentioned, but without an exact location.

The location of the Late Roman–early Byzantine harbour, also called “Panormos”, is discussed by several authors. Strabo (2007 ed., 14, 1, 20), during the 1st century AD, places it on the southern side of the Küçük Menderes floodplain, between Pygela and Ephesus (Fig. 1), Foss (1979) and Hess (1985), however, presumed its location at the northern flank of the Küçük Menderes graben. Other possible sites were suggested at the northern end of the Kenchrios floodplain (Foss, 1979; Hess, 1985; Kraft et al., 2000), with later sites (from the 11th century AD onwards) at Pamucak and Kuşadası (Hess, 1985). Meriç (1985) locates the Panormos harbour on the northern flank of the marine embayment close to the village Zeytinköy, based on the fact that a paved road had been discovered under the alluvial sediments.

Kraft et al. (2000) are of the opinion that the area around Çanakgöl might have been a suitable harbour site from late Byzantine

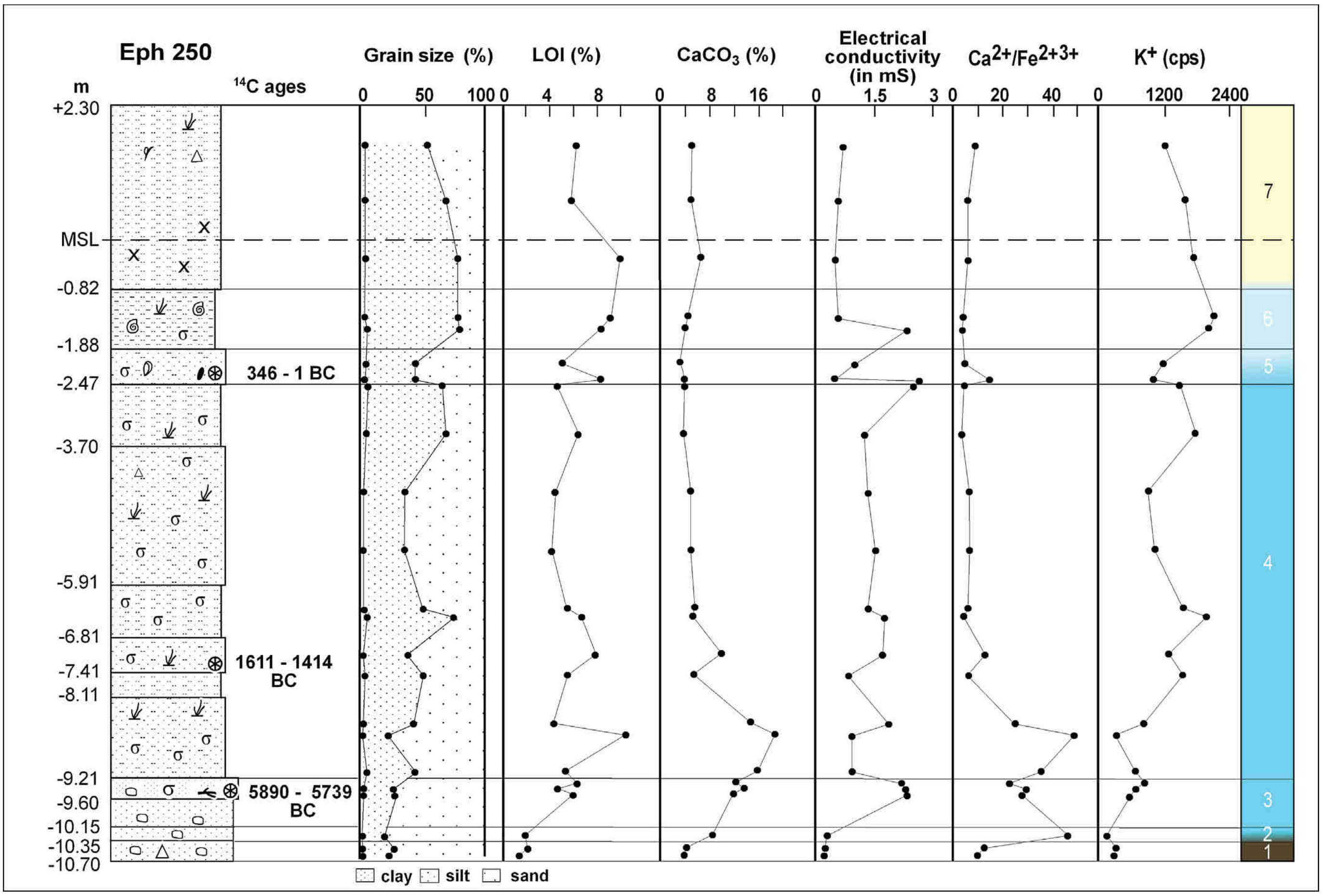

Fig. 2. Sediments and geochemical results of core Eph 250 to the north of the Arvalya valley. Points represent the depth of the measured samples, horizontal lines the boundaries of the units and dashed horizontal line the present sea level. Matrix and components are described in Fig. 5. K was analyzed semi-quantitatively using Itrax core scanner (cps = counts per second). Facies: 1) underlying stratum (late Pleistocene), 2) transgression facies, 3) and 4) shallow marine, 5) transition unit, 6) brackish, 7) alluvial.

to Turkish times. After the 16th century, no harbour is mentioned in literature (Steskal, in press).

3. Methods

In the northern Arvalya valley and around Çanakgöl, twelve half open vibracores were retrieved (diameters of augerheads: 6, 5, and 3.6 cm, maximum depth: 14 m). The work is based on the geo-archaeological research design published by Brückner et al. (2005), and Brückner and Gerlach (2011). Drill cores were carried out with the vibracorer Cobra mk1 (Atlas Copco Co.) and a hydraulic lifting device. The sediment cores were photographed. In order to establish a facies stratigraphy, colour (with Munsell Soil Color Charts), grain size, carbonate content and texture, as well as other characteristics were determined in the field according to AG Boden (2005). During fieldwork, ceramics, macro-fauna and -flora (bivalves, gastropods, plant remains, seeds, olive stones etc.) were sampled for determination and radiocarbon dating. Drill cores were sampled for geochemical and sedimentological analyses. The positions of the coring sites were measured with differential GPS (Topcon–Hiper Pro; accuracy: 2–3 cm in all three dimensions).

In the geo-laboratory at the University of Cologne, the samples were dried and pestled. Every sample (<2 mm) was measured with a laser diffraction particle sizer after removing the organic material with H_2O_2 (Beckmann Coulter LS13320 Mikro). The statistical analyses were done with Gravistat (Blott and Pye, 2001). Electrical conductivity was determined after Barsch et al. (2000). For loss on ignition (LOI), 5 g of sediment were dried at 105 °C overnight and heated for 4 h at 550 °C in an annealing furnace (Schlichting et al., 1995). $CaCO_3$ content was determined with the Scheibler apparatus (0.5 g of sediment was moistened and reacted with 10% HCl). X-ray fluorescence (XRF) analysis was done with an Itrax Core Scanner (Cox analytic system). It has an exposure time of 10 s; elements being measured reach from Al to Pb (Croudace et al., 2006). Usually it has a resolution of 2 mm. Due to the fact that the entire core was not available, only single samples were measured for cores Eph 250 and 266.

In four cores, detailed microfaunal analysis was accomplished in order to reconstruct the milieu of deposition. Ostracods and foraminifers are excellent indicators for the interpretation of palaeo-environments due to well-known ecological requirements. Foraminifers live in marine and rarely in brackish habitats, ostracods in all aquatic ones. The species distribution depends on factors such as salinity, temperature and water depth (Frenzel and Boomer, 2004; Frenzel et al., 2006). After sieving (mesh size: 100 μm) the samples of foraminifers and ostracods were determined after Meriç (2004). All individuals per sample were counted for the qualitative and quantitative analyses.

The determination of diagnostic ceramic fragments and AMS-^{14}C dating of plant remains, charcoal, olive stones and seagrass also helped to establish a chronostratigraphy. Marine samples were corrected with 390 ± 85 years (reservoir effect of the Eastern Mediterranean region; cf. Siani et al., 2000) (Table 1).

Table 1
Radiocarbon data of cores Eph 250, 266 and 268.

Sample	Sampled material	Depth (m) [a]	Lab ID (UGAM)	$\delta^{13}C$ (‰)	^{14}C age	Age cal BC/cal AD (2 σ)
Eph 250/10F	Olive stone	−2.24	11437	−14.9	2100 ± 40	346–1 BC
Eph 250/22Sg	Seagrass	−7.32	11436	−26.5	3570 ± 25	1611–1414 BC
Eph 250/29P	Plant remain	−9.54	11438	−25.3	6940 ± 30	5890–5739 BC
Eph 266/4P	Plant remain	−0.93	11082	−27.3	140 ± 20	AD 1671–1953
Eph 266/10H	Plant remain	−3.18	11086	−27.4	2060 ± 20	164–1 BC
Eph 266/15H	Grape seeds	−4.20	11084	−26.9	2160 ± 20	354–117 BC
Eph 266/21Sg	Seagrass	−6.80	11085	−16.9	5680 ± 25	4269–3939 BC
Eph 268/2HK	Charcoal	−1.76	11089	−24.8	2030 ± 25	152 BC–AD 51
Eph 268/14H	Plant remain	−6.34	11088	−27.2	2050 ± 20	164–1 BC
Eph 268/15H	Charcoal	−6.94	11083	−26.3	2110 ± 20	195–55 BC
Eph 268/24K	Olive stone	−11.14	11087	−26.9	2000 ± 25	48 BC–AD 60

The samples were dated in the Center for Applied Isotope Studies, University of Georgia, Athens (USA). All ^{14}C ages were calibrated with Calib 6.0 (Reimer et al., 2009) and are calculated with a standard deviation of 2 σ (probability of 95.5%).
[a] Depth reference is mean sea level.

4. Results and facies identification

Twelve cores were drilled around Çanakgöl and in lower alluvial plains of the Arvalya and Arap Derç valleys, in order to discover the Late Roman and Byzantine harbour sites (Fig. 9). A representative example for the general stratigraphy of the investigated area is core Eph 250, described in detail below.

4.1. Core Eph 250

Eph 250 was drilled north of Arvalya valley, 160 m south of the old course of the Küçük Menderes. A depth of 13 m below surface (b.s.) and 10.70 m below present sea level (b.s.l.) was reached. Seven different stratigraphic layers were differentiated (Figs. 2 and 3).

From the base up to 10.35 m b.s.l. dark yellowish brown medium sand with angular stones occurs (unit 1), void of micro- and macro-fossils and with low values of electrical conductivity, LOI, $CaCO_3$, K and Ca/Fe ratio. The stratum was deposited under terrestrial conditions, probably during late Pleistocene or early Holocene times (Fig. 2).

It is overlain by 20 cm of brown coarse sand and pebbles containing marine foraminifers (*Elphidium crispum*, *Ammonia tepida*, *Ammonia compacta* and *Lobatula lobatula*). Most probably, these are the first transgressive sediments encountered (unit 2).

Up to 9.21 m b.s.l., this unit is overlain by poorly sorted grey medium sand with pebbles at the base (unit 3). The increased values of electrical conductivity, carbonate content, LOI, K and Ca/Fe ratios are indicators of a facies change. Plant remains at the base date to 5890–5739 cal BC. Marine gastropods and bivalves as well as the marine foraminifers *L. lobatula*, *E. crispum*, *Rosalina bradyi*, and *Rosalina floridensis* are present.

Unit 4 from 9.21 to 2.47 m b.s.l. is evidence of low energy marine sedimentation with a high variety of microfauna dominated by *L. lobatula*, *R. bradyi*, *R. floridensis*, *Rosalina globularis* and *A. tepida*, and macrofauna characterized by echinoid spines and gastropods. Seagrass is intercalated from 8.50 to 6.81 m b.s.l. and dated to 1611–1414 cal BC. This sequence has abundant plant remains and a coarser matrix than above. The Ca/Fe ratio as well as LOI, K and

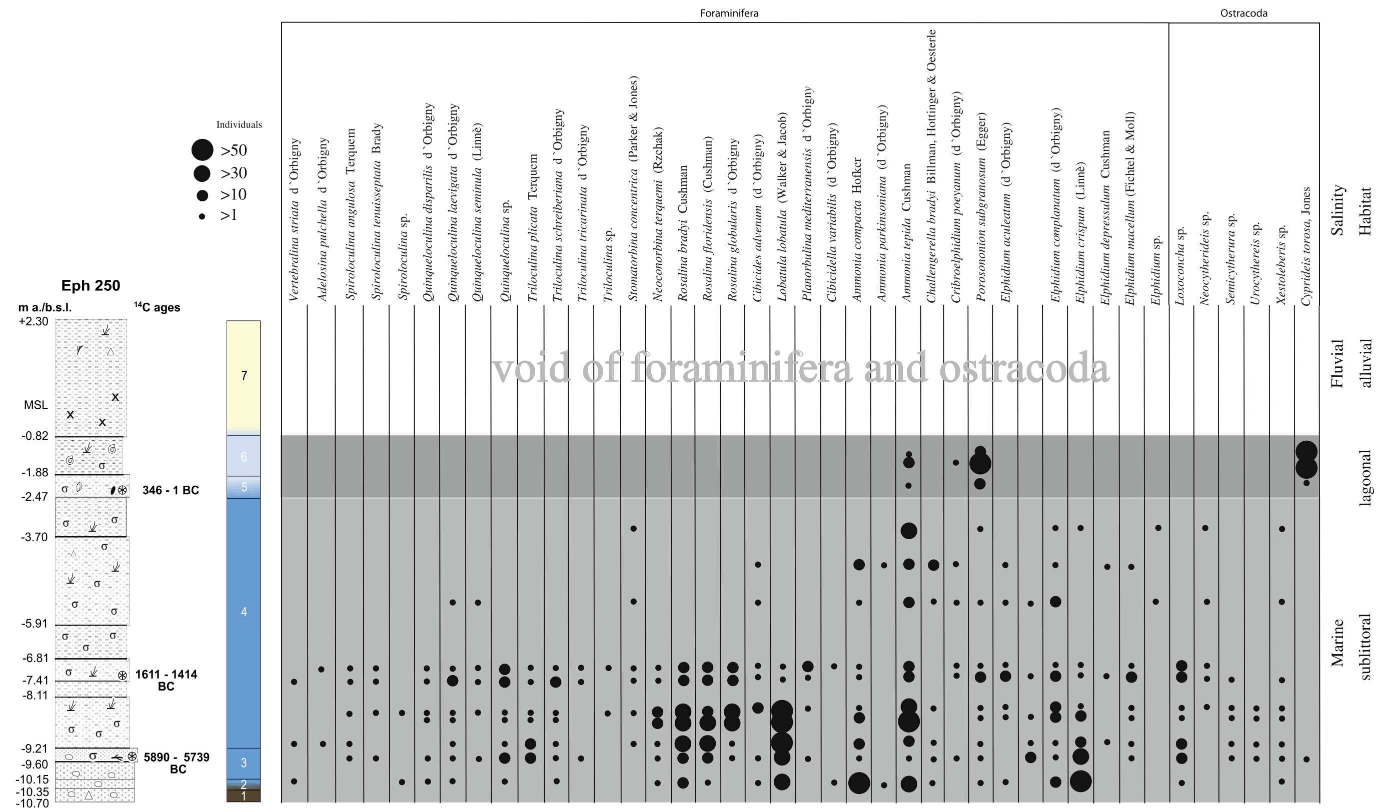

Fig. 3. Distribution of foraminifera and ostracoda of the sediment core Eph 250.

electrical conductivity show higher values. Fine sands dominate from 5.91 m b.s.l. upwards. Lesser organic material was deposited in the upper metres.

In unit 5 from 2.47 to 1.88 m b.s.l., grain size increases and *Balanus* sp. and *Cerastoderma glaucum* are present. Electrical conductivity declines upwards. An olive stone at 2.47 m b.s.l. was ^{14}C-dated to 346–1 cal BC. Angular and subangular clasts are more common. Geochemical and sedimentological data suggest a higher energetic environment with increased terrestrial input.

The following stratum (unit 6) up to 0.82 m b.s.l. is characterized by a sharp contrast, where dark grey clayey silts represent less-energetic sedimentation. Organic content and the K values rise. While most of the marine species disappear, the brackish foraminifers *Porosononion subgranosum*, *Cribroelphidium poeyanum* and *A. tepida* are present. The brackish water ostracod *Cyprideis torosa* also occurs in high numbers indicating a decreasing salinity as evidence of the development of a temporary lagoonal system. From 1.11 m b.s.l. upwards, dark yellowish brown sand layers indicate the terrestrial influence.

A transition layer up to 0.53 m b.s.l. indicates the process of siltation. From 0.53 m b.s.l. to 2.30 m a.s.l. (above present sea level) the colour changes to brown and yellowish brown (unit 7). Angular mica schist, limestone and quartz stones as well as carbonate concretions occur in the silt dominated matrix.

4.2. Cross section in Arap Derç valley

Two drillings (Eph 246 and 247) were carried out west of Kaleburun Tepe and north of Kara Tepe in a north–south striking valley called Arap Derç (maximum width: 200 m). The alluvial plain is surrounded by hills with an altitude of 73 m (Kaleburun Tepe) and 71 m (Kara Tepe), respectively (Fig. 5).

The base of Eph 247 (max. depth: 2.81 m b.s.l.) is characterized by strong brownish sandy loam with many angular stones similar to the alluvial fan of the lower Derbent valley to the south of the Artemision. The loam is overlain by compact clayey silt to silty clay, most probably a freshwater environment close to the river. Eph 246 is located 118 m northwest of Eph 247, 7.39 m b.s.l. It displays a different stratigraphy. At the bottom of the drill core appear mostly dark grey silty micaceous fine sands. Intercalations of seagrass with marine microfauna *A. compacta, E. crispum*, *R. bradyi*, as well as marine gastropods and echinoid spines occur, typical for a marine environment close to the coast. Geochemical analyses indicate a high value of electrical conductivity, and a high content of $CaCO_3$ due to the calcareous fauna. A transitional layer up to 1.54 m b.s.l. with sand and pebbles was interpreted as a regressive beach deposit. It is overlain by medium sand-dominated dark yellowish brown sediments up to 0.81 m b.s.l. containing many subangular stones (mainly limestone, mica schist and quartz up to 5 cm). The absence of macro- and micro-fauna and decreasing geochemical values, especially electrical conductivity, indicate a different milieu of deposition. In both cores, alluvial fan deposits continue up to the surface, in Eph 247 with rockfall debris (quartz, limestone, mica schist) in the upper 3 m. In Eph 246, ceramic fragments, burnt clay and charcoal occur at 0.04 m b.s.l. and 0.34–0.38 m a.s.l. Kitchen ware and a skyphos/kantharos fragment date back to the Hellenistic–early Roman period, i.e. 3rd–1st century BC. The cores show that at the mouth of the Arap Derç valley a harbour site in Roman times can be excluded.

4.3. A tell in Arvalya valley

In order to reconstruct the maximum landward position of the shoreline and its spatiotemporal shifts while trying to find potential

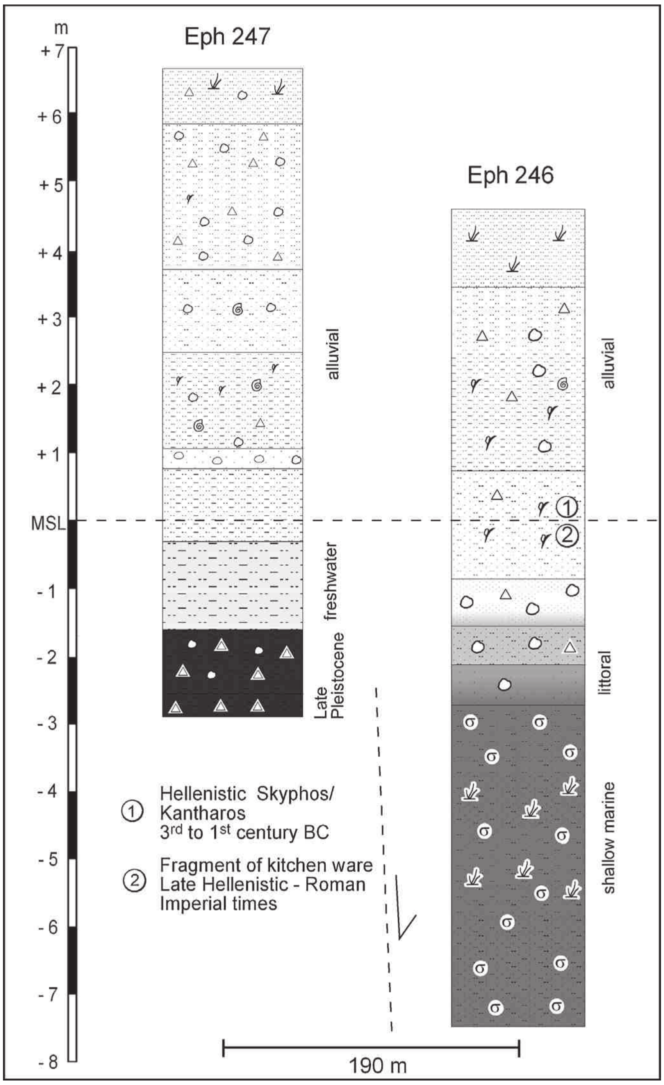

Fig. 4. Synopsis of Eph 246 and 247, cored in the Arap Derç valley. Sedimentology and facies are described in Fig. 5, position of coring sites in Fig. 9.

harbour sites, four cores with a maximum depth of 13 m b.s. were performed in the Arvalya valley (Fig. 5). Eph 346 was cored in the top of a small elevation 1.5 km south of Eph 308, and the other coring sites are located in the lower floodplain of the Kenchrios (Fig. 9).

Working in this area offered the opportunity to investigate a possible prehistoric site in September 2012 and to clarify its principal stratigraphy. The so-called Arvalya Höyük or Gül Hanım (Figs. 6 and 9) is known as a prehistoric site, with surface finds in the mid-1990s published by Evren and İcten (1998). Due to the massive destruction of the area in recent times, the definition of its size, function and dating remain vague (Horejs et al., 2011).

The strata in Eph 346 identified this apparently small hill as a distinct settlement mound composed of cultural layers. From 6.00 to 3.50 m b.s., alluvial sediments were deposited. They are covered by 3.50 m of settlement layers with ceramic flitters, charcoal, fragments of flint tools and even fragments of painted plastering material. Additional new surface finds around the Arvalya tell revealed a spectrum comparable to Çukuriçi Höyük, the second known tell in the Ephesos region, intensively excavated since 2007 (e.g. Horejs, 2008; Horejs et al., 2011). A few pottery sherds, fragments of tools and flakes of local flint and imported obsidian as well as fragments of polished stone axes of different raw materials show strong similarities with the assemblages of the neighbouring Çukuriçi Höyük in its Neolithic and Chalcolithic layers (phases ÇuHö IX-VII: Horejs et al., 2011; Galik and Horejs, 2011). Both tells are situated in similar palaeographic settings, in the plains of neighbouring valleys open to the sea and about one to two kilometres away from the former coastline (Horejs et al., 2011). With the drilling Eph 346 and additional archaeological material studies of surface finds in 2012 a distinct tell site can be defined in the Arvalya valley, presumably dating to Neolithic and Chalcolithic periods. To date, nothing is known about a potential harbour site during that time. It can only be said that, if it existed at all, it was not directly adjacent to the tell.

4.4. Cross section in Arvalya valley

Summarizing the cross-section, the vibracores Eph 308, 248 and 250 are dominated by terrestrial sands and silts with pebbles and angular stones at the base, whereas Eph 249 (drilling progress was stopped at 2.58 m b.s.l. due to a massive log) is characterized by silts and sands. The first marine transgressive facies – medium sand with pebbles and marine microfauna – appears in Eph 250; it was dated to the 6th millennium BC. The continuously rising of the sea level created a marine embayment. A layer of Eph 250 with an abundant marine microfauna dates to the middle of the 2nd millennium BC. During Hellenistic time, clayey silts dominate with *C. glaucum*, small plant remains and a ceramic fragment. Eph 248 revelaed terrestrial strata with land snails. Clayey silts may be evidence of the existence of a small water basin close to the coast. It silted up due to the prograding river. Later, fine-grained freshwater and lagoonal sediments accumulated over terrestrial sediments in Eph 248 as well as in Eph 250. The rising potassium content in Eph 250 and 249 characterises the fluvial facies of the Kenchrios and Küçük Menderes. After the formation of a sand barrier, brackish stillwater sediments were deposited. The lagoon in Eph 250 turned to freshwater, but was still influenced by the sea, maybe during storm events. Eph 249 is dominated by fluvial silts of the Küçük Menderes up to the surface. It was drilled only 60 m south of the river. Alluvial fine-grained sediments (alternating clayey and sandy silts) of the Küçük Menderes form the upper metres of the cores, often with ceramic and brick fragments.

4.5. Vibracores around Çanakgöl

Çanakgöl, a residual lake, is situated west of the Arvalya valley (Figs. 8a and 9e) in an area surrounded by small hills – Çanakgöl Tepe (36 m) in the north and Ideli Tepe (50 m) in the west. To the east a small elevation separates the area from the Arvalya valley. On this elevation, a 10,000 m^2 villa was discovered during geophysical research in October 2012 (Österreichisches Archäologisches Institut, 2012). Five cores to a maximum depth of 12 m b.s. were drilled to decipher the palaeo-geographic evolution.

On Schindler's (1897) map, Çanakgöl still had a connection to the ancient Küçük Menderes river. Eph 267 and Eph 266 are located in the east of the lake, only 27 m and 70 m west of the hill slope. The sediments of Eph 266 and 267 differ from those of Eph 268, 282 and 283 (carried out in the north of the lake). In the deepest layers of the latter, homogeneous silts with microfauna of marine origin occur. At the base of Eph 266 and 267 well-rounded pebbles of a beach environment dominate (transgression facies). With the rising sea level, coarse sand with gravel was accumulated; seagrass with marine shells and gastropods are intercalated. Geochemical analyses (low K and high LOI and $CaCO_3$ values as well as elevated Ca/Fe ratios) show a changing environment. Ca/Fe ratio and $CaCO_3$ value are good indicators for a foraminifer or shell rich layer as shown at

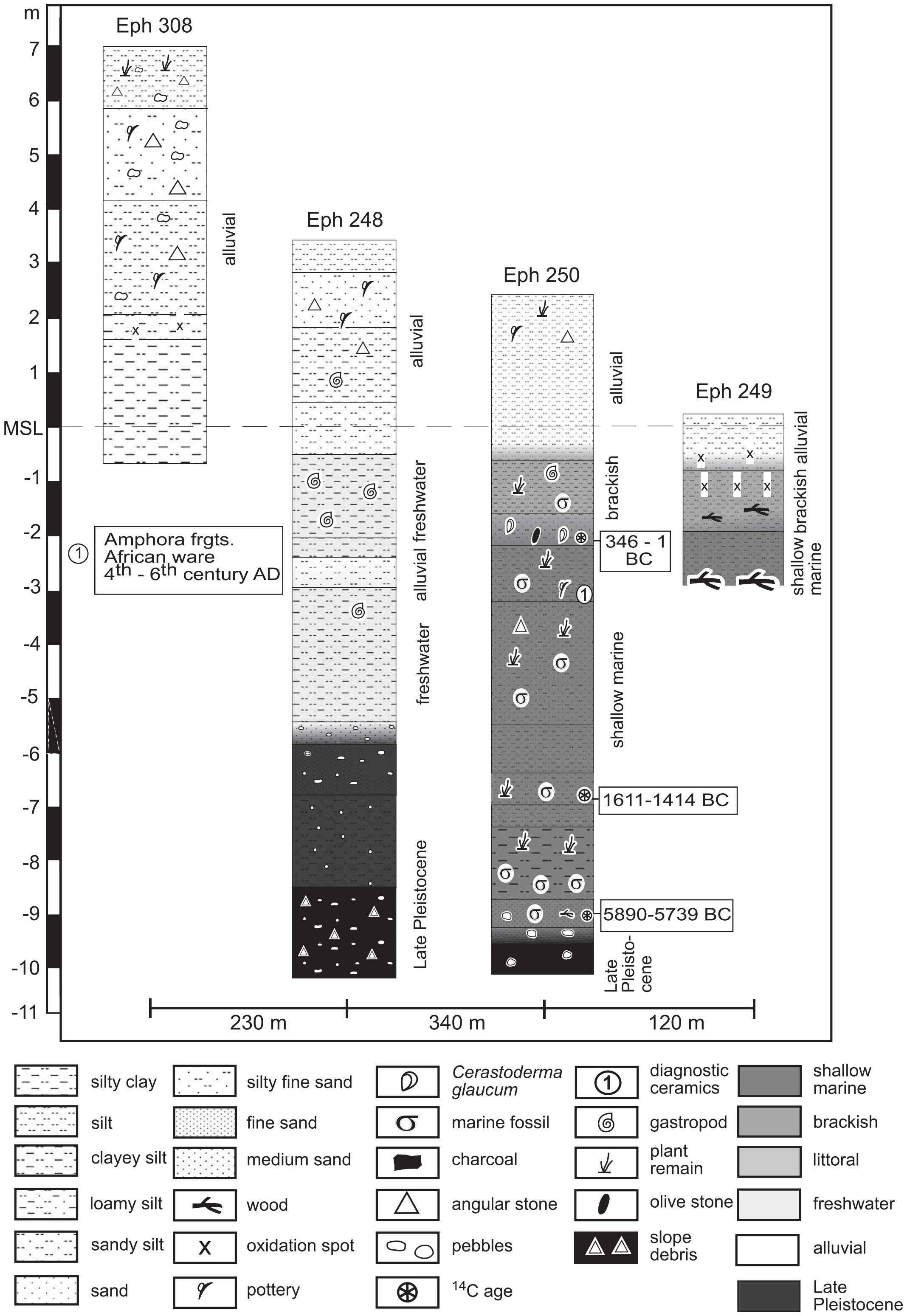

Fig. 5. Cross section through Arvalya valley from south to north. The legend also applies for Figs. 2, 4, 7 and 8. Position of coring sites in Fig. 9.

the base of Eph 250 (Vött et al., 2002; Rothwell and Rack, 2006; Croudace et al., 2006). Foraminifers (*Elphidium complanatum*, *E. crispum*, *A. compacta*, *R. bradyi*, *Rosalina globulosa*, *Cibicides advenum*, *Spiroloculina angulosa*, *L. lobatula*, *Vertebralina striata* and *Triloculina* sp.) and ostracods (*Aurila* sp. and *Loxoconcha* sp.) are evidence of a marine environment close to the coast. Seagrass at the transition to the bottom layer dates to 4269–3939 cal BC. This sublittoral milieu ended during Hellenistic times (354–117 cal BC). The marine transgression reached Eph 267 as well.

In Eph 268, an olive stone at 11.14 m b.s.l. (48 BC–60 cal AD), a diagnostic piece of pottery at 10.04 m b.s.l. (1st–2nd century AD) as well as plant remains (195–55 cal BC) and charcoal (164–1 cal BC)

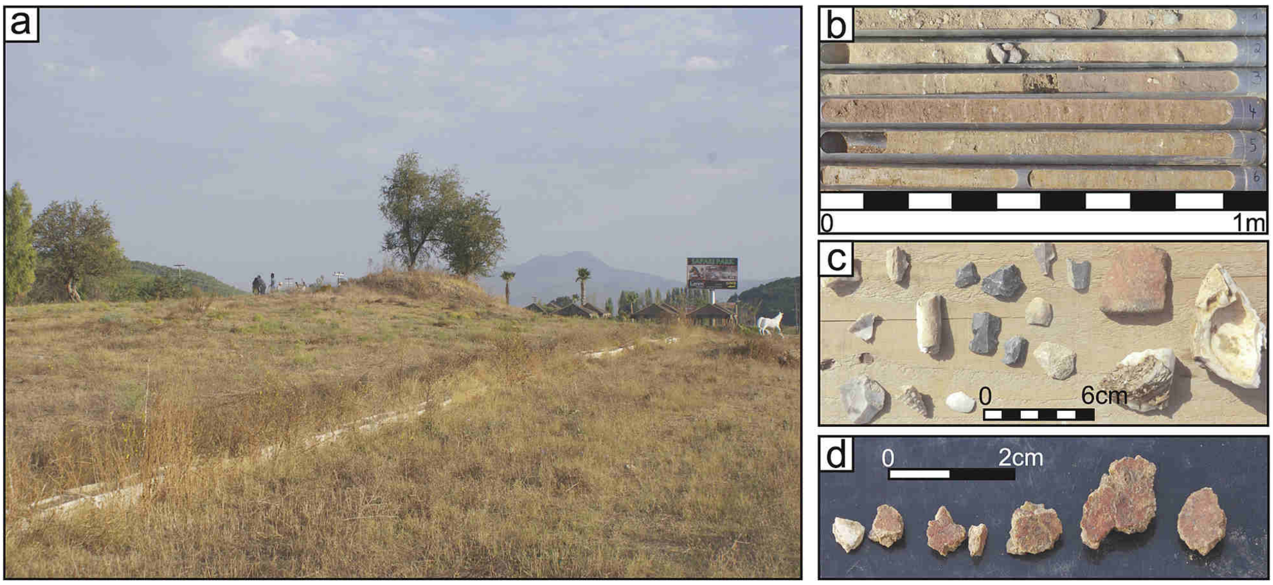

Fig. 6. Settlement mound called Arvalya Höyük or Gül Hanım in the Arvalya valley. Position of mound in Fig. 9. (a) View of Arvalya Höyük. (b) Sediment core of Eph 346, drilled in the top of the mound. (c) Finds of a surface survey. (d) Painted plaster from core Eph 346 encountered at a depth of 2.26–2.28 m b.s.

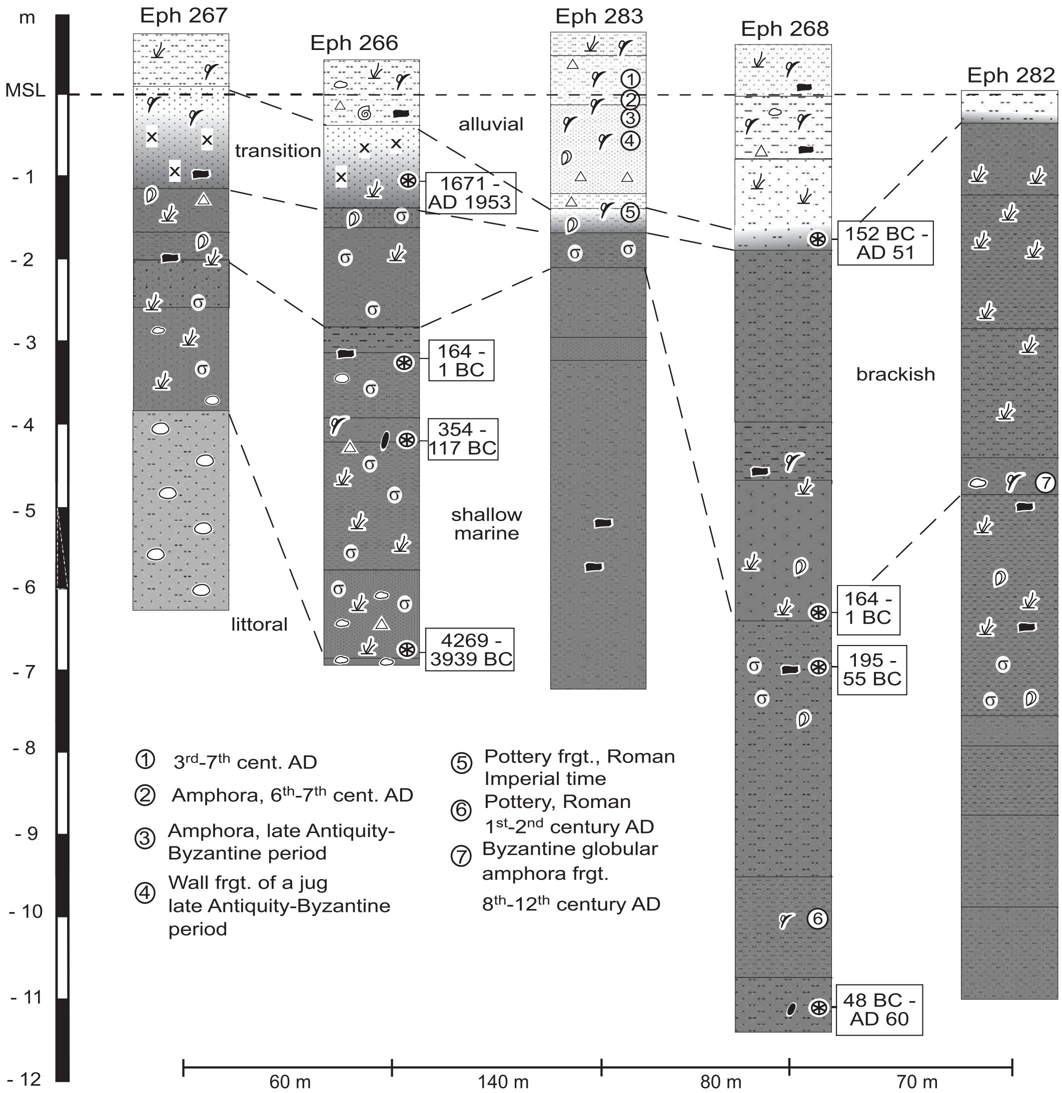

Fig. 7. Five cores around Çanakgöl. Legend for sedimentology and facies in Fig. 5. Position of coring sites in Fig. 9.

at 6.34 and 6.94 m b.s.l., respectively, all date to Hellenistic and/or Roman times.

In Eph 266, nearly 1 m of silty and sandy sediments was deposited from the beginning until the end of the Hellenistic period. The advancing foreset beds of the delta – in Eph 268 from 6.29 to 4.83 m b.s.l. – are characterised by very homogeneous, sterile sand and silt layers with a thickness of up to 0.5 cm each. The granulometry and geochemical analysis led to the assumption that sediments were deposited in a stillwater environment at the coring sites Eph 268 and 266, probably due to the building of a sand barrier from the river (levee) which cut off the area from the open sea. During high floods, the river overflowed, thus depositing coarser sediments in the low energy environment. Geochemistry shows decreasing values of carbonate content and Ca/Fe and a rising value of LOI, Pb and K.

The first area where people could settle was at the sites Eph 268 and 282. The oldest artefacts in Eph 283 date from the Roman era; they are followed by Byzantine ceramics. During this period, Eph 282 was still under the influence of the Küçük Menderes. In this coring, a ceramic fragment at a depth of 3.94 m b.s.l. dates to Byzantine time. Fluvial sediments characterised by sterile olive brown medium sands with very little shell debris were deposited at Eph 266 and 267 between the 17th and 20th centuries AD (^{14}C age in Eph 266, Figs. 7 and 8). In the upper metres alluvial sediments consistent of clayey and sandy silt with ceramics and mortar dominate. As the LOI, Ca/Fe and the $CaCO_3$ contents increase, the Pb value decreases.

5. Discussion

5.1. Ancient landscape reconstructions on the southern flank of the Küçük Menderes graben

The cores around Arvalya valley and Çanakgöl revealed the shifts in the coastline during the last eight millennia. Therefore, palaeogeographic scenarios can be sketched (Figs. 9a–e).

The marine transgression dates to the beginning of the 6th millennium BC. The maximum landward shoreline is shown between Eph 246 and 247 as well as 250 and Eph 248 (Fig. 9a). The question why no marine sediments were found in drill cores Eph 248 and 247 and the sea did not ingress into this area still remains unclear. At Çanakgöl, the deepest marine sediments (at a depth of −6.84 m b.s.l., Eph 266) were deposited at the beginning of the 5th millennium BC, post-dating the even deeper transgression facies, which was not reached at this site. When people started to settle the Arvalya valley, the coastline was situated about 2 km to the north. The sedimentation rate in the marine embayment was very low during this period (5 cm per century in core Eph 250) (Fig. 9b).

During the Hellenistic period (3rd–1st centuries BC), marine conditions still prevailed around Çanakgöl. Eph 246 had already been silted up. In the Arvalya valley, a freshwater lake developed in Eph 248 and a lagoon in Eph 250 (Fig. 9c). This can be explained by a developing sand barrier (levee) of the prograding Kenchrios river. The sedimentation rate increased from 6 cm (from the end of the 4th millennium BC) to 68 cm per century in Hellenistic–early Roman times at Çanakgöl, and to 37 cm per century in the Arvalya valley. This is in accordance with the proposed position of the Küçük Menderes delta front during that period (Brückner et al., 2008). At the end of Hellenistic–early Roman times, the first prodelta silts of the Küçük Menderes were deposited at Eph 268. Three ^{14}C ages and one diagnostic ceramic fragment at depths between 6.39 and 11.39 m b.s.l. date back to the Roman period. One possibility for this unusually rapid deposition of 4 m sediments may reflect a rapid sedimentation of the foreset beds of the approaching delta front in the marine embayment. Nevertheless, dredging and the deposition of sediments in this environs is more probable. During the Hellenistic period, Eph 266 and 267 were located closer to the coast in a more wave-dominated environment.

In Byzantine times, the area of the lower floodplain of the Kenchrios had been silted up as well as Eph 283 and 268 (Fig. 9d). A charcoal at 1.74 m b.s.l. in Eph 268, dated to the Roman age, was

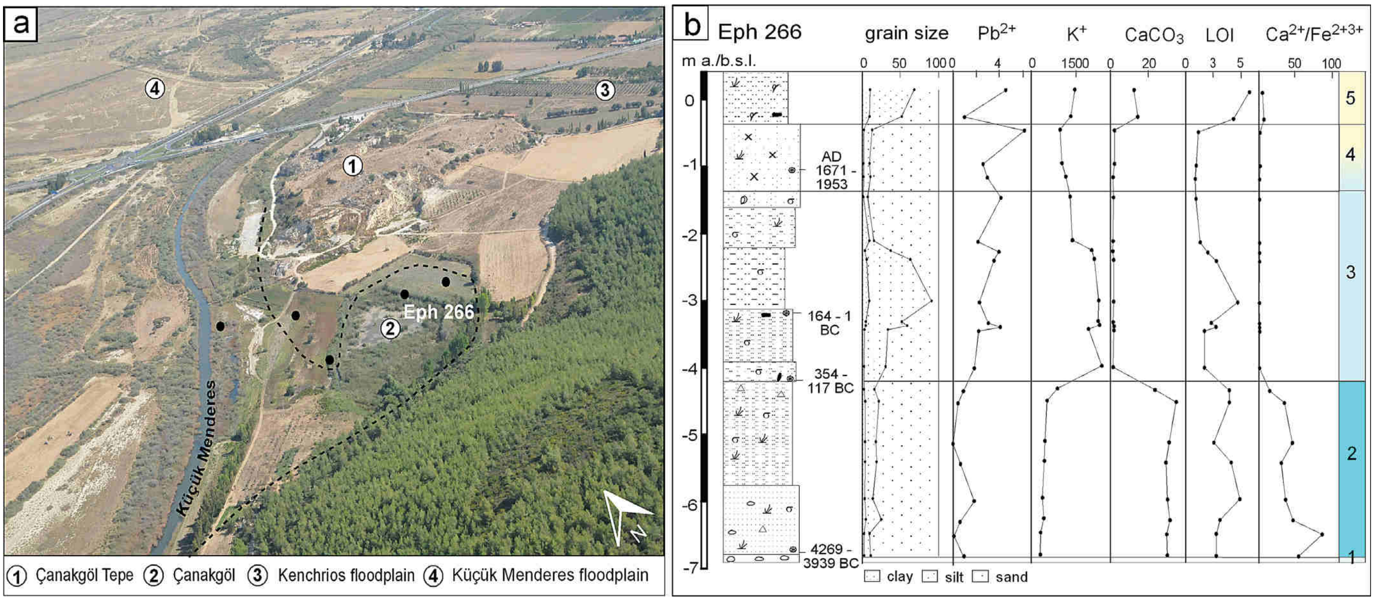

Fig. 8. The area around Çanakgöl. (a) View towards northeast (oblique aerial photography) on the remnant lake Çanakgöl and the former harbour basin (area consistent with rectangle in Fig. 9). It is situated in a natural embayment at the foot of the southern flank of the Küçük Menderes graben. b) Core Eph 266 with grain size, Pb, K, $CaCO_3$, LOI and Ca/Fe. Pb and K were analyzed semiquantitatively using Itrax core scanner (cps = count per second). Grain size, $CaCO_3$ and LOI are indicated in percent. Points represent the depth of the measured samples, horizontal lines the boundaries of the units. Matrix and components are described in Fig. 5. Facies: 1) littoral, 2) shallow marine, 3) brackish, 4) transition layer, 5) fluvial.

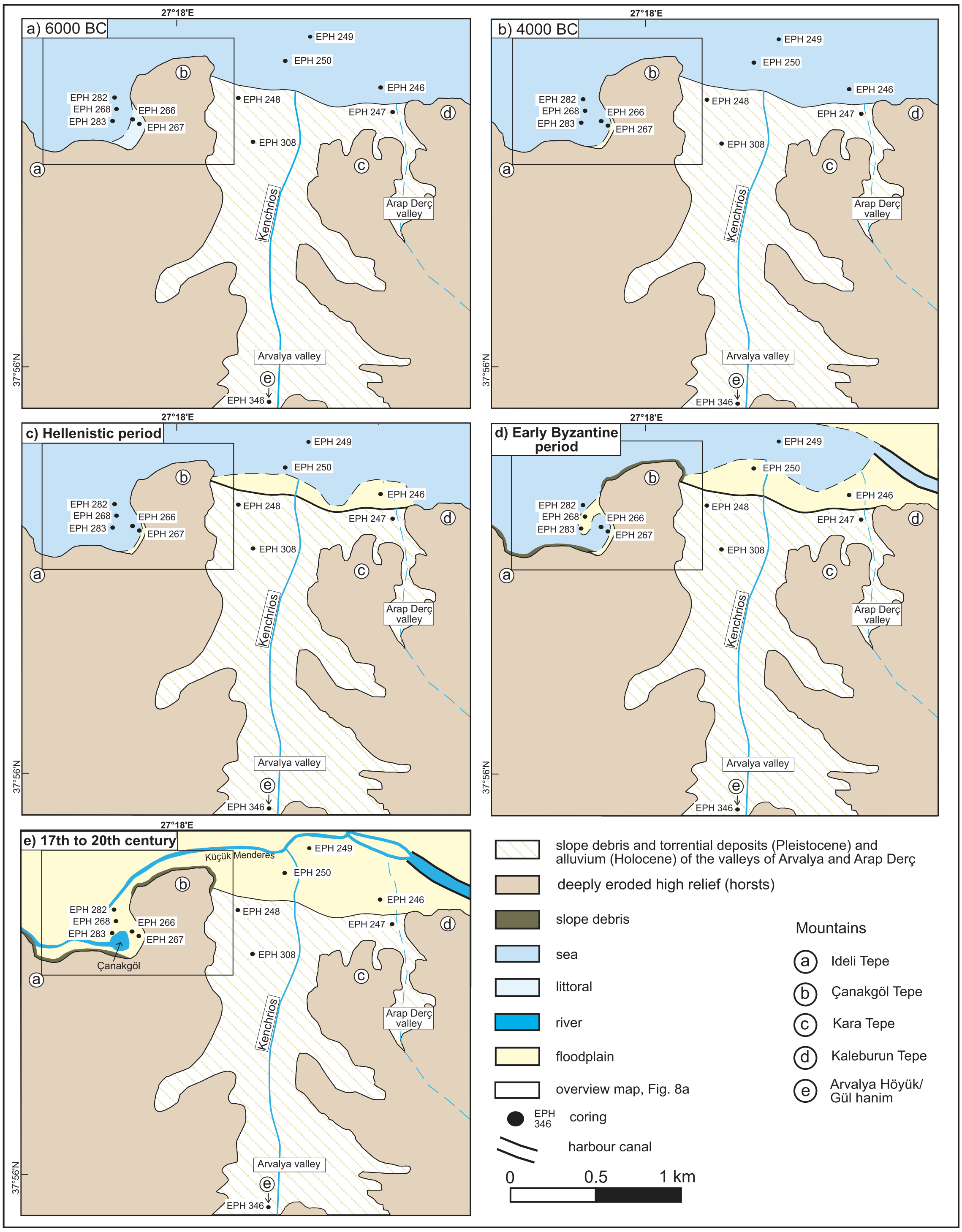

Fig. 9. Scenarios of the landscape evolution of the northern Kenchrios valley and the area of Çanakgöl for 6000 BC, 4000 BC, Hellenistic period, early Byzantine period, 17th–20th century.

most probably redeposited. The southern cores around Çanakgöl still represented a marine environment with connection to the sea. The barrier was sometimes breached by floods or storm events, so that fluvial silts were deposited.

Between the 17th and 20th centuries AD, fluvial sediments dominate Eph 266 and 267 (Fig. 9e). The sedimentation rate from Hellenistic to early Roman times until the 17th century decreased to 18 cm per year. The coastline was further west, probably near the remnant lake Çanakgöl. During this period, the bay was still connected to the sea (Schindler, 1897). At the latest after the regulation of the Küçük Menderes in 1934 with its redirection to the north of the floodplain, the lake lost its connection to the river and therefore to the sea (Güldali, 1979).

5.2. Late Roman and Byzantine harbours of Ephesus

An ideal harbour site should be located in a marine embayment or indentation, which is protected against the open sea so that a low-energy wave environment is present. One of the best examples is the famous Lion Harbour of Miletus (Brückner et al., 2006). An example from Ephesus is the Roman harbour, bordered by Bülbüldağ and Panayırdağ after the city centre had been shifted around 300 BC. The research presented herein focused on three areas which are one to three kilometres to the west of the ancient city centre at the southern flank of the graben.

The Roman harbour canal was flanked on both sides by a necropolis. The oldest objects in the necropolis area date to the end of the 1st century AD. At this time, the Roman harbour had to be connected with the canal to the sea (Österreichisches Archäologisches Institut, 2011). At least since that time, new anchorages farther to the west were needed.

One possible harbour site is located to the west of Kaleburun Tepe. It can be concluded that the sea never ingressed into this valley. The core inside the valley does not show any marine influence. To the north of the valley, however, close to the connection with the Küçük Menderes alluvial plain, core Eph 246 shows the existence of marine sediments. The area silted up in Hellenistic or Roman Imperial times at the latest, probably due to the vicinity to the surrounding mountains (colluviation) and a small river building up its delta (alluviation). As siltation started early and the site was not well protected, it could not have hosted a harbour.

In the Arvalya valley, Schindler (1897) and other authors had presumed the existence of a so-called Panormos harbour. However, coring revealed that the coastline did not reach far into the valley. Only the northern core, Eph 250, shows marine strata (Fig. 2). Thus, a small marine embayment was present, merely protected on the western side by Çanakgöl Tepe (Fig. 9). It persisted in Hellenistic time, but turned into a brackish residual lake, sometimes connected to the sea, thereafter. As in Hellenistic time sea level was about one metre lower than today, according to the sea level curve of Müllenhoff (2005), water depth was ~1.50 m in this area. In Antiquity, the Kenchrios built its delta into the marine embayment. Due to its steep gradient and the Mediterranean climate with torrential rains, the river occasionally carried coarse–grained sediment. As a consequence, a potential harbour would continuously have been threatened by siltation.

In principle, a site for a harbour in the north of the Arvalya valley is conceivable, protected by small hills to the west (Fig. 9). However, major problems caused by the delta progradation of the Kenchrios and the siltation processes by the Küçük Menderes are obvious. As pro-delta sediments were deposited in the area of Eph 268 in Roman times, this would have also affected coring site Eph 250 and the water depth in this area. If a harbour site existed, it could not have been used for a long period of time. However, in this area it seems more probable that there have been platforms further north (closer to the harbour canal entrance) for transferring goods into smaller boats. Thus, a much better harbour site is the area around Çanakgöl (Fig. 8).

The southern area around the remnant lake which represents the former harbour basin, silted up before the 16th–19th century, while the northern part did so in the Roman, or at the latest in the Byzantine period. At least until the end of the 19th century, the lake had a connection to the Küçük Menderes river. In Byzantine and also Venetian–Turkish times, when most probably the harbour at Çanakgöl was (still) in use, the area around Eph 283 was already silted up. The oldest dated ceramics reach to the Roman Imperial period. They are overlain by several pieces of amphora and a fragment of a pitcher dating to late Antique/Byzantine times. This site was accessible to people in late Antiquity. In this period, the area around core sites Eph 266 and 267, as well as Çanakgöl and the western part of the embayment, was still a brackish water environment and probably connected to the sea. Despite the silting process of the eastern part of the embayment (not later than 16th century AD around Eph 266 and 267), the area to the west and the east of the lake was still reachable by boat. As the delta sediments also influenced this site, it is probable that the harbour was dredged to maintain the function as a port. From the Roman harbour, it is known that it was dredged a couple of times (Kraft et al., 2000). Today, the ancient Küçük Menderes river course is very close-by, and still navigable; thus, it could have been used for a long time as a harbour or a landing site. The place fits very well for the proposed late Byzantine to Venetian harbour because it was navigable for a long time and easy to reach even after the coastline had prograded further west. The present lake seems to be the former harbour basin.

An indicator for the period of use is the pollutant Pb. XRF measurements of Pb revealed a rising concentration from Hellenistic time to the 17th–20th centuries (Fig. 8b). From other archaeological sites, it is known that pollutants such as Pb appear especially during the Roman period (Marriner and Morhange,

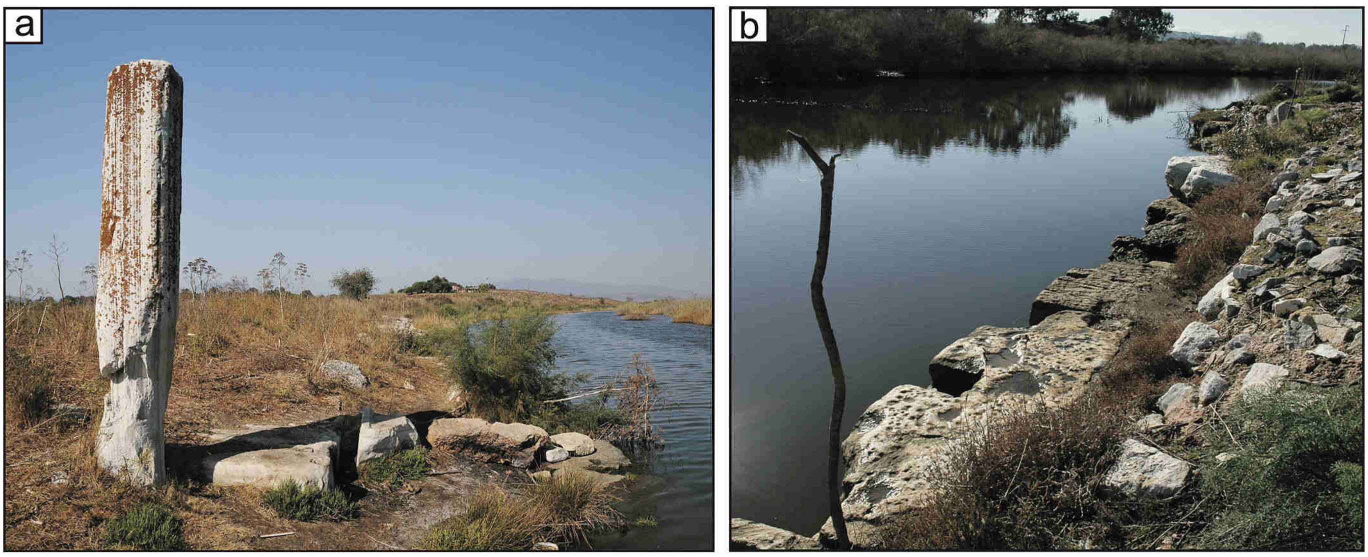

Fig. 10. Landing site discovered in January 2012. (a) Pillar at the northern side of the former channel of the Küçük Menderes. The landing site was established to the west of Çanakgöl, presumably in late Byzantine–Ottoman times. (b) View of the landing site with facilities to anchor ships.

2007). In general, a correlation exists between fine grained sediments, a high content of LOI and elevated Pb values (Pickering, 1986). The geochemical analyses show a decreasing grain size together with elevated LOI values from 3.40 to 2.20 m b.s.l. and increasing grain size (mostly sand) up to 0.45 m b.s.l. together with lower LOI values (Fig. 8b). In this area, the Pb values are not correlated to the grain size and organic content. Although grain size is coarse and low organic content consistent, the Pb values continuously increase. In sum, the elevated lead values seem to support the assumption that the site was used as a harbour during that time. More ^{14}C ages spanning the interval between the early Roman period and the 16th century have to be determined to establish a better chronostratigraphic correlation between the changing concentrations of this pollutant and the settlement history.

6. Conclusion

Geoarchaeological research in the environs of the ancient city of Ephesus leads to the conclusion that around 6000 BC, due to the transgression of the Aegean Sea, marine sediments were deposited at the southern flank of the graben. The north–south striking valleys to the east of the investigated area (valleys of Arvalya and Arap Derç) show only a minor marine influence since they were already filled with Pleistocene deposits. As a byproduct of our research, an elevated area inside the Arvalya valley could be identified as a settlement mound (tell), probably dating to the Neolithic period.

With the rising water table, the entire area around Çanakgöl became part of the marine embayment. When sea-level rise decelerated, fluvial influence became dominant, mainly the advancing delta systems of the Küçük Menderes and its tributaries from mid-Holocene times on which has permanently shifted the coastline westwards (e.g. see Brückner, 2005; Kraft et al., 2007, 2011). A major effect of the landscape changes was the siltation of the harbours. One reason for the relocation of the city of Ephesus to the area at the foot of Panayırdağ and Bülbüldağ by Lysimachos before 300 BC was the good anchoring ground there. With the advancing delta front, this area, too, was endangered by siltation. Therefore, the Romans dredged the place and turned it into a hexagonal harbour. It was the major harbour when Ephesus was the capital of the Roman province of Asia. However, the delta front continued its westward shift, thus forcing the Romans to react: a harbour canal was constructed. The latest geophysical and archaeological research indicates that on both sides of the canal tombs of a necropolis, dating from the late 1st century AD, were discovered and partly unearthed (Österreichisches Archäologisches Institut, 2011; Seren and Ladstätter, 2011). This is evidence that in late Roman times the delta front was west of the end of the harbour canal. Where then were the later harbours, especially in Byzantine times?

Çanakgöl is the best candidate since it is in the leeward position of the delta advance and the adjacent mountains do not deliver a large amount of rock debris. In Roman times, the area east of Çanakgöl was already silted in and fine-grained bottomset–foreset beds of the advancing delta front were accumulated in the direct environs of Çanakgöl. The northern part of the Arvalya valley is assumed to be accessible until (late?) Byzantine times. With the prograding deltas of Küçük Menderes and Kenchrios, the Çanakgöl also was endangered. It is possible that it was dredged to guarantee the continuation of the shipping operations. Geophysical measurements (geomagnetic – Fluxgate Magnetometer with optical distance, raster of 16 $\times$ 50 cm and georadar – Noggin with 250 MHz antenna, raster 5 $\times$ 25 cm) detected a huge villa in October 2012, but until now no harbour-related constructions of piers or storage houses (Österreichisches Archäologisches Institut, 2012). Measurements are needed in the direct environs of the remnant lake and former harbour basin. Until the end of the 20th century, Çanakgöl was connected to the river (now the former channel of the Küçük Menderes) which flows nearby.

The harbour site was in use for a long time; it even had a connection to the sea after the delta had advanced farther west. When it became too small, a new landing site with integrated spoils about one kilometre to the west was established on the right side of the Küçük Menderes as well as another harbour at Pamucak. The data suggest a Late Byzantine age of the quay. This has been confirmed by detailed research from archaeological and architectural studies. Both presumed harbour sites could have been important in Late Byzantine–Turkish times. During cleaning works in January 2012 on both sides of the ancient Küçük Menderes branch, a mole with a still-standing column was discovered on the northern side of the canalised river. It would still be a good place for landing and unloading goods (Fig. 10). Cores carried out in 2012 revealed that the southern part of the river was also rectified (core filling marble at a depth of 2–3 m b.s.).

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6. Neolithic settlement sites in Western Turkey – palaeogeographic studies at Çukuriçi Höyük and Arvalya Höyük[1]

[1] Chapter 6 is based on: Stock, F., Horejs, B., Ehlers, L., Knipping, M., Ladstätter, S., Seren, S., Brückner, H., submitted. Neolithic settlement sites in Western Turkey – palaeogeographic studies at Çukuriçi Höyük and Arvalya Höyük. Journal of Archaeological Sciences.

Neolithic settlement sites in Western Turkey – palaeogeographic studies at Çukuriçi Höyük and Arvalya Höyük

Abstract

Çukuriçi Höyük and Arvalya Höyük are two prehistoric settlement mounds (tells) located in parallel striking valleys in the environs of Ephesus, W Turkey. They were studied with geoarchaeological methods in order to reconstruct their environmental setting, areal extension and distinct settlement phases, as well as the vegetation history. Both tells are situated on small ridges flanked by rivers and their alluvial plains suitable for cultivation. The Neolithic coastline was located at a distance of c. 1.5–2 km to the north. Çukuriçi Höyük covers an area of c. 200 x 100 m; its strata have a total thickness of at least 8.50 m. The oldest remains, dating from the 7th millennium BC, represent an advanced Neolithic culture closely linked to the sea. The oldest foundations reveal that the site was intentionally chosen on the ridge within the still naturally wooded vegetated landscape. The settlement layers are rich in phosphorous and organic matter. Other than Çukuriçi Höyük, Arvalya Höyük has not yet been excavated. However, geophysical measurements and corings revealed that it covers an area of c. 100 x 60 m, and that it is constructed of several settlement layers with a total thickness of at least 3.50 m. Radar and geomagnetic images show building structures including fireplaces and pits, surrounded by a rampart-ditch construction as a potential enclosure.

Keywords: Neolithic settlement, Çukuriçi Höyük, Arvalya Höyük, Western Anatolia, palaeoenvironment, geoarchaeology

6.1 Introduction

Several Neolithic settlement sites have been excavated in Western Anatolia, especially in the last two decades (Özdoğan et al., 2012, 2013). However, until recently, systematic research concerning the prehistory in the broader area has been lacking. With the excavations of the Neolithic sites of Dedeçik Heybelitepe, Ege Gübre, Ulucak, Yeşilova, and Çukuriçi Höyük in the Izmir region (e.g. Çilingiroğlu, 2011; Çakırlar, 2012; Derin, 2012; Lichter and Meriç, 2012; Sağlamtimur, 2012), broader extensive studies of early farming cultures are possible for the first time in this particular region. It has been argued that these partially contemporaneous settlements make up a regional cluster in the 7th millennium BC, and are defined as Neolithic group at the centre of the Anatolian Aegean coast (Horejs, in press). Systematic prehistoric research has just recently been initiated around the ancient metropolis of Ephesus with excavations and interdisciplinary investigations at Çukuriçi Höyük and its environment starting in 2007. Due to extensive agricultural land use, this settlement mound (tell) was already partially destroyed when research started.

Several studies and excavation reports about the tell have been published (e.g. Galik and Horejs, 2009; Horejs et al., 2011; Galik, 2014; Horejs, 2008, 2012, 2014). Neolithic occupation started in the early 7^{th} millennium BC with several radiocarbon-dated settlement phases; the chronological sequence continues until the early 6^{th} millennium BC. The neighbouring Arvalya Höyük has neither been excavated nor studied in detail yet. Only Evren and Icten (1998) published surface finds of the site, and Stock et al. (2013) investigated the potential tell based on a drill core and described a few survey finds.

Geoarchaeological and geophysical research has been conducted on both settlement sites and their environs since 2008. For this study, drill cores were analysed according to sedimentological and geochemical properties. In addition, first palynological examination of a core from the Belevi swamps close to Ephesus reveals the early vegetation history. The chronostratigraphy relies on AMS-^{14}C ages from the drill cores and relative chronological dating of the survey finds by comparison with artefacts of the excavated Çukuriçi Höyük.

This study aims (i) to reveal the geoarchaeological context of the mounds by determining the thickness, extent and age of the settlement layers throughout the periods of settlement; (ii) to reconstruct their palaeoenvironmental setting; (iii) and to detect the vegetation history including the human impact during Neolithic and Bronze Age times.

6.2 Study area

The settlement mounds of Çukuriçi Höyük and Arvalya Höyük are located close to the ancient city of Ephesus in the two parallel N-S-striking valleys of the Derbent (max. 3 km wide) and Arvalya (max. 1 km wide) rivers (Fig. 6.1). Both tells lie at a distance of about 2 km to the main fault system which created the Küçük Menderes graben. The latter developed over pre-Miocene basement rocks of the Menderes Massif along an E-W-trending syncline. It has been filled with mostly continental deposits since Miocene times (Rojay et al., 2005). Both the Derbent and the Arvalya valleys are bordered by mountains up to 358 m a.s.l. (above sea level), composed of mica schist, dolomitic marble and bedrock from the Menderes gneiss core (Vetters, 1989).

With the rising sea level at the end of the last glaciation, a marine embayment formed reaching at least 20 km inland up to the swamps of Belevi (Brückner, 2005) (Fig. 6.1). Stock et al. (2013, 2014) proved that the maximum marine ingression also reached into the Arvalya and

Derbent valleys during Neolithic times. However, the distance from the settlement mounds to the sea was never less than 1.5-2 km.

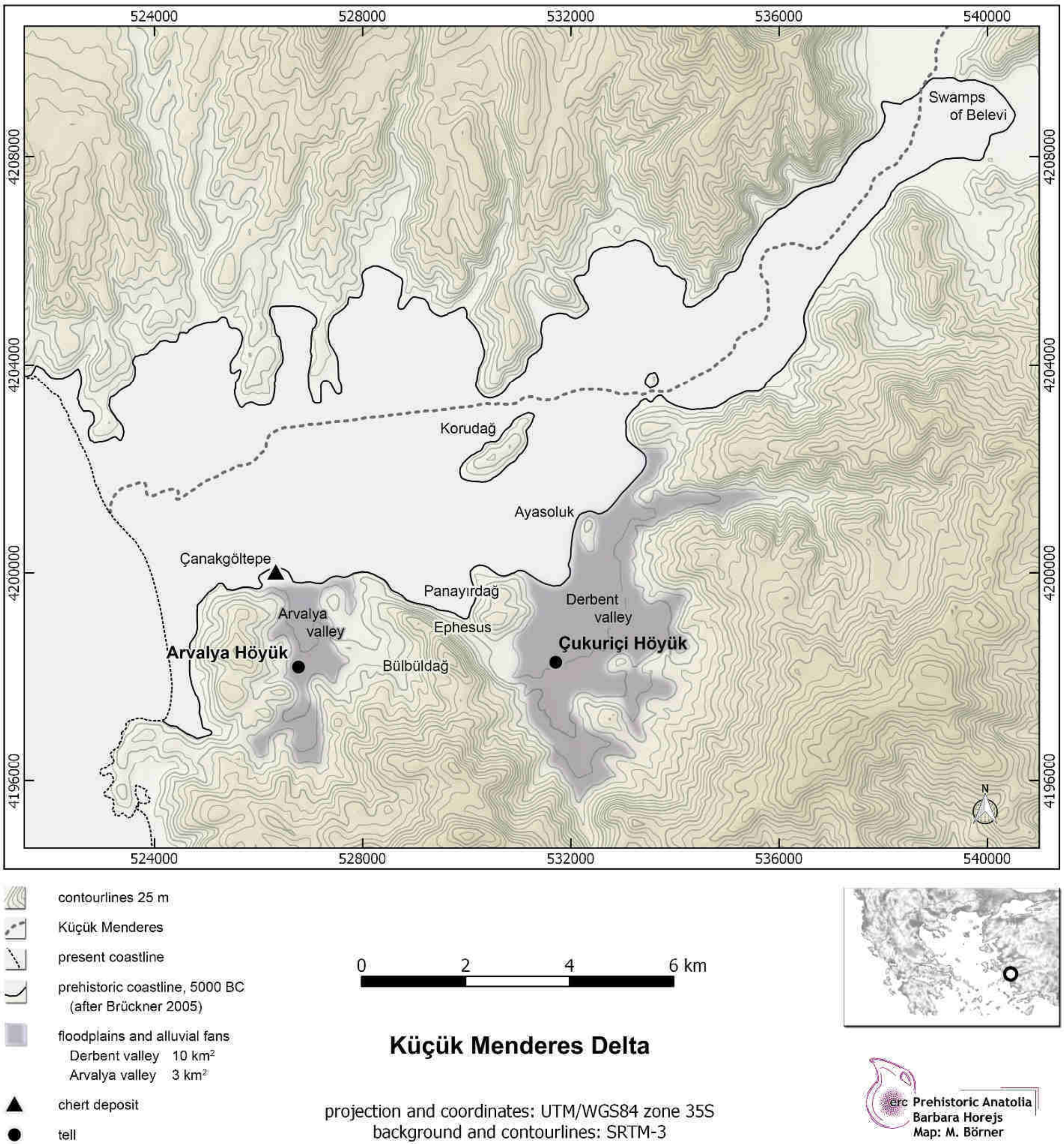

Fig. 6.1: Neolithic settlements and chert source within the lower Küçük Menderes basin. Reconstructed prehistoric coastline according to Brückner (2005) (Map: ERC Prehistoric Anatolia/M. Börner).

Thereafter, the continuous delta advance of the Küçük Menderes river (in Antiquity: Kaystros) and its tributaries since the 5th/4th millennia BC lead to a complete siltation of the marine embayment (Brückner, 1997, 2005; Kraft et al., 1999, 2000, 2001, 2005, 2007, 2011). Until the 1st millennium BC the siltation in the environs of the Çukuriçi Höyük was dominated by the rivers Derbent (in Antiquity: Marnas) and Selinus (for a detailed description see Stock et al., 2014), and in the environs of the Arvalya Höyük by the river Kenchrios. When the Küçük

Menderes delta reached the study area during the 1st millennium BC the settlements had already been abandoned (Horejs et al., 2011, 2012; Brückner et al., 2008; Stock et al., 2013, 2014).

Çukuriçi Höyük is located in the western part of the Derbent valley (Fig. 6.2a). It has partly been destroyed, because the terrain was levelled and planted with fruit trees (Horejs, 2012). In 2006, its surface area was presumed to be 100 x 80 m^2 (Horejs, 2008). On satellite images of the 1960s and 1970s, several river channels are visible in the vicinity of the tell site (Kurtze et al., 2012). The channel of the Derbent is located east of the street to Magnesia, another former river channel can be made out directly to the west of the tell (Fig. 6.2b). Arvalya Höyük is a just gently elevated area in the Arvalya valley, located mainly west of the new road to Kuşadası which destroyed most of the original surface (Fig. 6.3a). The tell is confined on the

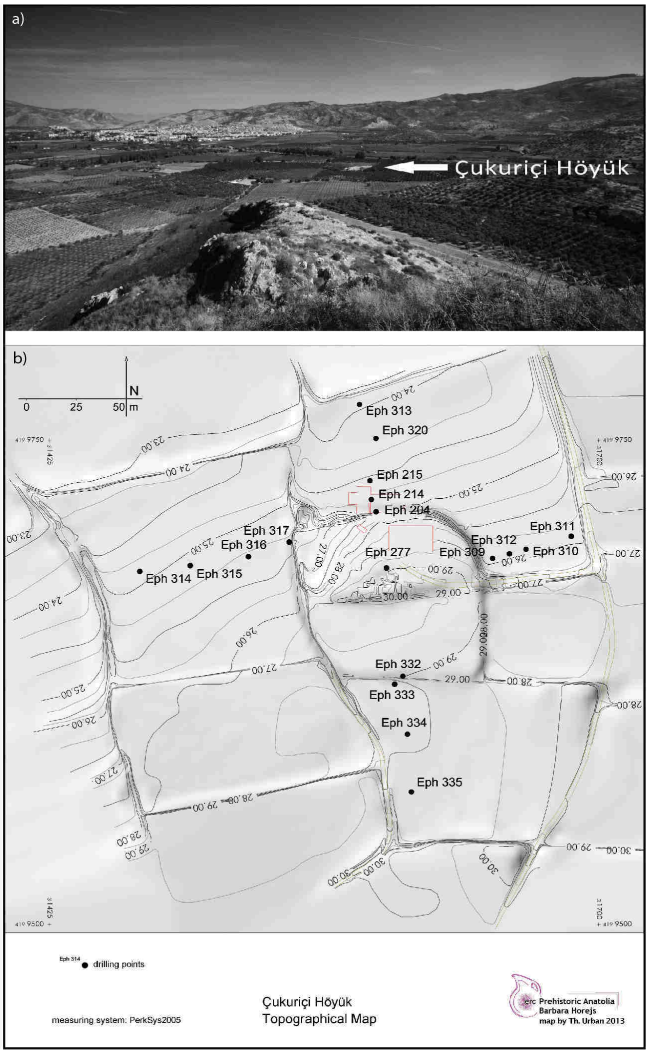

Fig. 6.2: a) View of Derbent valley and Çukuriçi Höyük. b) Topographical map of Çukuriçi Höyük (ERC Prehistoric Anatolia/Th. Urban).

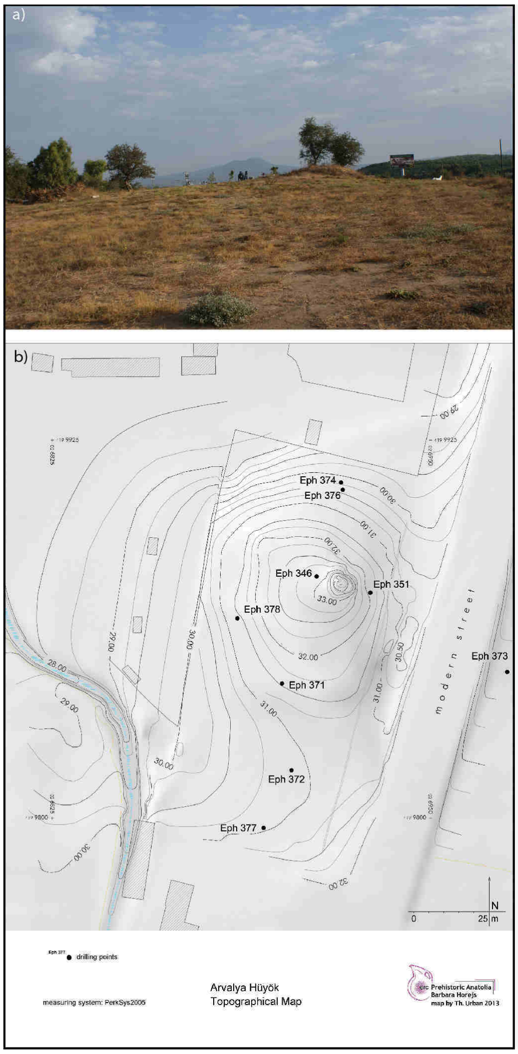

Fig. 6.3: a) View of Arvalya Höyük. b) Topographical map of Arvalya Höyük (ERC Prehistoric Anatolia/ Th. Urban).

northern side by a Safari park and on the western side by a man-made edge. The Kenchrios river channel flows to the west of the mound (Fig. 6.3b).

6.3 Methods

Both mounds and their environs as well as the swamps of Belevi were investigated with half open and closed drill cores (vibracorer Cobra mk1, Atlas Copco Co., diameters of auger heads 5 and 6 cm) up to a maximum depth of 8 m at the mounds and 15.40 m at Belevi. In the field, the sediments were described in terms of grain size, colour (Munsell Soil Color Charts), carbonate content (with diluted hydrochloric acid) and other characteristics (e.g. macrobotanical and -faunal remains, potsherds and lithic fragments, angular stones). All coring sites were measured with a DGPS (Topcon HiPer Pro; precision: 2 cm; altitudes refer to present mean sea level). In the laboratory, selected samples from the cores obtained at the tells were dried and sieved (<2 mm). They were analysed for grain size with a laser diffraction particle sizer (Beckmann Coulter LS13320 Mikro; statistical analyses with GRADISTAT; Blott and Pye, 2001), calcium carbonate content (Scheibler apparatus), total organic carbon content (TOC with a C/N Analyzer, vario EL cube, Elementar) and element measurements with an Atomic Absorption Spectrophotometry (AAS iCE 3000 series Thermo Scientific).

Sample Code	Lab code	Material	Depth (m) b.s.	Depth (m) a.s.l./b.s.l	$\delta^{13}C$	^{14}C age	Age cal BC (2σ)
Eph 371/12 HK	UBA-26795	charcoal	148	30.057	-24	4183±33	cal BC 2889–2638
Eph 378/9HK 160	UBA-26796	charcoal	160	29.783	-24.8	7311±40	cal BC 6237–6072
Eph 371/5HK 80	UBA-26797	charcoal	80	30.737	-28.9	4199±38	cal BC 2898–2640
EPH 346/4HK147	UGAMS 13058	charcoal	147	31.322	-26.1	7700±30	cal BC 6595–6470
Eph 204	UGAMS 6040	charcoal	194	23.902	-26.8	7590±30	cal BC 6478–6411
Eph 204-259	UGAMS 6042	charcoal	259	22.44	-25.6	7400±30	cal BC 6372–6224
Eph 215 - 195	UGAMS 6041	charcoal	194	22.613	-26.1	7400±30	cal BC 6372–6224
Eph 214- 345	UGAMS 6043	charcoal	345	21.301	-26.4	7690±30	cal BC 6592–6468
Eph 214-100	UGAMS 6044	charcoal	100	23.751	-25	7390±30	cal BC 6374–6216
Eph 214 297	Erl-14521	bone	297	21.781	-19.9	7568±39	cal BC 6477–6379
Eph 214 232	MAMS-10878	bone	232	22.431	-23.2	7409±33	cal BC 6377–6226
Eph 269 10,21 Cg	UGAMS 13570	*Cerastoderma glaucum*	1021	-6.75	-4.6	6440±30	cal BC 5095–4880
Eph 269/M 1315	UGAMS 13568	*Cerastoderma glaucum*	1315	-9.69	-8.7	6760±30	cal BC 5441–5281
Eph 269/1 Pf. 1496	UGAMS 13569	plant remain	1496	-11.5	-27.4	7320±30	cal BC 6234–6085

Tab. 6.1: Radiocarbon data chart. The conventional ^{14}C ages are calibrated with Calib 6.0 (Reimer et al., 2009) and are presented here with 2 sigma standard deviation (95.5 % probability). b.s. below surface, b.s.l. below sea level, a.s.l. above sea level. ^{14}C measurements were performed at the Applied Center for Isotope Studies at Athens, Georgia, USA (UGAMS), ^{14}Chrono Centre for Climate, the Environment and Chronology at the Queen's University Belfast, UK (UBA), AMS ^{14}C-laboratory in Erlangen, Germany (Erl), and at the Klaus-Tschira Laboratory for scientific dating in Mannheim, Germany (MAMS).

Geophysical measurements were conducted on Arvalya Höyük to investigate the subsurface of the tell. Geomagnetic measurements were performed on 6027 m² using a Foerster FEREX® Fluxgate magnetometer with 4 sondes. The processing of the data (subgrid shifts, line shifts, displacements, moving of the spikes and noise) and the visualisation carried out using the APMAG software (developed in ZAMG) and georeferenced for GIS implementation (Seren et al., 2004). 2787 m² were prospected with a Sensors & Software NOGGIN® georadar (250 Mhz antenna), processed and visualised with the APRADAR software (developed in ZAMG; Seren et al., 2004).

The archaeological objects (pottery, lithics, small finds) from the drill cores (Çukuriçi and Arvalya Höyük) and the surface finds (Arvalya Höyük) were documented and analysed. Pottery was categorised according to shapes and fabrics to be compared with the excavated assemblages from Çukuriçi Höyük.

Thus, together with radiocarbon age estimates, diagnostic pottery reveals the chronostratigraphy of the mounds and the swamps of Belevi.

Palynological studies were conducted with 2–4 cm³ sediment following Eisele et al. (1994). Identification of the pollen grains was carried out after Beug (2004), Moore et al. (1991) and Reille (1992).

6.4 Results and discussion

6.4.1 Drill cores at Çukuriçi Höyük

In order to study the thickness and the extent of the cultural layers 19 drill cores were obtained on the tell and in the surrounding area. They reached a maximum depth of 8 m and were arranged in cross sections.

6.4.1.1 North-south cross section

Eph 277 and 332 were drilled on top of the tell site. Eph 204 and 214 are located below the man-made edge within the excavation zone. Eph 215, 320, 313 and 335 were retrieved up to 100 m north of the edge in a tangerine grove. The southern cores comprise Eph 333, 334 and 336, located up to 60 m south of the southern edge of the mound (Figs. 2b, 4).

The base of the cores within the tell area is characterised by dark yellowish brown sandy silts mostly consisting of weathered angular stones (mica schist, quartz) up to 3 cm (Eph 332, 277, 204, 214, 215; Fig. 5). Geochemical analysis revealed low phosphorous and total organic

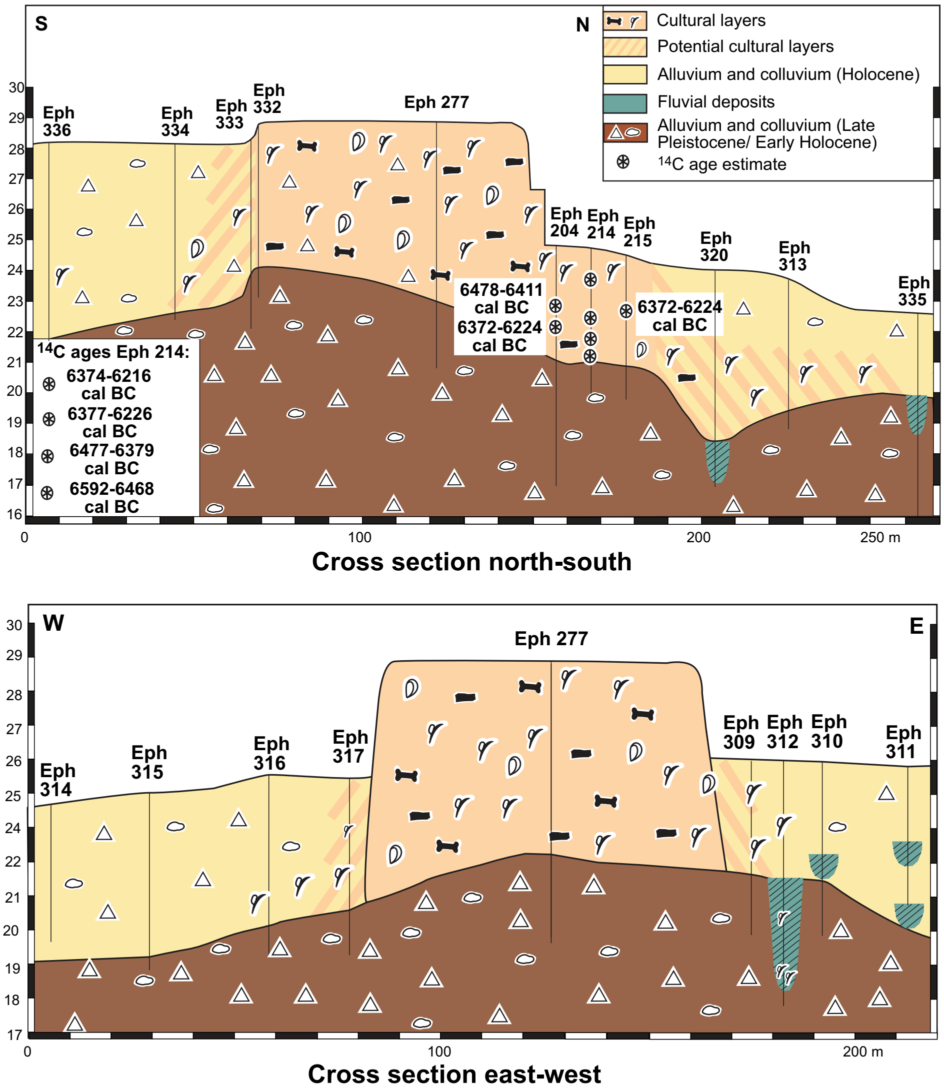

Fig. 6.4 North-south and west-east cross sections of Çukuriçi Höyük with facies interpretation. The maximum size of the mound is not known and can only be estimated. In order to get more precise information, further excavations are necessary. However, parts of this tell have been lost due to extensive bulldozing.

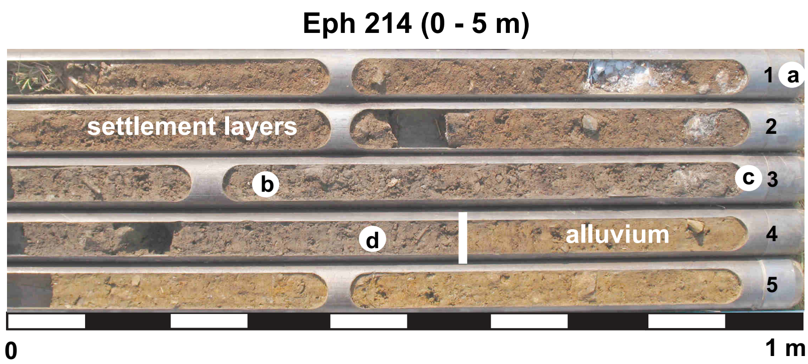

Fig. 6.5: Çukuriçi Höyük. Photo of coring Eph 214 with ^{14}C age estimates. Top of the coring in the upper left corner, end of the coring at 5 m below surface in the lower right corner. Diameter of augerheads: 6 cm. The gap in the 2nd metre is due to the coring process. a) 7374–6216 cal BC; b) 6377–6226 cal BC; c) 6477–6379 cal BC; d) 6592–6468 cal BC.

carbon (TOC) contents and no trace of carbonate (Fig. 6). Within the upper part of this unit, there is a slight decrease in grain size and an increase in iron.

A distinct unconformity to the overlying strata (sandy silts) is especially expressed in the colour change from yellowish brown to brown (Fig. 5). There is a noticeable rise in carbonate, carbon and phosphorous contents directly above the boundary. Settlement remains (charcoal, shell fragments, burnt clay, bones, potsherds, stone tools) are found in the following strata up to the top. At Eph 277 the still preserved settlement layers have a total thickness of 5.65 m, while they are reduced to 3.50 m in the northern cores due to bulldozing. 7 radiocarbon ages from drill cores north of the settlement layers (5 charcoal pieces, 2 bone fragments) date to the 7th millennium BC (time span: 6592–6216 cal BC). This roughly corresponds to the excavated AMS-dated samples going back to the early 7th millennium BC (Fig. 4; Tab. 1) (Weninger et al., 2014; Horejs, in press).

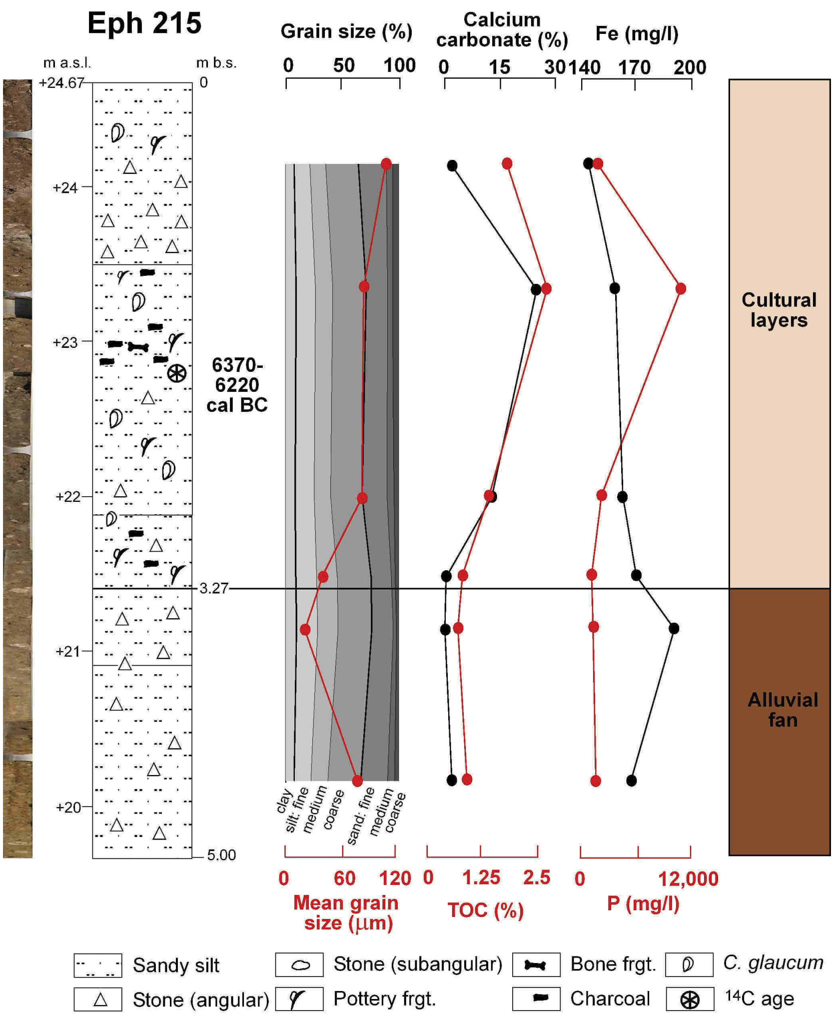

Fig. 6.6: Çukuriçi Höyük. Stratigraphy of core Eph 215 and results of geochemical and sedimentological analyses.

The lowermost sediments of the drill cores from the environs of the mound (Eph 336, 334, 333, 320, 313, 335) revealed similar characteristics: yellowish brown silts and sands with angular stones of quartz and mica schist. South of the tell (Eph 333 and 334) the overlying sediments are characterised by the presence of archaeological remains; the artefacts in Eph 334 are concentrated in the fourth meter. Several potsherds could be assigned to individual settlement periods. The southernmost core (Eph 336) and the upper part of Eph 334 contain components of quartz and mica schist and only very few scattered archaeological remains.

North of the tell, a transition unit of 1.30 m is composed of light greyish silts with laminations (Eph 320) and silty fine sands with coarser components ranging from fine sand to gravel, which is partly rounded (Eph 335). Up to the surface, all cores are composed of sandy silts with abundant archaeological remains which, according to results from the diagnostic pottery, date to the Pottery Neolithic period up until the Early Bronze Age. The cores located closest to the tell revealed a higher density of settlement remains than the others.

6.4.1.2 West-east cross section

Eight drill cores were retrieved up to 80 m to the west (Eph 317, 316, 315, 314) and 60 m to the east (Eph 309, 312, 310, 311) of the tell (Figs. 2b, 4). With the exception of Eph 314, the yellowish brown layer with angular clasts (see 4.1.1) was reached at a depth of 4–5 m b.s. (below surface). In all drill cores, the sediments up to the present surface consist of sandy silts with scattered weathered archaeological remains. The latter comprise mudbrick fragments and potsherds; only few could be determined and assigned to the Late Neolithic and Chalcolithic periods.

In the eastern cores Eph 312, 310 and 311, a specific stratum is intercalated: a brown greyish layer with fining upward sequence (gravel to sandy silts). In Eph 312 this layer is especially thick (2.50 m greyish clayey silts); it contains two rounded potsherds, a stone tool made of obsidian and a bone fragment.

6.4.1.3 Interpretation of the cored strata at Çukuriçi Höyük

The lowermost sediments can be interpreted as an alluvial fan from the Late Pleistocene/Early Holocene (Figs. 4, 5, 6). This is indicated by the common occurrence of weathered angular stones and by the dark yellowish brown colour. The angular components indicate a short transport from the nearby mountains. Since these strata are void of archaeological remains, the deposition must have taken prior to an initial settling at the site. A palaeosol has developed in the upper alluvium. It is decalcified and shows an enriched iron content. The alluvial sediments are topped by cultural layers, the maximum thickness of which was 5.65 m in drill core Eph 277. However, they were originally up to 8.50 m thick with visible archaeological remains on top of the tell site (Horejs, oral comm.). Besides the abundant occurrence of artefacts and charcoal there are many more indications of human impact: high contents in phosphorous (Holliday and Gartner, 2007; Gauss et al., 2013) and TOC (Schlezinger, 2000). Cultural layers were also detected in cores adjacent to the tell (Eph 309, 317, 333 and 334, 320 and 313). The higher density of finds in the northern cores may indicate the extent of the tell in this direction. However, this can also be due to the northwards sloping topography (see Fig. 4) with alluvial and colluvial processes having transported and redeposited the artefacts. An excavation could bring about clarity how far the tell actually extents in this direction.

Several drill cores in the vicinity of the tell with brown to yellowish brown sediments and only a sparse occurrence of archaeological remains are of alluvial/colluvial origin; they can, therefore, not be referred to as cultural layers. Nevertheless, the artefacts allow these strata to be assigned to the Holocene period.

The intercalated layers with fining upward sequences identified in Eph 310, 311, 320 and 335, can best be interpreted as fluvial channels. Shifts in the fluvial system of the river and its affluents were a common phenomenon. In Eph 312 predominantly fine-grained clastic deposits indicate low energy depositional conditions, or a stillwater environment. An excavation could clarify whether the deposit is of natural or man-made origin, such as hydrologic measures like damming.

With the help of the drill cores, the size of the tell can be estimated to a maximum N-S extension of 200 m and E-W extension of 100 m, i.e. roughly 16,000 m², if a quasi-ellipsoidal shape is assumed. It is evident, however, that the maximum extent of the tell varied considerably for each settlement phase from the early 7th to the 3rd millennia BC.

6.4.2 Arvalya Höyük

6.4.2.1 Geophysical investigations

The magnetogram shows in the northern and eastern parts a modern conduit and several recent iron objects (Fig. 7). This area is disturbed; no clear archaeological structures are visible. In the southern part there is a potential rampart-ditch construction or enclosure with an entrance area. The ditch or enclosure is up to 7 m wide, the wall c. 6 m. It is identifiable at a length of 50 m and disappears about 13 m west of the street, where it was probably destroyed during road constructions. Linear structures occur north of the rampart-ditch. They may indicate houses within the enclosure. Several pits and fireplaces were also detected.

The interpretation of the radar data is presented in Fig. 8 at a depth range of 0.2 to 1.3 m. Many structures are visible, except in the southern area, but identifiable only within the 1–2 m depth range. These structures may be interpreted as walls. In the centre of the measured area a distinct round structure with a diameter of 3.5 m appears. South of it a 12 m x 14 m ground plan can be identified as well as more walls further to the south. The structures in between can be vaguely determined; they are possibly walls as well. The presumed rampart-ditch cannot be detected with the radar technique. Fig. 9 shows a synoptic interpretation of the magnetic and radar images.

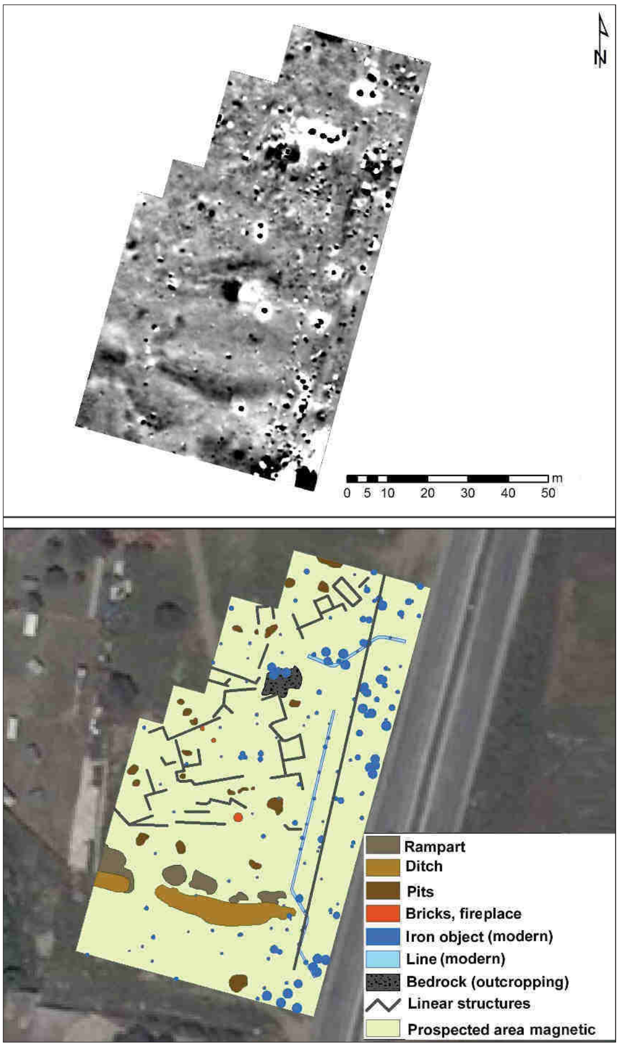

Fig. 6.7: Arvalya Höyük: Geophysical investigations. a) Magnetogram; b) Archaeological interpretation of the magnetogram.

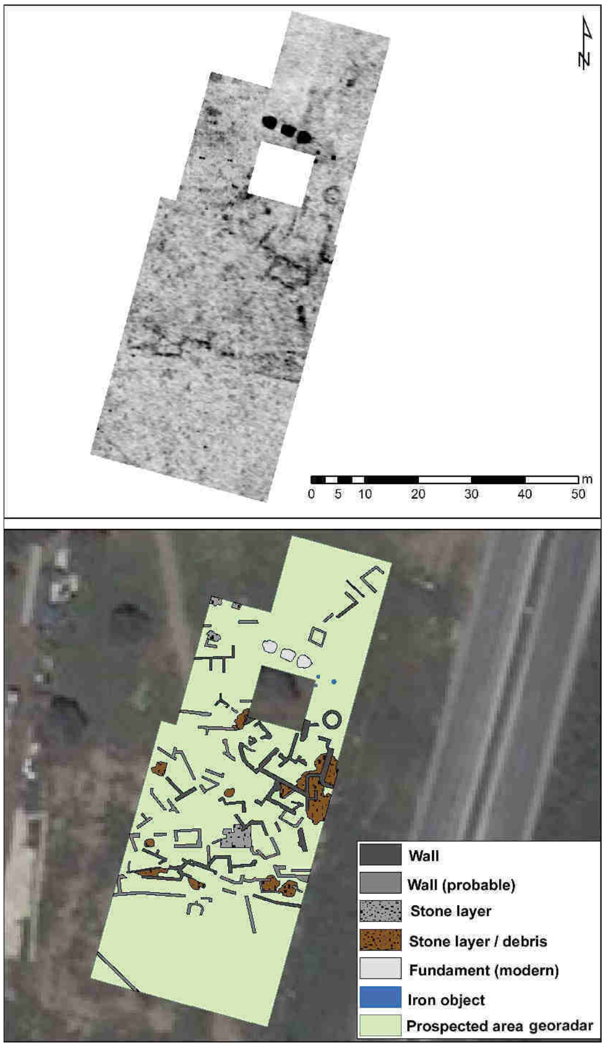

Fig. 6.8: Arvalya Höyük: Geophysical investigations. a) Georadar (depth profile 0.2-1.3 m); b) Archaeological interpretation of the georadar data.

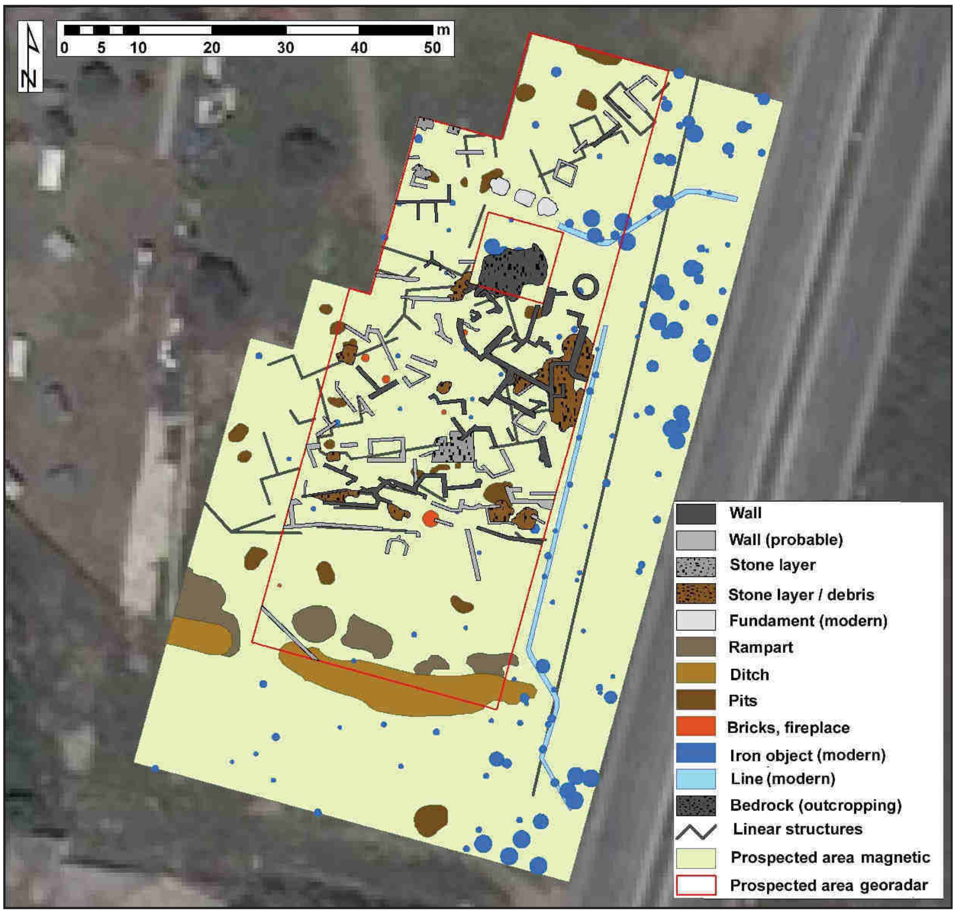

Fig. 6.9: Arvalya Höyük: Geophysical investigations. Synopsis of the geophysical prospection. Combined interpretation of magnetic and georadar results.

6.4.2.2 Drill cores

To verify the geophysical research, 9 drill cores with a total depth of 6 m were retrieved from the settlement and its surrounding areas (Figs. 3b, 10). All of them reveal a consolidated layer of clay and loam with small stones at the base. Overlying is a 2.90 m thick stratum, with lithics, bones, potsherds, burnt clay and shell fragments as well as charcoal. Only Eph 377, located at the southern border of the field, and Eph 373, drilled east of the street, are void of settlement remains.

One drill core was retrieved from the centre of the tell (Eph 346). It revealed ceramic flitters, charcoal, silex, a red plastered floor or wall (at 2.26 m b.s.), mica schist and quartz pebbles within the upper 3.50 m. Eph 351 was drilled within the round structure. The upper 2.80 m of this core are composed of silty sands with archaeological remains. On the northern part of the tell site (Eph 374 and 376) abundant settlement remains occur within the upper 1.65 m. Eph 378, drilled on the western part of the mound, shows human impact within the upper 2.80 m. In corings Eph 371 (inside a house structure) and Eph 372 (within the ditch), only scattered anthropogenic remains were found in the uppermost 2 m of the cores. In general, the pottery fragments date from the Neolithic period to the Early Bronze Age.

Four ^{14}C dates give a rough estimate of the chronostratigraphy (Tab. 1): two samples from the deepest settlement layers date to the 7th millennium BC (time span: 6595–6072 cal BC), the others to the 3rd millennium BC (time span: 2898–2638 cal BC).

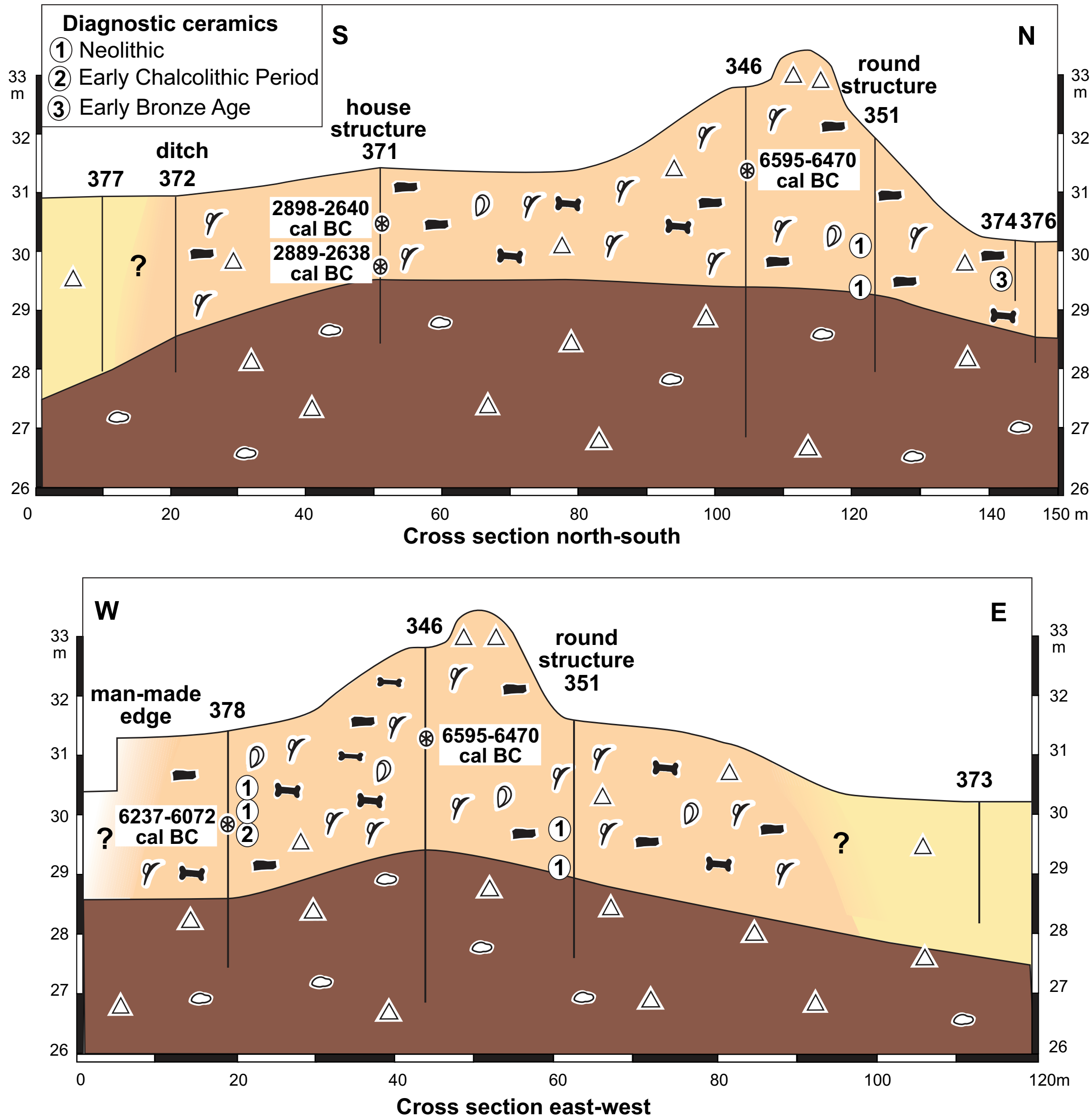

Fig. 6.10: North-south and west-east cross sections of Arvalya Höyük with facies interpretation. Legend in Fig. 6.4. The maximum size of the mound is not known and can only be revealed by excavations. However, parts of this tell are lost due to bulldozing and construction works.

6.4.2.3 Interpretation of drill cores of Arvalya Höyük

The base of the drill cores may be interpreted as the top parts of an alluvial fan, probably deposited during the Late Pleistocene/Early Holocene (Fig. 6.8). The overlying settlement layers have a thickness of up to 3.50 m (Eph 346, 351 and 378). The centre of the mound was probably in the northern and western parts of the investigated area which is suggested by the high number of finds; it may, however, have shifted over time.

Taking all the results into account, a minimal N-S extension of 100 m and an E-W extension of 60 m can be estimated, with an overall quasi-ellipsoidal surface of at least 5,000 m². However, it appears more likely that the settlement area was considerably larger, which could not be confirmed because no coring could be carried out further to the north and west.

6.4.2.4 Archaeological analyses

Despite massive modern destruction of the site and former collections of surface finds has occurred (Evren and İcten, 1998), non-systematic surveys could provide good assemblages of pottery, lithics and a few small finds. Of the 58 gathered pottery fragments only very few are characteristic pieces, like rims or base fragments. The analyses of their fabrics and wares reveal similarities to excavated Çukuriçi material, making it possible to use the same classification system and allowing assumptions in terms of chronology. 33 ceramics are corresponding to already defined and well-known pottery wares, which are characteristic for specific chronological periods in the neighbouring valley. Their distribution show a clear dominance of Neolithic to Early Chalcolithic wares (Fig. 11; phases ÇuHö X-VIII; 64 %) followed by Late Chalcolithic wares (phase ÇuHö VII; 30 %), and only rarely Early Bronze Age pottery (EBA, phases ÇuHö IV-III; 6 %). The lithic material consists of obsidian and chert

Fig. 6.11: Neolithic and Late Chalcolithic pottery from the surface of Arvalya Höyük. (ERC Prehistoric Anatolia/photo: J. Traumüller).

Fig. 6.12: Chert artefacts from the surface of Arvalya Höyük (flake cores, flakes and debris). (ERC Prehistoric Anatolia/ photo: B. Milić).

artefacts, also comparable to already known types and raw materials of the Neolithic period. Of particular interest is the chert assemblage of retouched tools, flakes cores and debris (Fig. 12). It should be pointed out that the only material source of local chert known so far is Çanakgöltepe located near the entrance to Arvalya valley (Fig. 1). The Neolithic material spectrum of lithics and pottery can be integrated very well into the already discussed and supposed archaeological group of the centre at the Aegean Anatolian coast that include Ulucak, Ege Gübre, Yeşilova, Dedecik-Heybelitepe and Çukuriçi Höyük. Arvalya Höyük appears as another 7th millennium tell settlement integrated in this archaeological group of Pottery Neolithic period. This result corresponds to the radiocarbon-dated drill cores. Although there are no ^{14}C ages indicating a 4th millennium occupation, the pottery also hints to a Late Chalcolithic site. Finally, the singular EBA ceramics can be related to ^{14}C ages of the 3rd millennium, indicating a settlement which is contemporaneous to at least phases Çukuriçi Höyük IV and III.

Combining these results with drill core analyses and geophysical interpretations (s. above), it can be stated that Arvalya Höyük comprises several layers of occupation dating to different periods from the Neolithic to the Early Bronze Age. This massively destroyed tell site was probably larger in its original extension (Fig. 12). The various architectural and domestic remains detected by means of geophysics (Figs. 7–9) show differing orientation and settlement patterns covering each other. Although a proper chronological classification of these structures cannot be established without an excavation, it has been suggested that although the significant enclosure (rampart-ditch) could be correlated with all detected periods, it appears similar to the Late Chalcolithic ditch at Çukuriçi Höyük VII (and other sites), which is 4–5 m wide and up to 2.5 m deep (Horejs, 2014). However, a comparison with massive enclosures known from the 3rd millennium BC, e.g. Bakla Tepe or Liman Tepe could also been made (e.g. Erkanal, 2008a, b).

6.4.3 Palynological analysis

A palynological study has been carried out for drill core Eph 269, retrieved from the swamps of Belevi (Fig. 13). The lower 7 m comprise the period from the 7th to the 3rd millennia BC (15.40–8.06 m). The base (15.40–9.78 m) reveals silts with an intercalated sand lens (13.33–12.46 m) dating from the end of the 7th to the beginning of the 5th millennium BC. Microfossils at the base indicate freshwater to brackish conditions, followed by a brackish-marine environment still connected to the sea (unpublished data). The palynological analysis revealed a high number of indeterminate pollen grains and *Isoetes* spores (pollen assemblages zones (PAZ) 1a+b). They and a greater part of the palynomorphs were probably transported into the marine embayment were most likely transported by the Küçük Menderes river. This part of the profile indicates a natural vegetation dominated by deciduous oak (*Quercus robur-/cerris*-type). However, more than 5 % of Cerealia type pollen may suggest early agricultural activity and human impact on the landscape already at the beginning of the 7th millennium BC.

The overlying stratum (9.78–8.06 m) is characterised by pale yellow sediments of a lake, rich in calcium carbonate, with brackish and freshwater ostracods and foraminifers (unpublished data). Thus, the connection to the sea was interrupted as early as during the 5th millennium BC. PAZ 2 is dominated by a rapid decline of indeterminates and *Isoetes* spores and now indicates the absence of sediments transported by the Küçük Menderes river. The macro remains are represented by the swamp and water plants *Typha*, *Najas* and Characeae. Deciduous oaks (*Quercus robur-/cerris*-type) still dominate the tree pollen with up to 50 % of the terrestrial pollen. In the direct vicinity of the swampy environment, crop cultivation is rather unlikely. The discontinuation of *Polygonum aviculare*-type pollen (common on areas with trampling stress) also confirms this assumption.

6.5 Palaeoenvironmental reconstructions

The results prove the existence of two settlement sites dating back to the Neolithic period. The inhabitants intentionally chose the locations due to the advantageous topography in the early 7th millennium BC. They seem to have been the perfect spots for first sedentary lifestyles, lying on small elevations (Çukuriçi Höyük 1–4 m, Arvalya Höyük c. 1–2 m above surface; Figs. 4, 10), at a distance of about 1.5–2 km from the coast, surrounded by fertile alluvial plains. At Çukuriçi Höyük, finds of fish bones, echinoid spines, crabs as well as many molluscs from sandy and rocky habitats have proven that the inhabitants used the sea intensively (Galik, 2008; Galik and Horejs, 2009; Horejs et al., 2011). During the time of occupation, several rivers flowed in the direct vicinity of the tell sites. The elevated terrain provided safety from the torrents. The initial settlement is associated with warm and humid conditions (Mudie et al., 2007); it took place before the rapid climate change dated to 8600–8000 BP in the Aegean region (Mayewski et al., 2004) and to the 8.2 ka event in the North Atlantic (Alley et al., 1997)), which caused cooler and more humid conditions the Aegean region (Harrison et al., 1991; Rohling et al., 2002). The effect of the cooler climate cannot be clearly stated yet (Weninger et al., 2014), but Çukuriçi Höyük appears to be abandoned after around 5900 BC until the 4th millennium BC.

Today, there are river beds noticeable to the west of both mounds. A multi-temporal study of aerial photographs and satellite images since the 1950s indicates that the torrential streams have changed their courses several times (Kurtze et al., 2012). It can be assumed that at one point the torrential streams flowed directly to the west and east of the tell sites. The diversity

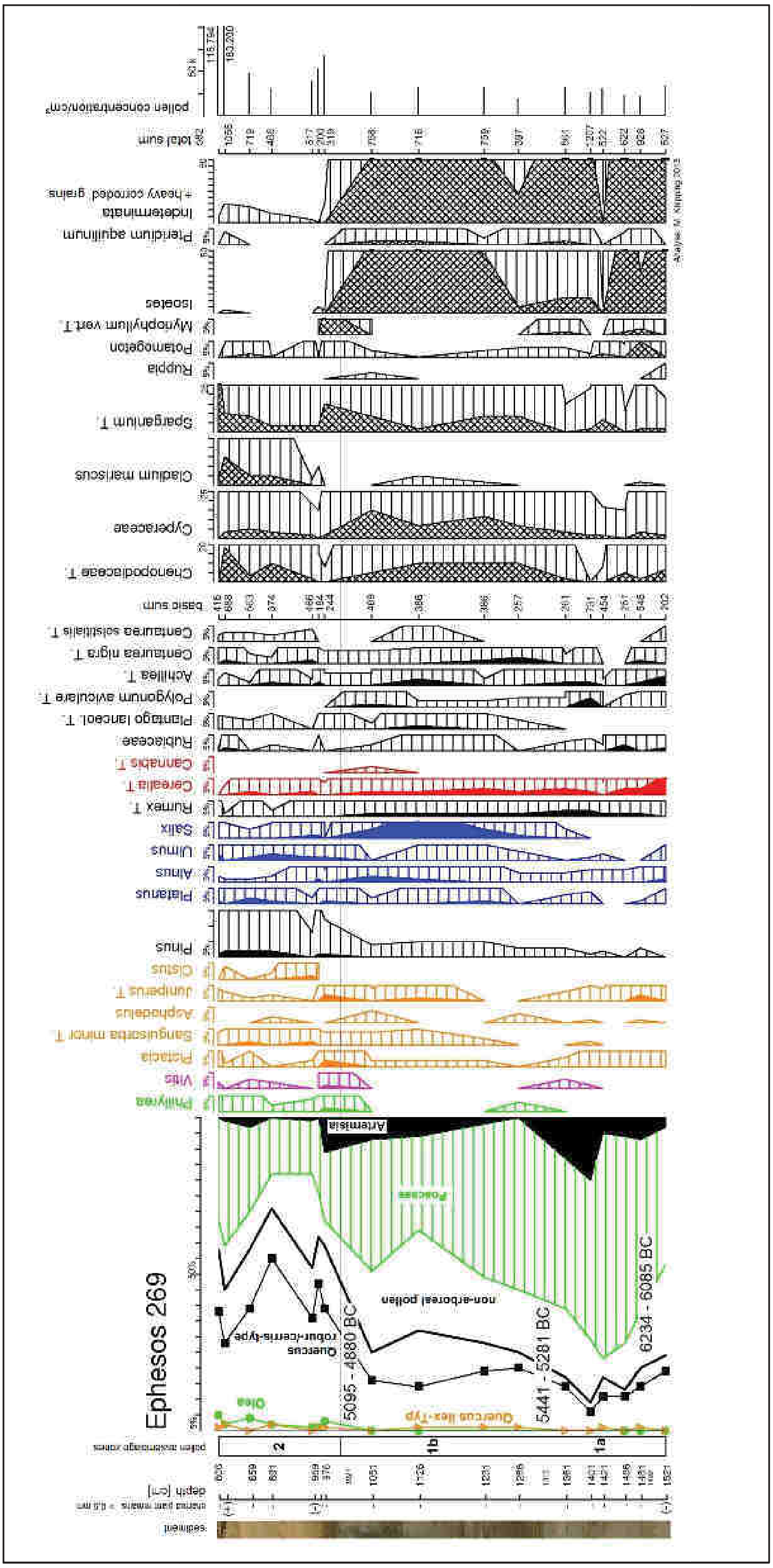

Fig. 6.13: Palynological analysis of the lower part of core Eph 269 from the swamps of Belevi.

of the fluvial layers is the result of discharge fluctuations due to climate variations or seasonality on the one hand and lateral migration of the stream channels on the other.

Çukuriçi Höyük was larger than Arvalya Höyük (roughly 16,000 m² vs. 5,000 m²) with altogether more preserved settlement layers (8.50 m and 3.50 m, respectively). These results are supported by the potential agricultural area: Çukuriçi Höyük had approximately 10 km² available whereas the rural area of Arvalya Höyük was more likely about 3 km² (Horejs, 2014). Archaeobotanical remains are represented by finds of barley and wheat as well as lentils, flax and figs (Thanheiser, 2008; Horejs et al., 2011). Moreover bones of domesticated animals were found (Horejs et al., 2011; Galik and Horejs, 2011; Galik, 2008, 2014). These results combined with other elements of the 'Neolithic package' (Horejs, in press) indicate a fully developed farming community. This is also supported by the finds of Cerealia pollen. Despite agricultural use, however, during the time of settling, a natural vegetation cover with deciduous oak on the surrounding slopes was still present during the time of occupation.

6.6 Conclusion

The geoarchaeological study of early settlement sites in Western Anatolia reveal a colonisation of the Arvalya and Derbent valleys south of the Küçük Menderes graben by the early 7th millennium BC. Çukuriçi Höyük and Arvalya Höyük are coastal mounds located 1.5–2 km south of the Neolithic coastline. The settlement layers overlie sediments of an alluvial fan, dating to the Late Pleistocene/ Early Holocene.

At Arvalya Höyük, radar and magnetic measurements indicate the existence of house structures, fireplaces and pits which are surrounded by a potential rampart-ditch construction. Drill cores prove a minimum of 3.50 m preserved settlement layers with a size of at least 100 m x 60 m, from which a settled area of 5,000 m² can be calculated. At Çukuriçi Höyük, settlement layers have a minimum thickness of 8.50 m, the tell has a size of c. 200 m x 100 m and a settled area of 16,000 m². Within the settlement layers the phosphorous content is increased.

Both mounds lie upon small elevations within alluvial plains with c. 10 km² (Çukuriçi Höyük) and 3 km² (Arvalya Höyük) available land for potential agricultural use. From excavations at Çukuriçi Höyük it is known that agriculture was practised already from the Neolithic period on. This is also attested by finds of Cerealia-type pollen in a drill core in the swamps of Belevi. However, in this early period, a natural vegetation with deciduous oaks still dominated the landscape. The elevations were probably chosen as protection against floods of the torrents in the direct vicinity of the tells especially during winter times.

7. Discussion

This geoarchaeological research focuses on a detailed analysis of the Holocene landscape development and coastline changes in the environs of the ancient city of Ephesus. In chapters 7.1–7.4, the working hypotheses and the research goals derived thereof, which were formulated in chapter 1.3, are discussed with special regard to human-environment interactions and landscape changes. Chapter 7.5 provides preliminary results of the swamps of Belevi and a perspective of the work in the Ephesia.

7.1 Delta progradation of the Küçük Menderes and Holocene sea-level changes during the Holocene

Working hypothesis 1: The Holocene transgression of the sea created a marine embayment which reached far inland. This embayment was later entirely filled in by fluvial sediments.

Goal 1: Detection of the spatial and temporal shifts in the coastline during the Holocene

The research this PhD thesis is based upon provides a detailed understanding of coastline changes, especially in the southern part of the Küçük Menderes graben (chapters 2–5). Field investigations proved a maximum inland extension of the marine embayment around 5441–5281 cal BC (chapter 6; Fig. 7.1). The sea reached up to the (later) swamps of Belevi c. 20 km inland. The presence of *Isoetes* spores and indeterminate pollen grains indicate fluvial input by the Küçük Menderes. This had been proven for the Büyük Menderes river as well (Knipping et al., 2008).

Regarding the development of the marine transgression into the Küçük Menderes graben since 6000 BC, the new data complement former field research (Brückner, 1997, 2005; Kraft et al., 2000, 2007, 2011). The sea started to transgress into Arvalya valley on the southern flank of the graben 5890–5730 cal BC (chapter 5). At Çanakgöl (Fig. 7.1; chapter 2) and to the west of Ayasoluk hill (Fig. 7.1; chapter 5), the lowest marine facies reveals an age of 4269–3939 cal BC and 4515–4237 cal BC, respectively. However, no transgressive facies could be identified at these sites. Brückner's (1997) age estimates from transgressive sediments in the Olympieion in Ephesus (5779–5688 cal BC) and north of Panayırdağ mountain (harbour site 2, Fig. 7.1; marine facies: 5322–5341 cal BC) correspond to the new age estimates given in this research. To conclude, the sea started to transgress into the graben around 6000 BC and reached its farthest inland extension during the middle of the 6th millennium BC.

The new results allow for a concise dating of the coastline retreat. The first noticeable coastline shift was observed in the swamps of Belevi 5095–4880 cal BC. A layer with brackish and freshwater species overlies the marine facies. Similar sediments are described in the Roman harbour of Ephesus (chapter 3) for the time when the direct connection to the sea had ceased. Thus, the delta advance must have started at the beginning of the 5th millennium BC. This corresponds well with Kayan's (1999) scenario who considered an onset of delta progradation during the 5th millennium BC along the Aegean coasts.

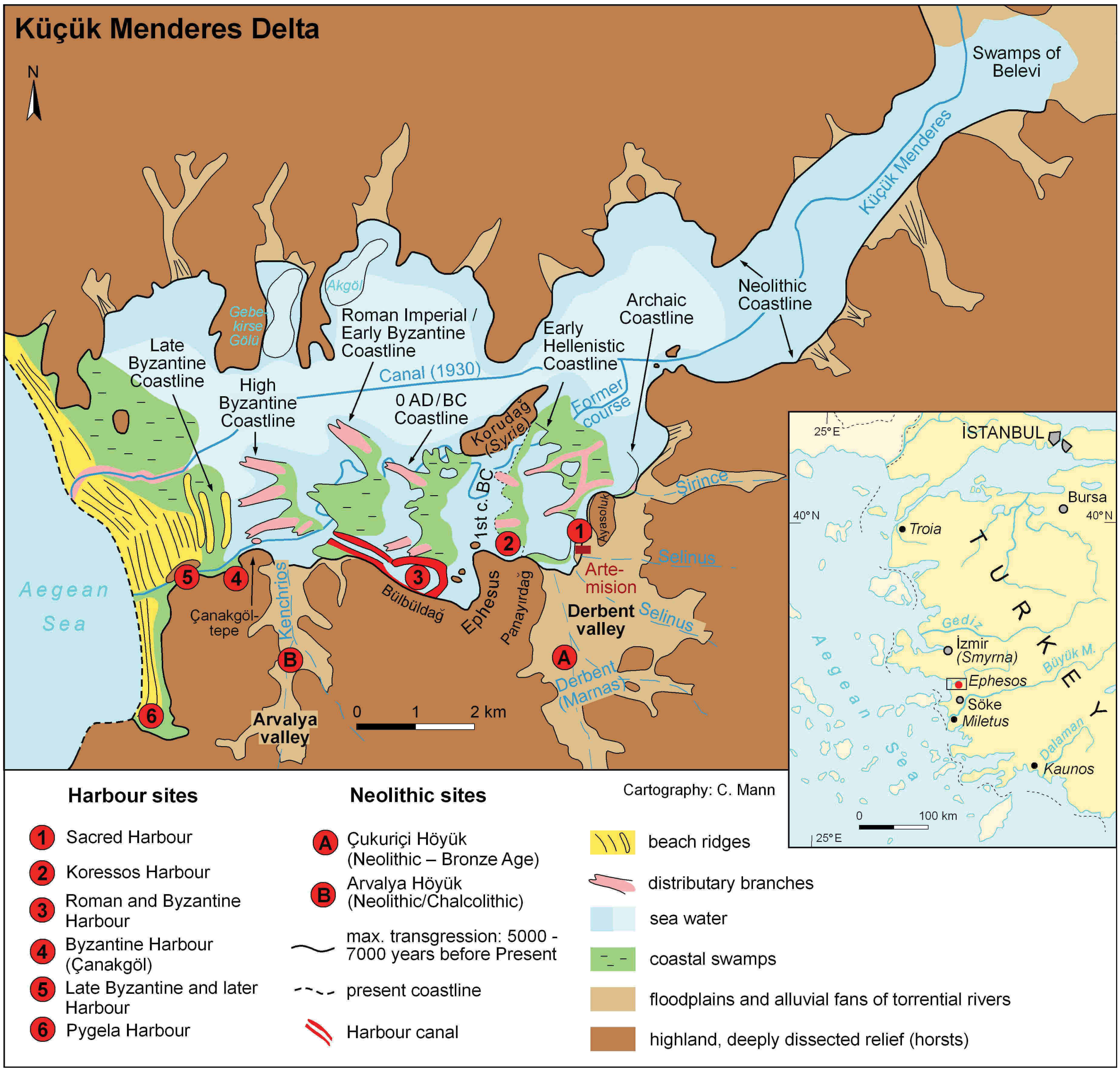

Fig. 7.1: Scenario of the delta progradation of the Küçük Menderes. All new data were added and the map enlarged up to the swamps of Belevi. Ephesus had four different harbour sites (the location of the Hellenistic harbour is not known; it is presumed close to the Roman harbour) being used from the 1st millennium BC onwards (1–4) and two further landing sites to the west (5, 6) (Brückner, 2005, supplemented).

In general, two phases of delta advance can be distinguished. From 5000 BC to the middle of the 1st millennium BC, the delta of the Küçük Menderes prograded for about 10 km with a rate of about ~2.2 km/1000 years (Brückner, 2005; Fig. 7.1, Archaic coastline). In the following 2000 years, it nearly entirely filled in the marine embayment for about 9 km up to the present coastline with a much faster advancing rate of about 4.5 km/1000 years. Today, the coastline is located 6 km to the west of the city; it is mainly dominated by coastal erosion because the delta lacks sediment supply and sea level is rising due to global warming.

This research also contributes considerably to reconstructing the coastline configuration in the Derbent and Arvalya fault systems in the southern part of the graben. Kraft et al. (2000, 2011) and Brückner et al. (2008) presumed a transgression of up to 1 km. New results show that the coastline did not extend more than 500 m into these valleys. Plus, to the east of Ayasoluk hill, no marine sediments were identified in the drill cores. Until the 1st millennium BC, coastline changes in Derbent valley were dominated by the progradation of the rivers Derbent, Selinus and Şirince deltas (Fig. 7.1). Channel migration of these rivers linked with delta progradation resulted in the formation of lagoons as well as coastal and freshwater lakes (chapters 2 and 5). The new data also reveal the formation of a coastal lake northeast of the Artemision. It was completely silted up by 300 BC (chapter 2) when the coastline had already retreated to the west of the Artemision.

Around the turn of the eras, new results confirm the coastline position close to the Roman harbour (Brückner, 2005). However, the first prodelta sediments of the Küçük Menderes were already deposited in the harbour basin during the 2nd/1st centuries BC. New ^{14}C ages from the western rim of the harbour canal reveal a siltation of this area at the end of the 1st century AD (chapter 3).

In the Early Byzantine time, the coastline retreated up to Arvalya valley. There, the coastline evolution was mainly been influenced by the channel migration and delta advance of the Kenchrios river (see Fig. 7.1). Only minor coastal changes occurred in the small embayment at Çanakgöl to the west of Arvalya valley; it was connected to the Küçük Menderes until the 19th century AD. Since field investigations were limited to the area south of the former course of the Küçük Menderes, this study does not provide any information about the siltation of the marine embayment to the north of the river.

Goal 2: Reconstruction of a sea-level curve for the Küçük Menderes graben

In the Ephesia, systematic research on sea-level changes has been lacking so far. All researchers agree that sea-level rise decelerated after 5000–4000 BC. The results for the time since the 5th millennium BC have not revealed a uniform pattern. Depending on the location, the relative sea level was either characterised by a fall after 3500 BC (Kayan, 1996; Kelletat, 2005) or 2000 BC (Müllenhoff, 2005), or a slow, continuous rise until today (i.e. Sivan, 2004;

Lambeck and Purcell, 2005; Vött et al., 2007; see also Brückner et al., 2010 for a compilation of sea-level curves of the Eastern Mediterranean).

Only a limited number of indicators for sea-level changes are present in the Ephesia (for a compilation see Pirazzoli, 2005; Brückner et al., 2010). Most of the available data are ^{14}C-dated paralic peats, formed between 2000 BC to AD 1000 (Fig. 7.2). In order to reconstruct the sea-level curve from 6000 to 2000 BC, in situ shells and plant remains were used; they are mostly from transgressive or lagoonal facies do, however, not reflect the former sea level with good precision. Specific archaeological finds may also be used as a complementary evidence for former sea-level positions (Flemming and Webb, 1986). In Ephesus, such evidence could be an 80 cm high wall on top of the Roman harbour mole as described by Zabehlicky (1999). This wall was probably built as compensation for a tectonic subsidence. However, as there are no detailed subsidence rates for the Küçük Menderes graben, the ancient Roman harbour site cannot be considered as a reliable indicator for deciphering the sea-level story.

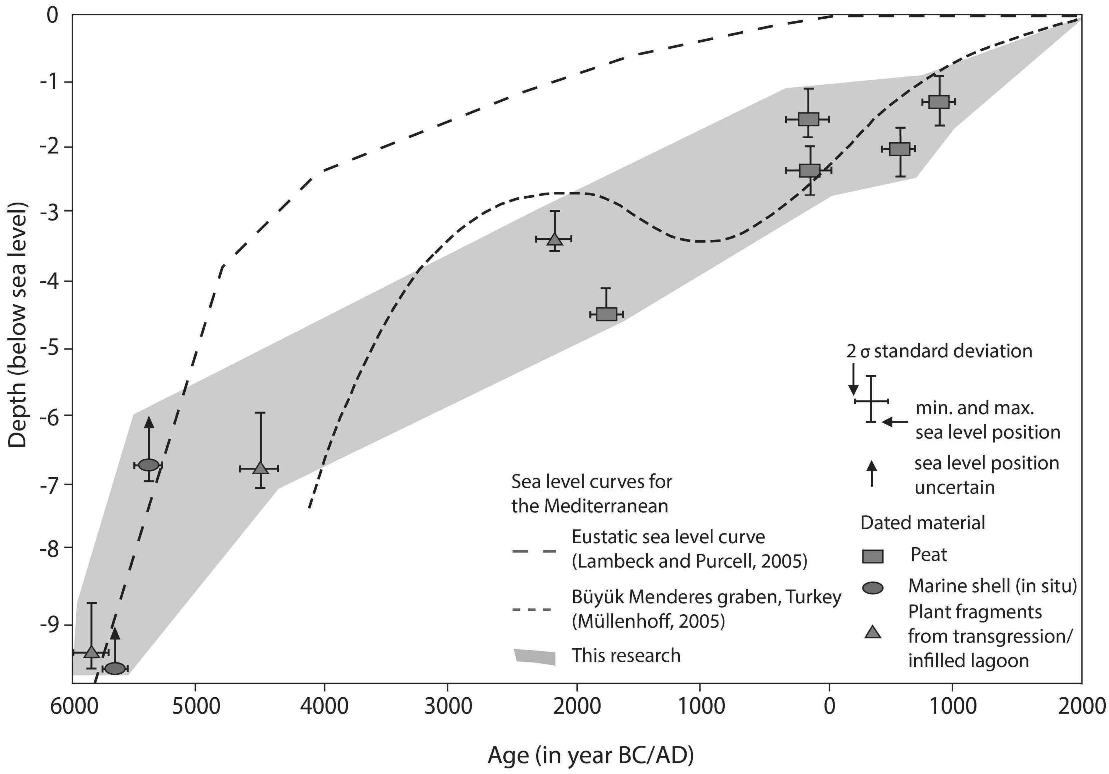

Fig. 7.2: Sea-level curve for the Ephesia and other curves for selected regions of the Mediterranean. Uncertainties of 20–50 cm below and above sampling depth are used for regressive paralic peat layers (see Allen, 1990; Vött, 2007; Brückner et al., 2010), a larger uncertainty exists especially above the sampling depth for shells and plant remains of the transgressive or lagoonal facies.

Taking all of the data together – with special regard to unpublished ^{14}C age estimates of paralic peat – it can be stated that the sea level in the research area has continuously risen until today (Fig. 7.2). This is in contradiction to Müllenhoff's (2005) curve for the Büyük Menderes graben

(Fig. 7.2) and Kayan's (1997) curve for the Troad who both postulate a falling sea level after 4000–3000 BC.

For the Ephesia, a rapid rise occurred until 5500–4500 BC when relative sea level reached 7–6 m below its present position (rate c. 2.5 mm/y from 6000–4500 BC). This result is in good agreement with the onset of the delta progradation since the 5th millennium BC. Lambeck and Purcell (2005), whose glacio-eustatic curve for the Mediterranean is based on geophysical arguments, reconstructed a deceleration after 5000 BC as well (Fig. 7.2 for that time they place the position of the sea level at 3.50–4.50 m b.s.l.

In the following millennia until the turn of the eras, the sea-level rise in the Küçük Menderes graben slowed down with a rate of c. 0.7 mm/y. At 2000 BC, a position of 3.50–5.50 m b.s.l. was reached, at 0 AD/BC 3.50–1.50 m b.s.l. However, due to a lack of data between 4500 to 2000 BC, a reconstruction for this time period remains a challenge. Lambeck and Purcell (2005) assume that the present position was already reached by 0 AD/BC. Müllenhoff (2005) reports a sea-level fall from 2000 BC until c. 500 AD which has not been observed in this research in the Ephesia.

Many peat layers developed between 300 BC and AD 1000; they represent the continuous siltation of the marine embayment in the vicinity of Ephesus. Along with peat formation, the sea level rose even more slowly (rate c. 0.5 mm/y), which is in contrast with the general tendency of Lambeck and Purcell's (2005) model. During the last 1000 years, the relative sea level in the Ephesia did not rise for more than 1 or 2 m up to its present position (rate c. 1.5 mm/y).

The discrepancy of the sea-level position of 3–4 m to Lambeck and Purcell's (2005) for the Mediterranean may be explained by:

i) the subsidence of the Küçük Menderes graben. It will have played an important role as evidenced by the many earthquakes which are documented in the historical records of Ephesus. For southwestern Turkey, Flemming (1992) assumes a subsidence rate of 0.7 mm/1000 years; this area is, however, in another tectonic setting.

ii) compaction due to the fine-grained sediments and to the coring process.

iii) uncertainty of sea-level position when using shell fragments and plant remains.

Therefore, the relative sea-level curve presented here should only be regarded as a first attempt. It definitely needs further improvement.

⇨ ***The study proves a marine transgression of up to c. 20 km into the Küçük Menderes graben during the 6th millennium BC. From the 5th millennium BC onwards, the deltas of the Küçük Menderes and its tributaries started to prograde. Throughout the past millennia, the delta advance has continuously filled in nearly the entire marine embayment. The reconstruction of the relative sea-level changes for the Küçük Menderes graben reveals a continuous sea-level rise until today.***

7.2 Investigation of different harbour sites of Ephesus

Working hypothesis 2: Ephesus' harbours are excellent geo-bio archives.

Goal: Investigation of Ephesus' different harbour sites with regard to their stratigraphy

Field investigations were carried out in the so-called Sacred, the Koressos, the Roman and the Late Roman-Byzantine harbours (chapters 2–5). Our studies cleary proved that two additional harbour sites are located close to the present coastline (fig. 7.1). They were probably in use after the city had declined considerably. The sites of the so-called Sacred harbour, the Roman harbour and the Late Roman-Byzantine harbour are described separately; they reveal different stratigraphies and thereby different patterns of harbour use. The Koressos harbour was studied with regard to the historical accounts. Therefore, it is not described in detail (for stratigraphy see Brückner, 1997, 2005; Kraft et al., 1999, 2000, 2007).

'Sacred harbour'

The **location** of the so-called Sacred harbour of the Artemision was probably the same as the one of the Late Bronze Age to Archaic settlement on Ayasoluk (Kerschner et al., 2008; chapter 2). Thus, the harbour must have been in a small embayment at the foot of Ayasoluk hill northeast of the Artemision (Fig. 7.3). Another possible embayment further to the west in the river deltas of Derbent and Selinus was not suitable for a harbour use due to continuous channel shifts (lateral migration, aggradation) in these deltas. In the opposite direction – to the east of Ayasoluk – no traces of an embayment have been detected; a former assumption by Brückner (2008) and Kraft et al. (2007; see chapter 7.1) to the contrary cannot be confirmed. It has, however, to be stated that no definite harbour installations have as yet been found. The following arguments are therefore based on plausibility considerations.

Drill cores did not allow for a clear distinction of different phases of the **use** of this presumed harbour site. However, archaeological remains on Ayasoluk hill point to the persistence of the settlement from the end of the 2nd millennium BC until max. 400 BC. The ^{14}C ages clearly confirm Creophylos' description (see Jacoby, 1955) that the small embayment was silted up by the end of the 5th century BC.

During the Bronze age and the Archaic period, the most common sites to establish a harbour were natural beaches where the ships were just hauled onto, e.g. in Tyre (Marriner et al., 2008a), Beirut (Marriner et al., 2008b) or Sidon (Marriner et al., 2006c). A similar scenario is assumed for the so-called Sacred harbour, as only fine to coarse sand was found in the presumed harbour layers; traces of a mole or dam are absent (Fig. 7.3). With the ongoing siltation, the harbour site was most probably relocated to Koressos harbour in the 5th century BC (Fig. 7.1; see chapter 7.1).

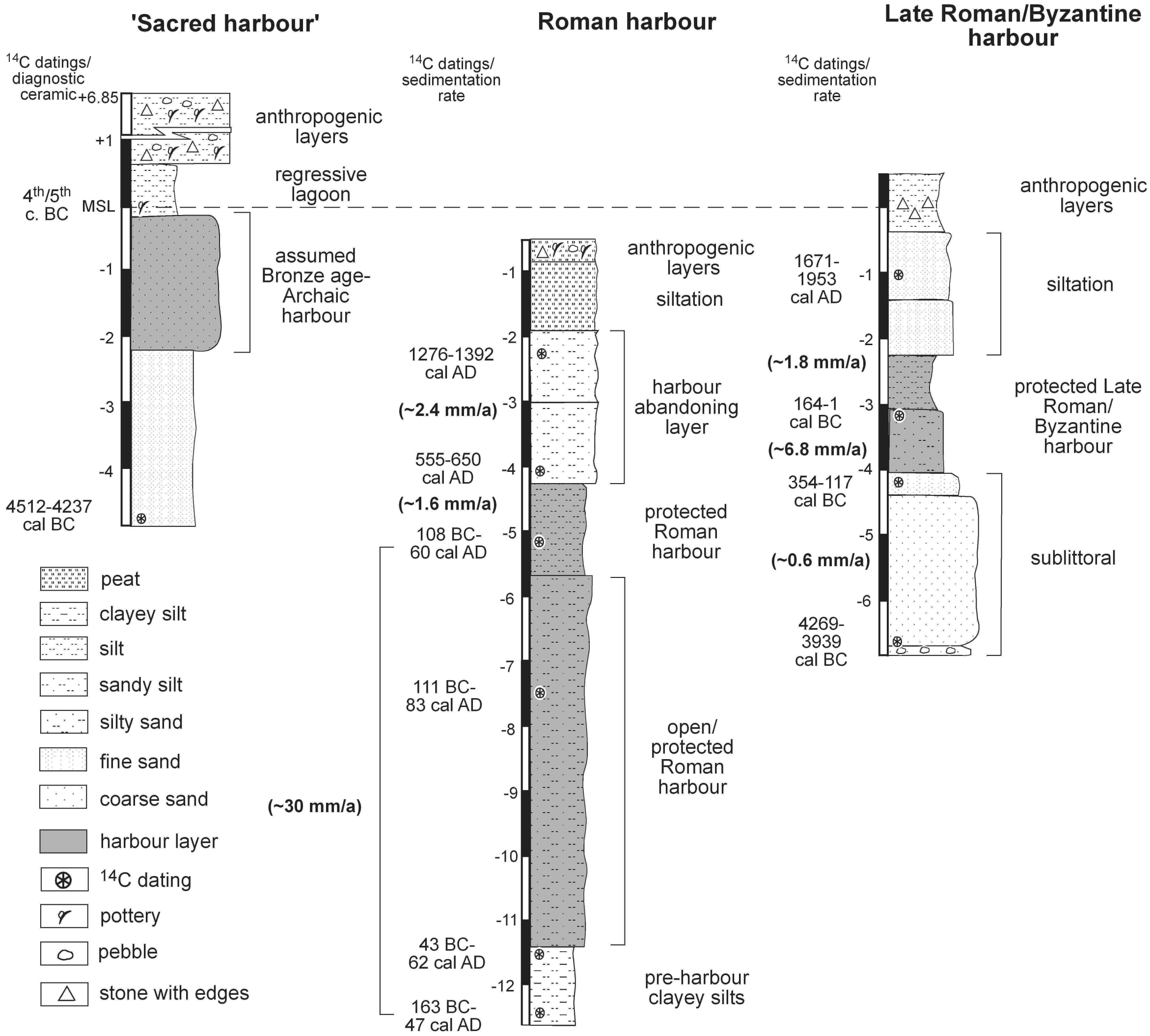

Fig. 7.3: Comparison of the three investigated harbours of Ephesus with stratigraphy, interpretation of harbour layers, ^{14}C ages and sedimentation rates.

Roman harbour

The Roman harbour of Ephesus shows characteristic features of a Roman port such as a consolidated mole and a protected harbour basin (Oleson, 1988). In the middle of the 2nd century BC (154–138 BC), a dam or harbour mole was constructed by Attalos II (Strabo, 1924: 14.1.24; see also Zabehlicky, 1995, 1999). The basin was expanded to a hexagonal basin during the 2nd century AD (Zabehlicky, 1995). In comparison to the Late Bronze Age/Archaic landing site, the Roman harbour reveals a very different **stratigraphy**. The basal layers are anoxic laminated strata with typical characteristics of a marine-brackish environment (Fig. 7.3). These undisturbed silty-clayey layers may be interpreted as pre-harbour sediments; they are comparable to the pre-harbour clays identified by Morhange et al. (2003) in the harbour of Marseille.

Then silty sediments follow; this typical facies has also been described for other sites in the Mediterranean (e.g. Marriner and Morhange, 2006a). They may be related to the construction of a harbour mole or a dam around 154–138 BC by Attalos II (Strabo, 1924: 14.1.24; see also Zabehlicky, 1995, 1999). During that time, the basin was still connected to the sea. Oxygenated conditions and detrital input prevail, probably due to a lot of freshwater input from the aqueducts, the river and surface runoff. The high sedimentation rate of ~30 mm/y (oldest and youngest age; deposition of c. 7 m in 221 years) may be related to enhanced deposition of the prograding Küçük Menderes delta or to the construction of the dam (Strabo, 1924: 14.1.24) causing a low-energy environment. Moreover, these rates correspond well to the ones observed in the Marseille harbour (20 mm/y; Marriner and Morhange, 2006a). Considerably higher rates of 20 cm/y (mean ages, deposition of c. 7 m in 35 years) as assumed by Delile et al. (2015) are rather unlikely; such high rates are not confirmed by other studies in the Ephesia. This high amount of sediment requires a special source; deforestation activities and erosion would surely not be sufficient. Scattered elevated values of magnetic susceptibility can be assigned to an annual deposition of sediments due to floods. To the top of this unit, an increase in sulphur along with very high values of magnetic susceptibility and an increased number of marine-brackish foraminifers occur. This sudden change may be related either to dredging activities (most likely) or a sudden subsidence caused by an earthquake. Both cases could have triggered a renewed quasi-marine milieu in the harbour basin.

Then, along with a dramatic decrease in the sedimentation rate (~1.6 mm/y), a sudden change in the depositional environment under anoxic conditions – alternations of pale yellow Ca-rich layers with brown, organic-rich layers almost void of sand layers – points to declining fluvial input. It is the probable result of the construction of the harbour canal and a protected harbour basin. The hexagonal basin was built during the 2nd century AD (Zabehlicky, 1995); since then, most of the water input derived from the drainage system. Geochemistry and microfossils indicate a declining salinity whereas elevated Cu and Pb values point to human activities and input from the aqueducts. The decrease in sedimentation rate is unusual in harbours, especially as this layer reflects the most intensive use of the site. Thus, removal of the sediment by repeated dredging is quite probable at a water depth of 3–4 m.

From the 6th/7th centuries AD on, geochemistry and sedimentology prove the development of a closed lagoon-like milieu. It likely marks the onset of the harbour abandonment phase when the harbour started to silt up and only smaller ships were able to come in. By this time, a new harbour site to the west were probably already used. Ca-rich sediments with freshwater fauna and aquatic plants indicate the development of a lake after the 7th century AD, correlating with the declining population of Ephesus. From the 13th century AD onwards, peat formation is evidence of the final siltation of the area.

A synoptic view of ^{14}C ages, sediment assemblages and the geochemical and sedimentological data leads to the conclusion that the most intensive harbour **use** must have taken place between the 1st century BC to the 6th/7th centuries AD. A progressively diminished harbour use has also been described for Tyre (Marriner et al., 2008a), Beirut (Marriner et al., 2008b) and Sidon (Marriner et al., 2006c) from this period on, along with a decline in population.

In historical accounts, several **dredging** and harbour maintaining activities are mentioned for the Roman harbour of Ephesus during the period 1st–3rd centuries AD (Kraft et al., 2000, 2001; Strabo, 1924: 14.1.24). A grain size change from sands to silts in the harbour canal during the 1st centuries BC/AD and 1st/2nd centuries AD, respectively, may point to dredging activities. An age inversion in two cores extracted from the basin and the canal may as well reflect dredging activities. The sudden decrease of the sedimentation rates in the harbour basin (from ~30 mm/y to ~1.6 mm/y) supports this interpretation. As a consequence, the occurrence of marine foraminifers may represent a re-ingression of the sea. Thus, the results of this research confirm historical accounts; however, the precise dating of the activities based on the geological record remains a challenge.

Late Roman to Byzantine harbour

The **location** of the Late Roman to Byzantine harbour could be identified (chapter 5). Similar to the search for the so-called Sacred harbour at the confluence of the Derbent valley, the presumed position close to the Kenchrios river mouth is rather unlikely (Kraft et al., 2007). The harbour was most probably located in the embayment to the west of Arvalya valley, where a small lake (Çanakgöl) still exists until today (Fig. 7.1, harbour site 4).

Diagnostic ceramic finds in the first alluvial sediments north of the embayment date to the Roman Imperial time. In a neighbouring core, four ^{14}C age estimates and a ceramic fragment in a 9 m-thick sediment yielded ages from the 2nd century BC to the 1st century AD. This hints to

dredging activities, the construction of a dam for the protection of this site or the evolution of a sand barrier.

Along with the construction of the dam/ development of barrier to the north of the harbour, an increase in sedimentation rates from c. 0.6 mm/y to c. 6.8 mm/y occurs during the 2nd/1st centuries BC (Fig. 7.3). The grain size decrease from sands to silts represents the development of a more and more protected harbour basin, comparable to several other harbours in the Mediterranean (e.g. Morhange et al., 2000; Marriner et al., 2005; Sarti et al., 2013). The shift from marine to lagoonal conditions is supported by geochemical analyses. The 1.70 m-thick silty sediments are present until max. AD 1000. This is an expression of the life cycle of this harbour. It also fits to the ancient harbour parasequences with an increase in the sedimentation rates within the harbour basin (Marriner and Morhange, 2006). The silts are overlain by sands that presumably reflect the destruction of the artificial dam or the sand barrier at the end of the 1st millennium AD when it was not in use anymore. Human activities are only traceable with slightly elevated Pb values. The scarcity of evidence is probably due to the fact that no settlement site is known to have existed adjacent to the Çanakgöl harbour. It is believed to have been a small site which was mainly used when siltation became a major problem for the Roman harbour basin. The Çanakgöl embayment was connected to the sea until the 19th century AD. However, even when it was still in operation, outer and larger harbours (see Fig. 7.1, harbour sites 5 and 6) were established closer to the sea. They were needed for ships with a higher draught.

The research results for the three distinct harbour sites of Ephesus presented here – the so-called Sacred harbour, the Roman harbour and the Late Roman to Byzantine harbour – revealed that sedimentological and geochemical analyses may be used in connection with other criteria for identifying potential harbour sites. Changes in grain size, sedimentation rates and microfaunal assemblages are particularly good indicators to trace the development of a protected harbour basin. Moreover, geochemical analyses combined with statistical methods (chapters 3, 4) help to demonstrate a change in salinity, oxic/anoxic conditions and detrital input. However, in the Ephesia, detailed investigations of harbour sites are only applicable from the Roman period onwards when people started harbour installations (e.g. jetty, dam, artificial basin).

⇨ **Investigations of three different harbours of Ephesus – the so-called Sacred, the Roman and the Late Roman to Byzantine harbours – demonstrated that harbour archives are only well suited for identifying their typical stratigraphy and the sedimentation processes if the sites were intensively used.**

7.3 Human impact in the Ephesia

Working hypothesis 3: The sensitive environment of the Ephesia directly reacted to human and climate impacts during the Middle and Late Holocene

Goal 1: Quantification of sedimentation rates

Scientists have been discussing for a long time if and to which extent human impact (e.g. Zolitschka et al., 2003; Broothaerts et al., 2014) and climate change (e.g. Vita-Finzi, 1969; Grove and Rackham, 2001) have influenced sediment dynamics in the Mediterranean. The calculation of sedimentation rates of the lower alluvial plain of the Küçük Menderes graben gives new insights into the respective roles.

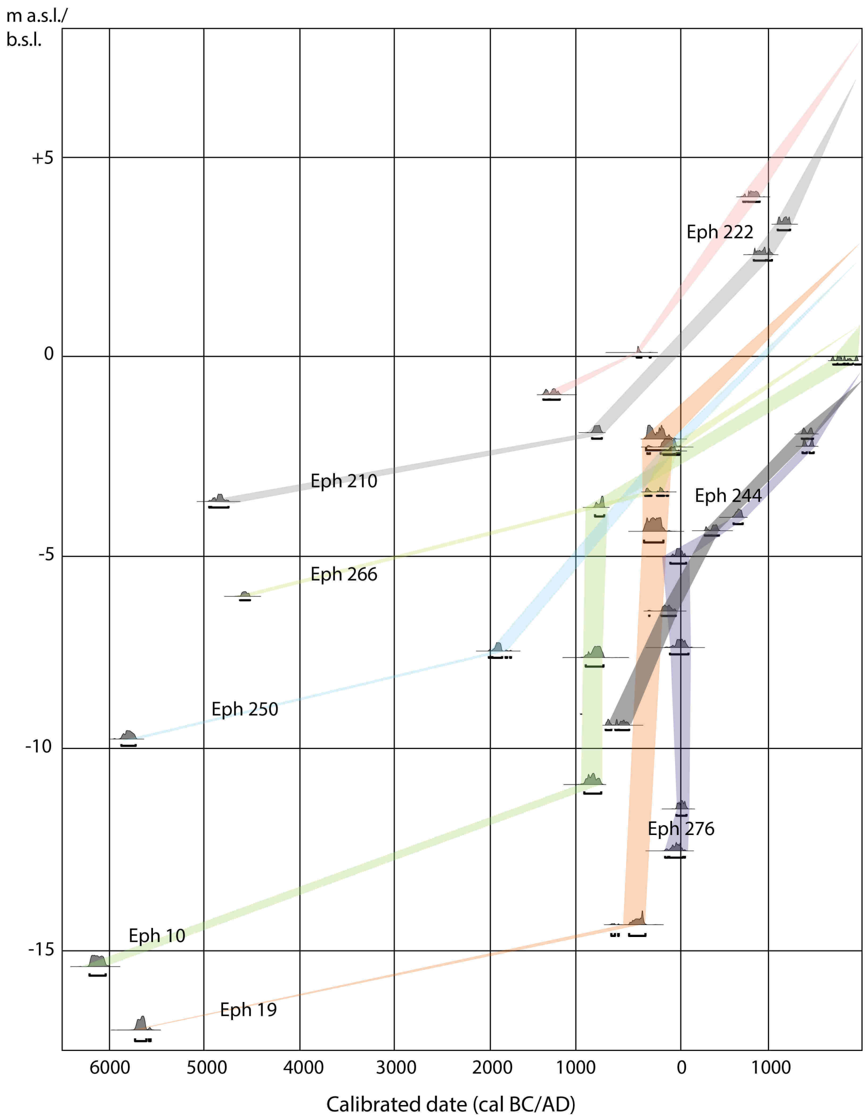

Fig. 7.4: Sedimentation rates of different drill cores from the Ephesia (Eph 19: Panayırdağ; Eph 10: Olympieion, Ephesus; Eph 276: harbour basin, Eph 244: harbour canal, Eph 250: Arvalya valley; Eph 210 and 222: Sacred harbour; Eph 266: Çanakgöl).

Fig. 7.4 shows a compilation of selected ^{14}C dates from this study and from former research (Brückner, 1997). The calculations are based on up to six age estimates of drill cores from different places in the Ephesia. Roughly speaking they show a similar trend; however, the site specific characteristic must not be underestimated.

From the 6th to the 1st millennia BC, low sedimentation rates are observed along with a slow delta advance of the Küçük Menderes (chapter 7.1). A sudden increase in sedimentation rates correlates with a faster delta advance, especially from the 1st millennium BC onwards as already described by Eisma (1978), Erinç (1978), Meriç (1985), Hess (1989) and Brückner (2005). It is noticeable that especially during Hellenistic and Roman times, rates are multiplied by a factor of 10 to 100. Archaeobotanical investigations confirm a high occurrence of *Pinus* pollen in the city for the Roman period whereas less than 5 % of *Pinus* pollen are observable in the pollen record (chapter 3). Obviously, the intensive use and need of wood (Heiss and Thanheiser, 2014) led to considerable deforestation activities (Axelrod, 1975; Knipping et al., 2008) in the vicinity and the hinterland of the city during Roman times. The missing vegetation cover was probably the main factor causing erosion in the drainage basin, and a subsequent deposition in the valley floor and the delta plain. Dusar et al. (2011) highlight intensive deforestation, especially during the Roman and Byzantine periods, which resulted in increased erosion rates on the hillslopes and high accumulation rates in the valley bottoms. For the Roman period, deforestation followed by a faster delta advance has also been proven for other Mediterranean deltas, such as the ones of the Büyük Menderes (Brückner et al., 2002), the Po (Simeone and Corbau, 2009) and the Rhône (Arnaud-Fassetta, 2002; for a compilation of Mediterranean deltas see Anthony et al., 2014).

From the 1st millennium AD on, most of the data confirm a slow decline of sediment deposition in the alluvial plain. The reason may have been a vegetation recovery on the slopes due to a less intensive use as a consequence of the declining population (see Koder, 1994; Müllenhoff, 2005).

This study clearly proved that the anthropogenic signal prevails. In the area of research with its more or less continuous settlement history since Neolithic times, it strongly overprints the climatic signal. We know from other sources about major and minor Holocene climate oscillations worldwide and also in the Eastern Mediterranean. However, the studied geo-bio-archives do not give any evidence about them. Human impact was clearly stronger, especially during the most prosperous phase from the late Hellenistic to the Byzantine periods. Definitely more datings and more suitable geo-bio-archives – such as the swamps of Belevi – are needed for a more detailed differentiation.

Goal 2: Identification of the human impact in sediment archives

In order to provide information about human impact in the Ephesia, palynological and parasitological analyses were carried out on the drill cores (chapters 3–4). Already during the Neolithic period, human impact has been proven with the onset of small farming communities practising agriculture. However, these activities had no strong regional impact (see chapter 7.4).

In the Roman harbour and its canal, finds of eggs of the intestinal parasites *Trichuris* sp. and *Ascaris* sp. from latrines of the city indicate anthropogenic impact from the 1st century BC to the 6th/7th centuries AD. Moreover, pollen from fruit trees, muskmelon and *Cannabis* occur in considerable numbers. Geochemical investigations revealed elevated Cu and Pb values from the 1st century AD onwards in the Roman harbour and the canal (chapters 3, 4). Although the concentrations are relatively high, larger workshops processing lead or copper are unknown; they probably originate from aqueducts and the city's waste and sewage (Ortloff and Crouch, 2001). In the Terrace House, lead pipes were installed. Thus, the elevated concentrations most likely derive from anthropogenic pollution. All of these finds correlate with Ephesus' most prosperous time. The connection of strong human impact with the large population during the Roman period (Büntgen et al., 2001) is likely, all the more, since the presence of anthropogenic indicators decreases parallel to the decline of the city. This has been proven in the harbour basin where the lack of organic material after the 6th/7th centuries AD may have been caused by decreased erosion from the hillslopes due to the partly recovered vegetation.

⇨ ***Human influence clearly impacted the study area. Along with a growing population in the 1st millennium BC and especially during Roman/Byzantine times, a high accumulation rate and a fast delta progradation are noticeable. A major reason for the human impact may have been deforestation in the catchment area of the Küçük Menderes and its tributary valleys. As yet, no evidence for the Holocene climate changes has been found in the studied geo-bio-archives.***

7.4 Landscape changes during the first time of settlement and vegetation history in Western Turkey

Working hypothesis 4: The Ephesia was suitable for settling already during Neolithic times.

Goal 1: Identification of and research about the spatial distribution of Neolithic settlements in the Ephesia

Until recently, systematic research about the settlement history before the 2nd millennium BC was still lacking in the Ephesia. Merely a few settlement mounds (tells) are known in the early 7th millennium BC in Western Turkey (Horejs, in press). The study of Arvalya Höyük and Çukuriçi Höyük (chapter 6) presents valuable new information about these early settlement sites.

In both cases settling started during the 7th millennium BC in a similar setting on small elevations above the floodplain. This corresponds to the topographical finds of other prehistoric sites, e.g. Çatalhöyük (Roberts and Rosen, 2009), Barcın Höyük (Groenhuijzen et al., 2014), Ilıpınar (Kayan, 1995b) and Aktopraklı (Karul and Avcı, 2011) in Western and Inner Anatolia, which are also all situated on elevated or terraced terrain close to a river or a lake.

Small farming communities lived on the mounds between the early 7th and the 3rd millennia BC (Horejs et al., 2011). ^{14}C ages and finds of diagnostic ceramics from Arvalya point to a colonisation during the same time span. Cultural layers (at least 8.50 m thick at Çukuriçi Höyük and 2.90 m thick at Arvalya Höyük) are rich in archaeological material; indicative is also a high phosphorous content. Several studies on other settlement sites have shown similar results (Egli et al., 2013; Gauss et al., 2013; Lubos et al., 2013; Ivanova and Marfenina, in press). Coring evidence revealed the extent of the tells: 200 m x 60 m for Çukuriçi Höyük and at least 100 m x 60 m for Arvalya Höyük. It is evident that the size of the different cultural layers varied according to the settlement intensity.

Goal 2: Reconstruction of the Early Holocene landscape

The landscape from the 7th to the 3rd millennia BC has been reconstructed, mainly based on information from drill cores (chapters 2, 6). In the vicinity of the tell sites, the valley bottoms were exclusively composed of alluvial and colluvial materials; no trace of marine sedimentation could be found. In both cases the nearest beach was located about 1.5–2 km to the north of the mound. In the direct vicinity of the settlement sites, river sediments alternating with colluvial and alluvial material at different depths point to an interplay between fluvial input and hillslope processes.

Most of the surrounding hillslopes were still forested from Neolithic times to the Early Bronze Age as attested by the palynological studies (chapter 6). Bottema et al. (2001) report a first degradation of forests during the Neolithic period that could not be observed in the Ephesia. The pollen diagram shows a landscape which is dominated by deciduous oak (*Quercus robur-/cerris*-type). Comparable studies in the Eastern Mediterranean region (Gölhısar Gölü, Eastwood et al., 1999; Iznik, Bottema et al., 2001; Bafa Gölü, Knipping et al., 2008) confirm the presence of an open landscape with deciduous forests from the Neolithic to the Chalcolithic periods (7^{th}–5^{th} millennia BC). However, first evidence for agriculture is traceable in the swamps of Belevi already for the 7^{th} millennium BC (Cerealia-type pollen). The swamps are located 14 km to the east of Çukuriçi Höyük; no Neolithic settlement is known in the direct vicinity. The evidence supports the assumption that farming took place in the hinterland during Neolithic times. It is possible that the climatic event of 8.2 ka BP characterised by colder and more humid conditions (in the Aegean between 8600–8000 BP; Mayewski et al., 2004; Weninger et al., 2014) may have impacted the study area, since the tell was probably abandoned around 5900 BC (Horejs et al., 2011). Many other archaeological sites all over the Eastern Mediterranean and the Near East (e.g. Jordan, Levante coast, Cyprus, Crete, Turkey and Greece) also show a hiatus in settlement continuity or at least no stable populations during this time span (Simmons, 2000; Efstratiou et al., 2004; Weninger et al., 2005, 2006, 2009; Berger and Guilaine, 2009; Ghilardi et al., 2012).

⇨ ***The first settling activities in the Ephesia can be proven by two mounds which persisted from the 7^{th} to the 3^{rd} millennium BC. Floodplains large enough for the practise of agriculture, the proximity to the sea and freshwater sources in the direct vicinity were probably the main reasons why Neolithic populations settled in the Ephesia. Although the human impact is identifiable by then, the surrounding slopes were still covered with woods.***

7.5 Preliminary results in the swamps of Belevi

A palynological analysis was performed on a drill core from the swamps of Belevi; the first results of the lowermost part (7^{th}–3^{rd} millennia BC) are presented in chapter 6. The upper half of the core reveals ~6 m-thick peat and lacustrine layers in which a composite ash layer was identified: 3 cm of an autochthonous fallout tephra overlain by at least 18 cm of an allochthonous tephra. According to geochemical investigations, it belongs to the Santorini eruption c. 1630 BC (figs. 7.5, 7.6). This is the first find of the ash in the Ephesia. Preliminary results of the pollen profile show that very few pollen grains were found within the event layer and shortly after the event, due to the reduction of the vegetation cover.

The detection of the Santorini tephra as an excellent marker horizon is an important result of the geoarchaeological work in the Ephesia. It is intended to study in detail the development of the swamps since this geo-bio-archive is an excellent record for deciphering the vegetation history since the 7^{th} millennium until today.

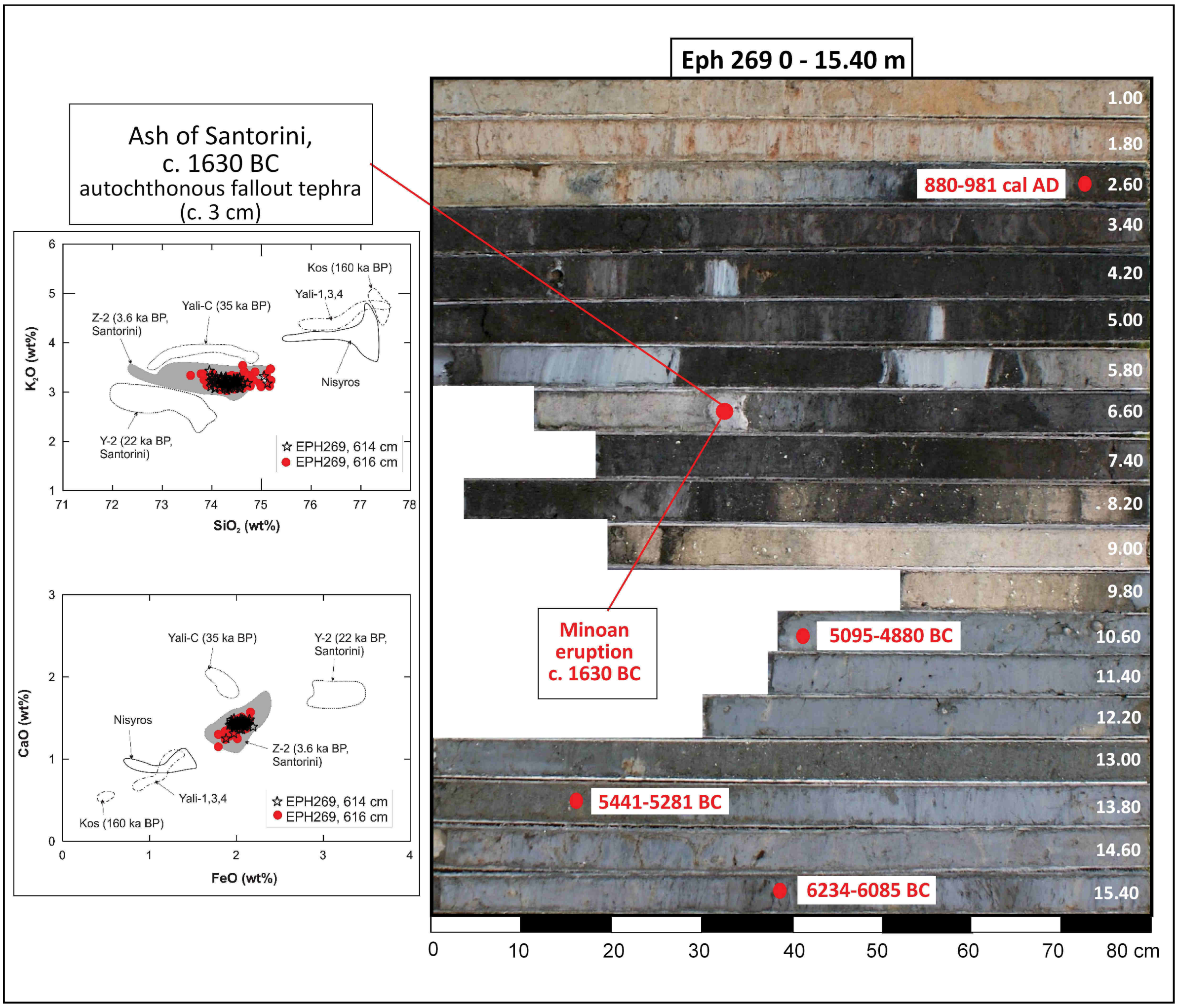

Fig. 7.5: Drill core Eph 269 from the swamps of Belevi with the Santorini ash layer of c. 1630 BC, its geochemical fingerprint, as well as ^{14}C age estimates.

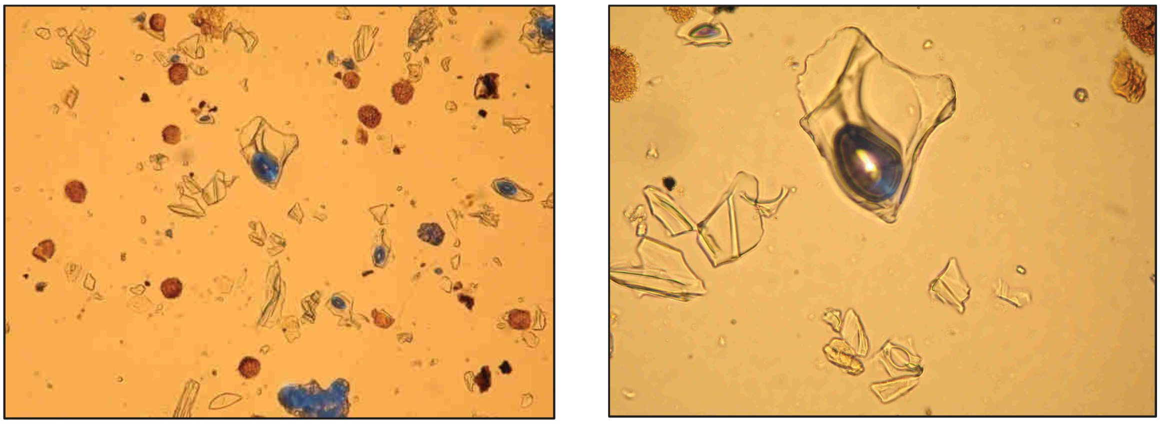

Fig. 7.6: Pictures of autochthonous volcanic glasses of the Santorini ash (left: overview, right: detail).

8. Summary and conclusion

This geoarchaeological study in the Ephesia provides new insights into coastline changes, settlement and harbour sites, as well as human-environment interactions and landscape changes since the Neolithic period. Drill cores were analysed using a multi-proxy approach.

Investigations in the swamps of Belevi attest to a marine transgression c. 20 km inland dating to the middle of the 6th millennium BC. The sea-level curve for the Küçük Menderes graben indicates a continuous rise in sea level until today. Since the 5th millennium BC, when sea-level rise decelerated, the delta progradation of the Küçük Menderes and its tributaries has nearly completely silted up the embayment. While slow progradation rates (~2.2 km/ka) are observed from the 6th to the 1st millennia BC, increased sedimentation with rates of ~4.5 km/ka characterise the last three millennia. In the Derbent and Arvalya valleys, both located on the southern flank of the Küçük Menderes graben, the sea did not transgress for more than 500 m inland. For the first time, the siltation history at the interfluves of these two tributary valleys with the main valley is reconstructed. It shows the evolution of lagoons, and coastal and freshwater lakes. Until the 1st millennium BC, the valleys were mostly influenced by the delta advance of the Derbent, Selinus, Kenchrios and Şirince rivers. Thereafter, the influence of the Küçük Menderes delta dominated the siltation process.

In the early 7th millennium BC, the area was settled by farming communities which persisted until the 3rd millennium BC. The Neolithic population settled on small elevations in the Derbent and Arvalya valleys at a distance of 1.5–2 km from the coast. During the 7th millennium BC, agriculture was already practised as evidenced by the pollen record.

Together with a growing population from the end of the 1st millennium BC onwards (especially in Roman and Byzantine times), the speed of sedimentation – inferred from different sites of the study area – indicates 10 to 100 times higher rates than before. Deforestation was probably the main cause with associated strongly enhanced slope denudation processes. The extensive use of *Pinus* in the city of Ephesus and low values in the pollen profile corroborate deforestation.

Due to the permanent retreat of the coastline, settlements and their harbours had to be relocated in a western direction. In this study, the so-called Sacred harbour, the Roman harbour and the Late Roman to Byzantine harbour were investigated in detail. Their sediment archives are well suited for studying different harbour stratigraphies and the respective sedimentation processes. The so-called Sacred harbour of the Artemision (Temple of Artemis) was presumably also the landing site of the Late Bronze Age and Early Iron Age settlement on Ayasoluk hill, being used from c. 1500 BC to c. 400 BC. Several locations formerly assumed for this harbour could be rejected given the absence of marine sediments. This harbour was presumably located to the northeast of the Artemision, at the foothill of Ayasoluk. There, a small embayment with sandy beach exists, onto which the ships could be hauled – a procedure typical for this period. The Koressos harbour, located in an embayment 1.5 km to the west of the Sacred harbour, was presumably in use from c. 500 BC onwards, because of its larger size and the beginning siltation of the Sacred harbour.

With the relocation of Ephesus by Lysimachos in 289/288, the harbour site was moved to the west once again. The location of the Hellenistic harbour is unknown; it is probably close to the Roman harbour. The research in the Roman harbour revealed an intensive use from the 1^{st} century BC to the $6^{th}/7^{th}$ centuries AD. Geochemical and sedimentological analyses from sediments of the harbour and the harbour canal show a clear distinction between pre-harbour and harbour sediments. The base is characterised by anoxic laminated sediments from a deep marine embayment. *Isoetes* spores from the hinterland indicate the proximity of the Küçük Menderes delta in the harbour area. Very high sedimentation rates (~30 mm/y) were inferred for the subsequent silty harbour facies, characterised by a brackish microfauna. It is well probable that this was a consequence of the construction of the harbour mole or dam in the middle of the 2^{nd} century BC, which is also mentioned by Strabo. The building of the harbour canal led to the development of a protected harbour basin at the turn of the eras. At the beginning of the 2^{nd} century AD, it was followed by a hexagonal harbour basin. The transition from grey silts to pale yellow and brown silty laminations with high copper and lead values may mark a shift to low sedimentation rates (1.6 mm/y). The high concentrations of these heavy metals derive from the city's waste and sewage. The change to slow sedimentation rates, unsual for harbour basins, may have been caused by dredging activities which then triggered a renewed ingression of the sea (presence of marine foraminifers). Possible dredging traces in the canal and the basin are confirmed by historical records. After the 7^{th} century AD, microfossils in harbour abandonment layers point to the siltation of the basin and freshwater conditions.

The Late Roman to Byzantine harbour was presumably located 3.5 km to the west of Ephesus in a protected embayment. Until the 19^{th} century AD, the small embayment was connected to the sea *via* the Küçük Menderes river. In a 9 m-thick sediment layer northwest of the site, several ^{14}C age estimates and diagnostic ceramics all date from the 2^{nd} century BC to the 1^{st} century AD. This fast deposition may be explained by the construction of a dam or the development of a sand barrier seaward to the site. According to a 1.70 m-thick fine-grained harbour layer with slightly elevated lead values and a rising sedimentation rate, the harbour seems to have been in use until approximately the 10^{th} century AD. Thereafter, coarse sands overlying the silts point to the destruction of the presumed dam or the breaching of a sand barrier.

From the palynological analyses in the swamps of Belevi, Cerealia pollen indicates agricultural activities in the hinterland already during the 7th millennium BC. Although human impact can be inferred during that time, the surrounding slopes were still covered by woods. Stronger human impact can be traced from the end of the 1st millennium BC until the 7th century AD when the population of Ephesus started to decline. Human presence was detected in the vicinity of the settlements and the harbours. Indicators are eggs of intestinal parasites (*Trichuris* sp. and the roundworm *Ascaris* sp.), elevated Cu and Pb values, as well as pollen of fruit trees.

To conclude, the geo-bio-archives in the Ephesia are very well suited to investigate human-environment interactions during the Holocene and for studying the coastline changes and settlement activities since the 7th millennium BC. This research contributes to a better understanding of sedimentation processes within the Ephesia, and their interaction with the development of human settlements and their harbours. The sea-level curve presented here is the first attempt for the Küçük Menderes graben. With data – particularly for the delta progradation in the northern part of the graben – the reconstruction will be improved.

9. References

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Paper Contributions

Stock, **F**., Pint, A., Horejs, B., Ladstätter, S., Brückner, H., 2013. In search of the harbours: New evidence of Late Roman and Byzantine harbours of Ephesus. Quaternary International 312, 57–69. **[Contribution: 85 %]**

Fieldwork: 95 %

Laboratory work: 90 %

Interpretations and evaluation: 75 %

Writing the article: 85 %

Stock, **F.**, Kerschner, M., Kraft, J.C., Pint, A., Frenzel, P., Brückner, H., 2014. The palaeogeographies of Ephesos (Turkey), its harbours, and the Artemision – a geoarchaeological reconstruction for the timespan 1500–300 BC. Zeitschrift für Geomorphologie (Annals of Geomorphology) 58, Suppl. Issue 2, 33–66. **[Contribution: 75 %]**

Fieldwork: 95 %

Laboratory work: 90 %

Interpretations and evaluation: 80 %

Writing the article: 65 %

Delile, H., Blichert-Toft, J., Goiran, J.-P., **Stock**, **F.**, Arnaud-Godet, F., Bravard, J.-P., Brückner, H., Albarède, F., 2015. Demise of a harbor: a geochemical chronicle from Ephesus. Journal of Archaeological Science 53, 202–213. **[Contribution: 30 %]**

Fieldwork: 95 %

Laboratory work: 30 %

Interpretations and evaluation: 30 %

Writing the article: 15 %

Stock, **F.**, Knipping, M., Pint, A., Ladstätter, S., Delile, H., Heiss, A.G., Laermanns, H., Mitchell, P., Ployer, R., Steskal, M., Thanheiser, U., Urz, R., Wennrich, V., Brückner, H., in review. Life cycle of the Roman Harbour of Ephesus – multi-proxy analyses of the sediment record. Earth Surface Processes and Landforms. **[Contribution: 70 %]**

Fieldwork: 95 %

Laboratory work: 65 %

Interpretations and evaluation: 70 %

Writing the article: 75 %

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Die von mir vorgelegte Dissertation ist von Prof. Dr. Helmut Brückner betreut worden.

Folgende Teilpublikationen liegen vor:

Stock, **F**., Pint, A., Horejs, B., Ladstätter, S., Brückner, H., 2013. In search of the harbours: New evidence of Late Roman and Byzantine harbours of Ephesus. Quaternary International 312, 57–69.

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Stock, F., Ehlers, L., Horejs, B., Knipping, M., Ladstätter, S., Seren, S., Brückner, H., submitted. Neolithic settlement sites in Western Turkey – palaeogeographic studies at Çukuriçi Höyük and Arvalya Höyük. Journal of Archaeological Science.

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