The "Lake of Olympia": geoarchaeological evidence of a lake environment in the vicinity of ancient Olympia (western Peloponnese, Greece)

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Abstract
Our results yield evidence of a large lake environment that existed near the ancient site of Olympia which was so far unknown. The limnic sequence reveals considerable changes in the ecological conditions over time, based on Direct Push sensing, sedimentary and micropalaeontological analyses. Radiocarbon data show that the "Lake of Olympia" existed from the 8th/7th millennium BC until, at least, the 1st century AD. The existence of the "Lake of Olympia" next to the cult site of Olympia has considerable historical, archaeological and geographical implications (e.g., as waterway or water supplier).

Keywords
ancient Olympia; direct push sensing; landscape evolution; micropaleontological analyses; sediment cores

Introduction

The site of Olympia (western Peloponnese, Greece) was used as a venue for the Panhellenic games between Archaic times and the 4th cent. AD (Sinn 2004). It is one of the best investigated archaeological sites of this period with systematic excavations having begun in 1875 by the German Archaeological Institute (Heilmeyer et al. 2012). In contrast, our knowledge on the overall landscape development and our understanding of relevant changes of the drainage pattern and the associated sedimentary burial of the site is still limited. The site is located at the northern fringe of the Makrisia Basin at the confluence of the Kladeos and Alpheios rivers and shows a complex tectonic setting (Fig. 1). Based on previous studies downstream the Alpheios River and along the coast of the Gulf of Kyparissia, we were able to show that the area was subject to strong tectonic uplift of minimum 13 m to a maximum of 30 m since the mid-Holocene (Vött et al. 2015, 2019). In addition, we found that the so-called Olympia terrace, which accompanies long sections of the Kladeos and lower Alpheios rivers, documents multiple phases of high-energy flood events and associated phases of strong siltation with their triggering mechanism still being evaluated (Vött et al. 2011, 2019). Against this background, recent studies focused on the direct vicinity of the site to gain more information on site formation and the overall landscape development.

Here, we present results based on high-resolution Direct Push Electrical Conductivity measurements (DP-EC) in combination with sediment coring and micropaleontological studies.

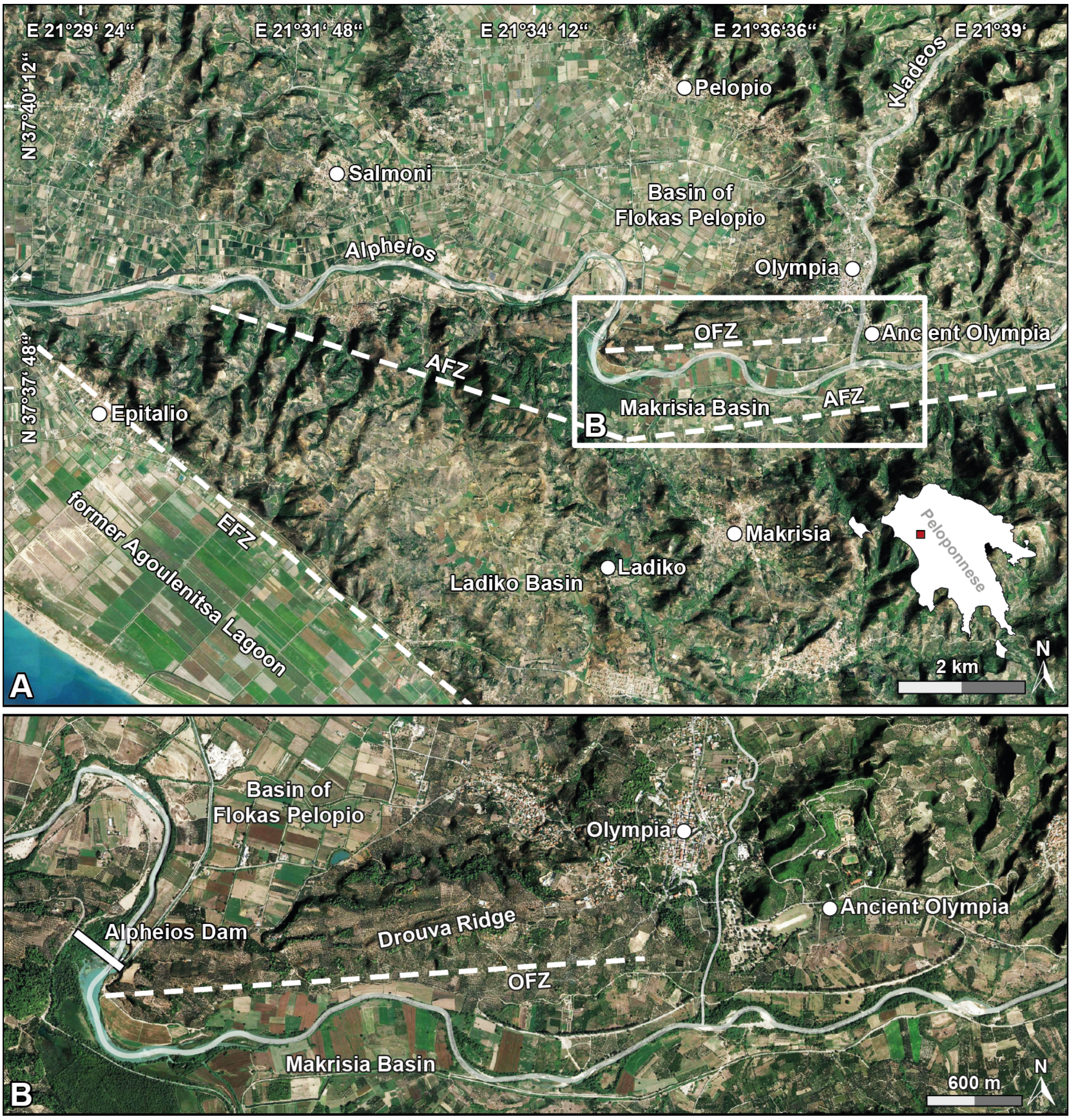

Fig. 1: (A) Topographical overview of the study area located in the western Peleponnese (Greece) showing the Olympia fault zone (OFZ), the Alpheios fault zone (AFZ) and the Epitalio fault zone (EFZ) (Vött et al. 2018, Papanikolaou et al. 2007) (B) Detailed view of the Basin of Makrisia showing the location of ancient Olympia (base map: Google, ©2023 CNES/Airbus, Landsat / Copernicus, Maxar Technologies).

Materials and methods

Direct Push (DP) sensing is a non-invasive method, which is applied increasingly in geoarchaeological research. DP-EC logging yields vertical centimeter-scale stratigraphic information since the electrical conductivity is mainly dependent on the predominant grain size. Higher conductivities usually correlate with finer-grained sediments and low electric conductivity values with coarser grained sediments. Detailed subsurface data obtained by DP-EC measurements help to concentrate coring activities to selected key sites. Compared to coring, DP sensing is more time-efficient and allows better investigation of non-cohesive sediments where boreholes often tend to collapse (Fischer

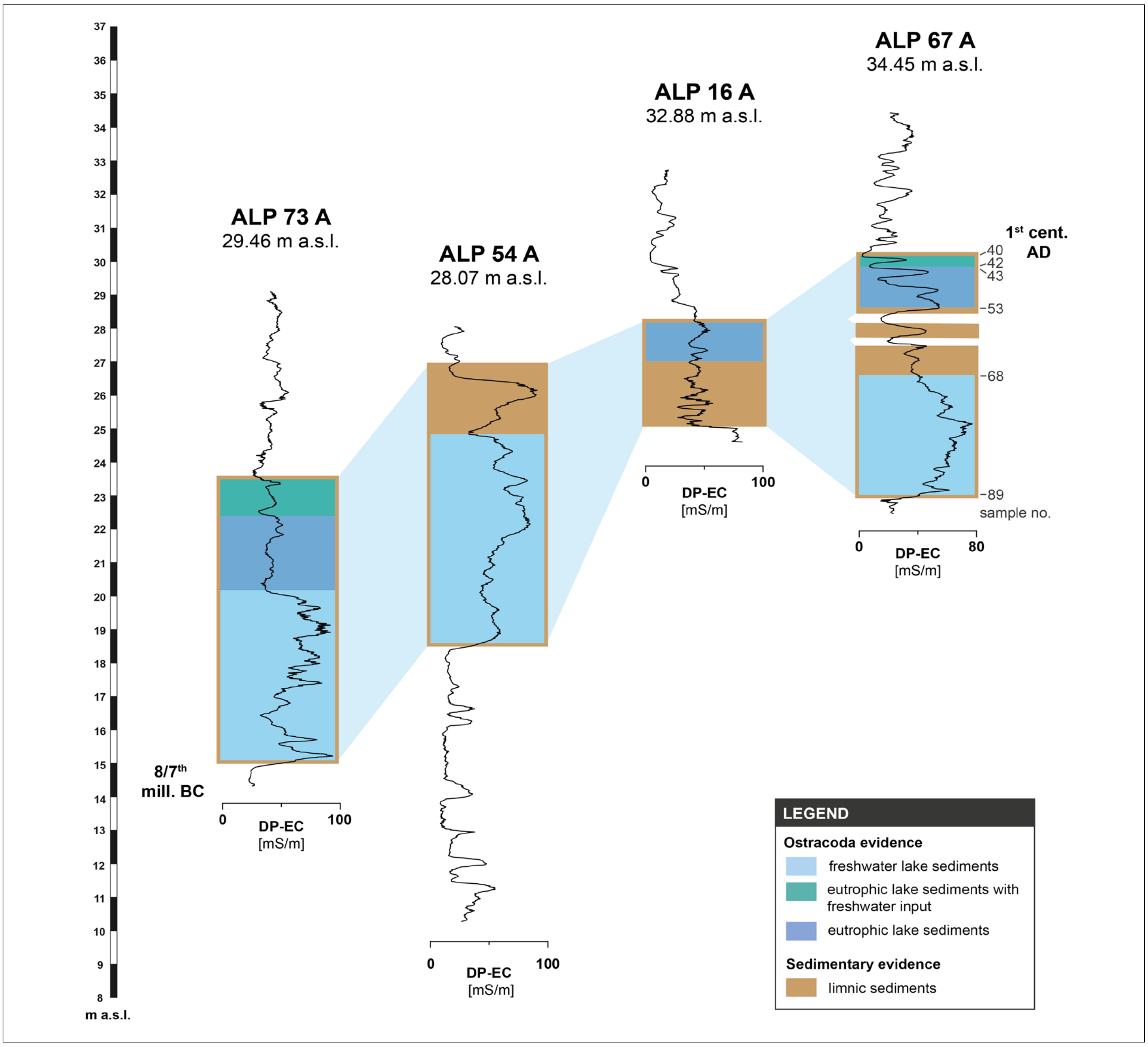

Fig. 2: Evidence of the "Lake of Olympia" based on sediment cores, DP-EC measurements and ostracod analyses. Our results allow differentiation between different lake phases. For location of coring and DP-EC sites, see Figs. 1 and 3.

et al. 2016). We use a Geoprobe SC520 soil conductivity probe mounted on a Nordmeyer RS 0/2.3 drill rig. The conductivity probe consists of four linear arranged electrodes operated with a Wenner electrode array that provides a vertical resolution of 0.02 m.

Micropaleontological studies were conducted in search of ostracod specimens within the limnic sediments. Ostracods are highly sensitive indicators for different kinds of environments. They occur in marine, brackish and freshwater environments such as lakes and ponds. We used microfossils as an important tool to reveal landscape changes and anthropogenic influences. Moreover, ostracods provide information on e.g., habitat structure and disturbance, salinity, land use effects and climate. Due to their size and generally high abundance, they are especially well suited for sediment core analyses, as only small sample sizes are required (Quante et al. 2022; Mazzini et al. 2022). We retrieved various samples from different depths and especially from core sections where fine-grained silt-dominated potentially limnic sediments were found. Samples were wet-sieved and taxonomically classified using Meisch (2000), Athersuch (1989) and Fuhrmann (2012).

ALP 67A	sample		Ostracods				Total number of ostracods	Number of different species
Facies	no.	depth [m]	freshwater	brackish	marine	others*		
V - eutrophic lake sediment with freshwater input	40	4.35	x	x		x	161	2
	41	4.45	x	x	x	x	51	2
	42	4.53	x	x			13	3
IV - eutrophic lake sediment	43	4.58		x		x	27	1
	44	4.68		x			2	1
	45	4.80		x		x	5	1
	46	4.89		x			5	1
	47	5.09		x		x	25	1
	48	5.14		x		x	74	1
	49	5.24		x			2	1
	50	5.36		x		x	3	1
	51	5.46		x		x	5	1
	52	5.57				x	2	-
	53	5.70		x			7	1
III - infill	59	6.45	x			x	4	1
	60	6.59					-	-
	65	7.35					-	-
II - freshwater lake sediment	68	7.77	x	x		x	7	3
	70	8.25					-	-
	72	8.65			x		1	1
	77	9.73	x			x	11	4
	80	10.25	x	x		x	173	6
	83	10.75	x			x	17	2
	88	11.37	x			x	75	4
	89	11.48	x	x	x	x	36	6
I - fluvial/ colluvial wdeposits	92	11.71		x			1	1

Tab. 1: Results of micropaleontological analyses of sediment samples from sediment core ALP 67A: Distribution, abundance and diversity. x means that taxa occur in the sample. * means genus and species indeterminate or fragment.

Results and discussion

Our results yield robust evidence of a large lake environment that existed near Olympia and that was so far unknown. The "Lake of Olympia", as we call it, covered large parts of the Makrisia Basin with the ancient site of Olympia directly located at its north-eastern shore. Geoscientific evidence for the existence of the lake comprises detailed sedimentary and stratigraphic data retrieved from numerous cores drilled in the entire basin, DP-EC logs collected at key sites and detailed micropaleontological analyses.

Figure 2 shows a transect of four DP-EC logs and associated sediment cores (ALP 73A, ALP 54A, ALP 16A and ALP 67A) located in the Makrisia Basin. The highlighted sections represent limnic sedimentary facies identified by significantly increased EC values related to fine-grained silt-dominated sediments. Micropaleontological analyses allowed further characterization and subdivision of the limnic sequences. Based on the occurrence and distribution of ostracod species, we are able to differentiate between different ecological conditions. In fact, periods of freshwater conditions, eutrophic conditions with significant

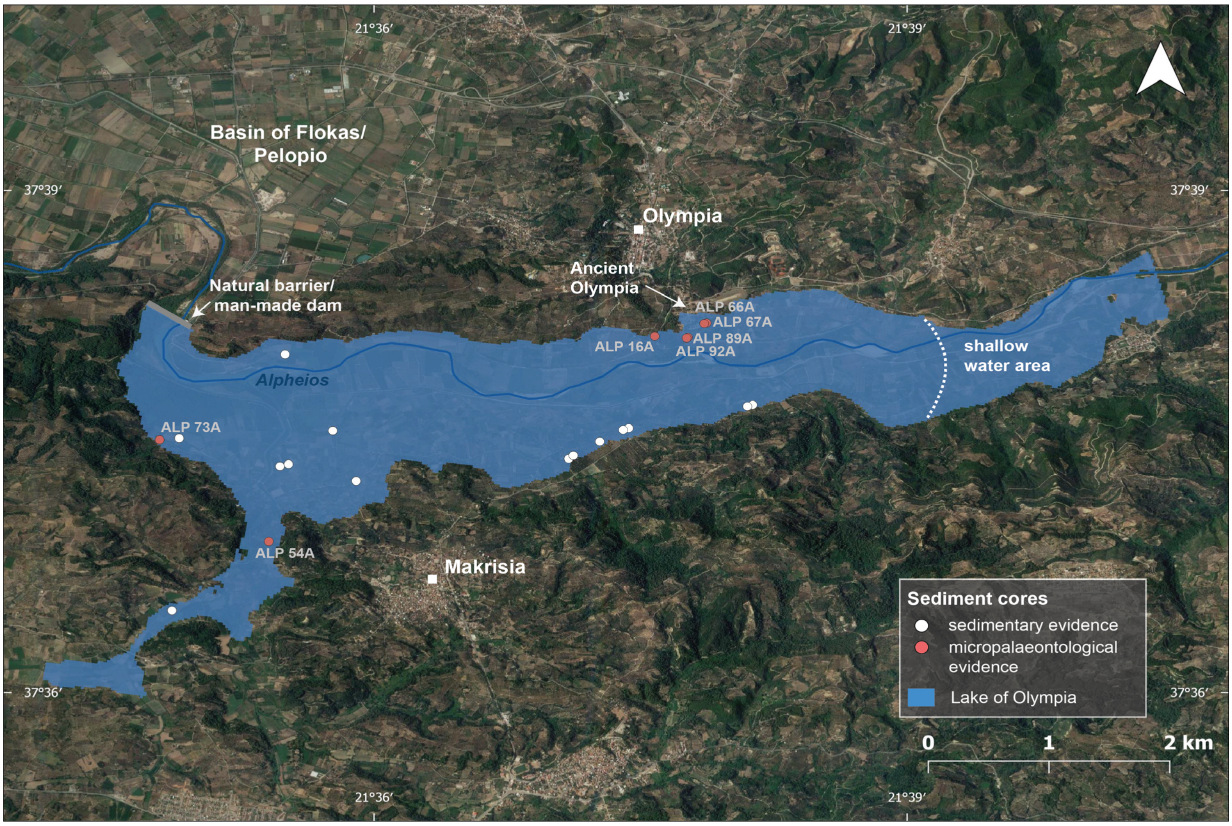

Fig. 3: Reconstruction of the extent of "Lake of Olympia" based on sedimentary (coring sites marked in white) and micropaleontological evidence (coring sites marked in red) (base map: Google, ©2023 CNES/Airbus, Landsat/Copernicus, Maxar Technologies).

freshwater input and strongly eutrophic conditions were identified.

Summarized results of the ostracod assemblage found for sediment samples from core ALP 67A are presented in Table 1. Ostracod species are separated into freshwater, brackish, and marine species depending on their preferred habitat. Based on the distribution of ostracods, the depositional sequence can be divided into five sedimentary facies. Three of these facies provide evidence of stillwater: facies II, facies IV and facies V. In facies II, freshwater species dominate; brackish to marine specimens occur only intermittent and in small numbers most probably brought in by birds. Within these facies, a high abundance and an increased diversity (number of different species) are discerned. The abundant freshwater species (e.g., *Candona* spp., *Ilycyprisbradyi*, *Limnocythereinopinata*) prefer stagnant or slow flowing water as habitat (Meisch 2000). In contrast, in facies IV, the brackish water species *Cyprideistorosa* is dominant and indicating strongly eutrophic conditions. Abundance is slightly reduced and diversity is low within these samples compared to facies II. In facies V, the total number of ostracods and their diversity are increased and freshwater species occur again; still, the samples are dominated by *Cyprideistorosa*. In facies I and III, both the total number of individuals and the diversity are significantly lower (no sample with > 1 different species). Based on sedimentological parameters, these facies are assigned as fluvial/colluvial deposits (facies I) and infill (facies III), respectively. Similar findings were found for other sediment cores (Fig. 3).

Based on sedimentary evidence from DP-EC logs, sediment cores and results of multi-proxy analyses in combination with the given topography, it is assumed that the maximum extent of the "Lake of Olympia" covered an area up to 6 km long and up to 2.5 km wide (Fig. 3). In Figure 3, coring sites marked in white provide sedimentary evidence of the lake, while coring sites marked in red provide additional microfossil evidence. However, the reconstructed scenario is based on the present-day terrain model and does not consider the tectonic activity in the area.

Based on radiocarbon data, the "Lake of Olympia" existed from the 8th/7th millennium BC until, at least, the

1st century AD. Hence, the lake period coincides with the use of the ancient site of Olympia as venue for Panhellenic Games. Preliminary results further show that the lake was repeatedly subject to massive changes of the lake level. This seems associated with phases of blocked discharge at the narrow breakthrough through the Drouva Ridge and subsequent catastrophic draining events forming, among others, the Olympia Terrace. The existence of a large waterbody next to the cult site of Olympia has considerable historical, archaeological and geographical implications. For example, it may be assumed that the "Lake of Olympia" was used as a waterway to reach Olympia and to provide adequate water supply. During summer months the visitors of the ancient Olympic Games used earthen cisterns that were fed by lake-controlled groundwater. The large cattle herds that were needed as supply for food and sacrifices may have grazed along the lakeshores and in shallow lake areas. Furthermore, shallow water conditions at the eastern fringe of the "Lake of Olympia" may have allowed the Alpheios River to be crossed by foot.

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