Paleoenvironmental variability and anthropic influence during the last 7,300 years in the western Mediterranean based on the pollen record of Cartagena Bay, SE Spain

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Abstract

In this paper, we conduct a palynological analysis of a high-resolution Holocene record from Cartagena Bay, southeast of the Iberian Peninsula, to establish paleoenvironmental variability of coastal areas in the western Mediterranean region at a centennial-scale over the last 7,300 years. Statistical analysis of four palynozones allows reconstruction of paleotemperature and paleohumidity conditions. *Pinus*, steppic, xerophilous, and Mediterranean taxa persisted continuously through the record, and only during periods of increased humidity did deciduous and Mediterranean taxa expand (Zones II, subzone IIIb). Cooler and dry conditions favored the development of Cupressaceae and scrubs between 7,300 and 7,000 yr cal BP. The mid-Holocene (Northgrippian) mesophytic optimum took place between 6,800 and 4,000 yr cal BP during which time a Mediterranean climate was present and open forest developed, predominantly consisting of Mediterranean taxa and deciduous trees. The gradual rise in aridity in the Meghalayan (4,000-1,700 yr cal BP) led to Mediterranean forest being replaced by steppic and xerophilous vegetation, a change related mostly to a decrease in summer insolation, with superimposed centennial-scale variability in humidity. In parallel with forest degradation caused by increasing aridity, the record shows marked evidence of human influence since 4,000 yr cal BP, which accelerated the progression of open landscapes from the Chalcolithic onwards, this change being especially marked during the Roman period. Significant denudation of the landscape can be attributed to the use of fire, as well as due

to agriculture and grazing, with a major contributor being intense metallurgical and mining activity in the area. The Cartagena Bay record reported herein shows centennial-scale oscillations in humidity and temperature that correlate with well-known climatic events during the late Holocene in the western Mediterranean region, synchronous with variability in solar and atmospheric dynamics. The alternation of persistent North Atlantic Oscillation modes is likely to have played a key role in regulating humid–arid periods.

Keywords: Pollen analysis, Holocene, aridification, human impact, Western Mediterranean, Cartagena Bay (Spain)

1. Introduction

Recent decades have witnessed a diversification of paleoclimatic records, together with the development of reliable dating methods. These advancements have allowed the reconstruction of the main paleoenvironmental changes at different temporal resolutions that have occurred through time.

These records and advances in our understanding of the mechanisms that govern climate changes have revealed significant natural variability operating at different time scales in the system (deMenocal, 2000; Mayewski et al., 2004; Crowley and Hyde, 2008; Rodrigo-Gámiz et al., 2011;), such as the orbital (~100,000 yr), suborbital (~10,000 yr) and historical (~1,000-100 yr) (Köhler et al., 2010) scales.

The number of well-dated Iberian multiproxy records has increased in recent decades, especially for the Holocene (Carrión et al., 2010) and, to a lesser extent, for the Pleistocene (González-Sampériz et al., 2010). However, Quaternary climatic variability obtained from terrestrial sedimentary sequences continues to be limited. In some exceptional cases, favorable geological conditions have led to the relatively undisturbed

accumulation of sedimentary sequences, some of them located in the Mediterranean realm of Europe (Tzedakis, 2007).

The analysis of long chronological periods allows inference of the dynamics of ecosystems at different time points, including climatic scenarios similar to current ones, but with distinct features, such as the influence of anthropic activities. In the current scenario of Global Climate Change influenced by human activities (van Kolfschoten et al., 2003), the Mediterranean region is more vulnerable to climate dynamics (Solomon et al., 2007) and should therefore be used as a model system within the geoscientific agenda.

Some paleoenvironmental studies in the western Mediterranean realm have detected a millennial- and centennial-scale link between the oscillations of the paleoclimatic proxies of sedimentary records with solar and atmospheric variability (i.e., North Atlantic Oscillation—NAO) (Di Rita et al., 2018, 2022) and/or ocean dynamics during the Holocene (Moreno et al., 2012; Fletcher et al., 2013; Rodrigo-Gámiz et al., 2014; Ramos-Román et al., 2018a,b). Most terrestrial records in the western Mediterranean region show cyclical changes on a millennial scale. In addition, records of montane and coastal lakes in southern Iberia show climate changes on a centennial scale (Carrión, 2002; Carrión et al., 2007; Martín-Puertas et al., 2008), some of them showing complex relations between rapid climate variability and ecosystem response in Sierra Nevada (García-Alix et al., 2012; Jiménez-Moreno and Anderson, 2012; Ramos-Román et al., 2016, 2018a,b; Mesa-Fernández et al., 2018) and on the southwestern coast of the Iberian Peninsula (Fletcher et al., 2007; Jiménez-Moreno et al., 2015). Therefore, higher resolution studies are needed to analyze the link between solar and atmospheric activity with oceanographic systems and terrestrial environments in this area on shorter time scales (i.e., centennial).

Sediments from lakes, peatlands and marine records of the western Mediterranean realm have documented a trend towards aridification during the late Holocene (Jalut et al., 2009; Carrión et al., 2010; Gil-Romera et al., 2010). However, this trend was superimposed by short-term climate variability and human impact, as shown by recent studies in the region (Carrión, 2002; Martín-Puertas et al., 2008; Fletcher et al., 2013; Jiménez-Moreno et al., 2013, 2015; Ramos-Román et al., 2016). The relationship between climate variability, cultural evolution and human impact during the late Holocene has been addressed in some recent paleoenvironmental studies (Carrión et al., 2007, 2010; López-Sáez et al., 2014; Lillios et al., 2016, Ramos-Román et al., 2018a). However, it is still unclear whether climate or human activities have been the main drivers of environmental change (i.e., deforestation) in this area during this period.

Furthermore, most of the sequences studied in the western Mediterranean realm are located at high altitude. In this regard, to better understand the paleoenvironmental characteristics of Mediterranean coastal areas during the Northgrippian and Meghalayan, we drilled a new core (E3) in Cartagena Bay. Of note, E3 contains a large, well-preserved record covering the the last 7,300 yr cal BP (11.1 m), thus allowing continuous sampling (with 3 cm intervals) for a high-resolution study. Moreover, intense amino acid racemization and radiocarbon sampling followed by a Bayesian analysis allowed the establishment of a reliable chronology (Ortiz et al., 2021). Therefore, E3 allows observation of plant dynamics over the last 7,300 years, thus making it an exceptional record in the coastal Mediterranean realm.

In brief, the palynological study of the coastal record of Cartagena seeks to contribute to a better understanding of 1) the centennial-scale paleoenvironmental variations that occurred in the western Mediterranean realm during the Northgrippian and Meghalayan

and to 2) discriminate the anthropic influence on vegetation in the area around the most important city in the region during prehistoric and historical times.

2. Geographical setting, climate and vegetation

Located in the southeast of the Iberian Peninsula, Cartagena Bay is an estuarine environment enclosed by craggy sierras (Fig. 1). To the north of the bay, the hills where Punics and Romans built their cities act as a partial lock, separating them from a wide marsh 2 m above the sea level, El Almarjal, which, after intensive drainage, is now covered by buildings.

An ephemeral stream, named Benipila Creek, with a catchment area of 72.5 km^2 (Conesa and García-García, 2003) runs along the southern boundary of El Almarjal marsh debouching at the southern corner of the bay at the "Mar de Mandarache", where navy facilities were built in the 18^{th} century. El Almarjal marsh received water and sediment from the Benipila, El Hondón and Saladillo Creeks. Other minor streams, which are wadis, built the small alluvial fans of Concepción and Santa Lucia, as well as several minor ones that now reach the bay through the sewage system.

This region is characterized by the predominance of a warm and semi-arid ombro climate (*BSh*) or arid warm Mediterranean climate: a subtropical steppe. The region has a mean annual temperature of 20°C and an annual rainfall of 270 mm, with a marked summer drought (Rivas-Martínez and Rivas and Sáenz, 2017).

2.1 Present vegetation

The coast of Cartagena is located in the "Murciano-Almeriense" Biogeographic Province, forming part of the Almería Sector, the Eastern Almería Subsector falling within this (Rivas Martínez, 2007). The vegetation in this subsector is composed of shrub formations that include palm hearts (*Chamaerops humilis*), mastic shrubs (*Pistacia*

lentiscus), wild olive trees (*Olea europaea* var. *sylvestris*), Wisley cream clematis (*Clematis cirrhosa*), and even Cartagena junipers (*Tetraclinis articulata*) in La Unión range (Sánchez Gómez and Guerra Montes, 2003; Nicolás et al., 2004).

In the plains, *C. humilis* and black hawthorn (*Rhamnus lycioides*) are dominant, except for the western area in which the jujube (*Zizyphus lotus*) predominates. In the pre-coastal mountain ranges, located in the northern area, *P. lentiscus* is abundant, while in the coastal mountain ranges to the south, the terebinth (*Periploca angustifolia*) is dominant. In the coastal sands, the geosigmetum of saline areas and dunes predominates.

Of note, the lower horizon of the thermomediterranean belt, to which Cartagena belongs, is an ecologically unique area that extends from Cabo de Gata to Cartagena, where it is possible to observe North African optimum endemisms such as *T. articulata*, red spike thorn (*Maytenus senegalensis*), rennet (*Withania frutescens*), etc., which grow in cornical formations with *M. senegalensis* subsp. *europaea* (Díez-Garretas et al., 2005) and *P. angustifolia* (*Mayteno-Periploceto* S.).

The landscape is a steppe with a predominance of scrub and shrubs. The pre-coastal mountains are wooded, with groves of pine and holm oak, and also mastic and kermes oak bushes. The coastal mountain ranges hold less vegetation, with more trees confined to the shady areas, and the bushes dominating the sunny ones. Coastal salt marshes are covered with meadows of halophilic and hygrophilous plants. This landscape has changed greatly over time. The vegetation cover found by Paleolithic man in this region can be described as a set of thick Mediterranean evergreen bushes, and immense areas of mastic shrubs, in addition to terebinths, Aleppo pines, kermes oak bushes, olive trees, palm hearts, esparto grass, etc. (Carrión et al., 1995; Carrión, 2003) The creeks were occupied by oleanders and reeds. The salt marshes were covered by French tamarisk,

salicornia and platebrush, and the coastal sandy areas by Spanish junipers, littoral junipers, and pines.

Despite the changes in vegetation that have occurred over time, the coastal mountain ranges of Cartagena, together with the coastal area that extends to the Cabo de Gata (Almería), are home to plant species of enormous scientific and cultural interest. The Iberian and North African plants —present only in this coastal area and in North Africa—stand out above all others, with species as unique as the araar or sictus tree (autochthonous specimens found only in the mountains of Cartagena within all continental Europe), the jujube, terebinth and caralluma plants, among others. Other species present only in the area of Cartagena (endemic) can also be found, such as the Cartagena rockrose (*Cistus heterophyllus* subsp. *carthaginensis*), and others with a distribution restricted to the south-east of the Iberian Peninsula.

3. Material and Methods

Core E3 (37°35′59.4"N/ 0°59′15.3"/7 m a.s.l.), reaching ca. 30 m with a diameter of 7 cm, was drilled using a rig with a conventional rotatory drill pipe and direct flow of natural mud. The sediment core was covered with clingfilm and then taken to the laboratory, where it was split in half longitudinally, photographed and stored in a humid chamber until analysis. The core was scraped to remove the most superficial part (ca. 1 cm) and thus avoid possible sediment contamination. Two zones were visually distinguished in the stratigraphic record: yellow-brown muds and sands were dominant in the lower part (30–11 m), whereas grayish to black muddy sands predominated in the uppermost 11–3 m, sometimes with clearly recognisable marine plant remains. The uppermost 3 m consisted of a recent infill comprising a mixture of black muds, pottery

sherds and broken bricks. We refer to the sampled horizons of the borehole by their depth, in cm, from top to bottom (e.g., level E3-750 is at 750 cm).

Chronology between 11.1 m and 3.0 m was obtained through radiocarbon dating (10 samples, Table 1) and amino acid racemization of ostracode valves (30 ostracodes valves from 12 beds, Table 2) (Ortiz et al., 2021). The numerical datings revealed that materials of the upper 11 m belonged to the Middle (8,300-4,200 yr cal BP or Northgrippian) and Upper (> 4,200 yr cal BP Meghalayan) Holocene. A chronological model was constructed for MIS 1 (Ortiz et al., 2021), which was created with the Bayesian R-code package "Bacon 2.3.7" (Blaauw and Christen, 2011), after 9,000 Markov Chain Monte Carlo iterations (Fig. 1 Supplementary Information).

3.1 Pollen and Non-Pollen Palynomorphs

A total of 109 samples from core E3 covering the upper 11.1–3.4 m were selected for palynological analysis. Samples were selected at ca. 6 cm intervals, representing 11 cm^3. Most of the samples showed enough pollen grains, except the interval 10.7–10.2 m and 34 samples that did not reach the minimum required in terms of the number of grains or taxa. In these cases, the pollen content was considered on the basis of presence. The scarcity of pollen in some beds can be explained by diagenetic processes that occurred in some sandy sediments and that may have affected pollen grain conservation. Some sand beds reflect a higher energy environment (fluvial), resulting in less sedimentation/preservation of pollen grains, as well as being an oxidizing medium, thus leading to the destruction of any pollen grains originally present. The extraction of pollen grains followed standardized acid- and alkali-based methods (Coûteaux, 1977; Girard and Renault-Miskovsky, 1969; Goeury and Beaulieu, 1979).

3.2 Screening

A total of 43 plant taxa were identified (14 of them were arboreal, 4 bushes, and 25 herbaceous), together with 5 aquatic taxa, spores (monolete and trilete), and 19 Non-Pollen Palynopmophs (NPPs) of diverse affinity (Fig. 2, 3). Pollen data were plotted as the relative frequency of each taxon in the pollen diagram using the TILIA® and TILIA-GRAPH® software package (Grimm, 1987, 2004). There was generally good preservation of pollen content, as reflected by a high abundance of grains, as well as significative taxonomic diversity.

Several representative taxa were selected, allowing the discrimination of 14 groups on the basis of their environmental significance, some of them formed by a single genus. Apart from aquatic taxa, spores (monoletes and triletes), *Glomus*, Concentriciste and 6 NPPs of diverse nature, the main groups were as follows (Table 3): *Pinus*, Cupressaceae, Mediterranean, deciduous, Riparian, Ericaceae, Rosaceae, Cistaceae, *Chamaerops*, steppic, xerophilous, Nitrophilous, *Asphodelus*, and Cosmopolitan plants.

In this regard, it should be considered that *Pinus* and Cupressaceae represented, together with deciduous and Mediterranean taxa, regional vegetation, whereas local vegetation was represented by Riparian taxa, Cupressaceae, Ericaceae, Rosaceae, Cistacea and *Chamaerops humilis*. Herbs were grouped considering xerophilous, steppic and Nitrophilous taxa, the remaining herbaceous taxa being included within the group of Cosmopolitan herbs. NPPs from diverse sources were identified, including those of Coprophilous origin, markers of edaphic humidity and fires, and dry, mesoeutrophic, and oligotrophic conditions. *Concentriciste* representatives are linked to erosive processes, and *Glomus* is associated with deforestation processes (Table 3; van Geel, 2001; Carrión and Navarro, 2002; Cugny et al., 2010; Miola, 2012; López-Vila et al., 2014).

Thus, taxa were also plotted following their ecological affinities in a synthetic histogram (Fig. 3). The relative percentages of arboreal, shrub and non-arboreal pollen were calculated on the basis of the abundance of pollen grains of the taxa within each group, thus providing a general picture of the relative proportions of Arboreal Pollen – Non- Arboreal Pollen (AP-NAP). However, some samples showed a low pollen content and had no AP *vs.* NAP representation, and in these cases, we only marked their presence (not the percentage). The percentages of spores and NPPs were calculated separately, based on their abundance, to obtain a consistent picture of the local and regional plant population.

To achieve a detailed description of the palynological record, a series of pollen zones were established through a hierarchical cluster analysis with the help of CONISS (Grimm 1987), together with a visual inspection based on changes in the main taxa groups. We also performed a Principal Component Analysis (PCA) on the main groups of pollen assemblages (*Pinus*, Cupressaceae, Mediterranean, deciduous, Cistaceae, xerophilous and steppic taxa) with the software Biplot 1.1 (Smith and Lipkovich, 2002) to clarify the identification of climate oscillations and to visualize the weight the different groups had on the landscape. PCA is a technique used to identify a smaller number of uncorrelated variables known as principal components (PC) from a larger set of data and increasing interpretability. These PCs successively maximize variance. The technique is widely used to emphasize variation and capture strong patterns in a data set. The orthogonal linear transformation that converts the data to a new coordinate system assumes that the directions (axis) with the largest variances are the most "important" (i.e, the most principal component-PC).

4. Results

The most notable observation in the Cartagena record was the predominance of steppic (*Artemisia*, Chenopodiaceae and *Ephedra*) taxa throughout the entire sequence (Figs. 2, 3). However, oscillations in this group, together with the abundance of other taxa, allowed us to describe the paleoenvironmental characteristics interpreted from the palynozones identified in the CONISS cluster analysis (Table 4).

From 7,300 to 7,000 yr cal BP (Zone IV), there was a marked predominance of Chenopodiaceae. Also the presence of Cupressaceae, Asteraceae and *Pinus* was remarkable, with other taxa present only in small amounts, In general, there was a progressive development of forest mass (AP) from 7,000 to 4,000 yr cal BP (Zone III), mainly *Pinus*, evergreen *Quercus*, *Olea*, and some deciduous and Riparian representatives such as *Ulmus*, *Alnus*, *Juglans Corylus* and deciduous *Quercus*, and Ericaceae, although steppic (Chenopodiaeae and *Ephredra*) and xerophilous taxa were present. It is worth noting the abundance of T-318, and NNP marker of humid conditions. This period was followed by a marked decrease in AP and the rise of herbs, with a sharp increase in *Artemisia* and *Chenopodiaceae*, which ended after 2,000 yr cal BP (Zone II). The pollen record ended (1,850-1,700 yr cal BP) with a sharp decrease in taxonomic biodiversity (Zone I), associated with the loss of tree cover and an overwhelming presence of steppic taxa (Chenopodiaceae and *Artemisia*).

These changes were related to relatively significant variations in the development of the pollen groups. The most representative taxa were plotted in the synthetic diagram (Fig. 4). In this study, we used mainly the oscillations of Mediterranean and deciduous taxa, along with steppic, xerophilous and Aquatic taxa, to determine paleoenvironmental and paleoclimatic variability in the study area. Our findings were confirmed by the results of the PCA (see section 4.1). Indeed, the fluctuations in AP, especially the Mediterranean species (e.g., evergreen *Quercus* and *Olea*), have been used previously in other records

of the southern area of the Iberian Peninsula (e.g., Sierra Nevada) and the western Mediterranean region as a proxy for paleoclimate changes, with an increase in the development of these taxa generally indicating greater humidity (Fletcher and Sánchez-Goñi, 2008; Jiménez-Moreno and Anderson, 2012; Fletcher et al., 2013, Ramos-Román et al., 2016, 2018a, b; Torres et al., 2020). In contrast, increases in steppic taxa (i.e., Chenopodiaceae, *Artemisia*, *Ephedra*) have been used as an indication of aridity in this area (Carrión et al., 2007; Anderson et al., 2011; Torres et al., 2020).

4.1 Principal Component Analysis

PCA provided a scaled pollen index roughly corresponding to paleoclimate variations and this was used to confirm the pollen assemblage zones. The aim was to identify and group samples with similar paleoenvironmental characteristics along the Cartagena record. Thus, we clarified the identification of climate oscillations and visualized the weight that the different pollen groups had on the landscape, as well as the variations they showed.

The main results of PCA for the Holocene samples are provided in Table 5. The variables (pollen groups) showed sufficient communality (the proportion of variance of such a variable shared with the others and accounted for by common factors) to validate the results. The scores obtained for PC2 and PC3 were selected for the paleoenvironmental interpretation as they were the ones that better established the clusters which were used to define climatic conditions. In contrast, the scores of PC1 were similar to most of the variables and could not be used to distinghish between paleoclimatic conditions.

Thus, the results of the PCA considering PC2 and PC3 were assembled into four main clusters (Fig. 5a). Cluster 1 (C1) was separated with respect to the others because

of its positive loading to PC2 and PC3, and it included steppic and xerophilous taxa, whereas Cupressaceae appeared as belonging to C2, characterized by a positive loading to PC2 and negative loading to PC3. C3 comprised *Pinus* and deciduous taxa and was separated due to its negative loading to both PC2 and PC3. Mediterranean taxa and Cistaceae were included in C4 and showed a positive loading to PC3 and negative loading to PC2.

PC2 explained 32.2% of the variance. Loadings of PC2 were markedly positive for steppic and xerophilous taxa (C1), typical of arid conditions, while they were negative for Mediterranean and deciduous taxa, typical in wetter environments. PC2 thus appeared to discriminate between herbaceous taxa (*Artemisia*, Chenopodiaceae, *Ephedra*) adapted to low atmospheric moisture (arid to semi-arid conditions), representing open landscapes, and a plant community (Mediterranean and deciduous) requiring adequate rainfall (forest taxa). Thus, PC2 allowed discrimination between open landscapes and forest development.

The PCA performed on the pollen dataset showed that 25.4% of the variance was explained by PC3, which was characterized by a positive loading for clusters C1 and C4 and a negative loading for clusters C2 and C3. PC3 thus appeared to slightly discriminate between colder (Cupressaceae) and more humid conditions (deciduous). Of note, steppic and Mediterranean taxa showed low positive loadings to PC3, which was interpreted as their presence both in warmer and drier conditions.

In this regard, the presence/absence and frequency of *Artemisia* have been traditionally interpreted as the development of cold steppe environments in Europe (Pons and Reille 1988; Follieri et al., 1988; de Beaulie et al., 1992; Reille et al., 2000). However, *Artemisia* was also found in warm/arid conditions in the southern area of the Iberian Peninsula, although at smaller percentages (Díaz de la Guardia and Alba 1998; Ruiz et

al., 1999; Sabariego et al., 2002; Torres et al., 2020). Furthermore, the presence of *Artemisia* has been also linked to warm/arid conditions in eastern Iberia during the Holocene (Aranbarri et al., 2014) and the Pleistocene (González-Sampériz et al., 2020). In contrast, the increase in Cupressaceae (*Juniperus*) has traditionally been found to be linked to cold episodes, specially in central and southern Iberian Peninsula (Valdeolmillos et al., 2003; González-Sampériz et al., 2010; Vegas et al., 2010; López-Merino et al., 2012; Iriarte-Chiapusso et al., 2016).

Therefore, C1 included steppic and xerophilous taxa, indicating arid scenarios; in C2, Cupressaceae was abundant, linked to colder and semi-arid conditions; in C3, deciduous taxa and Cistaceae were abundant within a warm-temperate/wetter scenario (Mediterranean-like climate with higher moisture); and in C4, Mediterranean taxa predominated in a temperate/wetter scenario (Mediterranean-like climate).

To summarize the main characteristics of all the data, we also used a box plot (Fig. 6), as it represents the global view of the frequency (qualitative and quantitative) of each variable (group) through the interquartile range and the maximum and minimum values. In brief, the box plot gives information about the distribution and symmetry or asymmetry of the data.

Taking these considerations into account, we described the changes in the palynozones in terms of paleoclimatological variations.

4.2 Pollen zonation

We identified four pollen assemblage zones (Fig. 4, Table 4), which corresponded to major shifts in Northgrippian and Meghalayan vegetation, these reflecting distinct paleoenvironmental conditions. The pollen concentration was somewhat lower during Zone IV, with an increasing trend in Zone III and Subzone II-d, followed by a decline in

Subzone II-c, and high pollen concentrations in Subzones II-b, II-a and Zone I (Fig. 4). The pollen zones are described below:

Zone IV *(11.1-10.7 m; 7,300 – 7,000 yr cal BP- Northgrippian)*

There was reduced tree cover, with the development of Cupressaceae and to a lesser extent *Pinus*, a reduction of Nitrophilic plants (*Plantago* and *Urtica*), the expansion of Cosmopolitan plants and mainly the development of steppic taxa (Chenopodiaceae). In this regard, the Mediterranean forest was represented (evergreen *Quercus*), with slight variations. Of note, palm hearts were present and, overall, drier conditions were detected. Based on the PCA, samples of Zone IV were included in C2 (Fig. 5 a, b). Thus, an open steppe developed, which consisted predominantly of Chenopodiaceae, *Artemisia* and *Ephedra*, linked to greater aridity, together with cooler conditions that would favor the development of Cupressaceae (*Juniperus*) and scrubs. The box plot (Fig. 6) showed high interquartile ranges (47.6-58.1) of steppic plants. Of note, Cupressaceae provided the highest interquartile range in the whole record (9.4-19); their low dispersion and high concentration make these taxa determinant elements in the distribution of the samples in the PCA diagram (C2). Deciduous (1.72) and Mediterranean taxa (2.9) showed low values.

Zone III (*10.14–6.54 m; 6,800–4,000 yr cal BP; Northgrippian and Meghalayan)*

It was characterized by the development of pine forest, the progressive loss of Cupressaceae, and the increase of Mediterranean taxa (evergreen *Quercus* and *Olea*). The presence of Riparian (*Ulmus* and *Alnus*) and deciduous (*Corylus* and deciduous *Quercus*) taxa was relatively constant, while steppic taxa decreased slightly compared to the previous zone, and the presence of xerophilous plants increased. The development of

scrubs, mainly Cistaceae, Ericaceae and Rosaceae, together with Cosmopolitan plants, was also constant, while there was a punctual development of Nitrophilous plants (*Plantago*). The differentiation of three subzones was based on the development of the groups considered (Fig. 2-4), as well as on the succession observed in the appearance of the NPP markers of dry conditions (T-3B and T-10) and those associated with wildfires (T-55C and T-7A). NPPs associated with humid conditions (T-315 and T-18) showed their highest content in subzones III-a and III-c,

The distribution of samples in the PCA (Fig. 5a, b) followed a dominant pattern, marked by the location of most samples in C3 and C4, defined by the dominance of deciduous and Mediterranean taxa. These observations were reflected in the box plot (Fig. 6), characterized by a clear decrease in steppic plants, whose interquartile range (15.1-31.7) explained their small weight in the distribution of the samples in the PCA. The interquartile range (6.5-15.0) of Mediterranean taxa was important for their classification, as was that of *Pinus* (with a range of 16.0-29.0). Another notable observation was the decline of deciduous taxa, whose range varied between 0.5 and 2.57. However, these plants were important for the classification of the samples in the PCA diagram because of the compensated weight of scrub development (Fig. 5a). The position of the samples along each of the clusters (Fig. 5b) revealed the differentiation of the subzones established in the pollen diagram (Fig. 4). Therefore, Subzone III-c (10.2-8.7 m; 6,800-5,650 yr cal BP) was defined by the samples belonging to C3 and C4, with some samples included in C1—dominated by steppic taxa—and C2; samples of Subzone III-b (8.7-7.4 m; 5,650-4,800 yr cal BP) were included in C3, with some also in C4 and C2. Finally, in Subzone III-a (7.4-6.54 m; 4,800-4,000 yr cal BP), the samples were located within C3 and C4. This distribution marked the decline of steppic taxa and the dominance of Mediterranean

taxa and scrubs, indicating the development of a Mediterranean climate, with lower humidity than in Subzone III-b and associated with a warmer temperature.

Zone II *(648-365 cm; ca. 4,000-1,850 yr cal BP age- Meghalayan)*

Its main characteristic was the considerable loss of tree cover due to a decrease in pine forest and a less pronounced decrease in other forest taxa. Cupressaceae showed a low and discontinuous presence, steppic (*Artemisia* and Chenopodiaceae) taxa dominated over xerophilous plants, and the presence of Cistaceae and the Cosmopolitan plants were more stable. Aquatic plants appeared with the lowest percentages, as did the NPPs associated with humid conditions (T-315 and T-18), and only a few spores were detected. In contrast, *Glomus* was present. There was a continuous presence of coprophilous NPPs (T-55A, T-113 and T-368), and NPP markers of wildfires (T-55C and T-7A) appeared sporadically. In this framework, the identification of four subzones was defined by the behavior of Steppic taxa, scrubs and Mediterranean taxa (*Olea* and evergreen *Quercus*) (Table 3). Thus, Subzone II-d (6.5-5.7 m; 4,000-3,000 yr cal BP) showed the lowest abundance of the forest taxa and Subzone II-c (5.7-5.3 m; 3000-2800 yr cal BP) low pollen abundance, although the pollen spectrum was similar to that of Subzone IId. Subzone II-b (5.3-4.8 m; 2,800-2,500 yr cal BP) was characterized by the development of a Mediterranean forest (*Olea* and evergreen *Quercus*), an increase in deciduous taxa (*Corylus*), and the decline of xerophilous plants. Subzone II-a (4.8-3.6 m; 2,500-1,850 yr cal BP) was characterized by a considerable increase in steppic taxa (Chenopodiaceae and *Artemisia*), a reduction of the Mediterranean forest and a slight expansion of *Pinus* and Cupressaceae.

Samples were located mainly in C1 of the PCA, dominated by steppic taxa, and some were placed in C4, in this case, due to the development of scrub. Thus, the box plot

(Fig. 6) reveals the clear dominance of steppic taxa, whose concentration or interquartile range (48.3-66.6) was the highest in the whole record and also presented a symmetrical distribution. It also revealed the low weight of the rest of the pollen groups considered, except for Mediterranean taxa, although this group presented a lower interquartile range than that of the previous zone. The classification samples within the clusters identified in the PCA (Fig. 5a) allowed identification of the subzones defined in the pollen diagram (Fig. 5b), with a dominance of the samples corresponding to Subzones II-d, II-b and II-a in C1, thereby marking an important change in humidity (strong decrease) in the area and, therefore, the type of landscape developed (very open). Only Subzone II-c was distributed between C3 and C4, together with the samples located in the boundary between Subzones II-b and II-a, although in this case they temporarily belonged to C2. All these observations reflect changing conditions in a globally dry context.

Zone I (*365-340 cm; 1,850-1,700 yr cal BP- Meghalayan)*

It was characterized by a sharp decrease in taxonomic biodiversity, associated with the loss of tree cover and an increase in steppic taxa (Chenopodiaceae and *Artemisia*). In the lower part, *Glomus* and coprophilous NPPs showed markedly increases, together with NPPs typical of dry conditions (T-3B) and associated with fire (T7A). Samples of Zone I were located between C4 and C1 in the PCA, following the trend shown in the samples at the top of Zone II, indicating continuity of the processes initiated in it. This observation explained why the box plot (Fig. 6) presented the highest values of steppic taxa and the lowest ones in the rest of the pollen groups.

5. Discussion

Here we used pollen analysis to interpret the paleoenvironmental changes that occurred in the sedimentary record of Cartagena Bay during the Northgrippian and Meghalayan. In this study, we used the variations between mainly steppic, Mediterranean and deciduous taxa, together with Riparian and Aquatic taxa, to reconstruct the natural paleoclimatic variability in the southwestern Mediterranean realm since the Northgrippian. Furthermore, we used the development of nitrophilic plant communities, together with some NPPs, to identify anthropic influence.

We also compared the pollen record of Cartagena with those of other localities in the Iberian Peninsula (Fig. 7a). It has to be taken in to account that Cartagena is included within a semi-arid climatological region (Rubel and Kottek 2010; Chen and Chen 2013), while Villarquemado (Aranbarri et al., 2014), Navarrés (Carrión and van Geel, 1999) and Siles (Carrión, 2002) belong to the Mediterranean climatic region (Fig. 1). In this regard, the steppic and xerophilous taxa showed a wide predominance along the whole Cartagena record, whereas in the other record did not show such adundance (Fig. 7a). In contrast, the increase in *Pinus* has also been considered a marker of aridity in the other records (Carrión and van Geel, 1999; Carrión, 2002; Aranbarri e tal., 2014). Furthermore, these pollen records are located at diverse altitudes, although the general pollen trends showed similar variations.

5.1 Thermo-mesophytic Middle Holocene (Northgrippian) optimum

During the Northgrippian, two phases were identified, an initial one (Zone IV) with a marked decline in forest between 11.1 and 10.7 m (ca. 7,300-7,000 yr cal BP). Of note, this event was one of the most significant decreases in Mediterranean and deciduous taxa (up to 5%), paralleled by an increase in Cupressaceae, which would indicate a cold and dry stage as there was also an increase in steppic taxa. This phase may have been due

494 to local altitude and proximity to the sea, although it could also be explained as a response
495 to strong evapotranspiration rates caused by a increase in summer temperatures (Laskar
496 et al., 2004; Fletcher and Sanchez Goñi, 2008; Jiménez-Moreno et al., 2012; Fletcher et
497 al., 2013). These conditions can be correlated with Bond episode 6 (Bond et al., 2001),
498 linked to cold conditions (Fig. 8). In this regard, a high coherence between loss on ignition
499 values in the Burg Lake (Pyrenees) and ice rafted debris (Bond events) has been also
500 observed, which indicates that submillennial climate fluctuations in the Pyrenees can be
501 linked to the North Atlantic influence (Pèlachs et al., 2011).

502 Later (ca. 6,800-4,000 yr cal BP), the pollen diagram showed forest expansion,
503 with the highest values (average 70%) of Mediterranean, deciduous and Riparian taxa
504 (Zone III). This mesophytic optimum supports the notion of wet thermo-mesophytic
505 conditions and forest maximum in the Mediterranean realm during the Northgrippian,
506 which was followed by a progressive rise in aridity and xerophytization between the
507 Northgrippian to Meghalayan. This mesophytic optimum is also detected in continental
508 sequences from the south of the Iberian Peninsula (Figs. 7a, 8), from lowlands (Pantaleón-
509 Cano et al., 1999, 2003; Fletcher et al., 2007) and mountainous areas (van Geel and
510 Carrión, 1999; Carrión, 2002; Carrión et al., 2004, 2007; Jiménez-Moreno and Anderson,
511 2012; Aranbarri et al., 2014; Ramos-Román et al., 2016, 2018 a,b; Mesa-Fernández et al.,
512 2018; Di Rita, 2022), to marine records from the southwestern Mediterranean region
513 (Fletcher and Sánchez-Goñi, 2008; Di Rita et al., 2018, 2022), and in North Africa (Lamb
514 and van der Kaars, 1995) in the period ca. 7,500–4,000 yr cal BP (Figs. 7a, 8). In this
515 regard, Anderson et al. (2011) suggest a certain difference in the age of the mesophytic
516 optimum between montane and subalpine records and coastal ones (Figs. 7a, 8). The
517 forest development and lake water levels could be linked to the different effect of
518 maximum summer insolation and the seasonality of effective rainfall during the

519 Meghalayan. Nevertheless, this optimum lasted until ca. 4,500 yr cal BP in the coastal
520 area of Almería (Pantaleón-Cano et al., 1999, 2003) and in the southern part of the Iberian
521 Peninsula (Gil-Romera et al., 2010), and ca. 4,000 yr cal BP in the coastal area of
522 Mazarrón (Carrión et al., 2018), only 50 km south of Cartagena, and in mountainous sites
523 in this area (Carrión et al., 2004, 2007). Of note, two periods with increasing aridity within
524 the thermo-mesophytic Northgrippian optimum showed a good correspondence with
525 other pollen records (Fig. 7a, Carrión and van Geel, 1999; Carrión, 2002; Aranbarri et al.,
526 2014).

527 Thus, the first phase was linked to humid conditions that can be correlated with
528 data from other records in the western Mediterranean region that also show similar
529 characteristics during Northgrippian and a transition towards drier conditions in the
530 Meghalayan (Carrión and van Geel, 1999; Carrión, 2002; Carrión et al., 2010; Anderson
531 et al., 2011; Fletcher et al., 2013; Aranbarri et al., 2014, among others).

532

533 *5.2 Dry Upper Holocene (Meghalayan)*

534 The pollen record indicated a significant transformation of vegetation during the
535 Meghalayan (ca. 4,000 yr cal BP), with the substitution of Mediterranean and deciduous
536 taxa for steppic and xerophilous species, in parallel with the progression of open
537 landscapes, thereby confirming a progressive tendency towards the aridification detected
538 in the south of the Iberian Peninsula (Fig. 7a). The tendency towards aridification can be
539 clearly seen in Sierra Nevada records, where there was little influence from human
540 activity (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Jiménez-Moreno
541 et al., 2013; Jiménez-Espejo et al., 2014; Ramos-Román et al., 2016, 2018b).

542 This aridification trend that has occurred since the beginning of the Meghalayan
543 is also found in other records of the western Mediterranean realm (Figs. 7a, 8; Lamb and

van der Kaars, 1995; Pantaleón-Cano et al., 1999, 2003; van Geel and Carrión, 1999; Carrión, 2002; Fletcher et al., 2007, 2013; Fletcher and Sánchez-Goñi, 2008; Carrión et al., 2010, 2018; Aranbarri et al., 2014). Similarly, there was good correspondence of our findings with general aridification phases inferred from pollen ratios on the Mediterranean coasts of France and Spain (Jalut et al., 2000).

This decline in forests in the western Mediterranean region between the Northgrippian and Meghalayan was related to a decrease in winter rains as a consequence of a northward shift of the westerlies (a positive NAO trend), which induced drier conditions in this area (Jiménez-Moreno and Anderson, 2012; Magny et al., 2012; Fletcher et al., 2013; Di Rita et al., 2022). In this regard, the predominant phases of NAO-like circulation (positive and negative) conditioned the climate pattern of the Mediterranean after 6,000 yr cal BP by modulating the long-term trend of intensity and position of the westerlies (Fletcher et al., 2013; Di Rita et al., 2022).

In addition, the decrease in summer insolation would have caused progressive cooling, with a reduction in the duration of the growing season, as well as a decrease in the sea surface temperature (Marchal et al., 2002; Fletcher and Sanchez Goñi, 2008), thereby bringing about a decrease in the land-sea contrast, which would be reflected in a reduction of the wind system and a reduced precipitation gradient from sea to coast during the autumn-winter season. Likewise, a climatic transition has been observed in the coastal area of the Apulia region (southern Italian Peninsula (De Santis and Caldara, 2015) at ca. 4,500 yr cal BP due to changes in the Mediterranean wind regimes.

5.3 Deforestation and anthropic influence

Anthropic impact can be detected on the basis of various palynomorphs. This is the case of nitrophilic plants, such as *Plantago*, Polygonaceae, *Rumex* and *Urtica* (Riera

et al., 2004), as well as Chenopodiaceae (Sadori et al., 2013). Some species of Cichorioideae have been described as nitrophilic taxa (Abel-Schaad and López-Sáez, 2013) and as indicators of grazing (Mercuri et al., 2006; Florenzano et al., 2015; Sadori et al., 2016). In addition, some NPP groups, such as the coprophiles (*Riccia*, *Sordaria*, *Podospora* and *Sporormiella*) and those linked to fires (*Neurospora* and type T-7A), are also used as indicators of anthropization and land use (van Geel et al., 1989; Riera et al., 2006; Carrión et al., 2007; Ejarque et al., 2015). Following van Geel et al. (1989), Morellón et al. (2016) and Sadori et al. (2016), we also considered soil mycorrhizal fungi, the NPP *Glomus* sp., and *Asphodelus* and *Pseudoeschizaeae circula* (Concentriciste) as indicators of erosive activity. To check anthropic influence we constructed a pollen index that consisted of the sum of Nitrophilous and Coprophilous taxa together with NPPs markers of eutrophication, fire, and erosive processes and these pollen taxa and NPPs taxa (Fig. 7b).

We detected evidence of human activity in the area at the top of the sequence (< 4,000 yr cal BP). Of note, during the Meghalayan, the pollen indicators of anthropic activities were discrete or sporadic, which would reveal a small amount of anthropic pressure on nearby ecosystems or far extensive activities. In contrast, in the last 4,000 yr cal BP, there were clear signs of the effects of significant anthropic activity on the environment, evidenced by marked deforestation, along with an increase in both Nitrophilic and Coprophilous plant taxa, as well as in NPP markers of eutrophication, fire and erosive processes (Fig. 7b). Thus, human activities drove ecological degradation in the coastal environment of Cartagena and led to a notable reduction of vegetation, with a very clear turning point starting at 4,000 yr cal BP, which was especially marked during the Roman period when maximum degradation occurred. In this regard, in the archeological settlement Punta de Los Gavilanes (50 km from Cartagena), the

anthracological sequence highlights extensive deforestation, which has been linked to the local impact of metallurgy since ca. 2,800 yr cal BP (García-Martínez and Ros-Sala, 2010; García-Martínez et al., 2013).

Thus, the increase in all these taxa points to considerable human intervention on the landscape, which would include the use of fire, agricultural activities, grazing, opening of the landscape, coinciding with the intense mining-metallurgical activity observed in the area of Cartagena since at least ca. 4,500 yr cal BP (Fig. 7b, Manteca et al., 2017; Ortiz et al., 2021, 2022). Moreover, fecal stanols, such as coprostanol and 24-ethylcoprostanol were abundant in the Cartagena record from the late Bronze Age (Fig. 7b), thus indicating a continuous presence of human populations and significant pollution input (Ortiz et al., 2022).

The changes caused by these activities occurred in a context of great environmental fragility, which may have accelerated their consequences. This intense anthropic activity is also detected in other sequences in the area, such as in the southeast area of the Sierra de las Moreras from the transition from the Final Neolithic to the Chalcolithic (Muñoz Amilibia, 1993; Ros Sala, et al., 2008). Similarly, Carrión et al. (2018) suggested that intense deforestation occurred in the area of Mazarrón after ca. 4,000–3,500 yr cal BP and may have begun earlier. Also, in Chalcolithic archaeological sites of Almería, Rodríguez-Ariza (2000) detected significant denudation of the landscape at ca. 4,600-4,300 yr cal BP. In this regard, the south-eastern area of the Iberian Peninsula, especially around Cartagena, is one of the regions in the western Mediterranean realm in which metallurgy first occurred, in particular since ca. 5,100 yr cal BP.

Therefore, the significant transformation of vegetation that began ca. 4,000 yr cal BP, with forest degradation and a rise in steppic and xerophytic vegetation caused by increased aridity ran in parallel with human activities, which accelerated the progression

of open landscapes from the Chalcolithic onwards, as also observed by Carrión et al. (2007, 2010).

Nevertheless, using a high-resolution analysis of fire-vegetation relationships, Gil-Romera et al. (2010) noted that the coastal highlands of southeastern Spain, which were consistently more populated than inland regions, present earlier and more abrupt fire activity, even during the Northgrippian. Indeed, Carrión et al. (2018) detected a burning pattern in palynozone 3 of Mazarrón.

6. Conclusions

The pollen analysis of the Cartagena Bay record allowed the paleoclimatic and paleoenvironmental reconstruction of the last 7,300 yr cal BP of the area and the western Mediterranean realm. This study, supported by comparison with other Mediterranean and North Atlantic records, points to a link between vegetation, atmospheric dynamics, insolation, and solar activity during the Holocene.

The Northgrippian was characterized by a generalized cold and dry episode at ca. 7,300 yr cal BP. A significant optimum was detected between 6,800 and 4,000 yr cal BP, when forest expansion peaked. This occurred as a response to humid winters and very hot and dry summers, as a response to greater seasonality. These interpretations come from pollen data for deciduous, Mediterranean and Riparian taxa. A climatic trend towards aridification occurred during the Meghalayan (ca. 4,000 yr cal BP), which was probably linked to an orbital-scale decreasing trend in summer insolation. This trend was observed in the pollen data, through a strong decrease in arboreal taxa (deciduous, Mediterranean and Riparian), as well as a marked increase in steppic taxa. These events can be correlated with climate variability on a regional and global scale. The cold and arid pulse identified in our study was almost synchronous with the cold events recorded in the North Atlantic

and with the decrease in rainfall in the Mediterranean area, probably linked to a persistence of a positive NAO mode.

The sharp decrease in Mediterranean, deciduous and Riparian taxa was associated with the development of open landscapes, which points to the installation of more arid conditions. In addition to the natural climate and environmental variability, there was strong evidence of human activities in the area during this period. This observation suggests that the tendency to natural aridification during the Holocene in the southern area of the Iberian Peninsula was intensified by human activities: mainly mining/metallurgical activities, and also open landscapes, agriculture, and grazing. In addition, the analysis carried out in the Cartagena record showed changes in the environment and climate that were almost coincident with the periodicities observed in solar, oceanic and NAO reconstructions and these changes could reflect a close cause and effect relationship between them.

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Tables

Table 1. Radiocarbon age (yr BP) of selected levels from E3 core and calibrated age (cal yr) converted using the Radiocarbon Calibration Program 7.0 (CALIB 7.0) (Stuiver et al., 2014) with the calibration dataset IntCal13 (Reimer et al., 2013) (Ortiz et al., 2021).

Sample No.	Level (m)	Material	$\delta^{13}C$(V-PDB)	Conventional age BP	Calibrated BP
CNA5242	3.81	charcoal	-21.3	2,022±28	1,972±76
CNA5243	4.50	charcoal	-23.6	1,955±28	1,907±79
CNA5244	4.83	charcoal	-26.7	2,023±27	1,972±75
CNA5245	5.82	charcoal	-23.0	2,174±28	2,263±45
CNA5246	6.88	Bivalve	2.8	3,817±29	4,219±78
CNA5247	7.41	Bivalve	0.4	4,253±29	4,839±25
CNA5248	8.01	*P. oceanica*	-11.7	4,731±38	5,455±129
CNA5249	8.07	*P. oceanica*	-11.2	4,052±36	4,525±103
CNA5250	9.00	*P. oceanica*	-9.8	3,787±36	4,185±105
CNA5251	10.95	charcoal	-27.4	7,017±46	7,843±103

Table 2. Mean aspartic acid and glutamic acid racemization ratios obtained in *C. torosa* valves from E3 core (Ortiz et al., 2021).

Level (m)	N	D/L Asp	D/L Glu	Age (cal. yr)
3.75	4	0.142±0.001	0.038±0.003	2,639±55
4.65	1	0.146±0.000	0.047±0.000	2,792
4.68	4	0.146±0.003	0.043±0.001	2,789±107
5.16	3	0.146±0.016	0.050±0.012	2,815±671
5.85	4	0.157±0.010	0.051±0.011	3,284±433
6.00	1	0.149±0.000	0.047±0.000	2,916
7.23	2	0.189±0.004	0.052±0.007	4,608±182
8.01	1	0.207±0.000	0.046±0.000	5,372
8.61	1	0.199±0.000	0.048±0.000	5,026
10.05	5	0.252±0.003	0.068±0.002	7,258±145
10.11	2	0.241±0.004	0.062±0.005	6,784±159
10.95	2	0.256±0.026	0.053±0.010	7,413±1073

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1034 **Table 3. Main taxa included in the palynological groups identified in the Cartagena record.**

Palynological Groups	Taxa
Pinus	*Pinus*
Cupressaceae	Cupressaceae
Mediterranean	evergreen *Quercus*, Oleaceae
Deciduous	*Castanea, Corylus, Fagus, Juglans, Tilia*, deciduous *Quercus*
Riparian	*Alnus, Betula, Salix* and *Ulmus*
Ericaceae	Ericaceae
Rosaceae	Rosaceae
Cistaceae	Cistaceae
Chamaerops	*Chamaerops*
Steppic	Chenopodiaceae, *Artemisia*, Ephedraceae
Xerophilous	Asteraceae liguliflorae (L), Asteraceae tubuliflorae (T), Poaceae
Nitrophilous	*Plantago, Polygonaceae, Rumex, Urtica*
Cosmopolitan	Rest of herbs
Spores	Monolete and trilete spores
Aquatics	Cyperaceae, *Alisma, Epilobium*, Ranunculaceae, *Typha*-m
NPP Coprophilous	*Riccia* or type 165, *Sordaria* or type 55, *Podospora* or type 365, *Sporormiella* or type 113
NPP edafic humidity	*Spyrogira* or type 18, *Zignema* or type 315
NPP dry conditions	*Pleospora* or type 3B, type 10
NPP mesoeutrophic conditions	*Valsaria* or type 140, Type 174, Type 181, Type 731
NPP oligotrophic conditions	*Rivularia* or type 170
NPP fires	*Neurospora* or type 55C, T-7A
Concentriciste	*Asphodelus*, *Pseudoeschizaeae circula*
Glomus	*Glomus fasciculatum* or type 207

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Table 4.

Age yr *cal BP*	Pollen assemblages	Landscape climate
47 taxa (16 arboreal, 4 shrubs, 27 herbaceous). 6 Aquatics, spores (monoletes and triletes) and 19 NPPs of diverse origin. Mediterranean climate with fluctuations in humidity and increase in anthropization		
< 2000	**Zone-I** Biodiversity decrease. Loss of forest cover. Increase of steppic (Chenopodiaceae). Presence of *Glomus* and NPP markers of dryness and fire. Lack of Nitrophilous taxa and Coprophilous NPP.	Dry Anthropic
2000 3000	**Zone-II** Decrease of biodiversity and arboreal taxa. Marked decrease of *Pinus* and Mediterranean taxa. Sporadic presence of deciduous and Riparian taxa. Absence of *Chamaerops.* Abundance of steppic (*Artemisia*, Chenopodiaceae) and xerophilous. Development of *Glomus* and Coprophilous NPP. Presence of humid NPP, dry NPP and NPP markers of fire. **IIa:** Development of Cupresaceae. Decrease of Cosmopolitan herbs. Increase of Coprophilous NPP. Presence of NPP markers of fire. **IIb**: Development of Mediterranean forest (*Olea*) and decrease of deciduous taxa. Increase of *Artemisia*. **IIc**: only presence of Mediterranean taxa, nitrophilous and coprophilous. **IId:** scarce arboreal cover. Expansion of *Artemisisa*, dry NPP and NPP markers of fire. *Pseudoeschizaea.*	Dry More anthropic influence
4000 5000 6000	**Zone-III** Expansion of AP (Mediterranean, *Pinus*, deciduous and Riparian). Decrease of Cupressaceae. Increase of Aquatics and humid NPP. More diversity of NPP. Punctual presence of *Pseudoeschizaea* (Concentriciste) **IIIa**: Maximum of AP (*Pinus*, evergreen *Quercus*, *Olea*, deciduous *Quercus*, *Castanea*). Rise of Aquatics and humid NPP. **IIIb**: increase of *Pinus* and presence of *Corylus*, *Fagus* and *Juglans*. Low content of xerophilous and steppic. Presence of *Chamaerops*. Decrease of Aquatics. More dry NPP than humid NPP. *Asphodelus*. **IIIc**: progressive decrease of Cupressaceae. Increase of biodiversity and abundance of Mediterranean, deciduous (*Corylus* y *Fagus*) and Riparian (*Alnus*, *Salix*, *Ulmus*) taxa, Aquatics and humid NPP. *Asphodelus* and NPP markers of fire. Low *Glomus*.	Mediterranean conditions Mediterranean relatively humid
7000	**Zone IV** Expansion of Cupressaceae. Low *Pinus* and Mediterranean taxa. Decrease of deciduous, Riparian and Aquatics. Presence of *Chamaerops*. Abundance of steppic (Chenopodiaceae).	Dry

Table 5. Principal component (PC) loadings (values higher than 0.5 are marked in bold), communalities and explained variance in PCA of Holocene sediments.

Variable	PC 1	PC 2	PC 3	PC 4	Communality
Pinus	**-0.723**	-0.363	-0.373	-0.234	0.794
Cupressaceae	-0.128	**0.595**	**-0.615**	-0.468	0.749
Mediterranean	**-0.769**	-0.345	0.115	-0.348	0.724
Deciduous	**-0.597**	-0.148	-0.404	**0.725**	0.542
Cistaceae	**-0.648**	-0.095	**0.545**	-0.135	0.726
Xerophilous	**-0.576**	**0.578**	0.086	0.240	0.674
Steppic	-0.354	**0.762**	0.277	0.036	0.783
% of Variance explained	38.78	27.20	20.40	10.42	

Figure captions

Fig. 1. A) Geographical location of Cartagena Bay and other records, including the areas of the Köppen climate classification (Rubel and Kottek 2010; Chen and Chen 2013). 1: Cartagena; 2: Alborán Sea; 3: Mazarrón; 4: Antas, San Rafael, Roquetas; 5: Siles; 6: Guadiana; 7: Villaverde; 8: Navarrés; 9: Villarquemado; 10: Tigalmamine; B) Geological setting of Cartagena with the location of E3 core: (1) El Armarjal marsh; (2) Barrio de la Concepción alluvial fan; (3) Benipila creek; (4) Navy port, formerly galley port of Mar de Mandarache; (5) El Hondón creek.

Fig. 2. Pollen diagram percentage of the main pollen taxa (Arboreal, Aquatic and NPP) plotted against depth (m) and age (ka). Pollen assemblage zones (Palynozones), defined from CONISS cluster analysis are indicated on the right.

Fig. 3. Pollen diagram percentage of the main pollen taxa (Shrubs and Herbaceous) plotted against depth (m) and age (ka). Pollen assemblage zones (Palynozones), defined from CONISS cluster analysis are indicated on the right.

Fig. 4. Pollen diagram inferred from Cartagenra record with the percentages of the main pollen assemblages plotted against depth (m) and age (ka). Pollen assemblage zones (Palynozones), defined from CONISS cluster analysis are indicated on the right and described in Table 4. The AP/NAP (Arboreal Pollen/Non Arboreal Pollen) ratio is included.

Fig. 5. a) Principal Component Analysis (PCA) from different pollen taxa showing the scatter plot with PC2 and PC3 axis; **b)** dowcore plot of the samples identified according to the clusters differentiated in the PCA.

Fig. 6. Box plots showing the frequence values of the main pollen groups (*Pinus*, Cupressaceae, Mediterranean, deciduous, steppic) in the palynozones.

Fig. 7. A) Comparison between the pollen record of Cartagena and that of other Iberian Peninsula localities: Villarquemado (Aranbarri et al., 2014), Navarrés (Carrión and van Geel, 1999) and Siles (Carrión, 2002). The location of these sites and the climatological region to which they belong are shown in Fig. 1. Dark dashed lines represent the Thermo-mesophytic mid-Holocene (Northgrippian) optimum (TMO) and the Dry Upper Holocene (Meghalayan) (DUH); and the red dashed lines represent two periods with increasing dryness. B) Comparison between the sum of pollen grains of Nitrophilic and Coprophilous taxa, as well as of NPP markers of eutrophication, fire and erosive processes, with the coprostanol/24-ethylcopostanol index indicative of fecal pollution (Ortiz et al., 2022) and anthropogenic Pb (Ortiz et al., 2021) along the Cartagena record.

Fig. 8. Comparison of paleoenvironmental episodes established for the Holocene in the Cartagena Basin from the pollen analysis (C) with those of other pollen records from marine [D: Fletcher and Sánchez-Goñi, (2008); E: Fletcher et al. (2013)]; coastal [F: Carrión et al. (2018); G: Pantaleón-Cano et al. (1999, 2003); H: Jalut et al. (2000)] and continental [I: Carrión (2002); J: Fletcher et al. (2007); K: Gil-Romera et al (2010); L: Lamb and van der Kaars (1995)] records for western Mediterranean. The solar output (A;

Perry and Hsu et al., 1999), and the percentage Drift Ice Index for the North Atlantic during the last 9 ka BP (B; Bond et al., 2001), are included. IRD, ice rafted debris. Sites location in Spain are shown in Fig. 1. The two horizontal grey bands marked the predominance of Mediterranean taxa and thus, thermo-mesophytic conditions.

Fig. 1 Supplementary Information. Bayesian age-depth models established for the Holocene record of E3 core (Ortiz et al., 2021) constructed using the software R-code package "Bacon 2.3.7". The black line indicates the single best model based on the weighted mean age for each depth, and the grey area shows 95% confidence intervals. Dates were obtained through radiocarbon, and amino acid racemization (Ortiz et al., 2021; Tables 1 and 2 Supplementary Information).

Figure 1

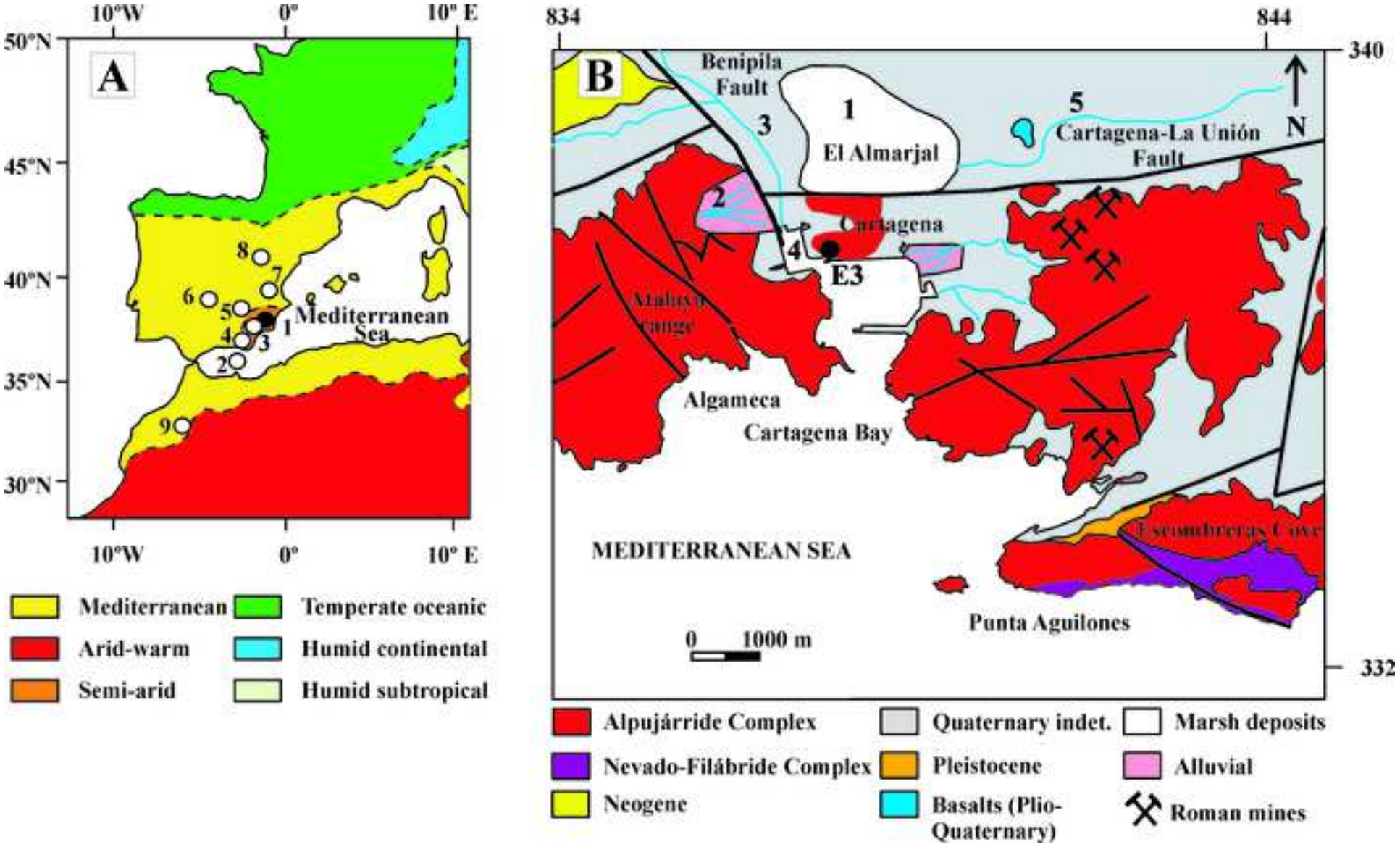

Figure 2

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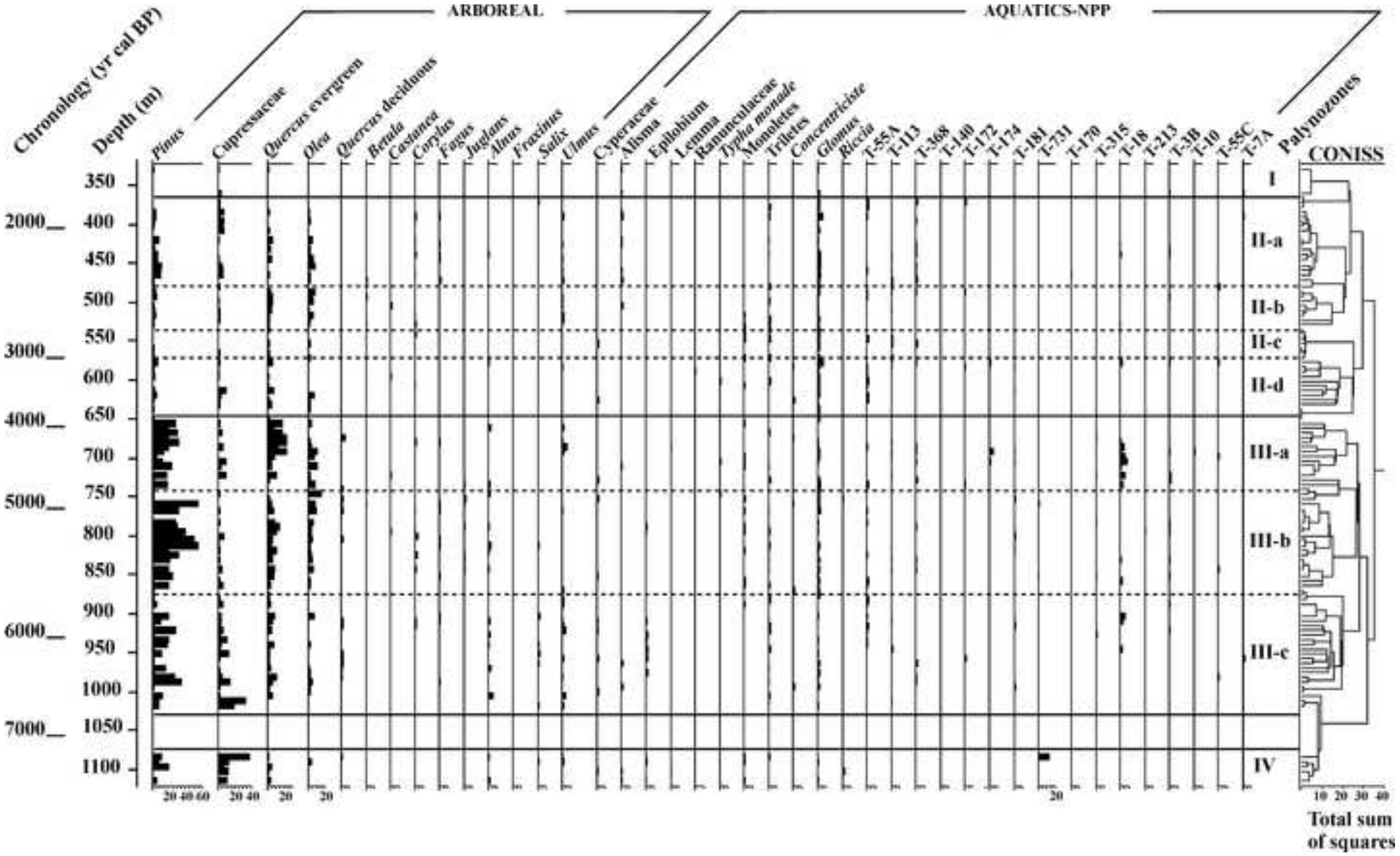

Figure 3

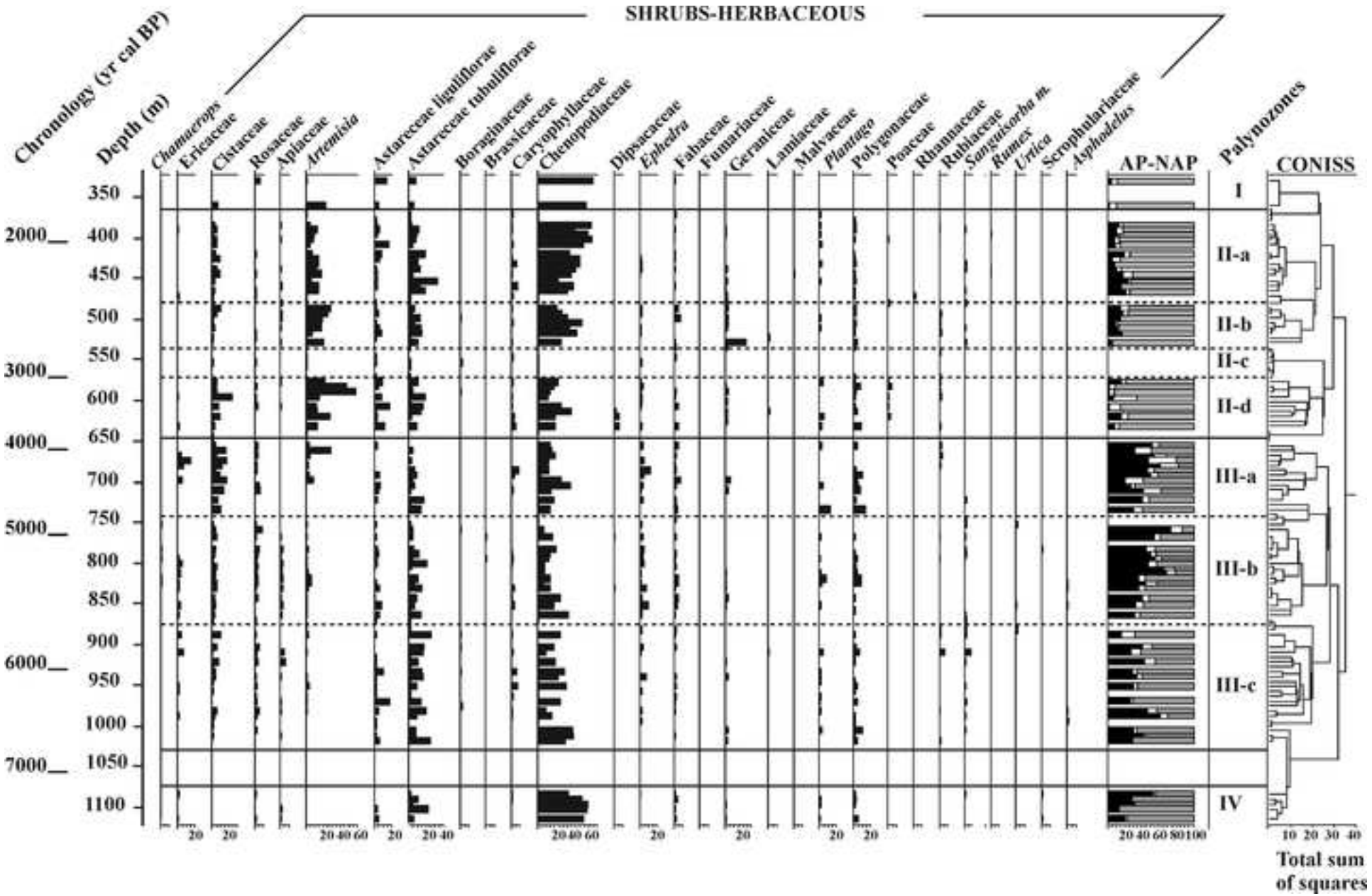

Figure 4

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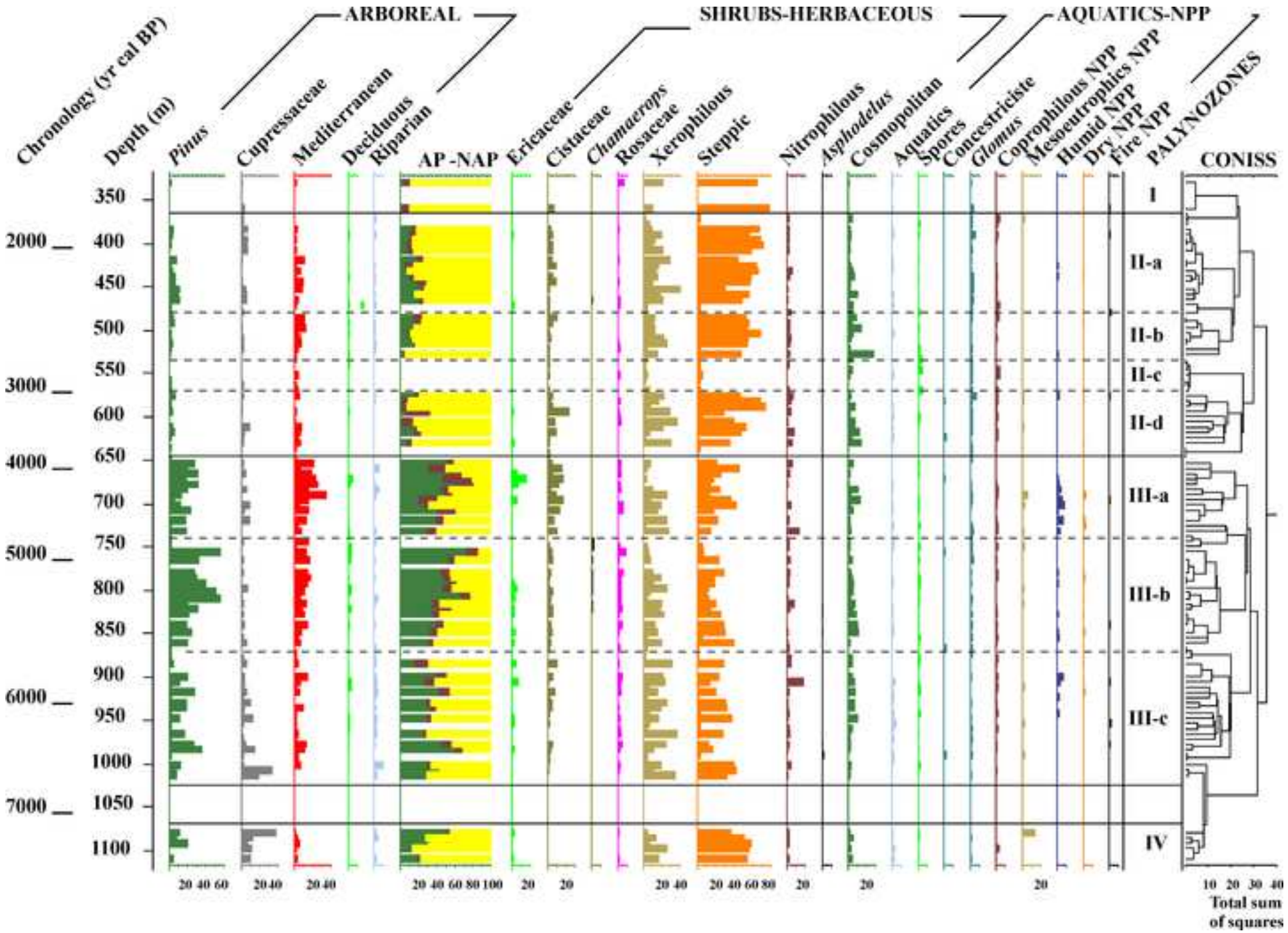

Figure 5

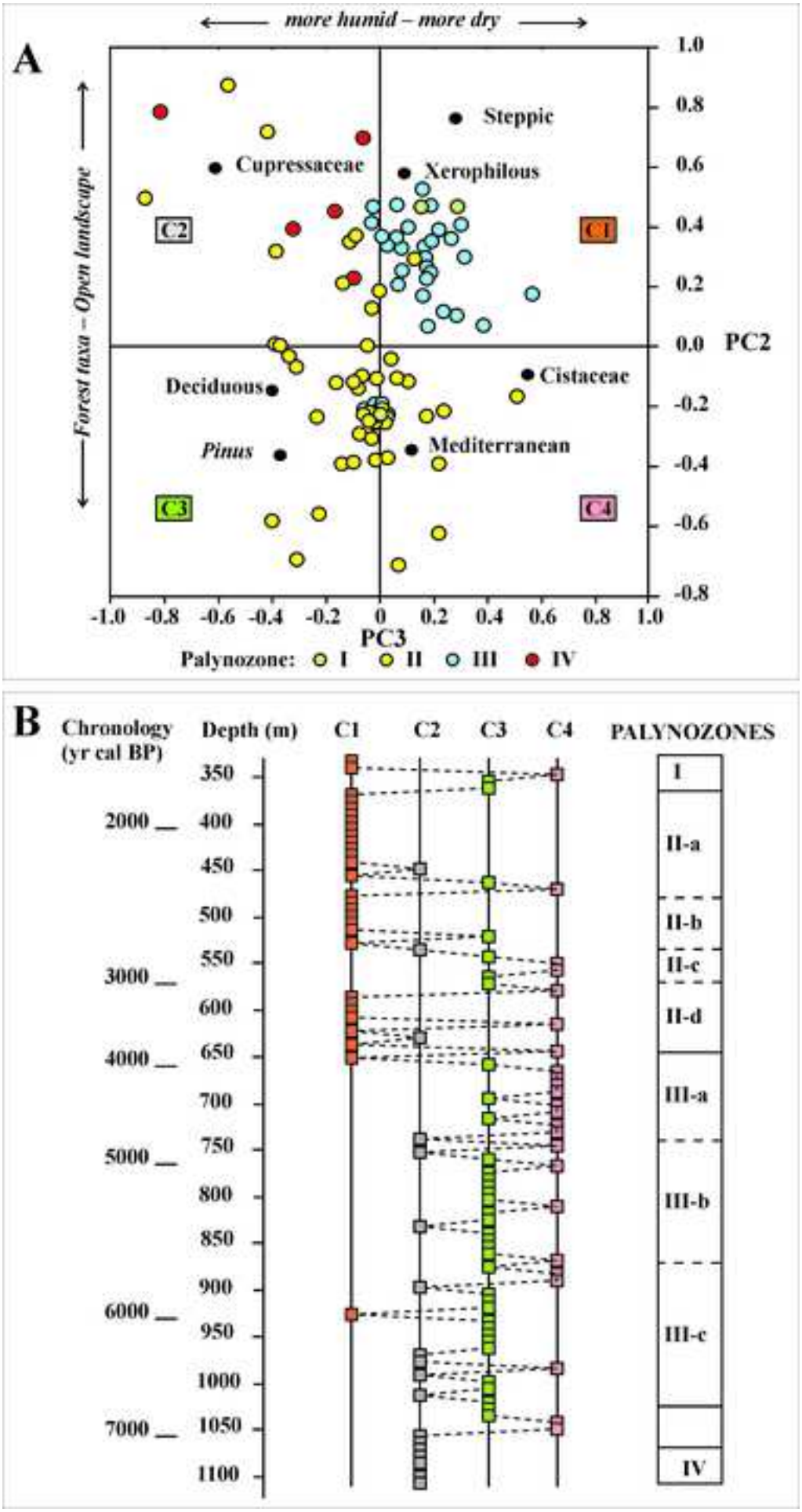

Figure 6

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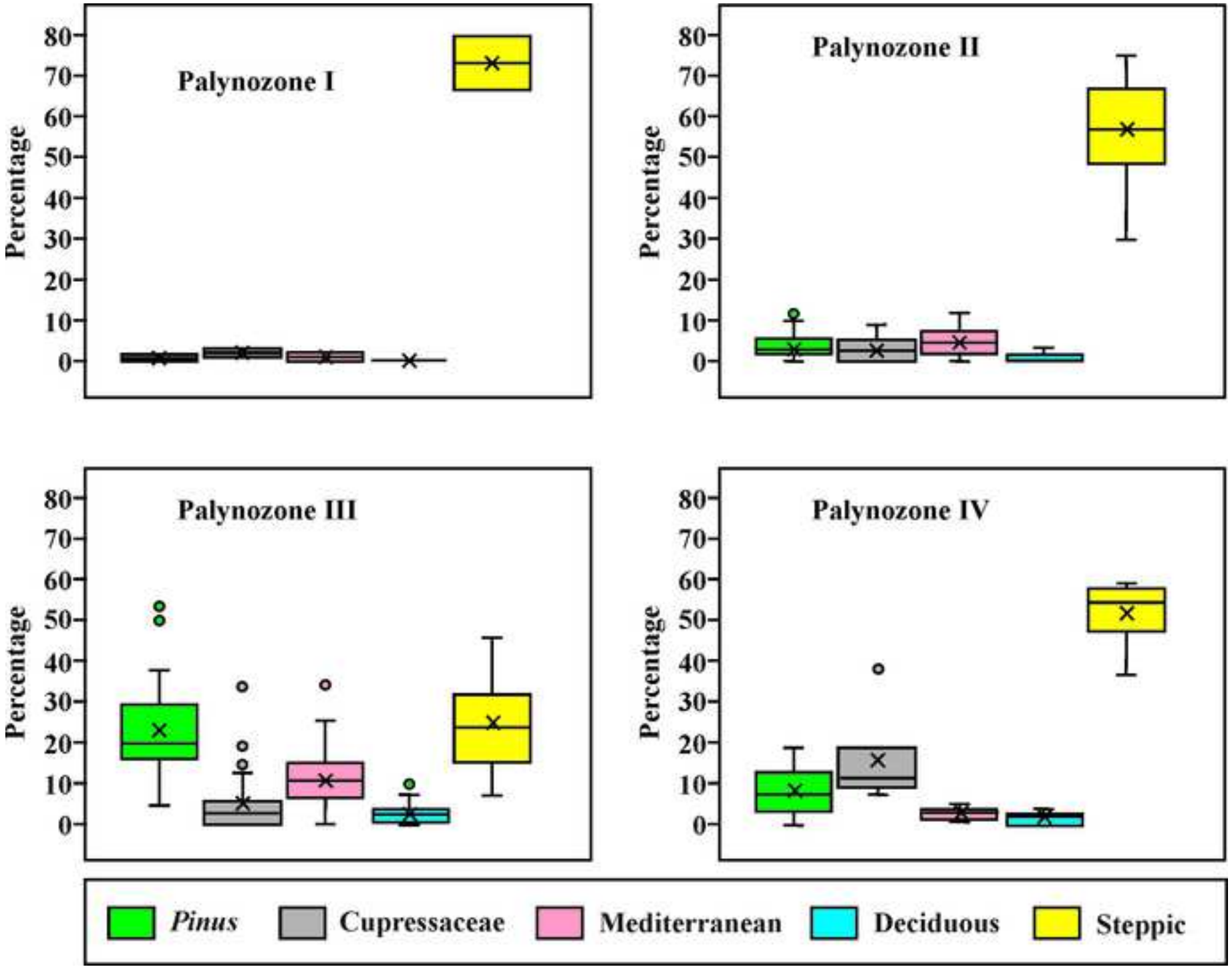
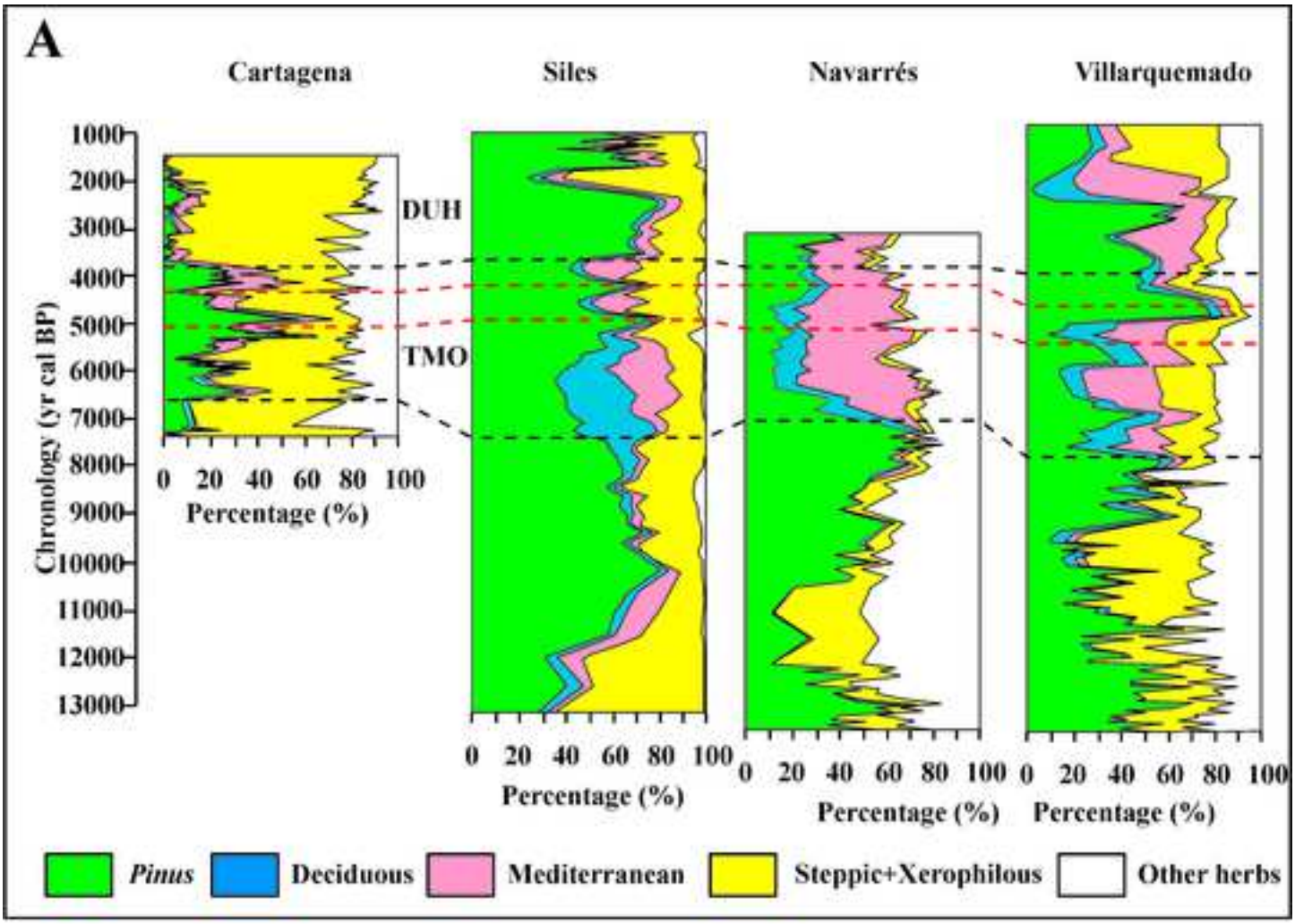


Figure 7



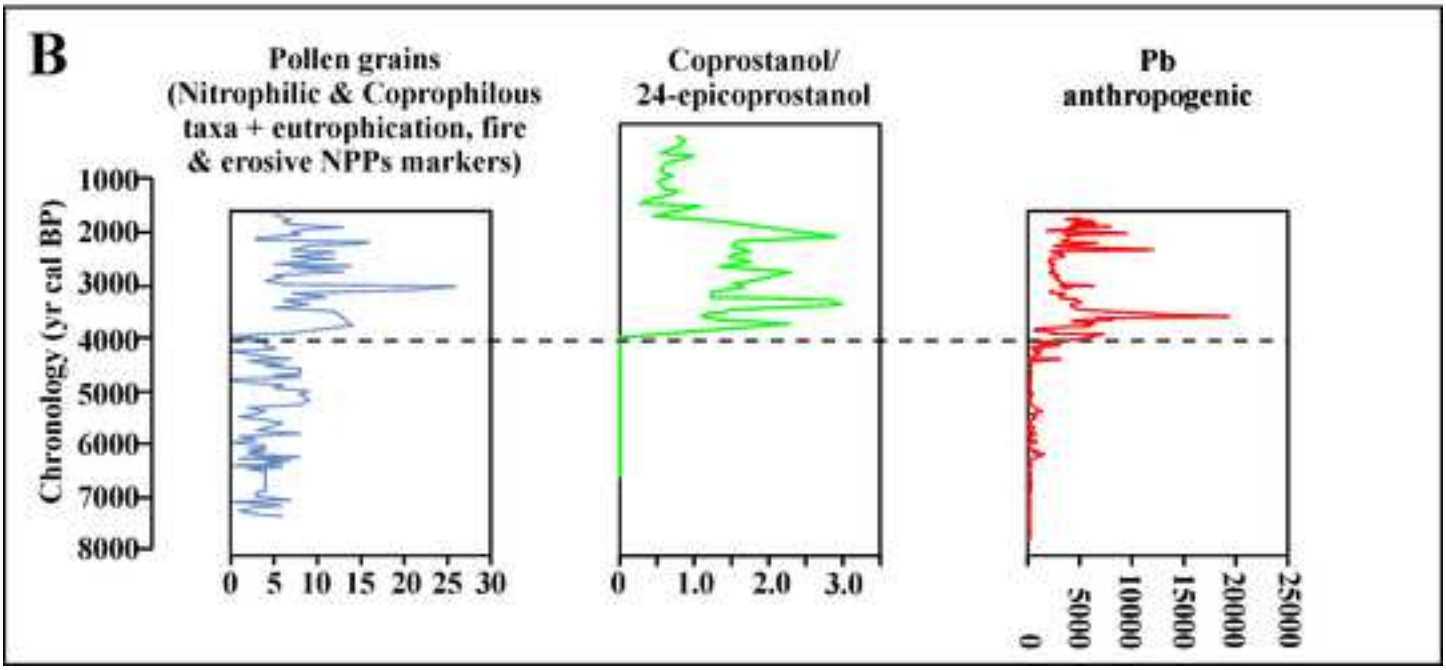


Figure 8

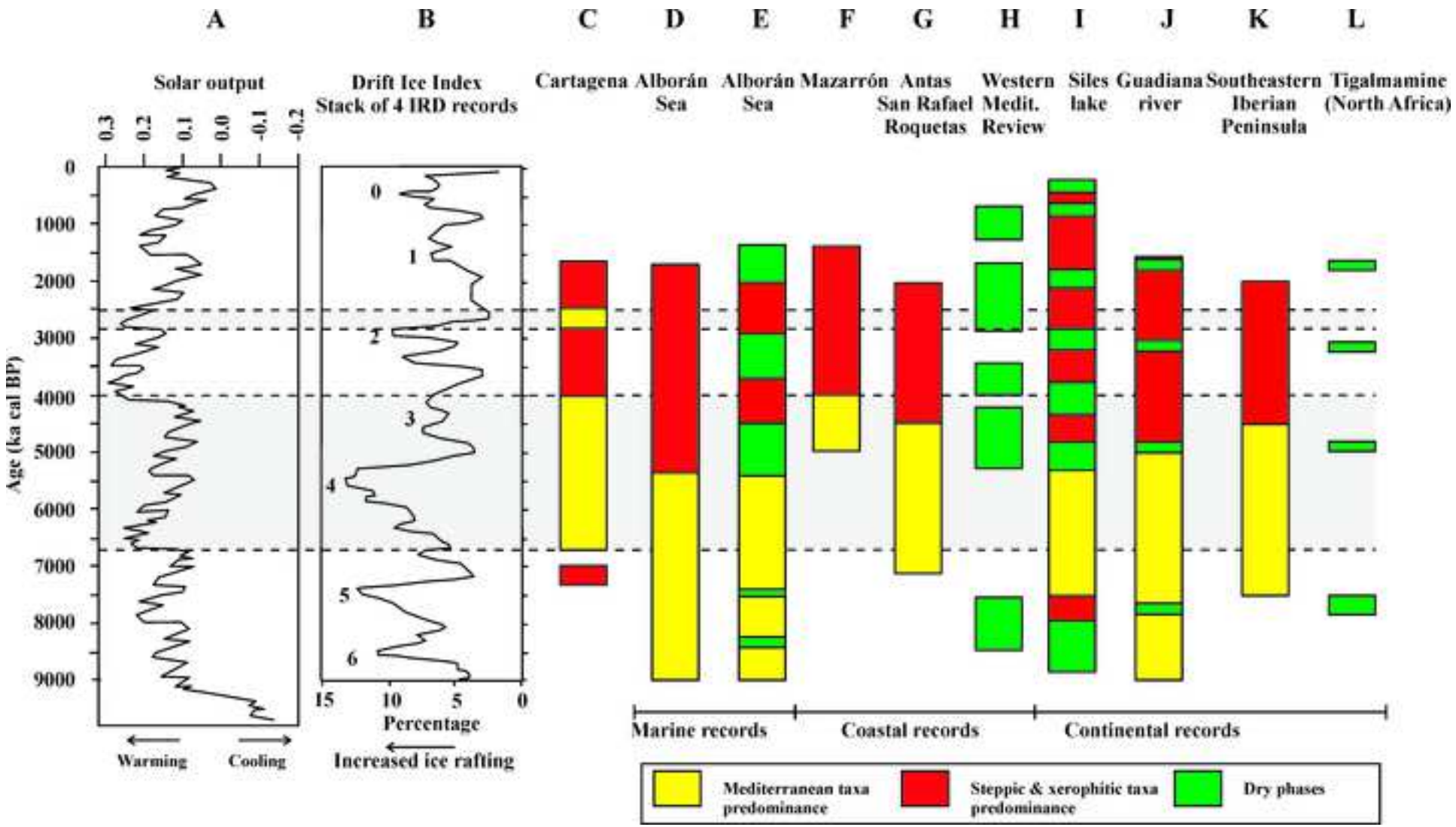


Figure 1 Supplementary Information

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