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Olive groves around the lake. A ten-thousand-year history of a Cretan landscape (Greece) reveals the dominant role of humans in making this Mediterranean ecosystem.

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Abstract

The reconstruction of millennial-scale interactions between ecosystems and societies can provide unique and valuable references for understanding the creation of cultural landscapes and help elucidate their value, weaknesses and legacies. Among the most emblematic forms of Mediterranean land use, olive groves and pastoralism have occupied a prominent place.

Therefore, it is vital to know when, how, and with what ecological consequences these practices were established and developed. Located in the southern part of the Aegean Sea, Crete is the largest island of Greece. The island is characterised by a long human history of land use, but our understanding of past environmental changes for the entire Holocene is fragmentary. This paper presents a new investigation of Lake Kournas in Crete, where recent coring provided a 15-meter sequence covering ten millennia of land cover and land-use history. The study of this new core involves the analysis of the sediment dynamics, flood deposits, pollen, diatoms, fungal and algal remains, and microcharcoals. Results show that ecosystem development near Lake Kournas was not a linear process. They reveal linkages and feedbacks between vegetation, biodiversity, fire, human impact, erosion, and climate change. A possible human occupation and agro-pastoral activities around the lake may have been detected as early as 9500 cal BP, perhaps in a transitional phase between the Mesolithic and the Neolithic. At 8500 cal BP, climatic conditions may have promoted the expansion of the evergreen oak woodland. However, human impact was probably the most important driver of ecosystem change with the establishment of an agro-system after 8000 years ago. Thereafter, the trajectory of Kournas' lake and catchment ecosystems from the Mid to Late Holocene follow the rhythm of land-use change. Among the traditional Mediterranean land uses, olive cultivation locally played a major role in the socio-ecosystem interactions, providing economic benefits but also destabilising soils. During the last six millennia, three main phases of olive cultivation occurred during the Final Neolithic-Minoan period, the Hellenistic-Roman-Byzantine (HRB) period and Modern times. Along with the changing land use under the successive political and economic influences rules, the resilience capacities of vegetation permitted it to shift back to higher biodiversity again after decreasing phases. Forest vegetation was always able to recover until the onset of the Venetian period (13th century), when woodlands were dramatically reduced. Only during the past century has forest vegetation slightly recovered, while the flood regime had already been altered during previous centuries. During the past 100 years, biodiversity markedly declined, probably in response to the industrialization of agriculture.

Keywords

Palaeoecology, Anthropisation, Human impacts, Olive grove, Holocene, Crete, Mediterranean, Socio-ecosystem, Land-use, Biodiversity

1. Introduction

One of the main current environmental challenges is the possible response of socio-ecosystems to global change, including climate warming (IPCC Report 2019) and a dramatic trend of biodiversity loss (IPBS Report 2019). The Mediterranean is a hot spot of global change (e.g. Giorgi, 2006), and its islands are especially threatened by these ongoing environmental issues, as is the case for the Aegean Islands (Vogiastzakis et al., 2016). Extreme events such as drought, megafire, flood or storminess are already affecting Mediterranean anthropo-systems, but their magnitude and frequency are expected to intensify in the coming years (e.g. Sarris et al., 2014; Tapogoulou et al., 2019). Moreover, because of past climate changes and millennial land-use history, Mediterranean biodiversity and soils can be highly vulnerable to erosion (e.g. Collins et al., 2010; Walsh et al., 2019), putting Mediterranean landscapes and associated resources in danger.

The reconstruction of millennial ecological dynamics can provide key documents for understanding the processes of long-term interaction between ecosystems and societies, and their present legacies. They document land-cover change and land-use practices that shaped the cultural landscape and may explain their value and weaknesses (e.g. Whitlock et al., 2018). Among the most emblematic Mediterranean land uses, olive groves and pastoralism have occupied a prominent place. Therefore, it is vital to know when, how, and with what ecological consequences these practices were established and developed. Furthermore, the relationship between socio-environmental changes and the Holocene climate – notably during the major climate transitions (e.g. Magny et al., 2013; Cheng et al., 2015; Finné et al., 2019; Azuara et al., 2020) or Rapid Climate Changes (Mayewski et al., 2004) is a hot debate in the archaeology and paleoecology scientific communities and echo present-day challenges. In the eastern Mediterranean, recent studies emphasise and/or attempt to model the role of climate changes on societies and their practices (e.g. Weninger et al., 2009; Kaniewski et al., 2013; Wiener, 2014; Rohling et al., 2019) or on the opposite side criticize and demonstrate the limits of deterministic scenarios (e.g. Knapp and Manning, 2016; Chapman, 2018). Societal development and environmental changes linkages have been investigated at a regional scale in Southern Greece, based on palaeoenvironmental archives and archaeological sites (e.g. Izdebski et al., 2020; Kouli et al. 2018, Weiberg et al. 2016; 2019). They highlighted regional trends but they also underlined the importance of local-scale well-documented sequences to better understand adaptive strategies of human society to environmental changes.

Located in the southern part of the Aegean Sea, Crete is the largest island of Greece characterised by many landscape types along an altitudinal gradient from the seashore up to mountains: the White Mountains in the West, Psiloritis in central Crete and Dikti mountains in the East. The island is well known for its numerous endemic plants, but it also has a very long history marked by numerous human colonisations and cultural changes (Rackham and Moody, 1996). Today, the threats to ecosystems are mainly due to tourism and population growth on coastal areas, overgrazing on the mountain slopes and intensive agricultural practices in lowlands in which olive groves have an important place (e.g. Ispikoudis et al., 1993; Fielding and Turland, 2008; Kosmas et al., 2016). For decades, the focus of archaeological investigation in Crete has been the Minoan civilisation (5000-3000 cal BP), with some important excavated sites such as the cities of Knossos, Malia, Phaistos (e.g. Marangou, 1992) along with Chania in Western Crete (Andreadaki-Vlazaki, 1997). Recent investigations highlight numerous other archaeological sites over time and space, although they are generally less well documented than those of the Bronze Age (e.g. Nowick, 2014; Rackham and Moody, 1996). Our current understanding of past vegetation and environmental changes during the Holocene is based on only a few sedimentary archives and pollen analyses. Apart from a two millennia peat bog sequence located in the White Mountains (Atherden and Hall, 1999; Jouffroy-Bapicot et al., 2016), most palynological records available are located in the coastal lowland areas of Crete (Moody et al., 1996; Bottema and Sarpaki, 2003), the most recent being performed in the framework of geomorphological studies of the littoral floodplains near important archaeological settlements such the Minoan sites of Phaistos (Ghilardi et al., 2018, 2019), or Palaikastro (Cañellas-Bolta et al., 2018). The chronology of these sequences is often limited in duration, documenting short time-window histories, and until now, no published sequence covers the entire Holocene environmental history of Crete. However, Bottema and Sarpaki (2003) highlighted the great potential of Lake Kournas for palaeoecological studies. This paper presents a new investigation of the lake where recent coring provided a 15-meter sequence covering ten millennia of land cover and land-use history. The study of this new core involves the analysis of the sediment dynamics, flood deposits, pollen grains, fern spores, fungal, algal and diatom remains, and microcharcoals. This paper has three main goals: 1) to propose a detailed and multiproxy reconstruction of environmental changes in the surrounding of the lake for the last 10 millennia, 2) to document the long history of human occupation and practices in this region, 3) to discuss the respective role of land use and climate changes on ecosystem dynamics, i.e. on soil erosion, fire and flood regime, lake productivity, land cover and plant biodiversity.

2. Regional setting

Located in the north-western part of Crete, Lake Kournas is the only natural lake on the island. Situated about 3 km from the coast, in the foothills of the White Mountains (Lefká Óri), at the southeast of the Peninsula of Chania, the lake covers an area of about 1 km^2 (Fig. 1A). It is fed by freshwater springs from the mountains, with the major one located below the lake level at the south side of the basin. In addition, two small ephemeral rivers at the south and west bring inflow during intense rainfall episodes. The lake feeds the Delphinos River which runs north to the sea. The central deep basin has a water depth of around 21-22 m, and the shores of the lake are characterized by carbonate platforms that extend up to 5 m in water depth towards the lake centre (Fig. 1C). The lake contains freshwater but with slightly elevated electrical conductivity (salinity) values up to ~1500 $\mu S.cm^{-1}$, and seasonal fluctuations in water level of up to 4 m. The lake itself has been the subject of several previous scientific studies, focusing especially on its aquatic biota (e.g. Vallianos et al., 1985; Tigilis 2007)

The lake surroundings consist of two different main zones: slopes in the west and south and a flat cultivated and inhabited area on the north-eastern part. The south-western part mainly consists of crystalline limestone, more or less karstic, while the north-eastern part consists of Miocene marine limestone (e.g. Pomoni-Papaioannou & Karakitsios 2002). Garrigue and phrygana dominate the vegetation of the slopes with patches of sclerophyllous woodlands near the lake, the flat zone is dominated by olive groves, with some vineyards and cultivated fields. Finally, a dense scrub littoral vegetation covers the lake perimeter, mainly made of chaste tree (*Vitex agnus-castus*) together with wild-grape vine (*Vitis vinifera* subsp. *sylvestris*) (Fig. 1C). The climate of Crete is typically Mediterranean, with cool and moist winters and hot and dry summers. The western part, exposed to Atlantic flux, is the moister part of the island, especially the White Mountains have the highest precipitations of Crete, including snow (Agou et al., 2019).

3. Material and method

3.1. Coring

The Aegean area in general, and Crete in particular, are located near the Hellenic subduction zone threatened by seismic activity, earthquakes, tsunamis and volcanism (e.g. Jusseret et al., 2013; Mourtzas et al., 2015). Thus, before coring, a seismic reflection survey using a single-channel 3.5 kHz pinger source provided the lake bathymetry and several high-resolution sub-bottom profiles, which have been used to establish a seismic stratigraphy of the most preserved part of the basin infilling. The digital acquisition was achieved by a stratabox SyQwest system

(High-Resolution Echo Sounders and Acoustic Systems for Precision lake floor Exploration) and conventional GPS positioning (Fig. 1D). Then, coring operations were directly guided by the images of subsurface sedimentary accumulation; a double overlapping parallel coring was performed in the deep basin (water depth: 21-22 m) within the well-stratified seismic units and avoiding chaotic Mass Wasting Deposits (MWD). The sediment-water interface was successfully recovered using a gravity corer (short core ca. 1 m length). Longer sediment cores were retrieved with a 3 m long UWITEC piston system operating from a floating platform. This study refers to the overlapping twin cores Kou11A and B, and Kou12A and B respectively taken in 2011 and 2012 at the following coordinates: 35.329715° latitude and 24.275945° longitude. The twin cores retrieved in 2011 cover the top 11 m of the lake sedimentation, while the maximum sediment depth reached in 2012 was 16 m below the water-sediment interface (Fig. 1D).

3.2. Dating

The chronology is based on a combination of radiometric markers derived from short-lived radionuclides (^{210}Pb and ^{137}Cs) for the topmost 25 cm of the sediment record, and of 28 AMS ^{14}C ages measured on terrestrial plant macrofossils (leaves, seeds, charcoals and wood; Tab. 1; Fig. 3 and 4) sampled on the master core (see the following text section). For radiocarbon analyses, selected terrestrial macrofossils were isolated from sediment samples (thickness of 1 cm) by wet-sieving through a 100 µm mesh. All radiocarbon ages were calibrated with the Intcal13.14C calibration set (Reimer et al. 2013). Based on these chronological markers, Clam package (R software, R. Core Team 2018) was used to generate an Age Depth Model within a 95% confidence explicate and using a smooth cubic spline model (Blaauw, 2010).

The short-lived radionuclides on the core Kou11-P1 were measured using well-type Ge detectors at the Modane Underground Laboratory (LSM; Reyss et al., 1995; Fig. SM5). The measurement intervals followed sedimentary unit boundaries and resulted in a non-regular sampling of approximately 1 cm. The isotope ^{137}Cs was accidentally introduced into the environment at the end of the 1950s as a by-product of atmospheric nuclear weapons tests (peak at AD 1963) and during the Chernobyl accident in AD 1986 (Appleby et al., 1991). ^{210}Pb excess was calculated as the difference between total ^{210}Pb and ^{226}Ra activities. The chronological for short-lived radionuclides was established with the serac R package (Bruel and Sabatier, 2020).

3.3. Sediment analysis

The cores were horizontally split in two halves, scanned and logged in detail for magnetic susceptibility, spectrophotometry and X-ray fluorescence, and thereafter sub-sampled for discrete analyses: grain size and energy-dispersive spectrometry. Magnetic susceptibility (MS; Fig. 1E, 2 and 3) was measured at 5 mm stratigraphic-resolution with an MS2E1 surface-scanning sensor from Bartington Instruments mounted on a Geotek multi-sensor core logger (Vannière et al., 2004). These analyses, performed on all split-core sections, allowed us to establish stratigraphic correlations between them and construct the master core (Kou11-12MC), guaranteeing complete records without any gaps (Figure 1E).

Grain Size (GS; Fig. 2, 3 and SM1) measurements were undertaken on 312 samples distributed at an average of 5 cm along the whole sequence and using a laser diffraction particle analyzer (LS230 Beckman-Coulter). Before analysis and for all samples, 1 cm^3 of wet sediment was digested in a 30% solution of hydrogen peroxide to remove organic matter. The residual mineral fraction was finally dispersed in a solution of sodium-hexametaphosphate by ultrasonic treatment. A few samples were not analysed for grain-size because they were destroyed during chemical processing.

Spectrophotometric (SP; Fig. 3 and SM2) data have been obtained by the measurement of sediment reflectance at 1 cm stratigraphic intervals with a Minolta CM 2600d. The illuminant was D65, which corresponds to average daylight, and the wavelengths belong to the extended visible domain from 360 to 740 nm. The measurement aperture was set to 8 mm and the step of measurement to one centimetre. By taking the optical lightness L_ (White/Black) vs 700/400 ratio, it is possible to distinguish the different sedimentary end members that constitute the sediment (Mix et al., 1992; Debret et al., 2011). Unfortunately, a few limited parts of the sequence do not have SP data because they were sub-sampled before spectrophotometric measurements were taken, hence the gaps in the Q7/4 and L*(D65) profiles in Figure 3.

X-Ray Fluorescence (XRF; Fig. 2, 3 and SM3) analysis was performed on the split core-sections' surface at a 1 cm stratigraphic interval in two distinct runs using a non-destructive Avaatech core scanner. The relative geochemical contents (intensities), expressed in counts per second, were obtained at two tube settings: 10 kV at 1.5 mA for Al, Si, S, Cl, K, Ca, Ti, Mn and Fe, 30 kV at 1 mA for Br, Sr, Rb, Zr and Pb, and each run lasting 60 s (Richter et al. 2006). Because of the influences of variable water content and grain size on the sediment matrix, the XRF scanner only provides a relative estimation of geochemical variables, and the acquired counts are semi-quantitative (Tjallingii et al., 2007). Therefore, normalization of element counts to the total count numbers was completed to partially correct drifts (Revel et al., 2010). Only elements that offer a significant variability without too much noise are presented in this paper. The sedimentary unit “Pebbles” was not measured for XRF and MS analyses.

Complementary geochemical analyses were performed on a few localized samples after looking for glass shards as a proxy for crypto-tephra deposition (Fig. SM6). So first, a contiguous 5 cm thick sub-sampling was undertaken and then increased to 1 cm resolution when glass shards were observed. To isolate and observe the glass shards, each sample was treated with a 10% solution of acetic acid to remove carbonates, and a 35 % solution of hydrogen peroxide to remove organic matter. Then, the samples were sieved at 40 microns. The particles larger than 40 µm were further separated into two groups using the density separation method (Blockley et al., 2005). Particles with a density lower than 2.5 have been observed with a binocular lens and an optical microscope. Thereafter, energy-dispersive spectrometry (EDS) analyses of glass shards were performed using an EDAX-DX micro-analyser mounted on a Philips SEM 515. The ZAF correction procedure does not include natural or synthetic standards for reference and requires analysis normalisation at a given value (which is chosen at 100 %). Analytical precision is 0.5 % for abundances higher than 15 wt. % 1 % for abundances around 5 wt. %, 5% for abundances of 1 wt. % and less than 20 % for abundances close to the detection limit (around 0.5 wt. %). Interlaboratory standards include ALV981R23 (basalt), CFA47 (trachyte), KE12 (pantellerite, Cioni et al., 1998). Accuracy of measurement is around 1%, a value analogous to that obtained using WDS, as tested by Marianelli and Sbrana (1998). Comparison of EDS and WDS micro-analyses carried out on the same samples showed differences of less than 1 % for abundances greater than 0.5wt. %.

3.4. Biostratigraphic analyses

For the analyses of pollen and non-pollen palynomorphs (NPPs), sub-samples were taken at a mean interval of 100 years on the lowest two-thirds of the core, and from 50 to 10 years on the upper part, producing a total of 140 samples. Samples were prepared according to standard techniques described by Fægri and Iversen (1989) adapted to the protocol used in the Chrono-environnement laboratory, Besançon, France. Half of the samples were analysed at the IPS and OCCCR laboratory, Bern, Switzerland and at the Chrono-environnement laboratory, Besançon, France for the other half. An average of 400 total land pollen (TLP) was achieved. Pollen grains were identified with the aid of keys and photographs (Reille, 1999; Chester and Raine, 2001; Beug, 2004) and reference to each of the two laboratories' modern pollen collections. Identified and counted NPPs here are algal and fungal remains. They were identified using published descriptions and photographs (Jankoska and Komarek, 2000; van Geel, 2001; van Geel and Aptroot, 2006; Cugny et al., 2010), and the counting was achieved following recommendations of Etienne and Jouffroy-Bapicot (2014). NPPs are expressed in accumulation rates (#/cm^2/yr). The pollen, fungal and algal remains diagrams were constructed using Tilia Graph (Grimm 1991-2018). Pollen are expressed as percentages of the Total Land Pollen (TLP), fern spores, aquatic and hygrophilous taxa being excluded from the TLP sum. Zone boundaries were identified using CONISS, based on the square root transformation of the stratigraphically constrained data set, respectively, the TLP-, the total fungal remains- and the total algal remains sums.

For the microscopic charcoal analysis, 177 sub-samples at a mean interval of 55 yrs were prepared following the method described in Doyen et al. (2016); the counting followed Finsinger and Tinner (2005).

Preparation of the 50 samples for diatom analysis followed standard methods adapted from Battarbee et al. (2001), with 300 diatom valves counted on each slide where possible. Full details are reported in Field (2015). Species identification is based on Krammer and Lange-Bertalot (1991a; 1991b; 1997a; 1997b; 2000), hereafter KLB. Zone boundaries were identified using CONISS and transfer function training sets provided by the European Diatom Database (EDDI) (Juggins 2015). The combined salinity training set was used by weighted averaging with inverse deshrinking and carried out using C2 software (Juggins 2003-2006). Detrended Correspondence Analysis (DCA) was used to assess the similarity between the species and the samples using the software PC-ORD.

All samples analysed for the bio-proxies are free of sedimentary event deposits that correspond to rapid accumulation layers like flood deposits and Mass Wasting Deposits (MWD, see section 4.1.1.).

3.5. Pollen diversity

We used a statistical analysis that has been successfully developed and/or tested in different areas to calculate pollen richness and evenness as described in Colombaroli and Tinner (2013). We used rarefaction analysis to estimate the number of pollen taxa that would be encountered if the pollen sum was to be kept constant (Birks and Line, 1992), which is the pollen richness, and we used the probability of interspecific encounter to estimate the palynological evenness. The pollen sum for each sample was standardized on the minimum pollen sum (n=363). We also calculated an evenness-detrended palynological richness to evaluate the effect of palynological evenness on richness (Colombaroli and Tinner, 2013). All analyses were performed with the program R statistics (R Development Core Team 2018).

4. Results

4.1. Sedimentary dynamics

4.1.1. Sedimentary units

Figure 1E shows the Magnetic Susceptibility (MS) records for the two cores Kou11 and Kou12 and highlights the main correlations between them. These correspondences allowed all the core sections to be tied together to construct the master core, which was subsequently used for further analysis. XRF recordings of the core sections confirmed these correlations. For the main part of the record, Lake Kournas' sedimentation is dominated by light brown silty carbonate marl with an important in-situ biochemical component of either carbonate or biogenic silicate precipitates (Fig. 2). Binocular microscope observations of sediments allowed us to identify micrite, algal oncoids and plant encrustations, but also diatom frustules. Standard deviation variability of grain size classes (Fig. SM1, Sabatier et al., 2008) shows four main populations of particles: 0.9-3 µm (clay), 6-20 µm (silt), 40-200 µm (fine sand), 300-650 µm (coarse sand). Spectrophotometric analyses are represented in a Q7/4 diagram: the values of brightness (L_) vs 700/400 ratio (Debret et al., 2011), and are organized close to an end member "clayey deposit" with a more or less significant contribution of organic-rich components for a few parts of the sequence and a meaningful contribution of "altered organic matter" at the bottom of the sequence.

Principal Component Analysis on the XRF measurements (Fig. SM3 and SM4) indicates four end-members of geochemical elements that may be used to discriminate the successive sedimentary units and the variability in sedimentary facies (see below). The detrital elements group is represented by Al, K, Ti, Fe, Rb, Zr and Pb, the carbonate and organic matter group by Ca, Sr and Br, with Br reflecting organic matter content (e.g. Bajard et al., 2016), and the last one, Si, is related to the silicate content. Ca and Si can be both of authigenic and allochthonous origin. Thus, the relative biogenic silica content was assessed using the XRF-derived Si:Ti ratio, Ti representing the allochthonous component (Peinerud et al., 2001). In freshwater marl lakes, the Sr:Ca ratio of $CaCO_3$ precipitates in the water column and is usually controlled by biochemical fractionation and has much lower values than detrital marine carbonate from the watershed substrate that have been inorganically precipitated in other conditions. Sr-rich sediments may also reflect shallow-water sedimentation (Martín-Puertas et al., 2011). Additionally, Zr:Al or Ca:Al can also be used to track the grain-size variations (Wilhelm et al., 2013), where Zr corresponds to the coarse fraction while Rb and Al are respectively more influenced by silt and clay classes. Thus, increases of ratios Zr or Ca vs. Al represents coarser sedimentation.

According to the MS, spectrophotometric, XRF and grain size measurements, six main sedimentary units and facies can be identified through the sequence of Lake Kournas and have been named: Colluvium, Pebbles, Swamp, Lake, Flood and MWD (Fig. 3, SM2 and SM4). The "lake" sedimentary unit has been thereafter subdivided into seven sedimentary sub-units to highlight periods of higher primary productivity vs. periods of higher allochthonous contribution to sedimentation.

Between the depths of 15.99 and 14.73 m (below the sediment-water interface), the "Colluvium" sedimentary unit corresponds to a clayey colluvial sediment characterized by high MS signal, detrital elements, some high values of the Sr:Ca ratio and sparse decomposed organic remains (Fig. 3). There was no lake at this stage. The sedimentation then abruptly switches to an 18 cm thick "Pebble" layer (14.73 to 14.55 m depth) with centimetric carbonate pebbles within a clay matrix. The following sedimentation results in a sandy and dark sedimentary unit (14.55 to 14.40 m depth). Br content indicates organic-rich sedimentation that initiates a major change in the sedimentary dynamic with the presence of almost permanent water and organic matter accumulation. From 14.40 m depth, less detrital (MS and XRF proxies) and much more carbonate deposits reflect lacustrine type sedimentation (Fig. SM4). First stage L0 still corresponds to a shallow lake as indicated by the high Sr values, the altered organic matter content and the coarse carbonate concretions. Phase L1 begins with high MS values and an increase in fine detrital inputs that record the watershed contribution to sedimentation. But it is also accompanied by a gradual increase of the Si:Ti ratio that reflects a rise in lake level and primary productivity (Fig. 3). L2 corresponds to the complete lake stage with the maximum biogenic silica contribution to sedimentation (Fig. 3 and SM4). Phase L3 is well marked by a decrease of the Si:Ti ratio and a grain size distribution toward smaller grains (more silt). By contrast, phase L4 records an increase in grain size with more sand, also represented by an increase in the Zr:Al and Ca:Al ratios, which was not the case during phase L2. With phases L5 and then L6, the sedimentation is less driven by in-lake processes. There is an increased contribution of detrital carbonates as shown by the higher Sr:Ca ratio, which attests to erosion of the surrounding soils, also confirmed by detrital elements, e.g. Ti, Zr (Fig. SM3). The phase L6 is particularly well identified by the higher content in coarse grains, while biogenic silica content estimated from the Si:Ti ratio reaches a minimum, similar to phase L0.

Two sedimentary facies, both coarse-grained, frequently and sharply interrupt the background sedimentation described above (Fig. 2 and 3). These numerous layers result from sedimentary events of two main types. The first type corresponds to grey-brown deposits with thicknesses ranging from 0.3 to 14.5 cm. Seventy-six layers, corresponding to a total of 193.5 cm thickness, have been identified through the core, in sedimentary sub-units L1 to L6, by higher values of magnetic susceptibility and a dominant fine-sand fraction. They are marked by increases in Mn that could have been precipitated in the form of Mn-oxyhydroxide (Wilhelm et al., 2016; Sabatier et al., 2017) and an increase in the detrital elements such as Al, Zr and Rb. XRF and grain-size analyses revealed that these sedimentary events could be graded and/or present multiple layers, as shown on figure 2 between 18 and 28 cm, where two coarse brown deposits are interbedded and covered by greyish silty-clay ones. Although these deposits' elemental composition can vary slightly (Fig. SM4), and even if it is impossible to say that they are all sorted, these events can legitimately be distinguished from the background sediment in the MS XRF data (Fig. 2 and 3). The deposits' pattern combined with the detrital composition and the grading of the event layers may reflect typical river discharge and a flood sediment signature as shown in the literature (Gilli et al., 2013; Vannière et al., 2013; Wilhelm et al., 2016).

In addition, a second type of event layer can be observed as a light grey to beige deposit (Fig. 2). These deposits show a coarser grain size, attested by the presence of the 300-650 µm fraction and a higher Zr:Rb ratio. They are also better sorted with 75% of grains coarser than 40 µm, depleted in detrital component (e.g. low values of MS, Al, Zr and Rb) but enriched in Sr in particular (Fig. 2 and SM4). Binocular observations show numerous carbonate concretions typical of the littoral platforms that belt the lake. Thus, these light grey deposits are of lacustrine origin and may correspond to subaquatic mass-movements and so results from the carbonate platform material reworking and the mixing of lacustrine sediments from the slopes and the shores of the lake (Vannière et al., 2013). Five Mass Wasting Deposits (MWD), ranging between 1.0 and 6.5 cm thickness, of this second type of event layer, have been identified along the entire sequence for a cumulative thickness of 16.6 cm.

4.1.2. Tephra geochemistry

Only one sample from Lake Kournas contained glass shards (sample Kou11 A3-1 71, Depth MC 845 cm), which are of rhyolitic composition (Tab. SM1, Fig. SM6) and belong to the high-K calc-alkaline series (Fig. SM6b). Likely Holocene sources of tephra layers in the study area are from Aegean and Turkish volcanism (Sulpizio et al., 2013). Considering the tephra layer's rhyolitic composition, we can exclude the Gölcük and Kula volcanoes (central-western Turkey) as their alkaline products never reached the rhyolitic field (Elitok et al., 2010). In turn, explosive products from Cappadocian volcanoes are too evolved (SiO_2 in excess of 75 wt%, Druitt et al., 1995; Develle et al., 2009; Hamann et al., 2010; Fig. SM6a). Having excluded most of the Holocene sources of Turkish volcanism, the high-K calc-alkaline affinity of the Kournas tephra indicates an origin from the Aegean arc volcanoes. Among them, the most prominent is Santorini (Thera) volcano, where at least 12 major volcanic eruptions have occurred since mid-Pleistocene times (ca. 300 ka, Druitt et al., 1989, 1999; Wulf et al., 2020). This is confirmed and strengthened by geochemical data, which show a good correspondence using major element data (Tab. SM1, Fig. SM6), also comparable with published distal data (Sulpizio et al., 2013).

4.1.3. Chrono-stratigraphy and sediment accumulation rate

To build the age-depth model, flood deposits and MWD (see 4.1.1. above) were removed from the chrono-stratigraphy because of their instantaneous deposition that contrasts with the long-term background sedimentation.

Thanks to the serac R package (Bruel and Sabatier, 2020) we applied the CFCS (Constant Flux Constant Sedimentation) model to the $^{210}Pb_{ex}$ activities, which estimate a mean sedimentation accumulation rate of 1.621 +/- 0.102 mm/yr (r^2= 0.9439, Fig. SM5). ^{137}Cs activity in the upper 25 cm of the core shows a well-defined peak at 70-75 mm depth (Fig. SM5), which is interpreted as the 1963 maximum atmospheric nuclear weapons tests in the Northern Hemisphere (Appleby, 2001). The results from radiocarbon and short-lived radionuclides analyses were combined to produce an age-depth model showing that the upper 14.5 m (Fig. 3), 12.4 m after the flood deposits and MWD were removed, records the last 9600 years (Tab. 1, Fig. 4).

Because of reversed ages, the age-depth model excludes five radiocarbon measurements. The inverse chrono-stratigraphic distribution of these five radiocarbon dates argue for measurement done on reworked older organic material during a period of very fast sedimentation of about 9 mm per year due to erosion of the lake platform and/or of the soils in the watershed (Fig. 3 and 4). Except for this particular period of rapid accumulation between 2700 and 2300 cal BP, the mean sedimentation accumulation rate for the bottom part of the record is on average 0.8 mm per year and 0.6 mm per year for the upper part.

The radiocarbon age measured from the wood sampled 1 cm above the tephra layer is 3460 ± 90 cal BP. This agrees with the Minoan eruption of the Santorini (Thera) volcano, which is dated around 3500 ±50 cal BP (Driessen, 2019).

The estimated ages of the main sedimentary units are: the Colluvium unit is older than 9600 cal BP, the Swamp unit sedimented between 9600 and 9540 cal BP, the first lake phase L0 spans between 9450 and 8500 cal BP, L1 lasts about 2000 years between 8500 and 6500 cal BP, L2 is the longest phase between 6500 and 2700 cal BP, the high sedimentation accumulation rate phase L3 occurred between 2700 and 2300 cal BP, L4 and L5 end respectively around 2000 and 1700 cal BP, L6 goes up to the present day.

4.1.4. Sedimentary event chrono-stratigraphy

The analysis of the event layers frequency indicates three periods marked by more than one flood deposit per century: between 8100 and 7700 cal BP, 5700 and 5300 cal BP, 4600 and 2000 cal BP (Fig. 5). All periods of increased flood-deposit frequency are also well marked at their start by significantly thicker deposits (more than 7 cm thick, seven deposits in total) that might indicate the erosion of a larger quantity of material in the watershed and/ or more intense event (Giguet-Covex et al., 2012; Wilhelm et al., 2013). Sedimentary event deposits are thicker than the mean (more than 2 cm thick 28 deposits in total) between 8400 and 8150 cal BP, 6600 and 5700 cal BP, 3900 and 450 cal BP. No flood deposits have been recorded between 9600 and 8500 cal BP, 7300 and 6600 cal BP, 450 cal BP and the present-day.

MWD-type deposits are much less frequent than flood ones; only five are recorded and during a relatively short period between 3900 and 1300 cal BP (3860±85, 3435±60, 2390±140, 1980±105, 1280±140; Fig. 5). The thickest MWD deposit (6.5 cm) is associated with the tephra record, the glass shards having been detected within the layer that caps the MWD.

4.2. Biostratigraphy

4.2.1. Pollen

Four main local pollen zones (PZ, Fig. 6 for selected taxa and SM7a-7b for the complete pollen diagram) were identified by means of stratigraphically constrained cluster analysis. During PZ1 (~ 9600-8500 cal BP), the arboreal pollen (AP) curve, which was around 35% in the oldest sample, rapidly increases up to 70-80%. *Q.* deciduous-type pollen increases throughout the period and dominates the assemblages. Mediterranean taxa, such as *Quercus ilex*/*Q. coccifera* and *Pistacia* are already present. The *Vitis* percentages are important, around 10% of the TLP. Herbaceous taxa that represent 60% in the first samples stabilize around 30% from 9500 cal BP onward. Poaceae do not exceed 10% of the TLP, and the herb diversity is already significant. *Cerealia*-type pollen are present from the first sample, with grains as big as 45 µm. We notice occurrences or continuous presence of weeds and ruderals such as *Centaurea cyanus*-type, *Plantago lanceolata*-type, *Rumex acetosa*-type, *Mercurialis* or *Urtica*.

An abrupt and significant reversal characterises the transition between PZ1 and PZ2 (~ 8500-5900 cal BP) in the *Quercus* proportions: *Q.* deciduous-type fall from 60% to 15 % of the TLP while *Quercus ilex*/*Q. coccifera* rises from less than 10% to 50%. Some new taxa appear during the subzone 2a (~8500-7000 cal BP), namely *Fraxinus ornus* and the sclerophyllous taxa related to maquis species such *Erica* and *Phillyrea*, together with *Olea*. During subzone 2b, *Phillyrea* and then *Q. ilex*/*Q. coccifera* decrease. Herbaceous taxa assemblages do not significantly change except the aquatics with a *Myriophyllum* curve in the first half of subzone 2a (~88500 - 7500 cal BP). Between 7500 - 6700 cal BP the temporary disappearance of some herb's taxa, such as *Senecio* sp. *Lotus*-type, *Ranunculus* or *Rhinanthus*/*Veronica* is noticeable.

The PZ3 (5900-2400 cal BP) is characterised by an important increase of *Olea* pollen, which changes from 3% to 22% after 6000 cal BP, while *Q. ilex*/*Q. coccifera* decreases accordingly. A rise of *Rosa*- and *Rubus*-type occur during subzone 3b, substituted by *Sarcopoterium spinosum*-type and *Phlomis*-type in subzones 3c and 3d. An important peak in *Q.* deciduous-type is localised around 3700-3500 years BP at the beginning of zone 3c. During subzone 3c, *Ulmus*/*Zelkova* pollen became more abundant. Finally, the percentages of *Olea* are lower in subzone 3d. The main change in herbaceous taxa assemblages is the sustained decrease of *Galeopsis*-type, Brassicaceae, Ranunculaceae and *Rhinanthus*/*Veronica* at the end of subzone 3b.

PZ4 (2400 cal BP to the present day) begins with a new huge and rapid increase in the proportion of *Olea*, which oscillates between 20% and 35% of the TLP during the entire subzone 4a (2400 - 1400 cal BP). Its decrease during subzone 4b runs alongside a higher amount of *Q. ilex*/*Q. coccifera* pollen that decreases again after 1000 cal BP. Subzone 4c is characterised by a slight presence of both evergreen and deciduous *Quercus* pollen and the increasing presence of introduced and/or potentially cultivated trees and shrubs, such as *Juglans*, *Castanea*, *Vitis* or *Styrax,* for example. An increase of *Q. ilex*/*Q. coccifera*, *Olea*, and to a lesser extent Cupressaceae is observed in the most recent samples. A change in herbaceous taxa assemblages is mostly visible in the subzone 4c with an increase of Poaceae, *Plantago lanceolata*-type, *Rumex acetosa*-type, *Artemisia* and the Cichorioideae, together with an increase in *Myriophyllum*, *Alisma* and the regular occurrences of *Juncus*.

4.2.2. Pollen biodiversity

Globally, both richness and evenness trends agree and have the same trend, illustrated by evenness-detrended palynological richness (DE-PRI) that mirror richness (Fig. SM8). The global trend of Pollen Richness (PRI) and DE-PRI are in good accordance all through the sequence with one exception, the first part of the sequence between 9600 and ~ 8500 cal BP. This discrepancy indicates that pollen richness is affected by unevenness, as caused by a few dominant taxa, here *Q.* deciduous-type (peaking at 8500 cal BP with PIE < 0.6). Thereafter, we can then assume that species richness estimates (PRI) are rather unaffected by evenness biases, and PRI can be used as a proxy for plant biodiversity change (Colombaroli and Tinner, 2013, Fig. 7). From 8750 cal BP onward, both PRI and DE-PRI increase, reaching a first maximum around 8000 cal BP. Between 8000 and 7000 cal BP PRI declined; subsequently, it rises again and stabilizes at a high level for ca. three millennia between ~ 6000 and 3000 cal BP, which corresponds roughly to pollen zones PZ3a to PZ3c. Between 3000 and 2500 cal BP, the pollen richness index decreases continuously (PZ3c). A lower level of pollen richness is recorded from ~ 2300 to 1250 cal BP during PZ4a. After a new continuous rise of the PRI between 1250 and 500 cal BP, the last 500 years are characterised by a high level of pollen richness despite a slight decline. The last 60 years (PZ4d) initiates a decreasing trend anew.

4.2.3. Fungal remains

The identified fungal remains are all saprophytic and coprophilous taxa, except Glomus (HdV-207), an arbuscular mycorrhizal fungus found in association with the roots of various plants, which is often used as erosion indicator (Kolaczeck et al., 2013). Their assemblages have been statistically divided into three major fungal remains zones (FZ, Fig. SM9). During the first zone FZ1 (9600 – 8500 cal BP) a very low quantity and diversity of identified fungal remains appear. However, the main coprophilous fungal spores, namely, *Sporormiella*, *Sordaria* and *Podospora (Baker et al., 2013)* are present in the older samples. The transition between FZ1 and FZ2 (8500 - 3500 cal BP) displays an increase in both quantity and diversity of fungal remains. *Sporormiella* is now already present, and *Sordaria* and Xylariaceae/Coniochaetaceae spores are regular. Only the short-lasting subzone 2b, between 3700 and 3500 cal BP, is free of remains. FZ3 (3500 to present day) is characterised by an overall increase of all the taxa previously registered. The phenomenon reaches a maximum between 2500 and 1950 cal BP (subzone 3b), together with the appearance of new taxa such as *Pleospora* and *Triposporium elegans*. After 1500 cal BP, all taxa sharply decrease during zone 3c and even more during subzone 3d. Only *Sporormiella* is observed throughout the most recent samples.

4.2.4. Algae remains

Aquatic remains were regularly present on pollen slides, even abundant in some samples. Despite the fact that a recent study demonstrates that algal remains on pollen slides are not a direct reflection of biomass (Stivrins et al., 2018), in the Kournas sequence, four main algal remains zones (AZ) were determined (Fig. SM9). During the earliest phase, AZ1a (9600 - 8400 cal BP), the green algae *Botryococcus* sp. and *Tetraedron minimum* are regularly present but in low quantity. Then, *Botryococcus* increases sharply after 8800 cal BP, just followed by a peak of *Pediastrum boryanum* sp. some Volvocaceae and *Spirogyra* sp. During the subzone AZ1b (8400 - 7500 cal BP) all the previous taxa decrease significantly but continue to be present until 8000 cal BP for *Pediastrum* and 7500 cal BP for *Tetraedron*. Low amounts of algal remains characterise the second zone, AZ2 (7500 – 3000 cal BP). From ca. 7500 to 5400 cal BP, algal remains are almost absent, and after 5400 cal BP, only the presence of *Botryococcus* is registered, together with a peak of *Scenedesmus*-type around 3200 cal BP. A growing amount and diversity of algal remains characterise zone AZ3 (3000 - 1900 cal BP). Dinocysts, probably *Peridinium*-type (McCarthy et al., 2018), *Anabaena* sp. and Volvocaceae are the main taxa, together with the previously present *Botryococcus*. At the onset of the last zone, AZ4, during subzone 4a (1700-1200 cal BP), Dinocysts sharply decrease following an increase in Volvocaceae influxes. Then, all algal remains decrease in subzone 4b, and only some Botryococcus remain in the upper part of the core.

4.2.5. Microscopic charcoal

Four main zones can be visually distinguished in the microscopic charcoal record from the Kournas sequence (Fig. SM10). The first one, CZ1, lasting between 9600 and 7000 cal BP, shows high charcoal influx values briefly interrupted by a few short periods with a lower signal. The highest peaks attest to numerous fire events and/or quantity of biomass burned in the lake surroundings. During the second zone, CZ2, spanning between 7000 and 6100 cal BP, the sedimentary charcoal content is very low, which means that few fires occurred during nine centuries in the area except a single slight charcoal increase at ~ 6600 cal BP that may show increased regional fire occurrences. The longest zone CZ3, between 6100 and 1900 cal BP, corresponds to five successive and pluri-centennial episodes of microscopic charcoal inputs into the lake, separated from each other by a few centuries of very low charcoal signals. Then, with the fourth zone CZ4, from 1900 cal BP until the present day, the charcoal signal decreases to reach the lowest values of the sequence and near to zero, apart from a short phase of very slight increase between ~1100 and 700 cal BP. This fourth zone attests to a near-absence of fire in the region of Lake Kournas.

4.2.6. Diatoms

Diatom preservation was generally good, although in 9 out of the 30 samples, counts were reduced to 100 valves. A total of 36 diatom taxa were identified, and the stratigraphic diagram (Fig. SM11) shows those taxa present at >2% relative abundance. The diatoms are dominated by two centric genera, which are planktonic or facultative planktonic in life form, with benthic/periphytic taxa relatively uncommon. Together this suggests that relatively deep-water conditions prevailed through most of the lake record. Our results can be compared against those of John and Economou-Amilli (1990, 1991) using diatom plankton living in the lake today. They were dominated by two species of *Cyclotella*, one of which, *C. cretica*, was identified as a new endemic species, and which is likely to equate to *C. ocellata* in our analyses (SEM analysis would be required to differentiate them). *C. cretica* and *C. ocellata* appear to have similar ecological requirements, and taxonomic differentiation between them is therefore unlikely to substantially alter our palaeolimnological reconstruction, including the former lake salinity.

Four major downcore assemblage zones can be recognised (DZ). Zone DZ1 (9600 to ~ 8500 cal BP) is characterised by *Cyclotella ocellata/cretica*, *Cyclotella meneghiniana* and *Cyclotella distinguenda* along with the araphid diatom *Fragilaria brevistriata*. Freshwater taxa account for around 59% of total diatoms in this zone. In DZ2 (~ 8500 to 7700 cal BP), *Actinocyclus normanii* abruptly increases, reaching a relative abundance of ~30%, and *S. tabulata* (araphid planktonic) also increases to a maximum of ~41%. *A. normanii* is an indicator of a saline and/or marine environment, and diatom-inferred electrical conductivity (DI-EC) increases markedly in this zone to >8000 $\mu S/cm^{-1}$. DZ3 (~ 7700 to 1500-1100 cal BP) is the longest of the zones, *C. ocellata/cretica* and *C. distinguenda* dominate, and DI-EC decreases to <1000 µS/cm, the period of lowest salinity in the entire Holocene record. DZ4 (~ 1500-1100 cal BP to present day) covers the last millennium and is associated with an increase in *C. meneghiniana*, which drives the DI-EC above 1000 µS/cm except in the uppermost sample.

5. Discussion

5.1. Kournas' landscape history

Some 10 000 years ago, the Kournas site was like a doline, at least seasonally dry. Around 9600 cal BP, after a mass movement of pebbles, the place became first a swamp. Quickly, probably from 9450 cal BP, the continuous sedimentation of carbonate marl, the dominance of planktonic diatoms, and taxa preferring low salinities indicate that Lake Kournas became a freshwater body progressively moving from a shallow to a relatively deep basin during the last ~8500 years.

5.1.1. An Early Neolithic occupation of the oak forest (9600-8500 cal BP)?

Before 8500 cal BP, a mixed forest of deciduous and evergreen oaks, with a majority of deciduous oak, covered the shallow lake's surroundings (Fig. 7). A few fire episodes occurred, but the woodland cover was apparently resilient and maintained stability for a millennium. The first millennium of the Kournas record corresponds to the transition from the Mesolithic to Crete's Neolithic. Very little is known about the neolithization of western Crete; the only clues about the Early Neolithic derive from the earliest occupation of Knossos located in the north-central part of the island. Research on this site has revealed a well-preserved stratigraphy of a pre-Minoan occupation (Efstratiou et al., 2013) with an initial phase dated between 9000 and 8550 cal BP (~7050-6550 BCE, Facorellis and Maniatis, 2013; Douka et al., 2017). This Pre-Pottery Neolithic

(PPN) phase most likely resulted from visits by Neolithic people from Anatolia, with a "package" of wild and cultivated plants and feral and domesticated animals (Efstratiou, 2013; Horwitz, 2013; Nowicki, 2014).

The Kournas record may document further or contribute to the debate about the early dating of the Neolithic onset in Crete. Indeed, the oldest samples containing pollen (~9600 cal BP) shows large pollen grains (grains with a size up to 50 µm and pores up to 10 µm) that fit with *Triticum*-type (Beug, 2004). *Triticum*-type pollen also includes some wild Poaceae species and therefore the local presence of wild Poaceae producing large pollen grains cannot be excluded. However, *Triticum*-type pollen's occurrence does not significantly change over the whole sequence, which would mean that the introduction of crop cultivation is not visible in the Kournas pollen sequence (Fig. 6 and SM7b). Weeds and ruderals taxa such as *Plantago lanceolata*-type, *Urtica* and *Rumex acetosa*-type are already present in the palynofacies between 9600 and 8500 cal. BP. In addition, the influx of dung fungal spores of *Sporormiella*, *Sordaria* and/or *Podospora* (Baker et al., 2013) in the three oldest samples are similar to those of the upper samples (Fig. 7 and SM9) where there is currently extensive sheep and goat grazing in the western part of the watershed. Of course, the earliest fungal spore signal might represent the presence of wild animals in the area. For example, the now-extinct genus of deer (*Candiacervus*) found in cave sites on Crete and almost certainly the subject of cave art representations in Asphendou Cave (Strasser et al., 2018). In addition, remains of other deer species are common in faunal assemblages that post-date this period (Moody et al., 2008). Pollen and fungal indicators are not sufficient on their own to attest to the presence of agro-pastoral activities as early as 9600 cal BP (~7650 BCE), namely five centuries before the oldest settlement at Knossos. However, considering that the Kournas basin at that time might have been an attractive zone for humans and animals because freshwater was one of the main concerns of the first settlers (Nowicki, 2014), and knowing from archaeology that the first waves of farmers spread to Cyprus at least one millennium before (10,600 years ago, Vigne et al., 2012), the hypothesis of a human presence around Kournas in the mid-eighth millennium BCE is worth considering.

5.1.2. Sclerophyllous woodland and Neolithic slash and burn (8500-6100 cal BP)

The lake sedimentary dynamics (phase L1, Fig. 3, SM2 and SM4) and all bio-indicators of the lacustrine setting show a major change around 8500 years ago, with the establishment of a true deepwater body (Fig. 7). The increase of algal remains together with the major change in diatom assemblages attest to this evolution, with the diatoms indicating a brief period when the lake was saline before becoming freshwater and deep (Fig. 3 and 7). At this time, there were also rapid and long-lasting changes in the surrounding vegetation, with a noticeable expansion of evergreen oak in the forest at the expense of deciduous oak. This vegetation shift took place during a period marked by fewer fire episodes.

For a period of two millennia from 8500 BP, a relatively stable vegetation cover prevailed. Mediterranean forest and maquis dominated the surrounding landscape of the lake with a few short periods of maquis species increase, especially *Erica* and *Phillyrea* (Fig. 6), while a few high amplitude charcoal peaks attest to fire episodes in the vicinity of the lake, notably around 8100, 7900, 7500 and 7150 cal BP. Consequently, the evergreen oak curve is irregular and the localised decreases are concomitant with a slight increase of pollen richness, especially between 8000 and 7000 cal BP (Fig. 7), i.e. when fire disturbed the ecosystem, likely promoting biodiversity (Lestienne et al., 2020).

The flood record starts from 8400 cal BP with a first thick flood deposit, and the frequency of events then increases above one event per century between 8300 and 7800 cal BP. They might have been driven by increases in soil erodibility associated with land-cover changes due to the advent of grazing pressure (e.g. Giguet-Covex et al., 2011; Vannière et al., 2013; Bajard et al., 2020) and/or climate oscillations around the 8.2 cal BP event (see part 5.2.5; Pross et al., 2009; Daley et al., 2011; Kouli et al., 2012; Dean et al. 2015). Indeed, the first thick flood layer of the record just follows the onset of the dung fungal spore reappearance and their long-lasting presence in the record. This period corresponds to a major cultural change in Crete, namely the onset of the Pottery Neolithic (Nowicki, 2014) with an Early Neolithic open-air settlement attested at Knossos around 8500 cal BP (~6550 BCE) (Efstratiou, 2013b). While we have little direct evidence for Neolithic activity around the Kournas catchment, the presence of well-known cave sites in this region, such as Gerani Cave, certainly suggest that Neolithic peoples were present. Tomkins (2008) argues for an expansion in settlement during the pre-Final and Final Neolithic. The higher areas beyond the immediate catchment of lake Kournas may well have seen activity during these periods. Around Lake Kournas, the best clue to agro-pastoral activities is the synchronous increase of the ruderal taxa and crop pollen along with the dung fungal spores. Thus, the fire episodes might reflect a controlled use of fire for land management by the Early Neolithic population (Vannière et al., 2016; Marriner et al., 2019). Therefore, the flood episodes might represent the first human impact on soil erosion, but they also happened during a period of climate change (Mayewski et al., 2004) (see part 5.2.5.).

Olea pollen, which was very scarce until then, is regularly identified after 7500 cal BP (~5550 BCE) (Fig. SM7a). The question about *Olea* as an endemic species in Crete or as an imported species by mean of overseas contact is still in debate (Bottema and Sarpaki, 2003; Langgut et al., 2019). Here, the absence or the late-Holocene appearance of olive wood or charcoal in archaeological contexts contrasts with the Cypriot and the Levantine data (Carrion et al., 2010; Badal and Ntinou, 2013). According to pollen records (Langgut et al., 2019) and genetic data (Besnar et al., 2017), Northern Greece is considered as part of the oleaster refugia area during the Last Glaciation; for southern Greece, the situation is less clear. At Kournas, wild olive trees developing in the sclerophyllous vegetation between 7500 and 6600 cal BP might be a plausible interpretation of the pollen record, be they the result of a natural process or an introduction by early settlers.

The end of this period, i.e. between 6600 and 6100 cal BP (Fig. 7), displays a decreasing woody land cover driven by the gradual fall of evergreen oak pollen, with an increase in pollen richness. A few flood deposits reappear, which might be related to regional climate change marked by wetter winters (Rohling et al., 2019) but may also be the consequence of changes in the vegetation cover and soil erodability (see part 5.2.5.) that also would have led the lake condition evolving towards greater productivity (Si:Ti increases, Fig. 3 and SM4).

5.1.3. The first phase of olive exploitation, Final Neolithic to Minoan (6100-2800 cal BP)

From 6100 cal BP (~4150 BCE), the key environmental changes in the surroundings of Lake Kournas correlate with a gradual decrease of the Mediterranean woodland and maquis formations, which were replaced by crops and pastures (Fig. 6 and 7). The amplitude of charcoal peaks is quite similar throughout this period and may correspond to the same type of regular fire regime driven by the same forces. A long-lasting increase of *Olea* pollen occurred around 6100 cal BP and may reflect the beginning of olive cultivation during the Final Neolithic. Indeed, *Olea* was almost absent in the oldest periods, and here, its rapid rise does not correspond to any increase of other forest or maquis species such as previously observed (see part 5.1.2). The olive pollen dynamic is comparable at Delphinos, a few kilometres away (Bottema and Sarpaki 2003), Tersana on the Chania peninsula (Moody et al. 1996) and two other recent pollen records from the central and eastern part of Crete which point to olive groves on the island from the Final Neolithic to the Early Minoan at Palaikastro (Cañellas-Bolta et al., 2018), and during the Early Minoan near the palatial site of Phaistos (Ghilardi et al., 2018). Furthermore, archaeobotanical evidence supports the establishment of Final Neolithic olive groves. The earliest evidence of olive oil in Crete takes the form of pottery residues from the Final Neolithic at the Gerani Cave site, which is located approximately 20 km east of Lake Kournas (Margaritis, 2013). At Lake Kournas, the establishment of olive cultivation was part of the landscape's environmental and cultural evolution during the transition from the fifth to the fourth millennium; changes that were accompanied by increasing fire and biodiversity (Fig. 7). Fire may have been used as a tool to clear vegetation, and biodiversity may have increased as a consequence of human-related disturbances or introduced plants. Simultaneously, flood frequency increased with the first few thick deposits, reaching more than one event per century between 5700 and 5400 cal BP. Thereafter, during the fourth and third millennia, the flood regime oscillated, slightly below the centennial regime value, and the deposits remain in the majority thin, perhaps because of the relative stability of soils.

In Crete, 5000 years ago, the onset of the Bronze Age corresponded to the rise of the Minoan culture, one of the most famous ancient civilisations in the Mediterranean. However, the Minoan period onset does not display any major change at Kournas. During the Early Minoan (from ~5000 cal BP), relatively stable land use was registered. Pollen and spore records indicate olive cultivation, crops and livestock breeding, but no fire during the first 500 years. Then, during the subsequent half millennium, sharp charcoal peaks clearly attest to fire events near the lake. The main features of the woodland (Mediterranean forest and maquis) and herbaceous formations remained stable. The socioeconomic importance of olive trees in Minoan Crete is documented by archaeological finds (e.g. Hamilakis, 1996; Riley, 2002), and is attested in Linear B tablets (Killen, 2016), and olive probably continued to be cultivated near the Lake Kournas. Nevertheless, any temporary abandonment of olive cultivation would not result in *Olea* pollen's disappearance, as olive trees form part of the Mediterranean vegetation assemblage. The large and quite obvious variations in sedimentary charcoal content reflect an irregular use of fire and possible land-use changes over the period. However, there is no evidence of change in sedimentary dynamics over this long period.

An increase of woodland characterised the Middle Minoan Period (from ~4000 cal BP), first dominated by evergreen oak and followed by a rise of deciduous oak formations. *Olea* pollen percentages also increased while *Cerealia*-type pollen, dung fungal spores and charcoals remained low (Fig. 7). These may indicate a lower local agro-pastoral activity, possibly except for olive cultivation. Nevertheless, a natural dynamic of olive trees as part of Mediterranean woodland is plausible as well. At the same time, flood frequency increased above one event per century between 4000 and 3600 cal BP (2050-1650 BCE). The last and third part of the Bronze Age, corresponding to the Late Minoan (from ~3700 cal BP to ~3100 cal BP), is deemed to have been affected by a succession of disturbances, leading to the end of the Minoan culture in Crete. They include, firstly, natural hazards such as earthquakes or volcanic activity, the most famous being the Thera/Santorini eruption some 3500 years ago, i.e. in the mid-16th century BCE (Driessen, 2019), secondly, socio-economic instability marked by internal crisis, sea raids and palace destructions (Knapp and Manning, 2016). In the Lake Kournas record, this period is characterised by a MWD in the lake basin and the Santorini Tephra, and an increase in charcoal accumulation. Simultaneously, a decrease of olive pollen grains favouring other crops and pastoral indicators (*Triticum*-type, *Rumex*, *Urtica*, Fig. SM7b or spores of coprophilous fungi, Fig. SM9) indicates a change in land use, favouring biodiversity increase. Woodland decreased, while no flood layers are registered.

All indicators suggest an abandonment of agro-pastoral activities between 3100 and 2800 cal BP (1150-850 BCE), i.e. during the first Iron Age (Fig. 7). The area of oak woodlands increased, *Olea* declined to its lowest levels since 6000 cal BP, while grazing (dung fungal spores) and fires (charcoal) decreased. Such a discontinuity in human activities after the Minoan Civilization's demise was also documented by palaeoenvironmental studies near Phaistos (Ghilardi et al., 2018).

5.1.4. The Greek, Hellenistic, Roman and Early Byzantine periods (2800-1150 cal BP)

With the Archaic Greek period, a major shift was initiated in all components of the anthropo-system and in the lake dynamics, which had been set up during the previous millennia.

Firstly, there was a major increase in the sediment accumulation rate (Fig. 3, 4 and 7, sedimentary unit L3), which increased fifteenfold, leading to a rapid accumulation of mainly silt-sized material in the lake basin: about 3 meters in no more than 500 years. This phase occurred between 2800 and 2400-2300 cal BP (850 to 450-350 BCE) and corresponded to the Archaic/Classical Greek cultural periods. Part-way through this phase, algal productivity increased in quantity and diversity. The dominant taxa, *Botryococcus,* Dinocysts of *Peridinium*-type and Volvocaceae suggest lake eutrophication (Jankoska and Komarek, 2000; McCarthy and Krueger, 2013) promoted by an increase in nutrient input into the lake. At the same time, sedimentation was interrupted by numerous flood deposits that reflect an increase in the event frequency up to 5-6 floods per century, i.e. more than once every 20 years. The fire signal remains low, and only a few variations are recorded in pollen assemblages dominated by the sclerophyllous woody taxa and with low olive representation. Pollen biodiversity is down slightly. In contrast, dung fungal spores steadily increase, in quantity (Fig. 7) and diversity (Fig. SM9), probably indicating a new phase of pastoralism in the watershed. The reversal of radiocarbon ages and the sharp increase in the sedimentation accumulation rate clearly indicate that, during this period, sedimentation was strongly augmented by reworked material and that the bio-proxies may have been contaminated. Our interpretations must therefore be viewed with caution, and assumptions about environmental dynamics may not be possible for this time period (see further discussion below, 5.2.4). However, it should be noted that the low charcoal signal is in any case evidence of a decrease in fires and that the increase in algal spores and dung fungal spores cannot be inherited from older sediments that were poorer in such indicators.

Secondly, i.e. from 2400-2300 cal BP (450-350 BCE) to about 2000 cal BP (~50 BCE) during the Hellenistic period, sediment accumulation rate and flood frequency gradually decreased (Fig. 3 and 7, sedimentary unit L4). At the same time, a sharp increase of *Olea* pollen, with percentages reaching 30% of the TLP, indicate that olives groves around the lake are very likely. A concomitant charcoal increase indicates the use of fire in this new phase of land clearing for olive cultivation at the expense of the deciduous oak stands that were connected to a biodiversity minimum. The influx of dung fungal spores reached a maximum, probably related to significant grazing pressure in the watershed of the lake.

Thirdly, after ~2000 cal BP, this new landscape was characterised by a patchwork of Mediterranean woodland (e.g. evergreen oak), maquis (e.g. *Erica* sp.) and phrygana (e.g. *Sarcopoterium*-type) with reduced biodiversity (Fig. 6 and 7). The presence of olive groves also remained stable for almost one millennium (until ~1300 cal BP), i.e. all the Roman and early Byzantine periods (from 50 BCE to ~650 CE). In Crete, some ancient historians refer to amphorae as a proxy for olive oil export (as noted by Gallimore, 2017). There is little doubt from Kournas that olive production was highly significant and may well have been exported. At this time, annual crop indicators remain low, but grazing indicators are still present, possibly connected to increased pastoral activities and/or animal manure being brought onto the olive groves. Only a few thick flood deposits and MWD occasionally interrupt background sedimentation that, however, slightly change to a more detrital and allochthonous source (Fig. 3 and 7, sedimentary units L5 and L6). Almost no fires are recorded, which attests to a change in agro-pastoral practices.

For the first time, local archaeological data are available. An important settlement developed about 6 km southeast from Lake Kournas during the Hellenistic period: the city of Lappa. Numerous amphorae stamps from the wider Mediterranean attest to Lappa's position in this Hellenistic exchange network. Lappa also flourished during the Roman period as an important node in the Roman economy, linked to both its productive hinterland and the wider Roman world (Bowsky and Gavrilaki, 2010, p. 199). Two Cretan cities, one of which was Lappa, continued to mint coins into the third-century C.E. Therefore, the city must have remained a significant economic actor up until at least this moment in time (Gallimore, 2011, p. 79). Moving into the First Byzantine Period, there is no clear archaeological evidence for settlement close to the lake. After 650 CE, a gradual and long-lasting decrease of *Olea* and a concomitant decrease of evergreen oak began together with an increase in biodiversity (Fig. 7). This coincides with the Arab conquest of Byzantine territories in regions such as the Levant and North Africa, and the first Arab siege of Constantinople (674-678 CE), which disrupted maritime trade in products such as olive oil.

5.1.5. From the Saracen conquest to Modern times (1150 cal BP to the present)

The onset of the last phase in the environmental history of Lake Kournas fits with a moderate-amplitude and short-lived period of fire increase, which is also the last one of the record, attesting to the disappearance of fire use by people in the area (Fig. 7). This step lasted from 1150 to 750 cal BP (800 to 1250 CE) and is contemporary with the Arab/Saracen occupation of Crete (824-961 CE) and the 2nd Byzantine Empire (961-1204 CE). The Mediterranean forest decreased continuously from 1000 to 600 cal BP (950-1350 CE), and the temperate woody species that had been present since the early Holocene almost disappear (e.g. deciduous *Quercus*, *Ulmus*/*Zelkova* pollen, Fig. 6). A coeval and long-term decrease of evergreen oak was also observed in the White Mountains, some kilometres south of Lake Kournas (Jouffroy-Bapicot et al., 2016). While maquis prevailed in the White Mountains, the openness of the landscape near the coast benefitted the herbaceous cover, leading to a biodiversity index increase. In terms of sedimentation, unit L6 (Fig. 3 and 7) is characterised by few event deposits but more allochthonous background sedimentation that reflects long-lasting soil erosion in the watershed.

From Venetian rule, which lasted from 1204 to 1669 CE, historical data document that the Venetian administration favoured grapes and other crops in Crete at the expense of olive cultivation (Stallsmith, 2007). At Lake Kournas, the continued decline of *Olea* pollen is in good agreement with historical data. Forests continued to decline as well, while human activity indicators like *Triticum*-type pollen and dung fungal spore percentages did not increase in quantity (Fig. 6 and 7). Regarding vine, it is very hard to identify viticulture phases with pollen analysis because wild vines have been an important part of the Lake Kournas littoral vegetation, and *Vitis* pollen is abundant throughout the sequence (Fig. 1, 6 and SM7a), especially as wild varieties may deliver more pollen than cultivated ones. To complete this discussion about Venetian land use in this area, a description of the lake by Christoforo Buondelmonti in the first part of the 15th century (Buondelmonte, 1981) was rather negative: “a deep and dark little lake that frightened men”. Thus, near Lake Kournas, the major depletion of woody cover may then be related to wood exploitation for timber and/or shipbuilding (Rackham and Moody, 1996; Nixon et al., 2009), as recently hypothesised for the coeval decrease of evergreen oak in the White Mountains (Jouffroy-Bapicot et al., 2016). It is coeval with an increase of herbaceous taxa, such as Poaceae and Cichorioideae; this fenestrate pollen-type (of the Asteraceae family and also named Cichorieae) is a good indicator of open habitats, related or not to pastoralism (Florenzano et al. 2015).

After a period of instability and war, the Ottoman conquest of Crete was completed in 1669 CE. At Kournas, from the 17th century CE onward, olive cultivation increased again locally. Historical sources show that in Crete, olive production, mainly destined for soap factories, became an economic activity favoured by the Turkish administration (Stallsmith, 2007). From the late 19th century onwards, the *Olea* percentages in the upper part of the sequence reach values comparable to those from the Hellenistic and Roman periods, olive groves being dominant in the present-day local landscape (Fig. 1).

5.2. From woodland to agro-ecosystems

5.2.1. The Holocene Mediterranean woodlands

The Lake Kournas sequence recorded almost ten millennia of local and regional vegetation dynamics and thus offers an opportunity to address the issue of natural vegetation in this part of Crete. First, throughout the Holocene woodlands represent a meaningful part of the land cover around the lake, while nowadays forests are scarce as in typical Aegean landscapes (Fig. 6 and 7). In these woodlands, deciduous and evergreen oaks, with a general dominance of the latter, were key species from the onset of the record.

During the Early Holocene, between ca. 9600 and 8500 cal BP, deciduous oak-dominated. Given that this period was very continental, it could well be that deciduous trees were advantaged by frequent winter frost, if compared to very frost-sensitive evergreen oaks. Nowadays in Crete, deciduous oaks, namely *Q. pubescens* and Q. *ithaburensis* subsp. *macrolepis* are scattered and located in inhabited places (Rackham and Moody, 1996; Fielding and Turland, 2008). Although we cannot assess the species, our analyses show that deciduous oak was an important part of the woodland during the early Holocene, and even after the sharp decrease at around 8500 cal BP, it remained important until the last century.

For ca. 8500 years, evergreen oak pollen dominated, although, unfortunately, pollen morphology does not allow the identification of the species. Nowadays, in Crete, two evergreen oaks cohabit: holm oak (*Q. ilex*) and kermes oak (*Q. coccifera*). Kermes oak is common in various habitats (Goedecke et al., 2018) and has high resilience capacity. It is particularly well adapted to drought, fire and grazing (Rackham and Moody, 1996) and can flower even in a degraded state (Fielding and Turland, 2008). Conversely, holm oak, which is more sensitive to human pressure as a taller late-successional species, is restricted to specific areas (Goedecke et al., 2018). Recent palaeoecological studies demonstrated that natural- or human-driven fires can disadvantage holm oak (Colombaroli et al., 2009). Declining fire activities together with *Q. ilex* expansions have been observed at many sites in the Mediterranean and can be explained by climatic shifts controlling both fire and vegetation change and/or complex fire-species interactions (Tinner et al., 2009; Beffa et al., 2016). At Kournas, during the first part of the Middle Holocene (between ca. 8500 and 6000 cal BP), evergreen oak pollen percentages rose during a period of moderate charcoal sedimentary accumulation and decreased sharply as biomass burning increased (Fig. 7). Thus, near the lake, holm oak may have had a more significant place in the Early- and Middle Holocene woodland when human impact was low, than in the present-day vegetation.

Temperate European trees that also grow outside southern Europe, namely *Alnus*, *Betula*, *Corylus* and *Fagus* but their pollen grains have been regularly registered throughout the sequence, except in the upper part (Fig. SM7a). They are currently absent in the Cretan flora, or, as for *Corylus avellana*, are doubtfully native (Fielding and Turland, 2008). Such observations indicate that these temperate trees might have been part of the original Cretan postglacial forest (e.g. Moody et al., 1996). Alternatively, the presence of such pollen grains could be the result of long-distance transport, as proposed by Bottema and Sarpaki (2003). The former may support the hypothesis that modern land use would not leave any space for temperate deciduous trees such as alder (*Alnus*), birch (*Betula*), hazelnut (*Corylus*), and beech (*Fagus*), and very little space for the small surviving elm (*Ulmus minor*) and the regional endemic *Zelkova abelicea*. First clues about maquis development occurred around 8000 cal BP with the occurrence of *Erica* and *Phillyrea* pollen grains. A growing representation of the phrygana occurred after ca. 3500 and is well illustrated by the *Sarcopoterium* pollen curve. This dynamic led to the present-day mosaic of vegetation accompanying olive groves in the surroundings of the lake.

5.2.2. Land use, land cover and biodiversity

In the highly anthropized current landscape around Lake Kournas, the olive tree occupies an important place (Fig. 1). *Olea* pollen is also of prime importance in the palynological record, indicating that olive, probably the most iconic tree of the Mediterranean (e.g. Izdebski et al., 2020; Kouli et al., 2018; Langgut et al., 2019) has had a major role in the local socio-ecosystem. The history of olive tree cultivation at Kournas can be divided into three main phases: the Final Neolithic-Minoan period, the Hellenistic-Roman-Byzantine (HRB) period and Modern times. A similar trend in olive pollen is observed across the whole of southern Greece (Weiberg et al., 2019). The first phase onset at Kournas, ~6000 yrs ago, confirms the age proposed by Langgut et al.'s (2019) recent synthesis based on published data from Greece (Avramidis et al., 2013) and Crete (see section 5.1.3). At that time, during the Final Neolithic, archaeologists argue for an expansion in settlement (Tomkins, 2008) and a significant increase in activity (Nowicki, 2014; Weiberg et al., 2016). There is little doubt that olive exploitation continued during the Minoan period. That is in good accordance with archaeological evidence of oil storage (e.g. Koh and Betancourt, 2010), presence of archaeobotanical remains of olive wood, fruits and pollen (Badal and Ntinou, 2013; Cañellas-Boltà et al., 2018; Ghilardi et al., 2018; Livarda et al., 2021; Moody et al., 2008). The second phase during the HRB period, with the persistence of olive cultivation together with stabilisation of other environmental markers (erosion, fire, biodiversity), is striking. Contrary to what Bonnier and Finné (2020) suggested in the North-Eastern Peloponnese at the regional level, we do not see here any adaptation and/or change in land-use during the drier conditions of the Late Hellenistic-Roman period. Young olives, in particular, require high levels of watering (Foxhall, 2007, p. 110); thus, the location of extensive olive groves adjacent to a lake makes perfect sense. Finally, the last phase of olive cultivation, beginning during the Turkish period, lays the foundation of the current land use and the current landscape.

Another land-use well documented by the lake Kournas record is pastoralism. Coprophilous fungi are recorded throughout the sequence from at least 8500 cal BP, and more regularly since 3500 cal BP. Today, flocks of sheep and goats extensively graze or browse mainly on the western slopes. The amounts of coprophilous fungi are comparable to the present-day quantities accumulated in the core-top sediments (an average of 100 spores of *Sporormiella*/cm^2/year). Combined with the assemblage of grazing-related pollen taxa such as *Urtica* or *Rumex acetosa*-type, we can probably consider they are robust indices of a persistent local presence of domestic and/or feral animals. The huge increase of these proxies' values during the Classical, Hellenistic and Roman periods correlate with the historical sources that highlight the importance of livestock breeding in Crete (Fig. 7). Milk and derived milk products represented a vital part of the food economy, and breeding became a specialized activity (Chaniotis, 1999). Nevertheless, the very high amplitude of the fungal spore peaks at that time may also be related to changes in the sediment accumulation rate and the related quantity of soil-eroded inputs. Fungal spore representation can be overestimated because of geomorphic processes like soil erosion (Etienne et al., 2013), maybe themselves favoured by grazing. Finally, we can also consider manuring across the olive groves or the purposeful movement of animals for short periods across the groves to fertilise. Indeed, high amounts of coprophilous fungal spores in the palynofacies may also originate from manured soils (Graf and Chmura, 2006).

How did these land uses throughout Kournas' landscape history interplay with plant biodiversity? As observed in other studies within the southern Mediterranean (e.g. Colombaroli and Tinner, 2013), the main changes in pollen biodiversity are correlated with land use during the Mid- and Late-Holocene. Apparently, some land uses and/or land management were more favourable to biodiversity development or conservation, while others were destructive. From 6000 to 3000 cal BP, i.e. the Final Neolithic to the end of the Minoan period, biodiversity was high (Fig. 7). Our data indicate a sustainable agro-pastoral system with a balance of pastoralism, annual crops and olive cultivation that led to manageable disturbances, i.e. with a level of intensity below the resilience ability of these anthropized ecosystems. For example, throughout the Minoan period, animal husbandry and crop cultivation led to more fires, a biodiversity increase and fewer flood deposits. Afforestation periods were matched by an increase of flood frequency and biodiversity decrease. It is thus possible to hypothesise that a diversity of land use and the related micro-scale diversity of ecosystems preserved soils from storm erosion and promoted landscape-scale biodiversity (Connor et al., 2019). These land uses with intermediate disturbance levels, maybe under different climate conditions, favoured vegetation biodiversity. Conversely, the 1300 years of long-lasting and well-established HRB land uses, involving extended olive cultivation and sizable livestock in the watershed, were coeval with a sharp decrease in the pollen biodiversity indicators (Fig. 7). These HRB pollen assemblages and biodiversity values are strongly comparable to the top core samples. Even considering the limits of the paleoenvironmental proxies used in this study, the HRB olive cultivation looks a lot like today's intensive land use. The commonalities might be rooted in the large-scale production of goods with specialization for long-distance trading. The vegetation biodiversity history of Kournas thus documents well the intermediate-disturbance hypothesis (Fox, 1979) and confirms other palaeo-studies supporting this theory in the Mediterranean basin, e.g. in Corsica (Lestienne et al., 2020) or the Alps (Colombaroli et al., 2013). Intermediate disturbance based on a controlled fire regime combined with non-intensive agro-pastoral activities may favour biodiversity while too intense or too few disturbances limit it. At Kournas, the non-linear biodiversity trend highlights the ecosystem's resilience, especially during the post-HRB decline in cultivation (Fig. 7). The decreasing trend in pollen-inferred biodiversity in most recent samples is in accordance with studies showing the role of agro-pastoral systems in land degradation since the mid-1980s, with a guilty role of intensive breeding on Crete (Ispikoudis et al., 1993; Kosmas et al., 2016) and of olive monoculture at the Mediterranean basin scale (Moreira et al., 2019).

5.2.3. A human-driven fire regime

Fire is a widespread and key disturbance in Holocene Mediterranean ecosystems, controlled by both climate conditions and humans (e.g. Vannière et al., 2008; 2011). Climate is proposed as the main driver of Early Holocene fire regimes even if the human role for this period is probably underestimated (Lawson et al., 2013) because of the lack of direct evidence. In contrast, farming practices certainly deeply modified if not controlled fire regime at least since the Neolithic throughout the basin (Connor et al., 2019, Vannière et al., 2016). Site-scale studies on several Mediterranean islands: Corsica (Lestienne et al., 2020), Sardinia (Beffa et al., 2016), Sicily (Tinner et al., 2009; 2016), Malta (Marriner et al., 2019) clearly show how fire occurrences were closely associated with land-use rhythms after about 7000 cal BP. They altered the "natural" frequency of events but likely also the intensity, severity, location and size-area of the fire events according to human purposes and land-use modes.

The synchronicity of charcoal peak-accumulation in lake sediments at Kournas with pollen indicators of human activities throughout the record argues for a causal link between humans and fire (Fig. 7). Moreover, several phases with high biomass burning may have occurred synchronously with wet and cold climate periods in Crete as documented by the literature (see section 5.3.1, Cheng et al., 2015; Dean et al., 2015; Finné et al., 2014, 2019; Rohling et al., 2002, 2015, 2019), which might have been expected to reduce fires in Kournas area. Fire has certainly been used as a pastoral management tool and was still used until recently in traditional mountain land management on Crete, where shepherds used burning to make the herb flora more abundant and palatable. Fire also seems to be involved in land clearing before the initial establishment of olive groves during Classical Greek times (Fig. 7). It is more difficult to characterise the first fire phase during the Early Holocene, i.e. before 8500 cal BP and to decipher an early human impact of some possible Mesolithic or PPN Neolithic groups.

5.2.4. Land cover changes and sediment dynamic responses

Since Vita-Finzi's (1969) assessment of historical Mediterranean soil erosion, the debate has almost never stopped about the causes and the degree of "degradation" of Mediterranean landscapes, mainly concerning soil loss (e.g. Lespez, 2003; Thornes and Wainwright, 2004; Butzer, 2005; Hooke, 2006; Fuchs, 2007; Walsh et al., 2019). Dusar et al. (2011) proposed a regional synthesis for the Eastern Mediterranean about the timing and drivers of Holocene sediment dynamics, and showed that since the mid-Holocene, with lags between sites according to local history, human impact can explain sediment flux to a large extent. The comparison of flood frequencies from Kournas with sedimentation history records during the Holocene from

Crete in particular (Macklin et al., 2010; Benito et al., 2015) or from the Eastern Mediterranean region (Dusar et al., 2011; Benito et al., 2015), does not show any clear regional pattern that could argue for climate as a dominant driver of Holocene flood history at Kournas.

Sediment started to accumulate in this lake basin from 9600 cal BP, but it is only from 8500 cal BP, probably because of the continuing marine transgression that real lacustrine sediments accumulated and from 8400 cal BP that the first fluvial deposit was recorded. From this first event, all flooding periods in Lake Kournas correlate remarkably well with other environmental changes connected, at least in part, with human impact. The first phase of flooding follows the evergreen oak expansion and the increase in grazing indicators (Fig. 7). Around 6000 cal BP, it likely derived from forest disruption (mainly evergreen oak) and just preceded the start of olive cultivation. Around 4000 cal BP, a rise in flood frequency matches again with a new increase in *Olea*. From 2700 to 2000 cal BP (800-200 BCE), the major flood events overlapped in time with the onset of the strong and long-lasting HRB olive cultivation and breeding land-use.

The thickest flood deposits often preceded an olive pollen maximum and were thinner afterwards. Only the initial phase, probably related to land clearing, was coeval with intense soil erosion (Fig. 7). Subsequently, olive cultivation likely included some soil management to mitigate erosion. Karamesouti et al. (2015) described such a process for the modern period in the Messara Plain in southern Crete (1950-2010). However, the continuous occurrence of flood deposits throughout the period of olive cultivation means that long-term changes in land cover must have led to fundamental hydrological changes in the watershed. For example, changes in the landscape connectivity, of soil thickness and properties, might have increased the transport capacity of water and the sediment mobilized through erosion after being initiated by deforestation and grazing (Hooke, 2006). Thus, the flooding record at Lake Kournas likely represents a signal of local land use, often resulting from vegetation disturbance for agro-pastoral purposes, such as observed at lake Nar in Turkey (Roberts et al., 2019).

The individual causes of the MWDs that represent internal lake sediment movements remain unclear, with the exception of the one that is coeval with the crypto-tephra signal. For the others, no precise chronological correlations can be established with the seismic activity reported in the literature (e.g. Mourtzas et al., 2016; Polonia et al., 2016; Jusseret and Sintubin, 2017). The first one followed the onset of woody vegetation 4000 years ago and some reorganization of land use around the lake with the start of the Middle Minoan period and palace construction. However, all MWD occurred during periods of intensified olive cultivation. The sedimentary dynamics also seem stronger after ca. 4000 cal BP elsewhere in Crete (Benito et al., 2015), in mainland Greece

(Lespez et al., 2003; Fuch et al., 2007; Engel et al., 2009) and in the wider Eastern Mediterranean (Dusar et al., 2011), as at Kournas. This new stage in regional sediment dynamics might be associated with the widespread increase of human population and a threshold passed in land cover. This transitional period has also been identified from the flood frequency record in the north-western Mediterranean due to the combined effect of land use and climate (Vannière et al., 2013; Rapuc et al., 2019).

Between 2700 and 2300 cal BP, a possible cause of the significant increase of the sedimentation accumulation rate was re-working sediment within Lake Kournas from the shallow (~5-6 m deep) shelf zone toward the deep basin. The reversal in ^{14}C ages during sedimentary unit L3 (Figure 4) clearly reflects the re-working of organic macrofossils, along with more diffuse soil carbon, and these may have been derived from sediments previously deposited in the shallow marginal zone of the lake. The 500 years of rapid accumulation in Kou11-12, overlaps with a longer hiatus seen in unpublished cores taken in the shelf zone by another project in 2000-2001 (Jason Curtis, pers comm.; Besonen et al., 2011). If so, then the most likely cause would have been a fall in lake level of a few metres, sufficient to alter the sediment limit in the shelf zone. With the marginal zone of sediment storage no longer in operation, eroded soil could have moved directly from the catchment into the lake's deep basin.

In the most recent pan-Mediterranean synthesis of erosion dynamics by Walsh et al. (2019), the Greek and Roman periods appear as critical moments, and more locally, a “Roman paroxysm” for sediment flux has also been recorded in Crete (Macklin et al., 2010; Ghilardi et al., 2018). The respective role of land management intensification during Greco-Roman Antiquity and the climate conditions needs to be further investigated (Benito et al., 2015; Walsh et al., 2019). In the Kournas watershed, the intensification of agro-pastoral activities during Greco-Roman Antiquity is obvious. It corresponds to a significant reduction in both the frequency and magnitude of floods but also to a coarser and a new carbonate detrital component in the lacustrine sedimentation (see ratios Sr:Ca, Ca:Al and Zr:Al, sedimentary units L4, L5 and L6, Fig. 3), which lasts and intensifies during the last two millennia. Thus, the hypothesis is that in the watershed of Kournas, soils may have been strongly modified during the first millennium BCE. The result of soil transformation might have been a new hydrological pattern associated, which might have led to a permanent and long-lasting erosion by Hortonian overland flows (Hooke, 2006), modifying consecutively, deeply, and for the first time in the Holocene, the regular lake sedimentation.

5.2.5. Climate Changes and environmental responses

Independent proxies from speleothems (Finné et al., 2014; Cheng et al., 2015), sea surface temperature (e.g. Rohling et al., 2015), terrestrial biomarkers from sea sediments (Gogou et al., 2007; Kouli et al., 2012) and lacustrine geochemistry (e.g. Dean et al., 2015) document Holocene climate variations in the eastern Mediterranean. The results are sometimes contradictory, and the recent synthesis by Finné et al. (2019) highlights the spatial complexity of past climate changes in the Eastern Mediterranean. Thus, any inference of a precise pattern of temperature and precipitation changes in the Eastern Mediterranean and, *a fortiori*, at the scale of Western Crete is still difficult.

From ca. 8700 to 7800 cal BP, the Kournas record is characterised by a rapid succession of events leading to one of the main shifts in the area's environmental history (transition from Kournas phase 1 to 2, Fig. 7). Sediments indicate an evolution from a shallow water body to a deeper lake basin (Units L0 to L1, Fig. 3) and the occurrence of flood deposits. This transition is recorded by the enrichment of the sedimentary content in algal remains and in particular, of *Tetraedron minimum* (AZ 1b, Fig. SM9), and an important change in diatom assemblage (DZ 2, Fig. SM11). *Tetraedron minimum* is a green coccal algae characterised by its ability to use inorganic carbon (van Hunnick et al., 2000) and likely benefited from lake ontogeny. The dominance of planktonic diatoms and taxa preferring low salinities indicates that Lake Kournas has been a relatively deep, freshwater body for most of the record. The exception to this occurred between ~8400 and ~7800 cal BP, when there was a very marked diatom-inferred increase in lake salinity. The dominance of the *Actinocyclus normanii* at this time could, in theory, have been caused by an incursion of marine water into the lake, which today lies close to the coast. This period coincides with the last significant rise in global eustatic sea levels (e.g. Perissoratis and Conipoliatis, 2003; Vacchi et al., 2016). On the other hand, at the same time, sedimentation became more detrital and enriched in numerous elements from the watershed (Fig. SM4). The likely interpretation is that the shift in sediment dynamics on the watershed, including the newly flood deposits, and combined with sea-level rise blocked surface water outflow from the lake. This may have been associated with a drier period around the time of the 8.2 ka climate event (Daley et al., 2011), which lowered the water level of Lake Kournas to become a closed (i.e. non-outlet) system, preventing solutes from been removed via the stream outflow. The 8.2 ka event, which is also described as a pluri-secular climate change period, is recorded elsewhere in the eastern Mediterranean as a period of climatic aridity (e.g. Dean et al., 2015) and cooling (Gogou et al., 2007) is registered in some regional pollen records by a short-lived decline in woodland (Pross et al., 2009; Kouli et al., 2012). This is not the case at Kournas, although a land cover change did take place from deciduous to evergreen oak-dominated forest at around 8400 cal BP, at the very onset of the salinity increase.

During the Mid and Late Holocene, there is no clear and obvious relationship between reconstructed or modelled climate shifts (e.g. Mayewski et al., 2004; Kouli et al. 2012; Rohling et al., 2019) and vegetation or the environment at and around Lake Kournas (Fig. 7). In contrast, the key steps in environmental change at Kournas can be connected to land use and so with human drivers. For instance, ~6000 years ago, a new increase in flood frequency and then fire signal were coeval with the *Olea* expansion and seem to have occurred before the onset of a "cold and wet winter period" at 6000-5000 cal BP (Mayewski et al., 2004; Kouli et al. 2012; Rohling et al., 2019). On the other hand, the change at Kournas was broadly coincident with the end of the regional phase of wetter Neolithic climate in the eastern Mediterranean (Finné et al., 2019), associated with the mid-Holocene climatic transition (Roberts et al. 2011), and this may have favoured taxa adapted to seasonal drought such as olive. More specifically, there is no evidence in the Kournas record of the 4.2 ka BP climate event, although there were changes at Kournas (e.g. flood events) during and after 3.2 ka BP, a period of regional climatic aridity that has been linked to the end of the Late Bronze Age world system in the eastern Mediterranean (Kaniewski et al., 2013). The major phase of increased sedimentation and flood frequency 2700 and 2300 cal BP, was partly linked to the establishment of HRB olive cultivation, but also possibly in the context of lake-level lowering and a drier climate (Benito et al., 2015; Finné et al., 2019). So, the onset of HRB land use and a change in precipitation regime may have both favoured soil erosion. Finally, during the Late Holocene, the Medieval Climate Anomaly and Little Ice Age coincided with some local environmental changes, including a slight diatom-inferred increase in lakewater salinity, but the politico-economical context also provides a valid explanation for most of these changes and their timing (see above part 5.1.5).

5.2.6. The Santorini Minoan Tephra and regional seismic activity

In the Aegean, the most discussed past volcanic event is the "Santorini/Thera" eruption and its environmental and social impact (e.g. Walsh, 2014: 20-23). A volcanic ash deposit, the so-called Minoan tephra, has been observed in many sedimentary contexts in Greece (e.g. Friedrich et al., 2006), in Crete (Driessen, 2019), and as far as western Turkey (Sulpizio et al., 2013) wind having favoured ash transport to the east. At Kournas, the question of this tephra and the subsequent effect on local vegetation was one of the goals of the Bottema and Sarpaki paper (2003). The authors identified a layer with pumice stones and volcanic glass in the Delphinos sequence that they related to the Santorini eruption, but did not regard it as in situ deposition. In the Lake

Kournas sequence, geochemical analyses have shown a crypto-tephra deposit within the lake sediment, dated between 3370-3560 cal BP. It caps a MWD (Fig. SM6) and has been recognized as the Thera eruption signature. The reworked sediment might have been the consequence of earthquakes that preceded or took place during the eruption and that are also responsible for damage to Minoan palaces (Jusseret et al., 2013; Driessen et al., 2019). However, there was no marine intrusion into the lake due to a tsunami, neither any flash-flood event following the tephra deposit. This seems to confirm that in West Crete, the eruption impact may have been lower than in the East (Driessen et al., 2019). Similarly, no significant shift can be identified in the vegetation around Kournas at or just after the tephra layer. Nevertheless, a change in agro-pastoral practices occurred at and after ca. 3500 cal BP (Fig. 7), when *Olea* declined and cereal cultivation expanded (Fig. 6, PZ 3c). As suggested by tree-ring analysis (Pearson et al., 2009), a more humid climate could have damaged olive trees and/or decreased their productivity, which may have released increased cereal farming. Riley (2004) already proposed volcanic damage to Late Minoan olive groves following Eastern and Central Crete archaeological evidence.

6. Conclusion

Kournas' record provides novel insights into the timing and nature of vegetation, biodiversity, fire, land use and environmental shifts. Ecosystem development near Lake Kournas was not a linear process but involved linkages and feedbacks between vegetation, biodiversity, fire, human impact, erosion, and climate change. Among these, human impact was probably the most important driver of ecosystem change during the past ~8000 years. Lake Kournas as a natural archive consequently has a high value in providing new insights about human history in western Crete, a region where archaeological remains are relatively scarce. Pollen and fungal remains suggest possible human activities around the lake as early as 9500 cal BP, perhaps in a transitional phase between the Mesolithic and the Neolithic. With more confidence, the establishment of an agrosystem after 8500 years ago means that the trajectory of Kournas' lake and catchment ecosystems during the Mid to Late Holocene follow the rhythm of land-use change.

The main exception to this was the period ~8500 - 8000 cal BP, when the local sediment regime, probably driven by sea-level rise and climate-related lake level changes, led initially to the establishment of a deep lake, then a period of lake outlet closure and salinity increase, climatic conditions may have promoted the expansion of the evergreen oak woodland.

Among the traditional Mediterranean land uses, olive cultivation locally played a major role in the socio-ecosystem interactions, providing economic benefits but also destabilising soils. During the last six millennia, three main phases of olive cultivation occurred, interrupted by periods when olive groves were abandoned or used less intensively; some of them lasted for millennia (e.g. from the Final Neolithic to the Minoan). The changing land use under the successive political and economic influences permitted the resilient vegetation to shift back to growing higher biodiversity again. Forest vegetation was always able to recover until the onset of the Venetian period (13th century), when woodlands were dramatically reduced. Only during the past century has forest vegetation slightly recovered, while the flood regime had already been altered during previous centuries. During the past 100 years, biodiversity markedly declined, probably in response to the industrialization of agriculture. Moreira et al. (2019) argued that in a global context of the growing demand for olives and olive oil, it is urgent to move to a more sustainable form of production that conserves biodiversity and preserves the soil. Kournas' environmental history provides a target for such a sustainable socio-ecosystem.

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Captions

Fig. 1: Regional Settings: A. Location of Lake Kournas in Crete (Greece); B. Present day olive grove next to the lake; C. Lake Kournas and its surrounding, oblique satellite image (© Google 2020, Image 1/9/2018) with the pattern of main vegetation assemblages, seismic profile and the coring point location; D. Bathymetry and seismic profile with the coring location and the cores id; E. Magnetic susceptibility logs of the cores and correlation between all the sections, bold curves indicate sections used for the master core studied thereafter with other proxies.

Fig. 2: Example of 1-meter core section of the Kou11-12 sequence illustrated by the core image, Magnetic Susceptibility (MS), grain size and geochemical XRF measurements. Grey bands (Flood facies) highlight increases of MS values, coarse grains percentage increases (sand: 40-200 µm),

and increases of a few terrigenous elements as Al, Zr, Rb and of precipitated Mn. The yellow band (MWD facies) highlights the coarsest grains deposits, and increases of Calcium and Strontium elements. The ratio Zr:Rb points the coarsest layer. The ratio Ca:Al shows the biogenic carbonate content.

Fig. 3: Description of the entire master core Kou11-12 with calibrated dates (all done on the master core sections) and geophysical, geochemical, and sedimentological proxies. Flood and MWD* facies are also shown. Grey bands highlight the main sedimentological units identified in the core: C-Colluvium, R-Pebble, S-Swamp, L0 - Lake phase 0 through L6 - Lake phase 6.'. Red lines and black dotted lines show moving averages. Marks on the Sr profile highlight MWD positions.

Fig. 4: Age-depth model of Kou11-12 sequence built with Clam 2.2 R-package (smooth spline, Blaauw 2010) and based on 23 radiocarbon ages (calibrated with IntCal13, Reimer et al. 2013, Table 2), short-lived radionuclides data and the Santorini Tephra (Driessen, 2019) identified in Lake Kournas sediments.

Fig. 5: Lake Kournas flood frequency with (in grey) the periods marked by frequency values above 1 event per century, Flood deposit (thicknesses, classed in three groups: <2 cm 2-7 cm, >7 cm), MWD deposit thickness and the position of the Santorini tephra glass shards.

Fig. 6: Lake Kournas percentage pollen diagram for selected taxa.

Fig. 7: Synthesis of the main proxy records from Lake Kournas core Kou11-12 with indication of the five environmental phases and comparison with the Cretan chrono-cultural periods (chronocultural phases of the Neolithic follow Tomkins, 2018) and East Mediterranean regional climate data. (Dung fungal spores included *Sporormiella*-, *Sordaria*- and *Podospora* sp.)

Table 1: Dates from cores Kou11 and Kou12. Radiocarbon ages calibration has been done with the IntCal13 calibration curves (Reimer et al. 2013).

Supplementary Material

Fig. SM1: Standard deviation of all Kou11-12 samples by grain size fractions. Grey-bands highlight four populations or grain classes: 0.9-3µm, 6-20 µm, 40-200 µm and 300-650 µm, which are used to plot grain size changes along the entire Kou11-12 sequence (see Fig. 2 and 4).

Fig. SM2: Q7/4 diagram (Debret et al., 2011) based on spectrophotometric measurements from Kou11-12 samples. The abscissa axis represents the 700/400 µm ratio (main slop of the raw spectrum) and the ordinate axis the lightness of the sediment L* (White/Black). Usual sediment product values are indicated. Samples are grouped by sedimentary units and plotted on two identic diagrams to avoid too much overlap. Sample envelops plotted in the upper graph are figured in the bottom graph to facilitate comparison.

Fig. SM3: Kou11-12 XRF data logs.

Fig. SM4: PCA of XRF data; Principal components one (PC1) and two (PC2), eigenvectors (arrows, left panel), and samples grouped by sedimentary units and facies (right panel, see Fig. SM3).

Fig. SM5: Chronology (with 1σ uncertainties) of the uppermost part of core Kou11-P1 based on the short-lived radionuclides thanks to serac R package (Bruel and Sabatier, 2020). On the right, the application of a constant flux constant sedimentation (CFCS) model to the ^{210}Pbex profile. NWT: Nuclear Weapon Test in 1963 AD.

Fig. SM6: Energy-dispersive spectrometry (EDS) analyses of glass shards from sample Kou11-A3.1-77 and comparison with other volcanoes glass shards analyses (Sulpizio et al. 2013).

Fig. SM7: Full pollen and spores diagram of core Kou11-12. 7a: Trees and shrubs pollen, 7b: Herbs pollen, ferns and bryophytes spores

Fig. SM8: Lake Kournas pollen diversity indices. PIE index: palynological evenness, PRI index: palynological richness and DE-PRI: detrended pollen richness (expressed as expected number of pollen type). Minimum sum used for PRI is n=363

Fig. SM9: Lake Kournas identified fungal and algal remains. The numbers of remains observed are expressed in accumulation rate (#/cm^2/yr)

Fig. SM10: Lake Kournas microcharcoal (10-200 µm) influx. Dark line and dotted lines respectively represent moving averages and zone averages.

Fig. SM11: Lake Kournas diatom diagram. Percentages of identified species and proportions of different taxonomic groups, along with reconstructed EC.

Table SM1: Energy-dispersive spectrometry (EDS) analyses of glass shards from sample Kou11-A3.1-77.