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Reconstruction of the landscape history around the remnant arch of the Klidhi Roman Bridge, Thessaloniki Plain, North Central Greece

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A B S T R A C T

This paper deals with the palaeoenvironmental reconstruction of the area surrounding the remnant arch of the ancient bridge of Klidhi, Thessaloniki Plain, Greece. 19th century travellers and 20th century historians discussed the age of the monument and concluded that it was built during Late Roman Times (3rd Cent. AD) and supported a branch of the Via Egnatia road. However, few studies have considered the environmental context of the construction of the bridge, and until now, only two hypotheses have been presented: The bridge was built on or over a junction of the Aliakmon and Loudias Rivers, or on a coastal barrier. Within the framework of a geoarchaeological project developed in April 2008, five boreholes were drilled and the sediment cores analysed for microfauna and sedimentology. Seven ^{14}C AMS dates provided a chronostratigraphic sequence and helped to define the geomorphological evolution of the area. Spatial interpretation of the results was possible using a Landsat TM image (False Colour Composite – FCC). Our data indicate the gradual transition of the site from a marine to a terrestrial environment during Ancient Times. Lagoonal conditions dominated during the construction of the bridge and the presence of a palaeochannel of the Aliakmon River was later revealed (transition from Byzantine and Ottoman periods), overlying sediments of a coastal barrier.

1. Introduction

Over the last 30 years a significant number of geoarchaeological studies have been carried out around the Mediterranean (Kraft et al., 1977; Fouache, 1999, 2003). Arguably the most important work comprises studies of remnant archaeological constructions such as harbours (Devillers et al., 2007; Fouache et al., 2005; Gifford et al., 1992; Goiran and Morhange, 2003; Marriner and Morhange, 2007; Marriner et al., 2005, 2007 and 2008; Vött, 2007b). The palaeoenvironmental reconstruction of the area surrounding ancient buildings has enabled the analysis of geomorphological processes and landscape reconstruction during the Holocene and in particular within historical times. Coastal areas are a suitable place to study the environmental history of Ancient cities (Brückner, 2005), or of archaeological artefacts, since stratigraphic and sedimentological studies can highlight the morphological dynamics responsible for the creation of deltaic areas (Ghilardi, 2007). Thessaloniki Plain, located in Northern Greece (Fig. 1), is the largest coastal plain in Greece, spanning an area of approximately 2200 km^2 and was mainly created during the late Holocene, from 4000 BC until the 3rd Century AD (Ghilardi, 2007; Ghilardi et al., 2008a,b). Over the last six millennia there has been intense human occupation, and the habitants have been forced to adapt to the rapid displacement of the shoreline by the (re)construction of harbours and bridges. Indeed, the ancient writer Livy mentioned that for example in 190 A.D., the Roman armies left Greece in the direction of the Hellespont through Ancient Macedonia and encountered several bridges built during the reign of Philip the 2nd, King of Macedonia (Livy, XXIX, 29: "Vias munivi, *pontes feci*. Commeatus præbui"). As a result, we can at present observe some of these remnant artefacts which inform us

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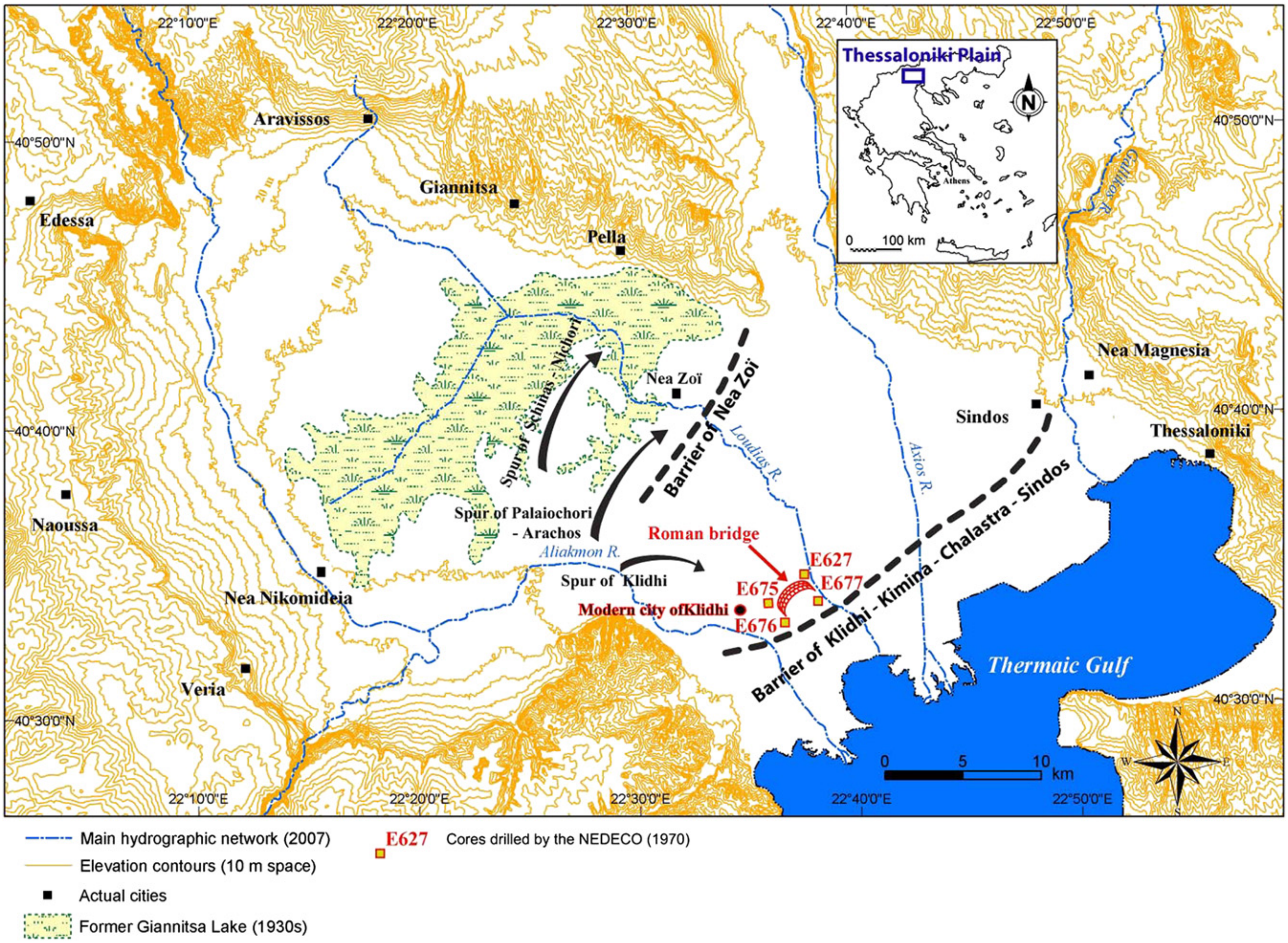

Fig. 1. Location map of the study area. Elevations were obtained from the derivation of the Shuttle Radar Topography Mission and included in Geographic Information System. The limits of the former Giannitsa Lake, totally drained in the 1930s (Ancel, 1930) are based on Ghilardi, 2007. The coastal barriers were identified by NEDECO (1970). The Roman bridge with a red symbol is the one of Klidhi.

about important geomorphologic processes during the historical period. The Thessaloniki Plain provides a particularly interesting case-study. The site of interest lies close to the actual cities of Klidhi and Trikala (Prefecture of Emathia), just one kilometre to the west of the modified course of the Loudias channel and 8 km from the actual coastline. Here a remnant arch, the ancient bridge of Klidhi (Fig. 2A), exists and is hydrographically isolated. Various sources (Delacoulonche, 1859; Edson, 1955; Bintliff, 1976; Astaras and Sotiriadis, 1988; Ghilardi, 2007) indicate the age of the arch is Late Roman circa 3rd Cent. A.D. and must have supported a southern branch of the Roman road Via Egnatia, running from Ancient Dyon to Thessaloniki (Ghilardi, 2007). The factors leading to the construction of this bridge, where only one remnant arch is still visible, are unclear. Various hypotheses (Cousinéry, 1831; Delacoulonche, 1859; NEDECO, 1970; Bintliff, 1976) suggest that is was used as a byway over rivers and/or as a coastal barrier. Our research, based on a geoarchaeological approach using the palaeoenvironmental data from five boreholes and a spatial interpretation, based on a Landsat TM imagery interpretation, aims to provide a better understanding of the evolution of the landscape surrounding the remnant arch of Klidhi Bridge.

2. Previous studies covering The Ancient bridge of Klidhi

2.1. Cousinery's description (1830s)

No historical studies mention the existence of this bridge during Ancient Times (archaic, classical, hellenistic and imperial periods) and few maps show its presence in the lower part of Thessaloniki Plain. Cousinéry (1831) mentioned briefly the remnant arch (Fig. 2A) and speculated that the bridge spanned the junction of the Aliakmon and Loudias Rivers (Cousinéry, 1831); however, unfortunately he did not describe the architecture more precisely nor estimate the age of its construction.

2.2. Delacoulonche's work: the most detailed historical and archaeological studies (1850s)

The most detailed work is that by the French archaeologist Delacoulonche (1859) who participated, with his colleague Léon Heuzey, in a mission to Greek Macedonia under the supervision of French Emperor Napoléon III, who was especially fascinated by the battlefield where Caesar's army fought. His description of the remnant arch included an estimate of the number of arches, probably between 8 and 10 (Delacoulonche, 1859, p. 65). He assumed that the remnant arch still visible (Fig. 2B) was the third or fourth largest assuming that size of the arches decreased towards the extremities. According to Delacoulonche's description, the total length of the monument was around 187 to 190 m (circa 70.40 m in the direction of Thessaloniki and 100.32 m on the other side of the arch) and thus was of comparable size to the Roman bridge of Norba-Caesarea (Alcantara, Extremadura, Spain) with similar symmetric arches (Delacoulonche, 1859). Particular attention has been paid to the architecture of the edifice, indeed the remnant arch was particularly helpful on this point. Following careful scrutiny

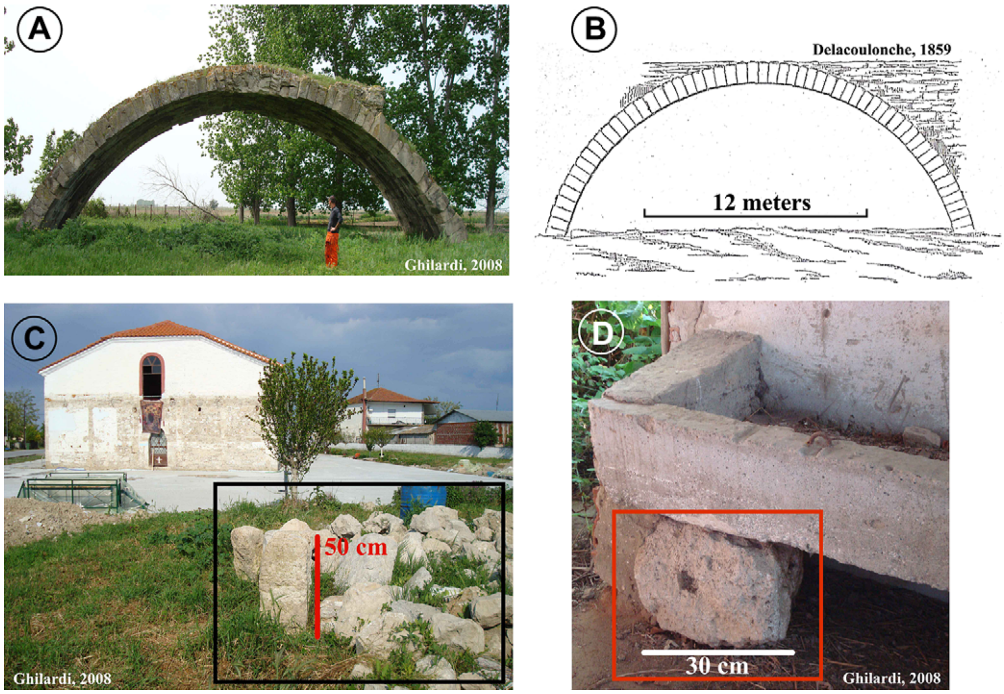

Fig. 2. A: The remnant arch of the ancient Klidhi Bridge. B: drawing of the arch realised by Alfred Delacoulonche in 1859, evident alteration of the edifice is visible in almost one and half century of time. C: Modern city of Klidhi, in the square we have rectangular stones carved into a travertine formation (*Poros* in greek; Delacoulonche, 1859); they were used first to build the roman bridge of Klidhi and then reemployed to build the church of the city in 1856 (date recorded on a wall). D: Ancient village of Kaliani, we have in the red square, a rectangular stone carved into the same travertine formation as the ones observed in the remnant arch of Klidhi. It is clear that local people used the stones from the ancient bridge of Klidhi to build houses, churches, etc. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

from Delacoulonche, it appears that the arch is formed in two parts (Delacoulonche, 1859, p.64): the base consists of 6 rectangular stones (length: 1.07 m, width: 0.73 m, height: 0.43 m) which supports the arch, and the remnant one is 17.14 m long (length measured just above the ground), 5.73 m wide and 6.52 m high. The dimensions of the stones are similar to the marble blocks used to build the base of the "Classical" Bridge at Amphipolis (Bakalakis, 1970). The main difficulty encountered in describing the monument precisely comes from the lack of other arches. These were probably used by the local people to build churches (Aghios Demetrios of Kaliani was present in 1820 but in 2008 the church did not exist, probably having been destroyed or abandoned) and houses in the vicinity. Delacoulonche's description of Aghios Demetrios indicates that the four corners of the church were built with massive blocks of worked limestone (length: 1.80 m, width: 0.62 m, height: 0.59 m). These large blocks probably supported the other arches of the Roman Bridge. Also, in the abandoned village of Kaliani, situated 2.8 km to the north–west, we can observe on the ground the presence of several large blocks formed in a massive travertine formation (Fig. 2D). During our fieldwork campaign, we observed similar blocks in the modern city of Klidhi, close to the church built in 1856 (Fig. 2C). Until today the last arch (called in Greek 'Kamara') has survived to the present because of the local legend which states that the people who initially removed the stones from the bridge to build their own houses died the following year (Delacoulonche, 1859).

2.3. A new examination of the remains (1908)

Following the valuable and unique study delivered by Delacoulonche in 1859, few archaeological and geomorphological investigations have been carried out in the area surrounding the remnant arch. Some sources have attempted to explain the geomorphological processes responsible for the landlocking of the bridge. A new examination, founded on Cousinéry's and Delacoulonche's indications, is provided by Strück who confirmed the Late Roman age (probably the 3rd Century A.D.) of the edifice (Strück, 1908). Strück suggested that by 200–300 A.D. the main road crossed the plain directly instead of skirting around it (the early Roman road run from Pydna to Pella through Veria – see Fig. 1 for the location of the cities mentioned). Re-examination of the evidence for the bridge's date confirms Strück's proposal, its construction fitting neatly with the shorter route of Peutinger Table (Tafel, 1841; Edson, 1955, p.178).

2.4. Hammond's historical study (1972)

Hammond, one of the most eminent authorities on the history of ancient Macedonia (Hammond, 1972; Bintliff, 1976; Ghilardi, 2007), cites a Medieval reference for use of both long and short routes (Hammond, 1972, 162). In 1078, the Emperor Alexis the 1st (Comnène, *L'Alexiade)* waited with his army between two arms of the Axios, near Chalastra and the ancient bridge of Klidhi (still used during Byzantine times), but his enemies did not take the direct route (i.e. the coast road) but came instead by the inland road (Bintliff, 1976). This historical source clearly shows that the Bridge of Klidhi, which supported the shorter road, was used in the same way as the Roman armies used it did during their travel from Pydna to Pella and/or Thessaloniki.

2.5. Attempts at landscape reconstruction around the arch (1976)

In 1970, a geotechnical assessment by the Dutch company NEDECO reported that the bridge could have had been built over a coastal barrier or over one or two rivers, probably the Aliakmon and Loudias. Based on the study of four boreholes (Figs. 1 and 3) drilled up to 6 m maximum depth, the sedimentological analyses revealed the presence of fluvial deposits (mean thickness of 4 m) overlying limnic deposits. Bintliff's interpretation is quite different, suggesting that the bridge spanned the junction of the Aliakmon and Loudias Rivers (Bintliff, 1976), but his hypothesis could not be proven due to the lack of palaeoenvironmental data, even if he considered the NEDECO reports. Later work by Astaras and Sotiriadis (1988) were no more precise, and until today no studies have been able to elucidate the palaeoenvironmental conditions prevailing at the time of the construction of the Roman bridge of Klidhi.

3. Geomorphological context

The Dutch company NEDECO have drilled four boreholes (Fig. 3) up to a maximum depth of six meters (E627, E675, E676 and E 677) and some sedimentological and geochemical analyses were performed in the area surrounding the ancient Bridge of Klidhi. The facies are dominated by three types of environment and can be described as follows:

- In the upper part of the core, lake shore deposits are present in two boreholes and are characterised by clay and organic matter of a total thickness of approximately 40 cm.
- Below the lake shore deposits, fluvial sands and silts (close to the actual surface topography) were deposited to a maximum thickness of 5.50 m (E676).
- At a depth of 5.90 in E676 limnic sediments with an organic matter content of 5% were identified.

Recent published work has highlighted the geomorphological background of the entire Thessaloniki Plain (Ghilardi, 2007; Fouache et al., 2008; Ghilardi et al., 2008a,b). The main finding is the rapid stranding of a large bay since the Mid-Holocene period, as a consequence of the slowing of the sea-level rise and the rapid infilling of the cove by the Aliakmon and Axios Rivers deposits. As a result, the Neolithic settlement of Nea Nikomideia (Fig. 1) must have been located on the margin of the sea ~6000 years ago and is presently landlocked 30 km inland (Bintliff, 1976, Ghilardi, 2007). The sea regressed south–eastwards and gradually the shoreline shifted in the same direction until it reached its present day position. Until late Roman times (circa 400 A.D.) the deltaic progradation was very important, but Pella was still connected to the sea via the Loudias channel (22.2 km long), the outlet of the former Loudias Lake (Stabo, VII). Subsequently there occurred a major slowing of the rate of shoreline displacement at the end of Roman times (Ghilardi et al., 2008a) and in this geomorphological context (relative stability of the coastline) the ancient bridge of Klidhi was built. Due to the rapid creation of the deltaic complex (Axios and Aliakmon lobes), the main rivers shifted gradually south–eastwards, to

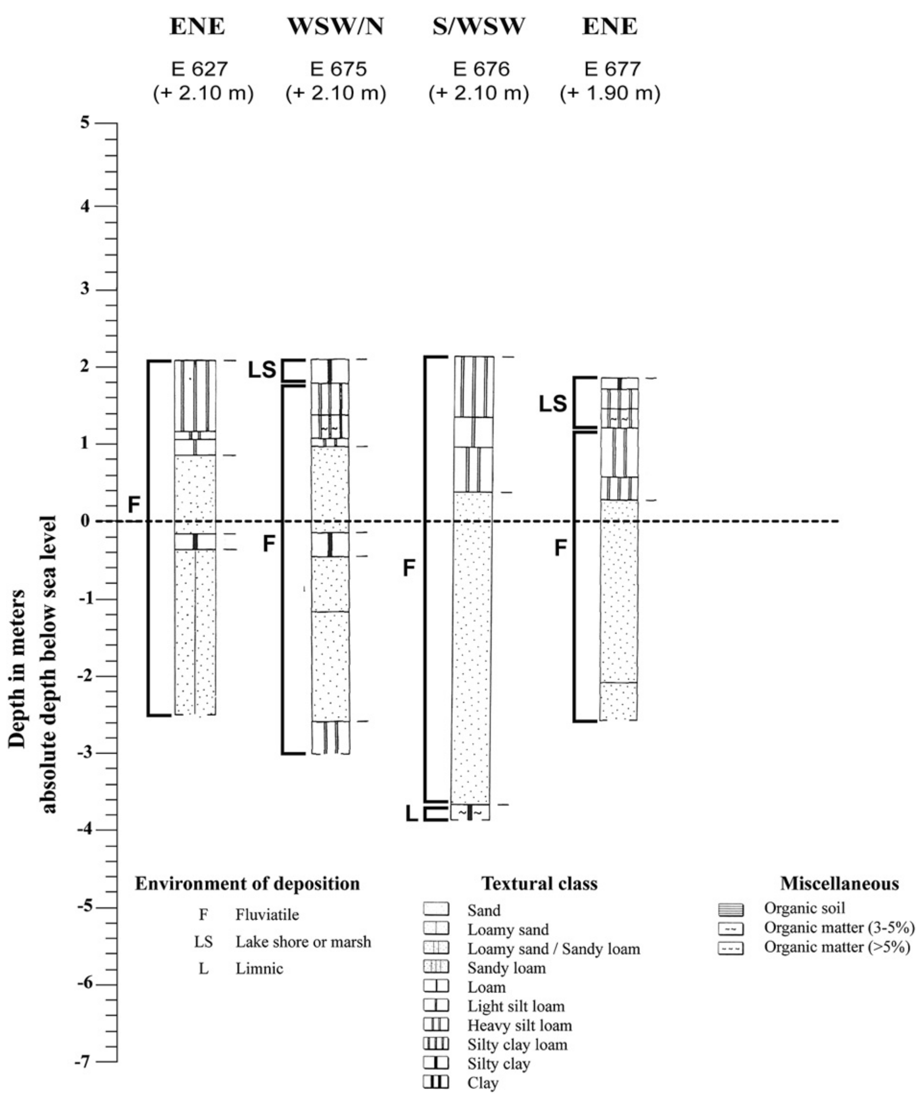

Fig. 3. Core profiles of cores E627, E675, E676 and E677. They are based on NEDECO report (1970).

their present position. The Aliakmon River followed a direction from the NW to the SE and the Axios River changed its course many times, flowing close to the actual city of Thessaloniki in ancient times (Herodotus) following a path similar to that in the 19th Century (Leake, 1836). All the levees created and later abandoned by the rivers created natural dams which later turned into coastal spits (spurs of Schinas-Nichori, Palaiochori-Arachos and Klidhi, Fig. 1), and similar geomorphological features have been described in the Rhone Delta (Arnaud-Fassetta, 2000). The morphological evolution of the Thessaloniki plain is directly controlled by the flooding events of the rivers: several levees of the Axios and Aliakmon Rivers where created and later abandoned. Similar morphological features occur in the central part of the plain (barrier of Nea Zoï; NEDECO, 1970 and Fig. 1) and close to the present day shoreline (barrier of Klidhi-Kimina-Chalastra-Sindos). A recent paper (Ghilardi et al., 2008a) confirmed the presence of a coastal barrier in the close vicinity of Arachos, since sedimentological analyses revealed the presence of well sorted sand deposited in a supra-tidal context.

The present study seeks to clarify the palaeoenvironmental history of this area; to detail and date the transition from a marine to a terrestrial environment; and thereby to better understand the geomorphological context of the construction of the Roman bridge of Klidhi.

4. Methods

Five 40-mm diameter vibracores were drilled in the vicinity of the remnant arch of Klidhi Bridge, up to a maximum depth of 10.45 m and at a maximum distance of five hundred meters from the remnant arch. They are situated outside of the formal archaeological area (see Fig. 4 for the exact location) and were mentioned in the authorizations delivered by the Greek Geologic and Mining Institute (I.G.M.E.). Each borehole was precisely located and subsequently levelled with Differential Global Positioning System (D.G.P.S.) measurements (Table 1). The authorizations delivered by the I.G.M.E. services permitted us to transport samples to France for laboratory analyses.

4.1. Microfaunal identification and AMS dating

In order to remove fine sand and silt from the fossiliferous sediments, as well as to clean the handpicked shells, all the samples were washed with water through a wire screen (0.40 mm mesh) and air dried at room temperature. The residue was inspected under

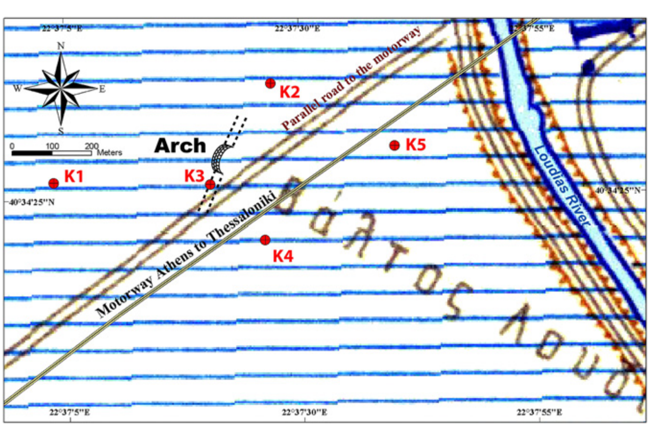

Fig. 4. Exact location of the five cores (K1, K2, K3, K4 and K5) drilled in the area surrounding the Ancient Klidhi Bridge. The topographic background corresponds to the topographical map edited by the Hellenic Military Geographical Service (sheet of Plati scaled at 1: 50000).

Table 1
Cores location.

Core id	Absolute elevation (m; ±10 cm)	Latitude (D°M′S″/ WGS84 - NUTM34)	Longitude (D°M′S″/ WGS84 – NUTM34)	Length (m)
K1	1.90	40°34′26.0″	22°37′03.8″	7.70
K2	2.10	40°34′33.9″	22°37′27.2″	8.25
K3	2.15	40°34′25.7″	22°37′20.6″	4.40
K4	2.06	40°34′21.1″	22°37′26.4″	5.50
K5	2.06	40°34′28.6″	22°37′40.5″	10.45

a binocular microscope and all the identifiable shells and characteristic fragments were selected and stored in separate plastic tubes. Palaeontological determinations were made to a generic and specific level.

The chronostratigraphy of the cores was determined using a series of seven AMS radiocarbon determinations undertaken on *in situ* marine shells and a wood fragment (Table 2). These analyses were performed at the *Laboratoire de Mesure du Carbone 14* (C.E.A., Saclay, France). Marine samples were corrected for the marine reservoir effect according to Siani et al. (2000) and Reimer and McCormac (2002), although it has to be acknowledged that the real (palaeo) reservoir effect — still unknown — varies widely in different marine environments such as lagoons, coastal swamps or littoral zones (Vött, 2007a). ^{14}C ages were subsequently calibrated using the Calib 5.01 Software (Stuiver and Reimer, 1993; Hughen et al., 2004; Reimer et al., 2004).

4.2. Grain-size analyses

Sedimentological analyses were conducted in the Laboratoire de Géographie Physique de Meudon (U.M.R. 8591 – Centre National de la Recherche Scientifique, France). Grain-size analyses were carried out at 5 cm intervals. The samples were mixed with a dispersing agent (0.5% sodium hexametaphosphate) and left in deionised water for two hours in order to disperse the clay particles, and were then ultrasonicated. The grain-size distribution was measured using a Coulter LS 230 laser granulometer with a range of 0.04–2000 microns, in 116 windows. The calculation model (software version 2.05) uses Fraunhöfer and Mie theory, which is applicable down to a grain-size of about 0.04 μm. For the calculation model, we used water as the medium (RI = 1.33 at 20 °C), a refractive index in the range of that of kaolinite for the solid phase (RI = 1.56), and absorption coefficients of 0.15 for the 750-nm laser wave length and 0.2 for the polarized wavelengths (Buurman et al., 1996). Samples containing fine particles were diluted using deionised water, so that we measured between 8 and 10% of obscuration and between 55 and 70% PIDS (Polarization Intensity Differential Scattering) obscuration.

4.3. Magnetic susceptibility measurements

All magnetic measurements were made in the Laboratoire de Géographie Physique de Meudon (U.M.R. 8591) and were performed on samples from five boreholes. Discrete samples ($2 \times 2 \times 2$ cm^3) in plastic non-magnetic cubes were taken for magnetic analysis at about 5 cm intervals, yielding 290 samples in total. Low and high frequency magnetic susceptibility (χ) was measured using a Bartington Instruments MS2B magnetic susceptibility meter with a resolution of 10^{-5} SI units. The measurements are expressed on a dry weight specific basis. In this paper we only refer to the results of the low frequency measurements (χ_{lf}).

4.4. Satellite imagery

A Landsat TM (NASA, 1997) image was used, and a False Colour Composite combining the spectral bands 2, 3 and 5 was realised

Table 2
Radiocarbon dating results.

Core id	Sample type	Depth below surface (m)	Depth below sea-level (m)	Dating method	Laboratory reference	δ13C	Age (14C BP)	±	Cal. BC/AD
K1	Shell (*Nassarius reticulatum*)	3.85	1.95	AMS	SacA 11504	−2,5	2230	30	177/347 AD
K1	Shell (*Cyclope neritea)*	4.18	2.28	AMS	SacA 11505	−4,3	2885	30	632/417 BC
K2	Shell (*Spisula subtruncata)*	8.12	6.02	AMS	SacA 11506	−1,6	2270	30	130/295 AD
K2	Shell (*Spisula subtruncata)*	8.23	6.13	AMS	SacA 11507	−0,5	2155	30	269/426 AD
K3	Wood fragment (*Quercus sp.*)	4.40	2.25	AMS	SacA 11510	−25,7	485	30	1419/1441 AD
K5	Shell (*Spisula subtruncata)*	9.20	7.14	AMS	SacA 11508	0,6	2155	30	269/426 AD
K5	Shell (*Spisula subtruncata)*	9.54	7.48	AMS	SacA 11509	0,2	2205	30	220/387 AD

using the Er Mapper software, version 7.0 and later integrated in a Geographic Information System. Important results using remote sensing techniques were recently obtained for Thessaloniki Plain's (palaeo) landscape interpretation (Ghilardi, 2007 and Ghilardi et al., 2008b). Former alluvial levees, palaeo channels and lake/swamps have been clearly distinguished.

5. Results

5.1. Stratigraphy

Based on the various laboratory analyses, seven sedimentary units can be distinguished and are described as follows:

- The first unit is only identified in the lower part of core K1, from 2.00 m below mean sea-level (b.m.s.l.) down to 5.80 m b.m.s.l. It consists of heterogeneous sediments, ranging from clay to fine sands, with χ_{lf} values in the range 45–130 × 10^{-8} m^3/kg. Within the sediments, we identified marine molluscs (Fig. 5). The most abundant species was the gastropod *Bittium reticulatum*, which belongs to the subtidal sands and hard substrate molluscan assemblage (Marriner et al., 2008). From the sedimentological and microfaunal analyses, we infer that this sedimentary unit is of marine origin in its lower part and which gradually changed to a lagoonal environment at the top. From the age model, the transition from marine to shallow marine/lagoonal conditions occurred around 632/417 BC (based on core K1 interpretation).
- The second unit is well represented and observed in cores K1, K2, K4 and K5. The grain-size distribution indicates sediments ranging from silts to very coarse sands (well sorted), and the χ_{lf} values range from 25 to 95 × 10^{-8} m^3/kg. In core K1, from 1.90 m until 3.35 m b.m.s.l. (Fig. 6), we found very abundant marine molluscal debris and *in situ* marine shells such as gastropods (*Cyclope neritea*, *Nassarius reticulatum*, *Ocinebrina* aff. *Aciculate*, *Mangelia sp.*, see Fig. 5) and bivalves (*Loripes lacteus*, *Cerastoderma edule*). *Cerastoderma edule* (an Atlantic species which is also called *Cerastoderma glaucum* in the Mediterranean) is usually found in lagoons and especially those still connected to the sea (Kevrekidis et al., 1996). Generally, it lives in abundance in very well sorted fine sand in low energy environments (Kevrekidis et al., 1996; Poluzzi et al., 1981), and where wave action is not observed (Boyden and Russel, 1972). For cores K2 and K5, the molluscan assenblages is relatively poor, with very few tests represented. The only species identified is *Spisula subtruncata,* in cores K2 (from 5.90 m down to 6.15 m b.m.s.l.) and K5 (from 7.05 m down to 7.40 m b.m.s.l.). This clearly indicates a shallow marine environment (Cardoso et al., 2007) and important freshwater influences can be clearly observed based on the shape of the molluscs (Fig. 5). In doing so, we can infer that above the marine sediments the second unit corresponds to lagoonal environments. Nevertheless, it is clear that the lagoonal stages observed in cores K2 and K5 are more influenced by terrestrial dynamics and the environment appears to be strongly affected by freshwater influxes. In contrast, the lagoonal sedimentary unit is richer in fauna and a connection with the sea seems to be evident. We infer a lagoonal phase in cores K1, K2 and K5 but the salinity conditions were different. Radiocarbon dating gives ages for the lagoonal unit from 632/417 BC to 177/347 AD for core K1, from 130/295 AD to 269/426 AD for core K2, and for core K5, we find similar ages as for K2, ranging from 220/387 AD to 269/426 AD.
- The third unit is found in cores K1, K2 and K5 (approximately 1.70 m thick) and is characterised by very fine grey-coloured sediments with a modal grain size up to 50 μm, thus indicating

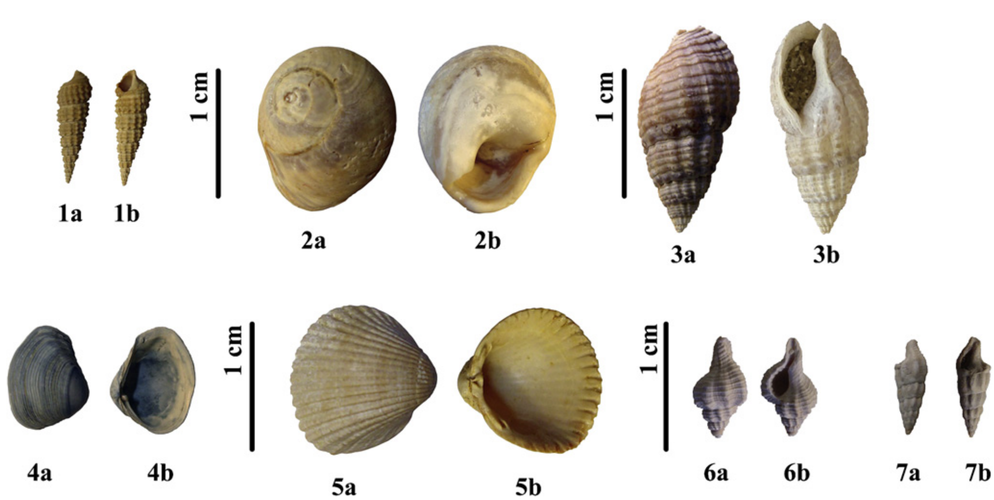

Fig. 5. Shell identifications. 1a and b: *Bittium reticulatum*; 2a and b: *Cyclope neritea*; 3a and b: *Nassarius reticulatum*; 4a and b: *Spisula subtruncata*; 5a and b: *Cerastoderma edule*; 6a and b: *Ocinebrina* aff. *Aciculate*; 7a and b: *Mangelia sp.*

a very calm depositional environment. Some small shell fragments occur within the sediments but unfortunately it was impossible to determine the species. This bio-sedimentary unit is found over the lagoonal deposits and terrestrial dynamics may have influenced the salinity. We infer that brackish conditions obtained and which were subject to terrestrial influences, probably caused by the presence of a river channel in the vicinity.

- The fourth unit is found only in cores K3 (from 2.01 m to 2.25 m b.m.s.l.) and K4 (from 2.17 m to 3.36 m b.m.s.l.) and is composed of very coarse grey sands in the lower part and by a mixture of grey and yellow/orange coarse sands at the top. The modal grain size ranges from 150 to 350 μm and the χ_{lf} values range from 70 to 155×10^{-8} m^3/kg. No intact fossils were identified (very small fragments) and generally little organic matter was found. We can infer that this sedimentary unit represents a coastal barrier.
- The fifth unit consists of dark grey sediments, with intercalated organic layers, and ranging from clay to sands. Peaks of up to 150 μm in modal grain size are observed in cores K2 and K5, but in general the modal grain size index does not exceed 50 μm. The χ_{lf} values range from 5 to 70×10^{-8} m^3/kg and distinct fluctuations are observed. No fauna were observed. We interpret this unit as fluvial deposits indicating a low river transport capacity, and that the depositional environment was calm.
- In the upper part of cores K1, K2, K3, K4 and K5 the sixth unit comprises coarse-grained sediments (yellow to orange colour reveals oxidation), interpreted as fluvial deposits. In cores K2 and K5, these sediments overlie the first fluvial sequence (the fifth unit described above). The modal grain size indicates alternations between silts and coarse sands, which are generally well sorted. χ_{lf} values range from $40–180 \times 10^{-8}$ m^3/kg. Fig. 7 shows the relationship between χ_{lf} and the modal and mean grain size. For the fluvial sediments of all the cores, there is a general increase in χ_{lf} with increasing grain size, indicating a tendency for detrital ferrimagnetic grains to be concentrated in the coarser sediment fraction. A fluvial sequence, recorded in cores K1, K3 and K4, was dated to 1419/1441 AD (radiocarbon dating was performed on a wood fragment, *Quercus* sp.) in the transition from coastal barrier deposits to fluvial sediments for core K3.
- The seventh unit, identified in cores K1, K3, K4 and K5, is composed of dark brown clay deposits and intercalated peat layers with a maximum thickness of circa 50 cm. A few land snails (*Helicidae sp.*) were found. χ_{lf} values are generally low, from $35–75 \times 10^{-8}$ m^3/kg. This last unit probably corresponds to continental swamps and there is insufficient data to confirm the NEDECO (1970, Fig. 3) interpretation considering that very recent lake shore deposits occur around the remnant arch of Klidhi Bridge. Furthermore, maps dated from the 19th Century and the beginning of the 20th Century (Strück, 1908) do not show the presence of a lake in the area instead, there was the junction of the Loudias and Axios Rivers.

5.3. Landsat imagery interpretation

The false colour composition based on the combination of spectral bands 2, 3 and 5 of a Landsat TM imagery (period: 11/05/1997) reveals the presence of wet (green-to-light olive-colour) and dry (light pink colour) areas (Fig. 8). According to previous work (Ghilardi et al., 2008a) in the western part of the Thessaloniki Plain, meanders of the Aliakmon River created several alluvial levees composed mainly of medium to coarse sands (permeable). We can observe in Fig. 8, with a dashed line (blue colour), ancient courses of the Aliakmon running from south–west to north–east, close to the actual Loudias channel and less than one kilometre northward of the remnant arch of the Klidhi Bridge. The deltaic geomorphologic context suggests that other branches could have developed to the south and could have flowed beneath the arches. All the cores contain yellow fluvial sediments in their upper part, close to the present surface level. The Landsat interpretation reveals that a first channel was meandering from core K1 to cores K3 and K4 with an east–west direction. A second channel, running some tens of meters to the north from cores K2 to K5, is also evident. Based on the combination of the Landsat imagery results and the core analyses, it is evident that a channel from the Aliakmon River flowed to the south beneath the bridge (the actual remnant arch), and due to the absence of the other arches to the north it is difficult to conclude that a second branch was flooding under the edifice. Indeed, based on the Delacoulonche (1859) and Strück (1908) estimations, it may be estimated that to the north of the arch, the bridge measured approximately 70 m and this is also the distance between the Klidhi arch and core K2, which records a very thin fluvial layer which probably marks the margin of the river.

The green-to-light olive coloured areas indicate the recent occurrence of saturated conditions in the subsoil. The uppermost part of all the cores analysed in the framework of our research indicate the presence of marshes (green-to-grey clay deposits). These marshes probably existed prior to the reclamation of the entire Thessaloniki Plain in the 1920s (Ancel, 1930). It is possible to consider these topographically low areas as ancient lagoons created within the general context of deltaic progradation where levees changed into coastal barriers.

6. Discussion

6.1. Palaeoenvironmental reconstruction of the area surrounding Ancient Roman Klidhi Bridge

According to Ghilardi et al. (2008a,b) and Fouache et al. (2008), and based on the results obtained in this article, the lower part of Thessaloniki Plain was a marine environment during the Archaic and classical periods (from the 7th to the 4th Century BC). The occurrence in cores K2 and K5 of lagoon shells at a depth of circa 7 m below the mean marine sea-level, dated to Roman Times, must be considered in the context of recent subsidence studies (Stiros, 2001; Psimoulis et al., 2007). These revealed significant rates of subsidence in the lower part of the deltaic complex of Thessaloniki Plain. Indeed, over the last 50 years, accurate measurements of the subsidence phenomena indicate values of around 4 m per year close to the present day shoreline (Psimoulis et al., 2007). It is easy to imagine that on a longer time scale (the last 2500 years), subsidence could had been more important.

During early Roman Times (from 168 B.C. to the 1st Century A.D.), there was general deltaic progradation which affected the whole area, and Strabo considers that at this time Pella was connected to the sea and that ships used to reach the ancient capital after navigating a narrow channel 22.2 km length (*Geography*, VII, frag. 20 and 22). Ghilardi et al. (2008a) revealed the shape of the coastline at that time and it is evident that marine to shallow marine environments occurred in the area of Klidhi Bridge. Several lagoons were in the process of being formed and coastal barriers were being created (Fig. 11). However, the bridge did not yet exist and neither Livy (in his *Natural Histories*) nor Strabo (in his *Geography*) mention the existence of a shorter road, along the shoreline. From this we can conclude that the bridge was not constructed during the first Century A.D.

Gradually, due to the growth of terrestrial dynamic influences (alluviation of the Aliakmon and Axios Rivers) and the constant

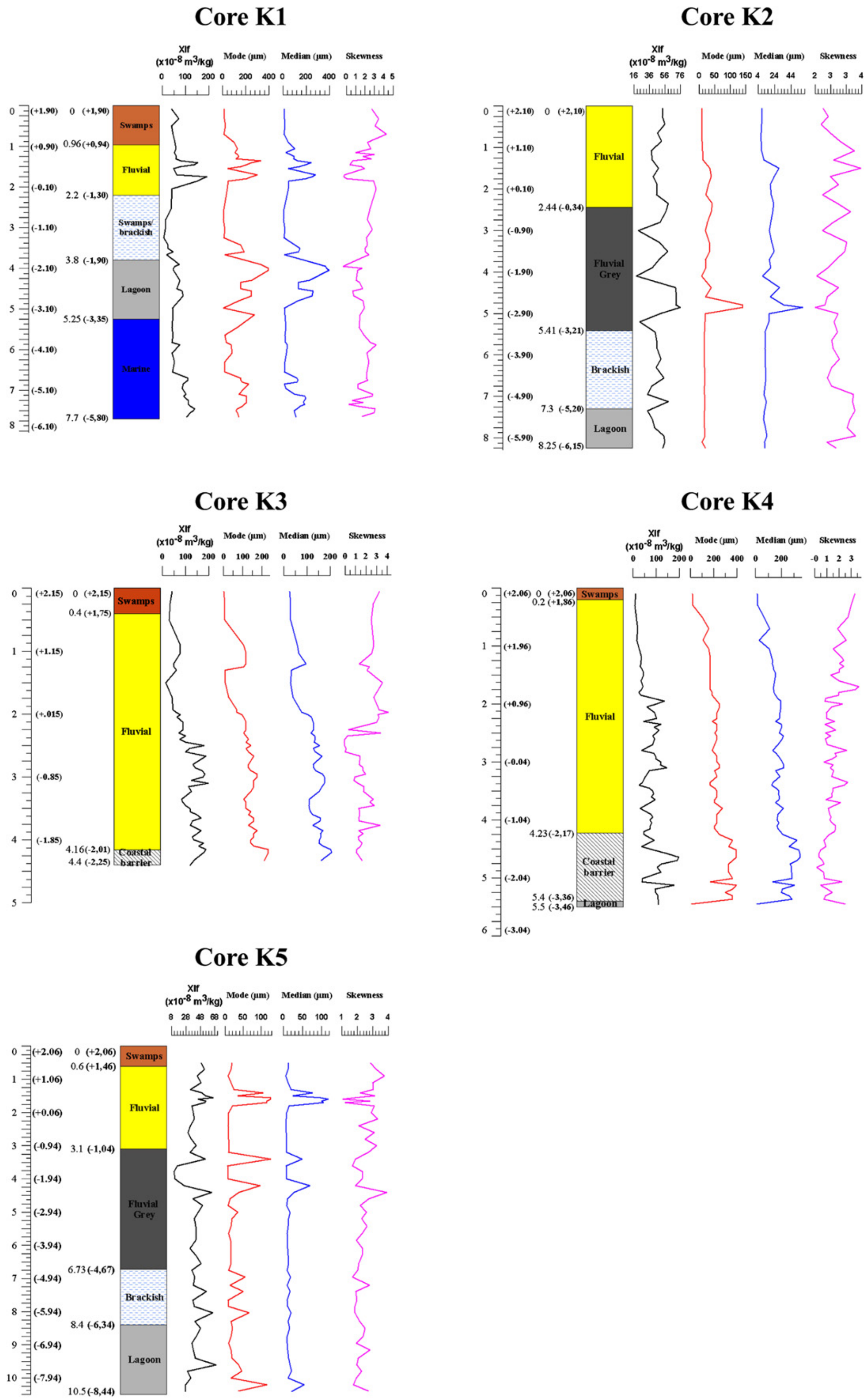

Fig. 6. Core profiles of cores K1, K2, K3, K4 and K5. Results for grain-size distribution and magnetic susceptibility are provided.

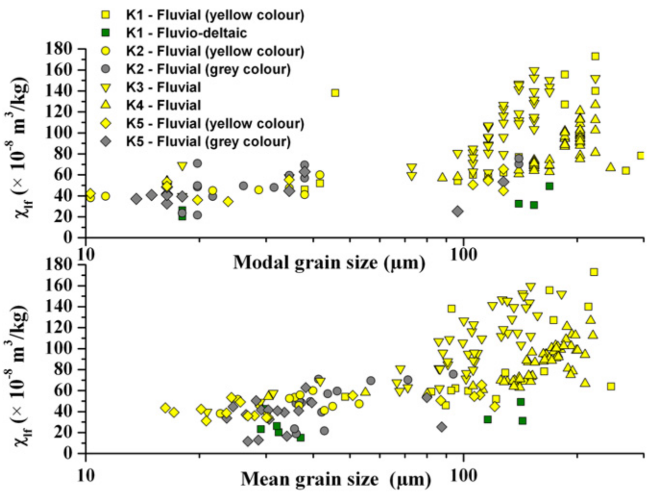

Fig. 7. Magnetic susceptibility measurements vs. grain-size distribution. Upper cartoon: Magnetic susceptibility (Lf) vs. modal index, downer cartoon: magnetic susceptibility (Lf) vs. Mean index

deltaic progradation, a transition to lagoonal conditions occurred during the Hellenistic period, and was well attested during Roman Times (Fig. 9). Such palaeoenvironmental conditions were probably caused by the creation of a series of coastal barriers, as suggested by the NEDECO report (1970) – probably the barrier called Klidhi-Kimina-Chalastra-Sindos (Fig. 1). The development of several isolated lagoons accumulating sediments, ranging from silts to medium- and coarse sands, was possible and connections with the sea still existed. This situation would have justified the construction of the Klidhi Bridge. Based on the microfaunal identifications done for cores K1, K2 and K5, and the various analyses of the sediments from cores K3 and K4, we conclude that two lagoons were separated by a coastal barrier. A shorter road (Bintliff, 1976) was then constructed, which branched from Pydna to Thessaloniki,

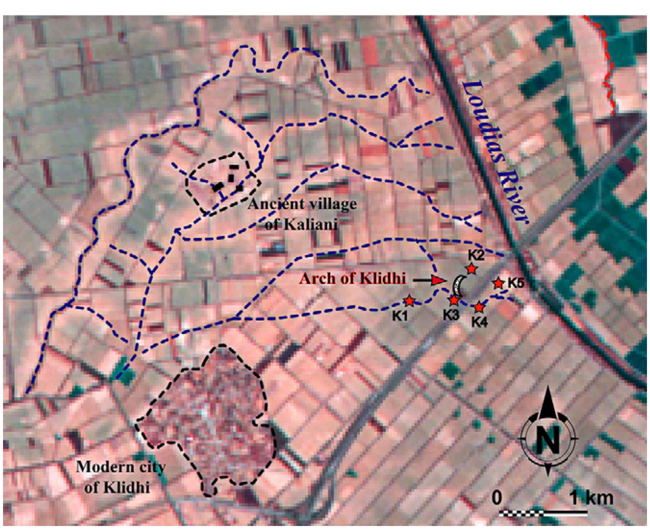

Fig. 8. LANDSAT TM imagery (11/05/1997), False Colour Composite established after the combination of the spectral bands 2, 3 and 5. The red stars indicate the location of the cores K1, K2, K3, K4 and K5. The black half circle is the remnant arch of Klidhi Bridge. The dashed blue lines correspond to old channels of the Aliakmon River. The dashed red line corresponds to an old channel of the Axios River (Ghilardi, 2007). The village of Kaliani is nowadays abandoned but Delacolounche stayed there during his travel to Macedonia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

to the Egnatia Road. Our work shows that the Roman road ran between two lagoons and was built over a coastal barrier at circa 300 AD (Fig. 11). The Roman engineers decided to establish a road in the lower part of the recently created Thessaloniki Plain. In order to avoid swampy/lagoonal areas, close to the shoreline, they elected to build the road on the highest topographic point. The course of the Loudias Channel, the outlet of Loudias Lake (mentioned by Strabo during the 1st Century A.D., *c.f. Geography*, VII, frag. 23) was probably moving laterally in the geomorphological context of the formation of lagoons. This channel definitely existed, and it had no precise lateral limits, e.g. many swamps occurred along the main channel, flooding under the central/northern part of the bridge. In doing so, the ancient Bridge of Klidhi was built on a coastal barrier, over the outlet of Loudias Lake which drained directly into a lagoonal complex, itself connected to the sea.

The change from lagoonal/brackish environments to a dynamic terrestrial environment is confirmed by the passage of a river, depositing coarse sediments, after the 15th Century AD (during the Byzantine and Ottoman periods, Figs. 10 and 11) under the central part of the bridge. The presence of a wood fragment (*Quercus* sp.) found beneath the ancient bridge of Klidhi in core K3 (probably a part of the bridge deck refurbished at the end of Byzantine Times/beginning of the Ottoman period. Indeed, oak was often employed for bridge construction since it was a hard material useful for supporting and protecting bridges in particular), at the transition between coastal barrier deposits and fluvial sediments, may indicate that it belongs to the bridge itself and suggests that a violent flood may have damaged part of the bridge. Furthermore, the multiplicity of several distributaries of the Aliakmon River and the close presence of the Loudias River did not result in the maintenance of the edifice and it was probably abandoned for another road. Based on the satellite imagery and the sedimentological analyses, we conclude that Aliakmon was flooding from the site of core K1, through the sites of cores K3 and K4 to core K5.

Until the mid fifteenth century (Fig. 11), it is probable that the rate of progradation of the Aliakmon and Axios rivers slowed down and lagoons still existed at those times and that the shoreline was still in the close vicinity, as it was during Roman times. Moreover, no rivers were flooding in the nearby area according to the detailed map constructed by Leake (1836): neither the Aliakmon (flowing further south–westwards) nor the Loudias River (connected to the Axios River, further to the east). It is likely that swamps still existed around the remnant arch. At this time, local villagers decided to remove the stones from the edifice in order to construct buildings such as churches and houses.

In the first half of the 20th Century, significant efforts were made to reclaim the plain and to drain the swamps (Ancel, 1930; Ghilardi, 2007; Ghilardi et al., 2008a). In addition, the major rivers were controlled and several dams were built to protect the fields from major floods. The present day topography was established, and numerous landforms which existed in the ancient landscape disappeared.

6.2. Evidence for the alteration of the status of Pella due to landscape changes during Hellenistic/Roman Times

In general, historians consider that wars and conflicts were responsible for the demise of kingdoms, and this was also the case for the Macedonian Realm (Hammond, 1972) – in particular for its former capital, Pella. Pella became the capital of the Hellenistic period (323–168 B.C.), and gradually, after the Roman conquest, political control of the Macedonian province and of the Mediterranean began to weaken. Thessaloniki became the most important city during late Roman Times and a major site during the Byzantine Period (Bintliff, 1976; Papazoglou, 1988). The

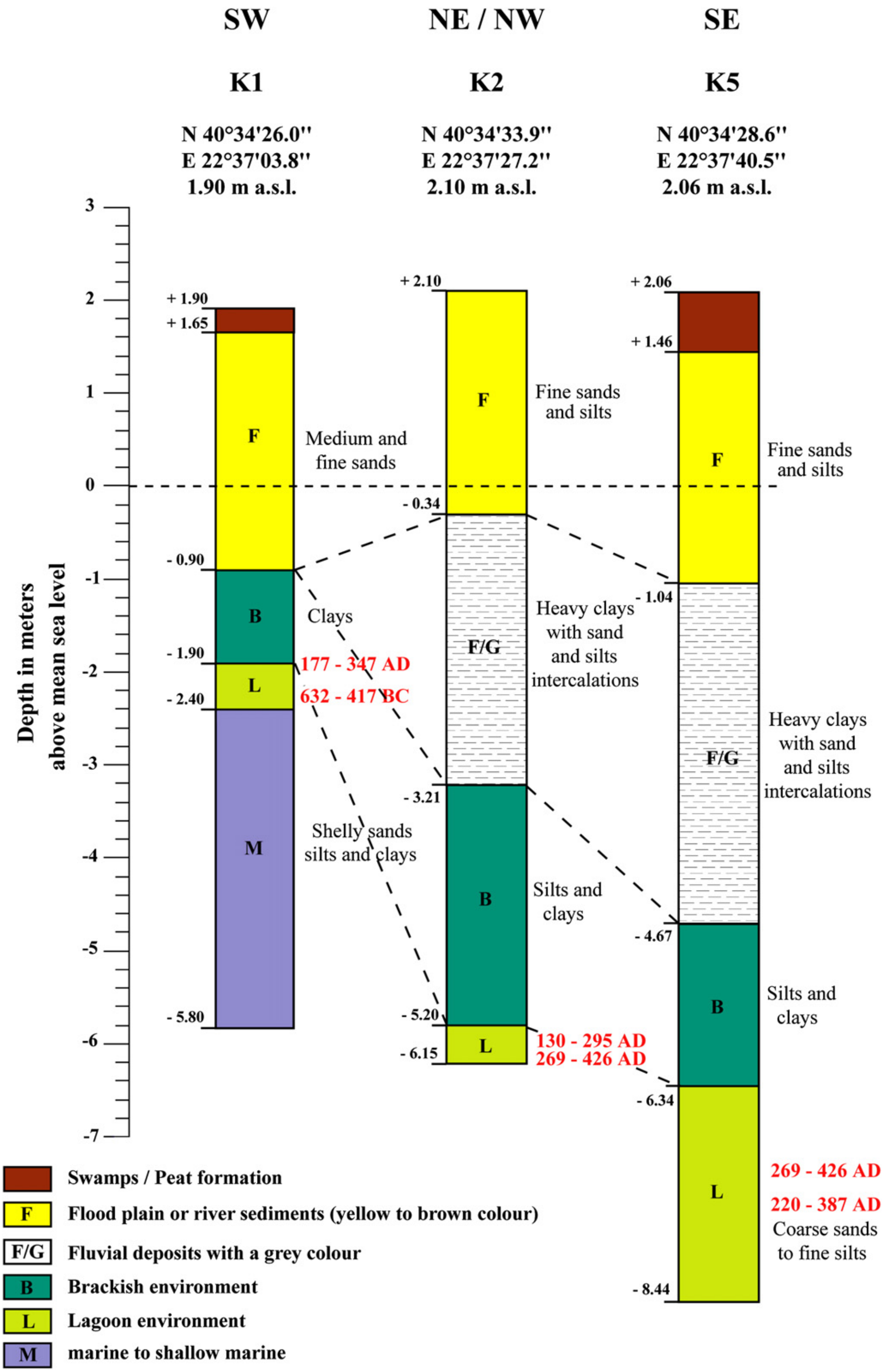

Fig. 9. Cross section using the results derived from cores K1, K2 and K5, the chronostratigraphic sequences are connected together to facilitate a spatial interpretation.

important point is the establishment of the Late Roman Road through the plain, along the coastline, which linked Athens – Pydna – to Thessaloniki. Pella was then situated on the margin of this main axis, landlocked inside the Central Macedonian Plain. At the present day, this branch of the Egnatia Way is only evidenced by the presence of the arch of Klidhi and it is probable that most of its pavement is buried by a significant thickness of fluvial sediments. Our work reveals that the rapid landscape evolution and the creation of the Thessaloniki Plain at the end of the Late Roman Times altered Pella's status. The emergence of Thessaloniki as the capital of the Roman province of Macedonia must be linked with the construction of new Roman roads across the newly created plain: at that time the distance between Athens and Thessaloniki was shorter, and the latter city was also situated on

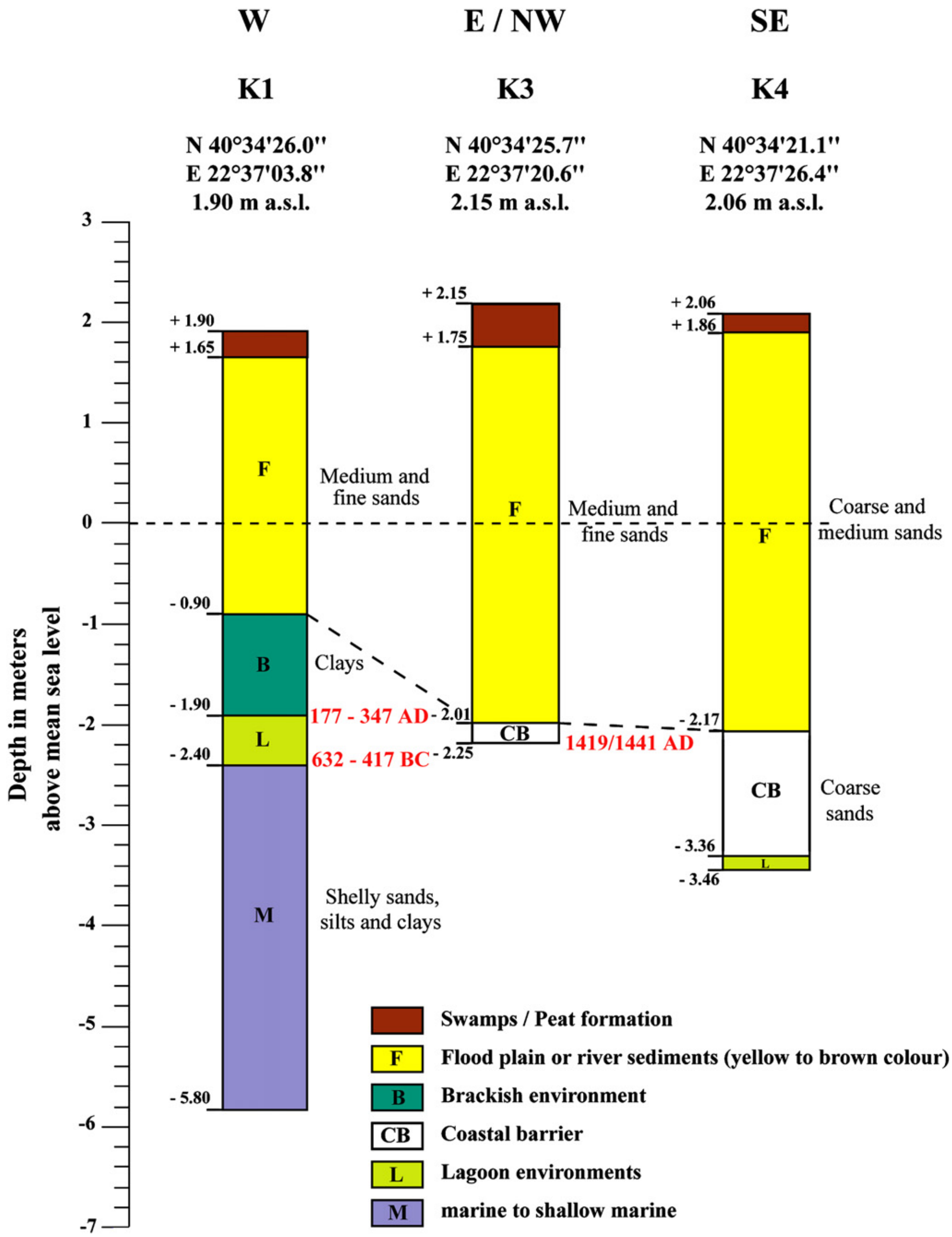

Fig. 10. Cross section using the results derived from cores K1, K3 and K4, the chronostratigraphic sequences are connected together to facilitate a spatial interpretation.

the main axis of the Egnatia Way, from Dyrrachium to Byzance (O'Sullivan, 1972).

6.3. Evidence for a river flowing under the remnant arch during the Byzantine–Ottoman periods: a possible consequence of climate control on the river dynamics, or the effect of human impacts on sedimentation processes?

Previous studies mentioned the possibility of a river (Bintliff, 1976), or the junction of two rivers (NEDECO, 1970), flowing beneath Klidhi Bridge during Roman times. From the results presented here, we can assume that marine to lagoonal conditions were predominant during the archaic, classical, hellenestic and imperial periods. Subsequently, sedimentological evidence indicates the presence of fluvial conditions and suggests that a river flowed beneath the bridge from the mid 15th Century until the beginning of the 19th Century. During his visit to the remnant arch at the beginning of the 19th Century, Cousinéry (1831) observed that 'new soils' had been deposited by a river and had almost buried the edifice. Presumably, therefore, the river was still active at that time. Furthermore, when Delacoulonche (1859) described the edifice in the mid 19th Century, no rivers were flowing beneath the remnant arch of Klidhi bridge. In Northern Greece, observations made in the Epirus area (Fouache, 1999) and in Eastern Macedonia (Lespez, 1999, 2003), point to an alluvial crisis affecting the major rivers during the Byzantine and the Ottoman periods. If anthropogenic factors (Lespez, 2003) are highlighted to explain significant fluvial activity, climate variability is also likely to have been an important influence (the Little Ice Age episode).

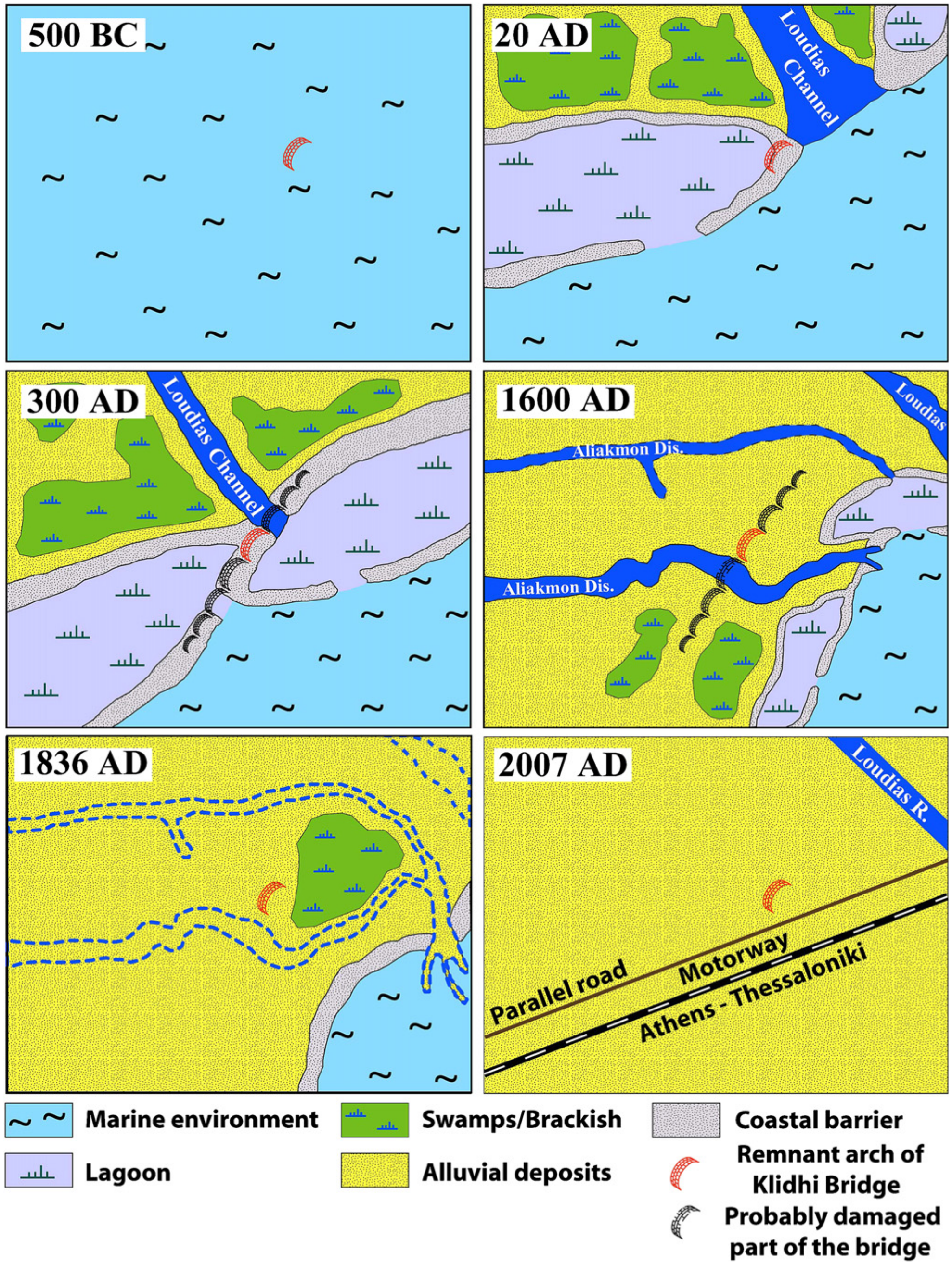

Fig. 11. Palaeogeographic reconstruction of the area surrounding the remnant arch of the Klidhi Bridge. The scenario is inferred after combining the results from the palaeoenvironmental study, the historical geography critical analysis and the remote sensing interpretation.

7. Conclusions

In previous work (Ghilardi et al., 2008a,b; Fouache et al., 2008), the main phases of the deltaic progradation of Thessaloniki Plain were detailed using a palaeoenvironmental approach. However, the lower part of the largest deltaic complex in Greece was little studied and palaeonvironmental reconstructions were not made for several important archaeological sites. The remnant arch of the Roman Klidhi Bridge has witnessed the rapid geomorphological evolution of Thessaloniki Plain, especially in its lower part. The palaeoenvironmental reconstruction presented in this paper confirms the research recently carried out in the area (Ghilardi, 2007) and provides a more detailed understanding of the geomorphological evolution of the landscape in the vicinity of the remnant arch.

The new results detailed here allow us to infer that a marine environment occupied the area during the archaic, classical and hellenestic periods. Shallow marine to lagoonal conditions obtained in mid and late Roman Times (from the 1st to the 4th Century AD) and the construction of the bridge dates from this period. The creation of a series of coastal barriers led to the isolation of lagoons, although some connections with the sea still existed. In order to establish a new road, connecting Southern Macedonia (the ancient city of Pydna) to Thessaloniki (and the Egnatia Road), Roman engineers decided to construct several edifices over the coastal barrier and to avoid swamps. Some bridges were built in areas of swamp in order to span the connections between the lagoons and the sea.

The geoarchaeological approach used here reveals that rapid landscape changes strongly affected not only the use of the Roman

Bridge of Klidhi but also influenced Ancient Pella's leadership in the province of Macedonia. After the connections between the deltaic lobes of Axios and Aliakmon Rivers, probably in the vicinity of ancient Klidhi, the Thessaloniki Plain was created and Pella was completely isolated inland and its status of a city with a harbour collapsed during roman Times. It is generally accepted that the Macedonian Kingdom started to collapse around the third Century BC (Hammond, 1972) and the battle of Pydna in 168 BC concluded the achievement of the one world's largest Kingdom, and around the 6th Century AD references to Pella disappeared completely from the written sources (Bintliff, 1976). At the same time, the period from the 4th BC to the 4th Century AD shows that the deltaic progradation of the Axios and Aliakmon River was very intense around the ancient Macedonian capital (Ghilardi, 2007; Ghilardi et al., 2008a,b). An important question now arises: was the roman invasion and occupation the only factors responsible for the end of the Macedonian Realm, or is it possible to consider that landscape changes determined the status of ancient Pella? It is difficult to separate both factors and the results presented in this article clearly indicate that archaeological studies must not be dissociated from landscape reconstruction.

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