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► To cite this version:

Federico Di Rita, Matthieu Ghilardi, Nathalie Fagel, Matteo Vacchi, François Warichet, et al.. Natural and anthropogenic dynamics of the coastal environment in northwestern Corsica (western Mediterranean) over the past six millennia. *Quaternary Science Reviews*, 2022, 278, pp.107372. 10.1016/j.quascirev.2022.107372 . hal-03542871v2

HAL Id: hal-03542871

<https://hal.science/hal-03542871v2>

Submitted on 26 Jan 2022

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Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Natural and anthropogenic dynamics of the coastal environment in northwestern Corsica (western Mediterranean) over the past six millennia

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ARTICLE INFO

Article history:

Received 31 July 2021

Received in revised form

21 December 2021

Accepted 3 January 2022

Available online xxx

Handling Editor: Yan Zhao

Keywords:

Corsica

Pollen

Palaeoenvironments

Isotope geochemistry

Geoarchaeology

Western Mediterranean

Holocene

ABSTRACT

The present paper provides new insights into the climatic and anthropic factors that influenced a 6000-year coastal evolution in northwestern Corsica, the third largest island of the western Mediterranean. Pollen, microcharcoal, sedimentary and geochemical analyses were carried out on a core drilled in the Crovani coastal wetland to reconstruct the regional drivers of landscape change. We show that anthropogenic and climate-induced fires favoured the development of Mediterranean maquis, dominated by *Erica* and *Quercus ilex*, from ca. 6000 to 3350 cal. BP. A change in arboreal vegetation triggered a short but intense sediment input in the Crovani pond between ca. 3350 and 3200 cal. BP. This is consistent with a coeval process of runoff recorded in several coastal sites of western Corsica and related to an arid climate change occurred in many sites of the western Mediterranean around 3200 years ago. We provide evidence of agriculture during the Late Neolithic from ca. 3900 BC, which is much earlier than any archaeological evidence previously available in this area of Corsica, followed by a progressive decline of arable farming practices. Human impact has been responsible for a degradation of the maquis only from approximately 3000 cal. BP, and it intensified in Roman times, when the area experienced the first phase of galena exploitation from the Argentella mines. Over the last 500 years, the present work evidences a major development of *Castanea* related to cultivation during the Genoese administration of Corsica. Our findings suggest that solar activity and the North Atlantic Oscillation had an influence on centennial-scale forest cover variations during the last 6000 years.

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1. Introduction

The island of Corsica hosts the largest number of coastal wetlands among the Mediterranean islands (Ghilardi, 2020, 2021). Most of them formed after the Mid-Holocene sea-level stabilization that occurred in the Mediterranean Basin between 7000 and 6000 cal. BP (Vacchi et al., 2016, 2018). Amongst the ~200 coastal

wetlands of the island, brackish lagoons and coastal ponds are the most common geomorphological features (Ghilardi, 2020).

The high potential of pollen analysis to trace the main changes in the coastal landscape of the island was first highlighted by the remarkable palynological work of Maurice Reille (Reille, 1984, 1991; 1992a). However, these pollen data were not provided with a robust chronology and did not include the analysis of Non-Pollen Palynomorphs (NPPs) and other palaeoenvironmental proxies from the same core.

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In the last few years, several Corsican wetlands situated at a short distance of the sea were the subject of multiproxy geoarchaeological research on the environmental impact of human activities, especially in Prehistoric and Protohistoric times (Early Neolithic to Final Bronze Age, ca. 7500 BP to 2800 BP) (Currás et al., 2017; Ghilardi et al., 2017a; Revelles et al., 2019; Vella et al., 2019, Fig. 1). The study of different palaeoecological proxies, such as ostracods, molluscs, and pollen, combined with the chronostratigraphy of sediments, has shown the interest of reconstructing both the paleogeography and the history of the vegetation of coastal Corsica starting from the ancient Neolithic (Cardial culture, starting from 7500 ± 200 cal. BP; D’Anna et al., 2001; Lugliè, 2018).

The information of palaeoenvironmental records from Corsica is paramount for detailed reconstructions of both land-use patterns and centennial-scale climate changes in the Mediterranean Basin. Indeed, the island was a crossroad for many European and North African populations in the conquest of the Mediterranean and occupies a strategic geographical location, potentially sensitive to both North Atlantic climate patterns and north African atmospheric drivers (Sabatier et al., 2020).

The aim of this paper is to outline the landscape evolution in northwestern coastal Corsica over the last six millennia, taking advantage of the recent progress in palaeoenvironmental reconstructions (Henry et al., 2020), chronological models (Reimer

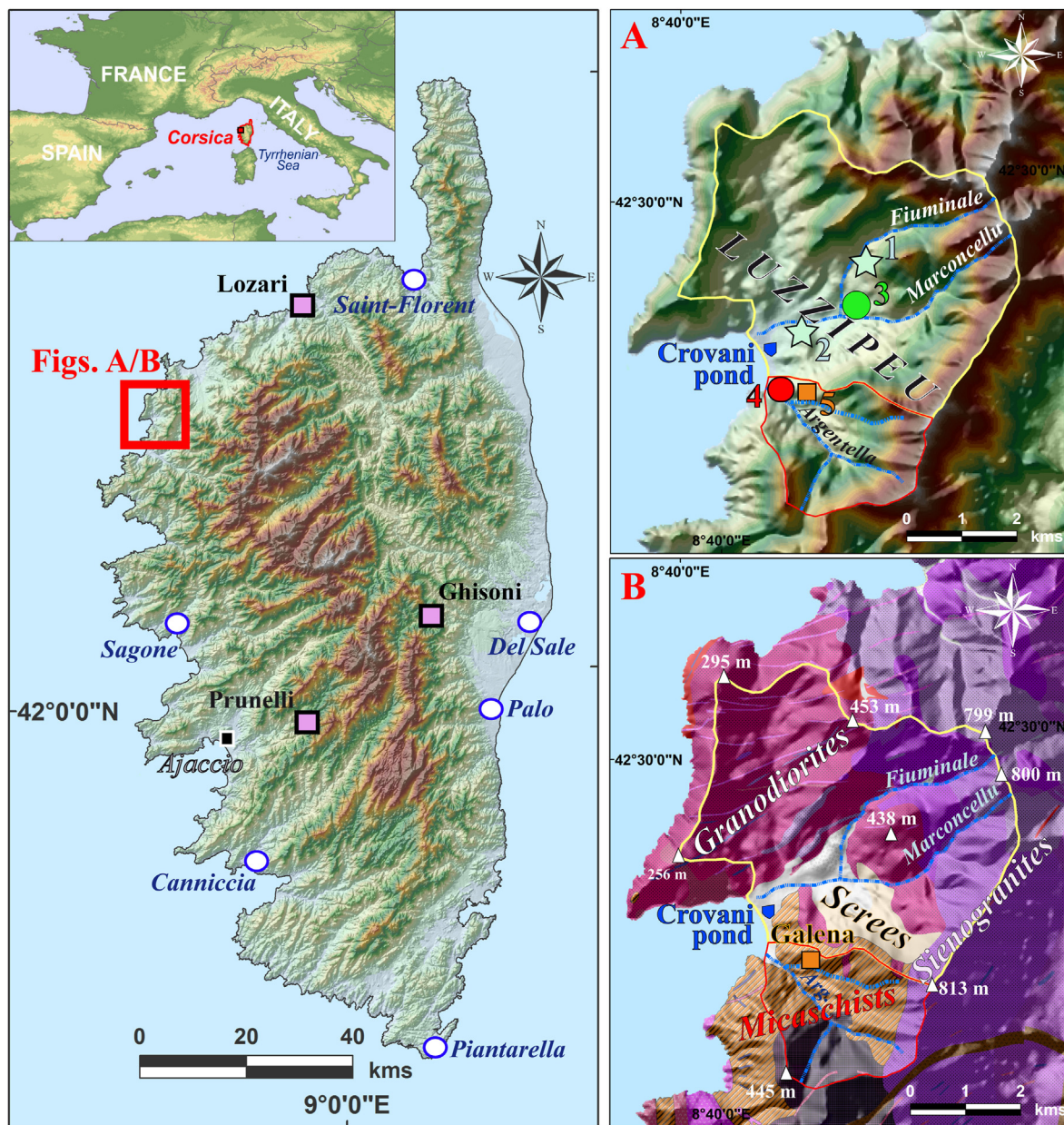


Fig. 1. Location map of the study area and coastal sites of previous palynological research (white circle) conducted over the last decade for Corsica island (Del Sale: Currás et al., 2017; Sagone: Ghilardi et al., 2017a; Palo, Piantarella and Saint-Florent: Revelles et al., 2019, Revelles and Ghilardi, 2021; Cannaiccia: Vella et al., 2019). The purple squares indicate the position of known mining sites of galena/lead in Corsica. A: Hydrography and archaeology of the catchment basins ending in the Crovani Bay, green circle: Final Neolithic to Bronze Age site; Red circle: possible roman site of occupation; Orange square: 19th to 20th Cent. AD mining buildings; light green stars: Medieval site; 1: San Larenzu, 2: San Quilicu, 3: Teghja di Linu, 4: lower Argentella, 5: upper Argentella. B: Simplified geology and topography of the catchment basins ending in the Crovani Bay; Orange square: mining site. Geographic coordinates are expressed in WGS 84 geodetic system. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

et al., 2020), and new insights into the centennial-scale patterns of atmospheric circulation during the Middle and Late Holocene (Franke et al., 2017; Di Rita et al., 2018a; Sabatier et al., 2020).

Our new palynological and stratigraphical data are addressed to contribute to prominent unsolved questions about times and drivers of vegetational change in Corsica, with a special focus on the replacement of *Erica* shrublands with *Quercus ilex* woody formations during the Middle Holocene. A second key topic is the origin and development of land use practices in northwestern Corsica. In Neolithic times, there is sparse archaeological evidence for cereal cultivation and pastoral activities along the coasts of Corsica. Cereal cultivation was revealed by pollen analyses only in the eastern plain of Corsica and in the Saint Florent and Bonifacio-Piantarella areas (Currás et al., 2017; Revelles et al., 2019), while the osteological identification of mammals buried in sheltered caves from southern and northern Corsica provided evidence about the development of stockbreeding (Vigne, 1984, 1987).

A third unsolved question is related to the controversial role of climate changes in modifying the vegetational landscape of Corsica. While at millennial time scale the influence of climate changes on the vegetation and fires has been clearly recognized (Reille, 1992a; Leys et al., 2013; Revelles et al., 2019; Lestienne et al., 2020a, b), the role of rapid climate changes (RCC) has been seldom evoked in the regional palaeobotanical narrative. The apparent lack of vegetation responses to centennial climate changes was attributed to either the overshadowing effect produced by local resilient shrublands (Revelles et al., 2019) or the geographical position of Corsica, located in a possible climate-insensitive transitional area between the central and western Mediterranean (Di Rita and Magri, 2019; Di Rita et al., 2022), two regions where RCC often produced contrasting moisture changes (Di Rita et al., 2018a).

New detailed palaeoenvironmental data from Corsica are thus needed to disentangle these questions, which are relevant for a better understanding of the natural and anthropogenic landscape changes in the Mediterranean during the Holocene.

2. Study area

2.1. Present day landscape and vegetation

The Crovani pond is located in NW Corsica, in the westernmost part of a ~1 km² coastal plain (Fig. 1A). The plain collects the waters from two catchment basins with intermittent flow: the Argentella-Cardiccia streams (catchment basin ~6 km²), incising metamorphic rocks (shales and mica schists) and syenogranite, and the Marconcellu-Fiuminale streams (total catchment area: ca. 23 km²), draining granodiorites, syenogranite, and Pliocene to Pleistocene screes in the lowermost river course (Fig. 1B).

Corsica has a typical Mediterranean climate highly influenced by its relief topography. The mean annual temperature on the whole Island ranges between 14.5 °C and 16.5 °C and the mean annual precipitation is 890 mm per year. On the coastal area, mean annual temperature is higher (17 °C) and freezing temperatures during the year are very seldom reported (Vella et al., 2019).

The Crovani wetland covers an area of ~0.3 km² behind a thick coastal barrier ≤5.30 m above the mean sea level (amsl), made up of large well-rounded pebbles and cobbles (Fig. 2). The pond, which is at 0.75 m amsl in the winter, is seasonal dry in the summer and has no direct link to the sea.

The surrounding wetland is a protected area, being included in the ZNIEFF (Zone naturelle d'intérêt écologique, faunistique et floristique) n. 940004139 'Etang et zones humide de Crovani' with the aim of preserving the following angiosperm species: *Euphorbia peplis* L., *Polygonum scoparium* Req. ex Loisel., *Ranunculus ophioglossifolius* Vill., *Staphisagria picta* (Willd.) Jabbour, *Tamarix africana* Poir., and

Vitex agnus-castus L. The pond is surrounded by a belt of *T. africana* and is characterized by a wet meadow covered by palustrine species dominated by *Bolboschoenus maritimus* (L.) Palla, *Juncus acutus* L. and *Juncus maritimus* Lam. The coastal bar is occupied by a population of *Pistacia lentiscus* L. and, on the top of the beach, by one of the most important Corsican populations of *Vitex agnus-castus* (<https://inpn.mnhn.fr/zone/znief/940004139>). In spring, the very rare *S. picta* grows among the pebbles (Jeanmonod and Schlüssel, 2006). The woody vegetation of the site consists of a degraded maquis with *Erica arborea* L., *Arbutus unedo* L., *Pistacia lentiscus* L., *Phillyrea angustifolia* L. and sparse *Quercus ilex* L. (Reille, 1992a).

2.2. Local archaeology and history of the human occupation

The first evidence of human settlement in Corsica dates back to the Mesolithic (Lugliè, 2018). Abundant archaeological material allows to reconstruct the Neolithic settling history of the island (Lugliè, 2018; Revelles et al., 2019). In northern Corsica a rich archaeological background is found in a Mesolithic to Early Neolithic occupation in the Nebbiu area, at the Saint-Florent/ Patrimoine sites (Revelles et al., 2019). In the Balagne area, an important human occupation in a coastal context is attested by the Early Neolithic site (Cardial culture) of La Petra, situated on a peninsula north of the modern town of L'Île Rousse (Weiss, 2010).

In the Luzziu sector, situated in the southern part of the Balagne micro region, where the Crovani pond is located (Fig. 1A), despite the paucity of recognized prehistoric settlements and uncovered archaeological material, there is evidence of occupation during the Final Neolithic (starting from ca. 2800 cal. BC) at Teghja di Linu (Fig. 1A). The last site consists in a small village composed of huts, located at an elevation of ~40 m amsl at ~1.5 km distance from the Crovani pond, where lithics were discovered together with a menhir statue (Sicurani, 2008; Sicurani and Martinet, 2019; Ghilardi, 2020). Possible evidence of occupation during Late Neolithic times was hypothesized, but the lithics uncovered are still under investigation (Sicurani and Martinet, 2019). Due to the presence of acidic soils, derived from the erosion of the granitic bedrock, preservation of biological remains and archaeological material in this stratigraphical context is difficult, so that there is no organic material left in the archaeological layers that may help to evaluate the type of activities developed at the Teghja di Linu site. Excavations conducted over the last two decades have revealed the existence of a habitat composed of several circular large structures, delimited by tremendous rounded granitic boulders.

Protohistoric settlements are hardly documented in the Luzziu lowlands. Bronze Age sites are situated more inland, generally on top of hills (Pêche-Quilichini, 2011). Iron Age and Roman times are poorly documented, but archaeological surveys have revealed the presence of *tegulae* within the mining complex of the Argentella, in use in the 19th to 20th century AD, indicating a first phase of galena exploitation (Leleu, 2021). This sparse human occupation from the Bronze Age to Roman times radically contrasts with the Medieval archaeological remains attested at San Larenzu and San Quilicu (Fig. 1A). Both are Romanic churches dated from the 11th century AD and nowadays almost disappeared due to their gradual destruction. From the Genovese administration to the French administration, the region was attractive for the exploitation of natural resources, especially galena minerals. Evidence for mining from the 16th to the early 20th centuries has been recorded (Leleu, 2021) but its impact in terms of landscape changes has never been investigated.

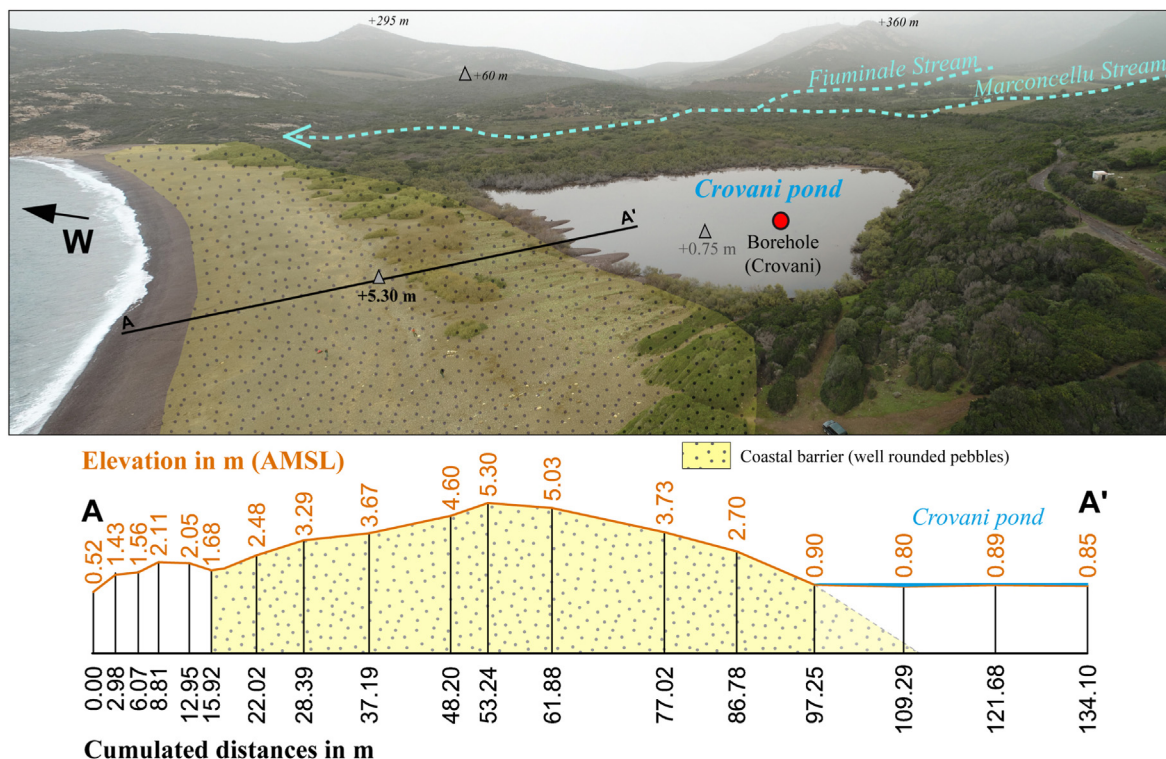


Fig. 2. View of the Crovani pond, borehole and Differential Global Positioning System- DGPS- profile (AA') locations. The light blue line (dash) indicates the present-day course of the rivers. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Materials and methods

In this paragraph we present a synthetic version of materials analysed and techniques we used. For a more exhaustive explanation of the methodology applied in this research, we refer to information reported in the Supplementary data.

The analyses presented in this study were carried out on a 6.25 m long sediment sequence, which was collected with a 50-mm vibracore (COBRA TT equipment – Atlas Copco) in the central part of the Crovani pond in August 2018 (Fig. 2).

The chronostratigraphy of the core was established using a series of 14 AMS radiocarbon determinations made in the Poznan and Gliwice (Poland) Radiocarbon Dating Laboratories (Table 1). The Bayesian age-depth model (Fig. 3) was constructed using the software Bacon version 2.5.5 (Blaauw and Christen, 2011) with dates calibrated using the IntCal20 curve (Reimer et al., 2020).

Table 1

AMS Radiocarbon ages obtained from the materials of Crovani core. The calibrated ages are based on IntCal20 dataset (Reimer et al., 2020).

LabID	Material	Depth (cm)	¹⁴ C Age ± error BP	Cal. yr BP (2σ)	Cal. yr AD/BC (2σ)
GdA-5806	Organic sediment	49	1585 ± 25	1527–1404	423–546 AD
Poz-115,796	Organic sediment	50	3090 ± 40	3389–3179	1440–1230 BC
GdA-5807	Organic sediment	77	2215 ± 30	2330–2146	381–197 BC
GdA-5808	Organic sediment	93	2280 ± 25	2349–2177	400–209 BC
Poz-110,261	Charcoal	125	3260 ± 90	3699–3252	1750–1301 BC
GdA-5809	Organic sediment	138	3090 ± 35	3382–3210	1433–1261 BC
GdA-5810	Organic sediment	154	3215 ± 30	3480–3373	1531–1424 BC
Poz-110,260	Plant + Peat	185	3420 ± 35	3823–3569	1874–1620 BC
GdA-5811	Organic sediment	229	4170 ± 40	4834–4577	2885–2628 BC
Poz-110,258	Peat	270	4175 ± 35	4835–4580	2886–2631 BC
Poz-109794	Charcoal	340	4470 ± 40	5297–4967	3348–3018 BC
Poz-110,198	Peat	397	4530 ± 30	5312–5051	3363–3102 BC
Poz-109887	Charcoal	450	4730 ± 40	5581–5325	3632–3376 BC
Poz-105992	Bulk Sediment	487	5080 ± 40	5917–5730	3968–3781 BC

Loss-on-ignition (LOI) measurements were performed on sediment samples of approximately 1 g taken at 10 cm intervals throughout the sequence, following the standard procedures published in Dean (1974) and Bengtsson and Enell (1986). (Fig. 4).

Samples used for LOI measurements were also analysed for granulometry. The grain-size distribution of the fine fraction (<2 mm) was measured by laser diffraction granulometry at CEREGE.

A C/N analysis was carried out on 28 samples from the core, selected according to their organic matter content: a minimum of 5% by weight of organic matter was required to continue. The method by Stax and Stein (1993) was used as a basis for the preparation of the samples. Results were obtained using an elementary analyser (Vario Microcube, Elementar) coupled to a mass spectrometer (Isoprime 1000) (Fig. 4).

The bulk mineralogy was measured on 28 samples in the upper

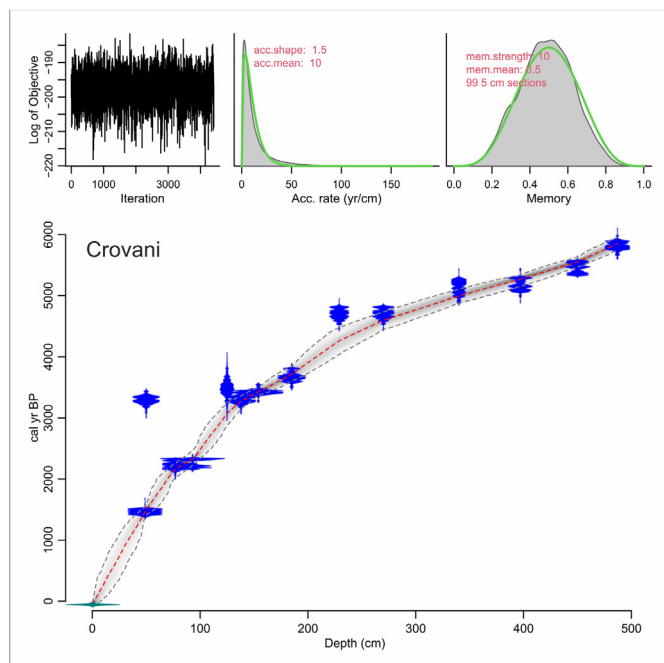


Fig. 3. Age-Depth Model of the Crovani sequence, calculated through a Bayesian method using the computer program Bacon 2.5.5 (Blaauw and Christen, 2011). The Model is based on 14 AMS dates calibrated using the IntCal20 curve (Reimer et al., 2020).

261 cm of the core. Most of the samples were retrieved from clayey sediments between 116 and 261 cm (20 samples), with a sampling resolution of 4 cm. In addition, 8 samples were retrieved between 11 and 106 cm. About 1 g of dried bulk sediment sample was hand ground for mineralogical analyses. X ray diffraction (XRD) patterns of non-oriented powders (Moore and Reynolds, 1997) were acquired between 2 and 30° 2θ angle by using a Bruker D8-Advance Eco 1 Kw diffractometer equipped with a ceramic copper ($K\alpha$ radiance with $\lambda = 1.5418 \text{ \AA}$). The XRD data measured under a current intensity of 25 mA and a voltage of 40 KV were recorded with a Lynxeye Xe energy dispersive detector in the laboratory AGEs at the University of Liège. The minerals were identified by their peak positions and their abundance was calculated from the intensity of selected diffraction peaks (Cook et al., 1975).

The bulk samples for Pb isotopes analyses were digested using a tri-acid attack of HF/HNO₃/HCl in a laminar flow hood. The Pb purification was made according to the procedures published in Weis et al. (2006). The Pb isotopes were measured by static multicollection in dry mode on a Nu Plasma I MC-ICP-MS instrument at the University of Brussels. The values were normalized using the recommended NBS981 values ($^{208}\text{Pb}/^{204}\text{Pb}$ 36.7219 ± 61, $^{207}\text{Pb}/^{204}\text{Pb}$ 15.4963 ± 17, $^{206}\text{Pb}/^{204}\text{Pb}$ 16.9405 ± 24) from Galer and Abouchami (1998). The Pb isotopes ratios were measured on 24 clayey samples retrieved in unit VI and VIII with a ~5 cm sampling resolution between 11 and 260 cm (Table S1).

In addition, some Pb-bearing minerals were collected in different Corsican ores or mineralized veins on the Paleozoic granites from west Corsica (Fig. 5). We have sampled the main Pb mineral galena (PbS) and also some Pb-bearing minerals like arsenopyrite (FeAsS). Galena was sampled in the mine of Argentella, 2.5 km from the Crovani pond, but also in the mine of Lozari (along the northwestern coast, east of Île Rousse) and in a mineralized vein in Prunelli (south of Porto - see locations in Fig. 1). In addition, an arsenopyrite mineral sample was collected in the Finosa Pb–Zn–Ag ore close to Ghisoni (Fig. 1).

Pollen analysis was carried out on 62 samples. Pollen extraction followed the standard procedures summarized by Magri and Di Rita (2015). Pollen grains and NPPs were identified by light microscope at 400 and 640 magnifications, with the help of both pollen morphology atlases (e.g., Reille, 1992b; Beug, 2004) and NPPs reference articles (e.g., van Geel, 2001; Cugny et al., 2010; Gelorini et al., 2011).

Microcharcoal analysis was carried out to reconstruct fire history, following the procedures described by Clark (1982). A series of 150 microscope fields were checked for each sample. Microcharcoals smaller than 5 μm were excluded from the sum. The computer program Psimpoll 4.27 (Bennett, 2009) was used to plot the percentage and concentration diagrams, as well as to subdivide the pollen record into 8 local assemblage zones, numbered from the base upwards and prefixed by the site abbreviation CRO, by means of the CONISS method (Grimm, 1987).

A REDFIT spectral analysis (Schulz and Mudelsee, 2002) using the PAST 3.2 software (Hammer et al., 2001) was applied to the unevenly spaced time series represented by the total Arboreal Pollen (AP) percentages to detect the possible occurrence of a fundamental tempo in the forest cover changes.

4. Results

4.1. Chronostratigraphy

Based on the laser grain size determination and on the organic matter/carbonate contents, eight stratigraphic units were defined from the bottom to the top (Fig. 4).

Unit I is found between 6.25 and 5.95 m depth. It consists of a mixture of well-rounded pebbles cemented within a sandy matrix and grey clays containing from 2 to 5% of organic matter. Due to the paucity of organic material, radiocarbon dating of this sedimentary unit was impossible.

Unit II is found between 5.95 and 5.45 m depth. It comprises medium to coarse grey sands with local intercalations of angular gravels (centimetric in size). Organic matter and carbonate content are very low (1–2%), hindering any radiocarbon dating of Unit II. No biomarkers were identified.

Unit III is encountered between 5.45 and 3.73 m depth (~6300–5170 cal. BP; ~4350–3220 BC). It consists of homogeneous grey clays. The organic matter content ranges between 10 and 15% while carbonate content shows values comprised between 6 and 9%.

Unit IV occurs from 3.73 to 2.95 m depth (5170–4760 cal. BP; 3220–2810 BC). It shows features similar to Unit II. It consists of coarse sands with intercalated layers of gravels with sharp edges, witnessing variations in the energy of deposition, in particular at the point of changeover with Unit III. In the lowermost part of Unit IV, a layer of 15 cm consists of angular gravels without sedimentary matrix. Organic matter and carbonate contents (both <2%) are low, like Unit II. Radiocarbon dating of this lowermost portion is consistent with a time interval encompassing the Late to Final Neolithic.

Unit V, between 2.95 and 2.72 m depth (4760–4630 cal. BP; 2810–2680 BC), consists of organic coarse sandy clays. Organic matter content increases upwards (1–7%). The carbonates content is lower than 2%.

Unit VI is found from 2.72 to 1.42 m depth (4630–3320 cal. BP; 2680–1370 BC) and exhibits sedimentological parameters similar to Unit V. It consists of organic clays with 10–20% of organic matter and ≤8% of carbonate. The XRD mineralogy (Fig. S1) reveals the dominance of detrital minerals (~50% of quartz, K-feldspars and plagioclase with traces of amphibole and chlorite). They are associated to clayey minerals (~30% of total undifferentiated clays), aragonite (3–8%) from biogenic fragments and evaporites

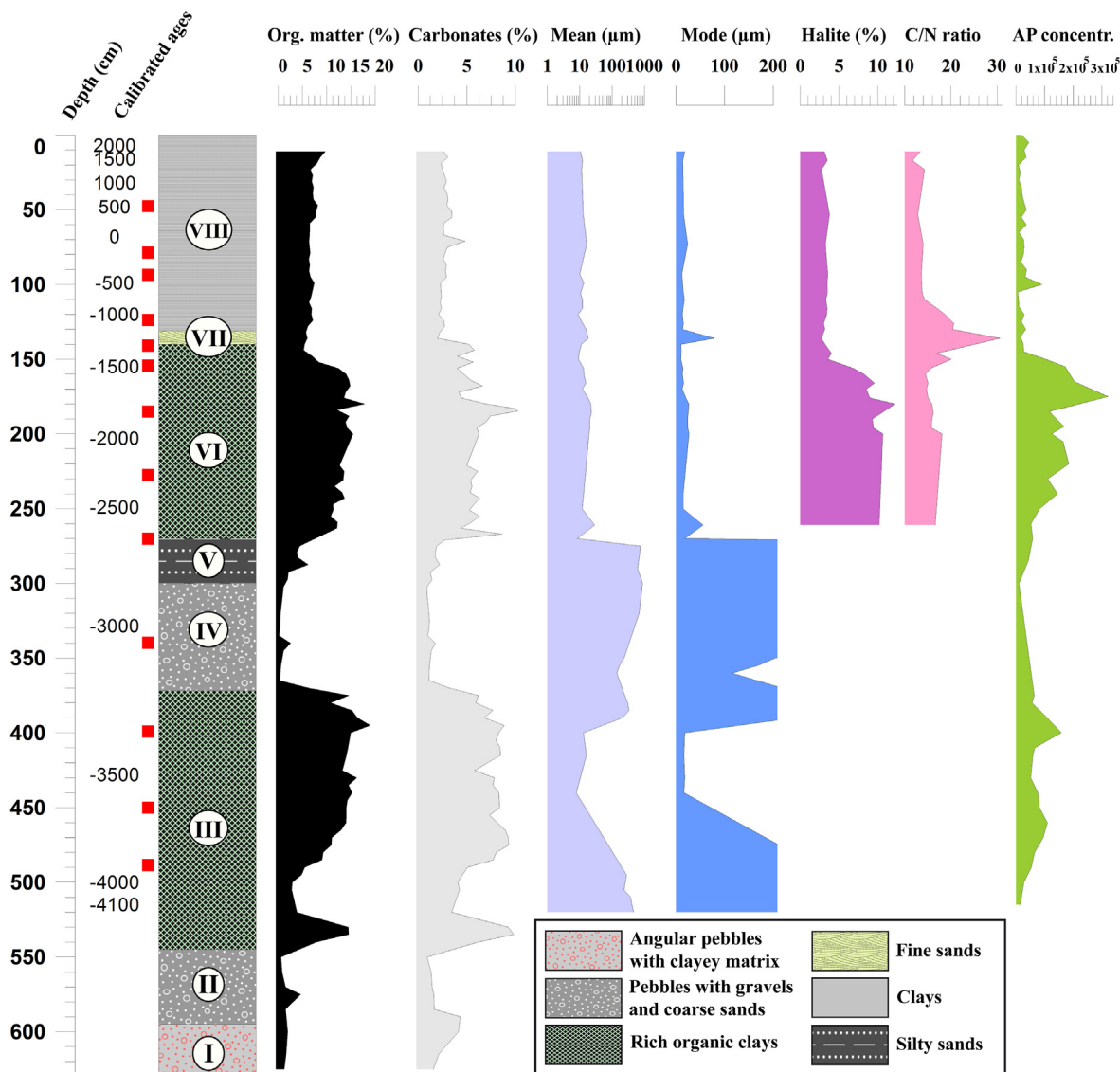


Fig. 4. Core lithology with ages expressed in cal. BC/AD and depths indicated in cm (left). For full details of the samples performed for ¹⁴C AMS dating method (red squares), please check Table 1. Curves from left to right: Loss on ignition measurements with organic matter and carbonate contents, granulometric indexes (mean and mode), mineralogical and geochemical proxies (halite, C/N ratio) and Arboreal Pollen (AP) concentration (grains/gram). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(8% < halite <12% - Fig. 4). Radiocarbon dating of the unit is consistent with a time interval ranging from Final Neolithic to Middle Bronze Age.

Unit VII is encountered from 1.42 to 1.32 m deep (3320–3190 BP; 1370–1240 BC). It consists in a thin layer (10 cm) of homogeneous yellow fine sands showing a modal index of 90 µm with a mean grain size of 20 µm (fine silts). The granulometric analyses exhibit a multimodal distribution of the particles. Positive excursion in detrital minerals (cumulated abundance over 70%). Is observed for Unit VII and corresponds to a significant increase in quartz (28%) and plagioclase (25%) and a relative drop in total clays minerals (13%) (Fig. S1).

Sedimentary Unit VIII is identified in the uppermost 1.32 m depth (3190–0 cal. BP; 1240 BC–1950 AD). Homogeneous grey clays record numerous traces of oxidation corresponding to rootlets. The organic matter content is homogeneous (6–8%), while carbonate content is low (2–3%). The XRD mineral association remains similar

to unit VI, except the abundance of evaporites. A drop of halite below 4% occurs between 166 and 150 cm, i.e. in the upper part of unit VII but close to the transition with unit VI (Fig. 4). The rate of sediment accumulation for Unit VIII is very low, with values of ~4.3 mm per century.

4.2. C/N results

The uppermost 2 m sediment, spanning the last four millennia, were investigated for C/N ratio (Fig. 4). The averaged C/N ratio is high (>10) and exceeds a value of 16 above 1.16 m suggesting a mainly terrestrial origin of the organic matter. The values range between 11 and 14 from 1.16 to 2 m, indicating a mixture of organic matter from vascular plants and algae. The highest value (~30) measured at 1.36 m indicates an episode of high input of sediments of continental origin, with a mix of vascular plants and cellulosic plants, dated ca. 1430 to 1260 BC.

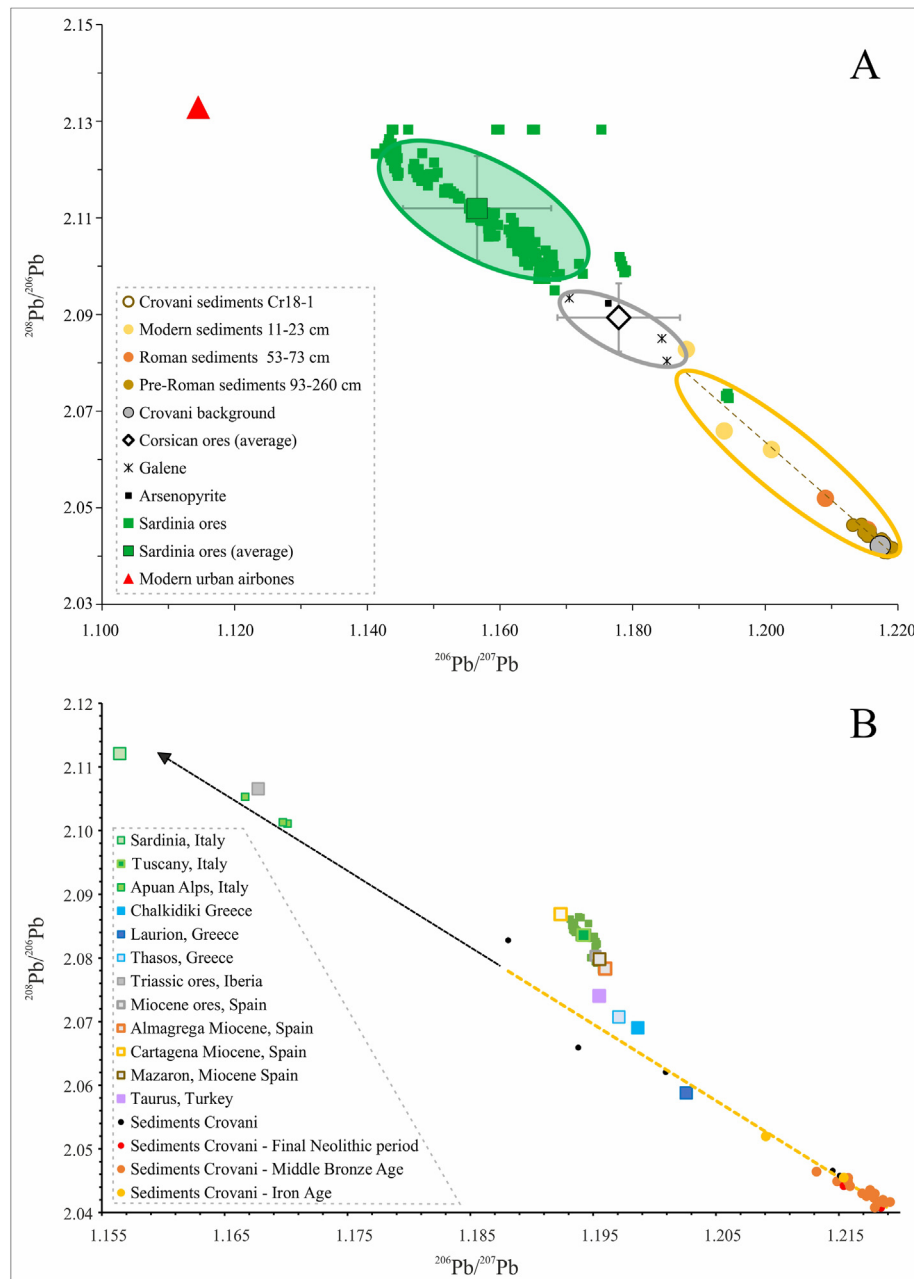


Fig. 5. A: Pb isotope results of the Crovani sedimentary core LCr18 reported in a binary diagram $^{207}\text{Pb}/^{206}\text{Pb}$ versus $^{208}\text{Pb}/^{206}\text{Pb}$. The dashed line indicates the linear regression trend between the Crovani samples. Circles: Crovani samples reported by different colors according to their stratigraphical position, i.e. pre-Roman samples, Roman and modern samples. The black circle indicates the average signature of the local geological background defined by the oldest measured Final Neolithic samples. Black symbols: samples from different Pb-bearing mineral collected in West Corsica. The red triangle gives the averaged composition of modern airborne particles collected above Roma in Italy (data from [Bollhöfer and Rosman, 2001](#)). Green squares: signature of Pb galene-rich ores from Sardinia. B: Close up emphasizing the representative signature of Pb ore mining districts surrounding the Mediterranean basin classed by country (green for Italy, blue for Greece, purple for Turkey and various colors from grey to orange for Spain ores). Data from literature reported in [Fagel et al. \(2017\)](#). The black arrow represents an extrapolation of the sedimentary mixing observed in core LCr18 in [Fig. 5A](#). It underlines the probable implication of the minerals of Tuscany in the Pb isotope signature of the Crovani sediments. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.3. Lead isotopes analyses

The three Pb isotopic ratios evolve in parallel in the 260-cm upper part, from Final Neolithic to present ([Fig. S2](#)). The $^{208}\text{Pb}/^{206}\text{Pb}$ ranges between 38.60 and 39.01 (average 38.9353 ± 0.0019), the $^{207}\text{Pb}/^{206}\text{Pb}$ between 15.65 and 15.68 (average 15.6703 ± 0.0007), and the $^{206}\text{Pb}/^{204}\text{Pb}$ between 18.61 and 19.11 (average 19.02 ± 0.0008) ([Table S1](#)). Even if some scattering of the data is observed for the studied pre-Roman period (i.e., 260–93 cm), the

isotopic Pb ratios depict a marked decreasing trend upwards. This major change starts at 73 cm ([Fig. S2](#)) during the Roman period and continues over the modern period. The lowest isotopic ratios are measured in the shallowest samples at 11 and 17 cm.

4.4. Pollen analysis and statistical analysis on pollen time series

The results of pollen analysis are presented as: 1) a detailed percentage diagram, including most of the pollen taxa and a

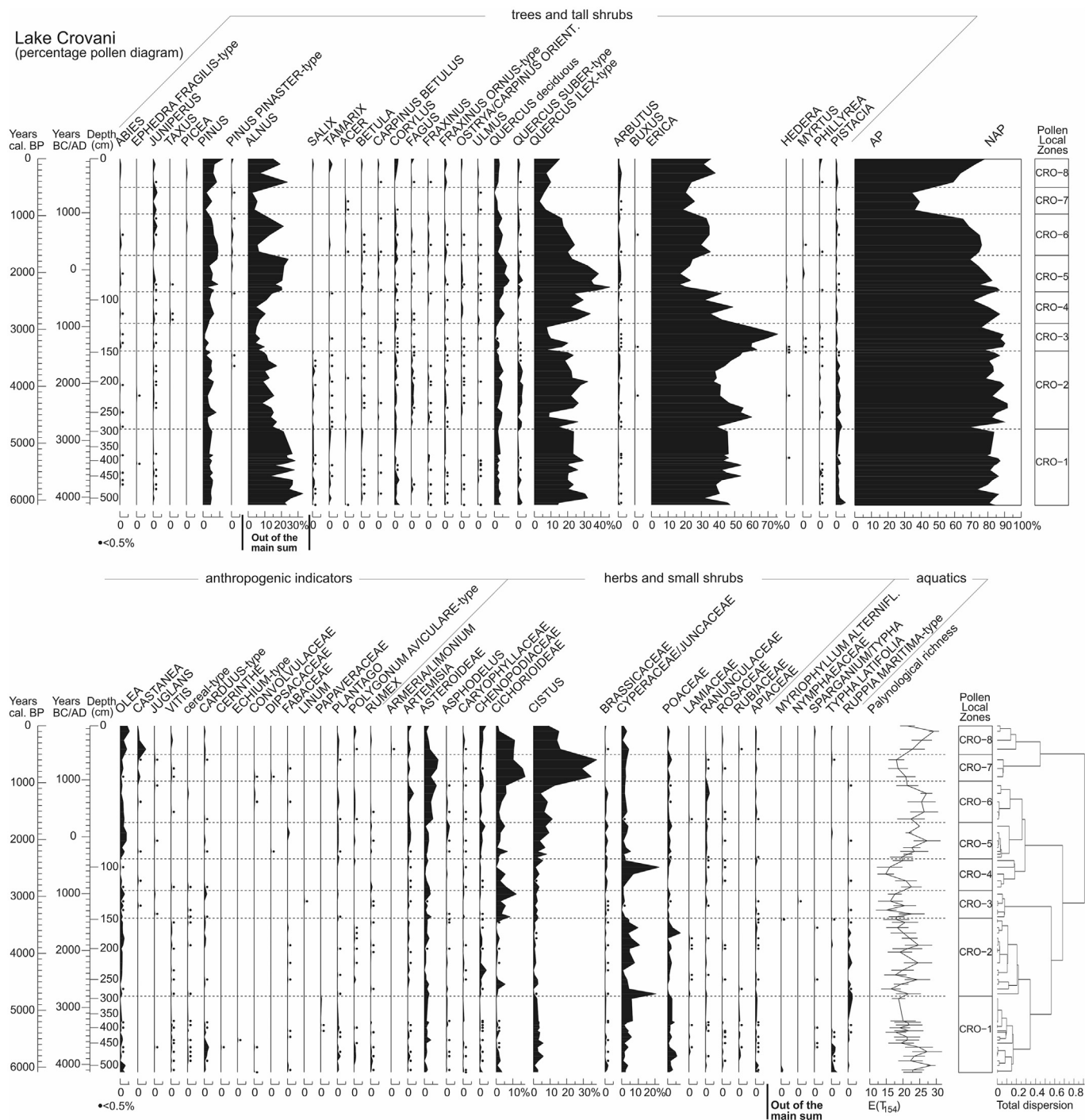


Fig. 6. Pollen percentage diagram of Crovani, including the pollen zonation calculated with the CONISS method (Grimm, 1987).

summary Arboreal Pollen (AP)/Non Arboreal Pollen (NAP) percentage diagram, plotted against age (Fig. 6); 2) a percentage diagram displaying the main NPPs (Fig. 7); 3) a synthetic diagram including cumulative pollen percentages of ecological groups (conifers, riparian trees, deciduous trees, evergreen trees and shrubs, OJCV (*Olea* + *Juglans* + *Castanea* + *Vitis*), anthropogenic herbs, other herbs, coprophilous fungi, and saprophytic and phytopathogenic fungi), AP percentage, the concentrations of AP and NAP, microcharcoals, and some climate proxies (Fig. 8).

The pollen preservation was good with percentages of undeterminable grains rarely higher than 4%. On average, 310 pollen

grains of terrestrial taxa were counted per sample. The biodiversity was represented by 92 different pollen taxa (terrestrial + aquatic plants) summed to 45 types of ferns, algae, fungi, and other NPPs. The palynological richness, estimated by rarefaction analysis (Birks and Line, 1992), is always over 15 terrestrial pollen types per sample. Total pollen concentrations vary from 7000 to 321,000 terrestrial pollen grains/g sediment. The features of the local pollen assemblage zones are summarized in the Supplementary Materials.

A REDFIT analysis was applied to the unevenly sampled time series represented by the total AP percentages, which show a clear fluctuating trend consistent with changes in forest cover rather

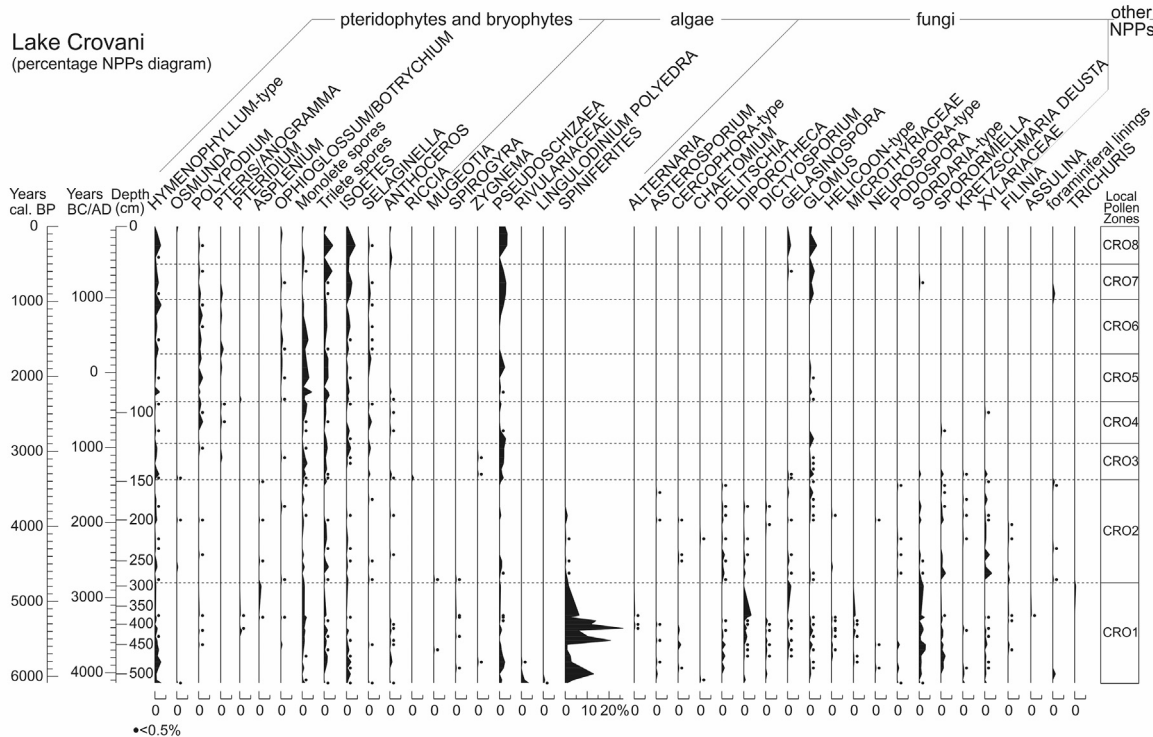


Fig. 7. Percentage diagram of Non-Pollen Palynomorphs from Crovani.

than random fluctuations due to pollen representation and preservation (Fig. 9).

The results of the REDFIT exhibit a peak in power spectrum exceeding 95% of the false-alarm levels of both χ^2 and Monte Carlo tests, corresponding to a statistically significant periodicity of ca. 228 years (time = 1/frequency), and less significant frequencies centred at 996 and 430 years, which however exceed 90% of the false-alarm levels of both χ^2 and Monte Carlo tests (Fig. 9).

5. Discussion

5.1. Evolution of the vegetational landscape

During the Middle and Late Holocene, from ca. 6100 to 1000 cal. BP (4150 BC–950 AD), the Crovani pond was surrounded by a dense *Erica*-dominated tall *maquis*, accompanied by several evergreen elements, such as *Q. ilex*, *Phillyrea*, *Pistacia*, and *Olea* (Figs. 6, 8 and

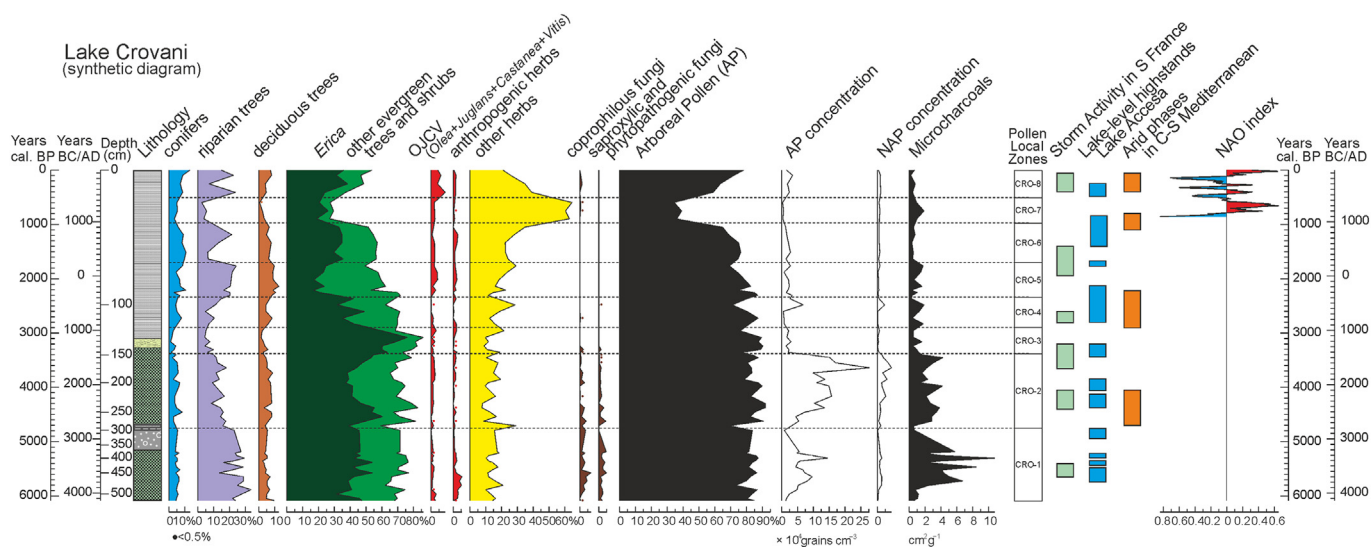


Fig. 8. Summary pollen diagram including the cumulative percentages of gymnosperms, riparian trees, deciduous trees, evergreen trees and shrubs, OJCV curve, anthropogenic herbs, other herbs, coprophilous fungi, and saproxylic and phytopathogenic fungi, the Arboreal Pollen percentage record, the concentrations of Arboreal Pollen and Non-Arboreal Pollen, and the microcharcoal concentrations. The light green bars indicate phases of high storm activity in southern France (Sabatier et al., 2012). The blue bars indicate lake level highstands at Lake Accessa in central Italy (Magny et al., 2013). The orange bars indicate phases of dry climate conditions in south-central Mediterranean (Di Rita et al., 2018a). The NAO index is based on Franke et al. (2017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

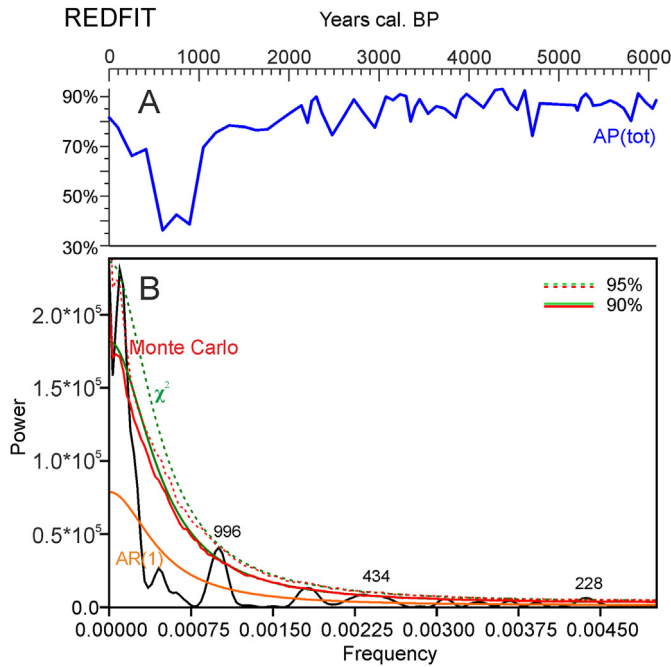


Fig. 9. REDFIT (A) analysis of the total Arboreal Pollen percentages (B) using the PAST 3.2 software program (Hammer et al., 2001). In the REDFIT spectral analysis the time series is fitted to an AR1 red noise model (orange line). The 95% confidence levels of the χ^2 and Monte Carlo tests are reported on the graph with a green dashed line and a red dashed line, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

10). This observation is consistent with other palynological studies from southern Corsica (Reille, 1975, 1984; Revelles et al., 2019; Vella et al., 2019) and on the Cavallo island, situated in the strait of Bonifacio (Poher et al., 2017). An almost continuous record of *Arbutus* indicates that strawberry trees was a common presence in the *Erica arborea* formations, as its pollen tetrads are poorly

dispersed. The most degraded sectors of this *maquis* vegetation were probably occupied by law shrublands of *Cistus*, which played a prominent role in the dune and sandy soil vegetation together with *Olea*, *Pistacia* and other thermophilous shrubs, as also reported from other coastal sites of western Corsica (Reille, 1992a).

The pollen record from Crovani provides new data to investigate the complex interplay between *Erica*-dominated and *Q. ilex*-dominated vegetation and their turnover in Corsica. According to Reille (1992a), *Erica* woodlands, representing the climax vegetation in lowland areas of western Corsica, underwent a major degradation process since the neolithization of the island, as a result of increasing human impact. It was largely replaced by *Quercus ilex* during the Mid-to Late Holocene (Reille, 1992a; Carcaillet et al., 1997). Recent palynological studies (Revelles et al., 2019) confirmed the anthropic causation of this vegetation turnover and suggested that it started with the development of agropastoral practices during the Early Neolithic, hence significantly earlier than the period previously identified by Reille (1992a). Similar vegetation dynamics were reported also in Sardinia, where a clear development of *Quercus ilex*, leading to a partial or complete replacement of the late successional *Erica* shrublands, is recorded since the 6th millennium BP (Di Rita and Melis, 2013; Beffa et al., 2016; Melis et al., 2017, 2018; Pedrotta et al., 2021). In contrast, the pollen record from Crovani (Fig. 6) indicates that the frequencies of *Erica* were continuously high until ~2900 BP and were not replaced by *Q. ilex*. Our pollen record even shows two temporary major increases in *Erica* at the expense of holm oaks in the time-intervals 4700–4300 and 3350–2900 cal. BP. High frequencies and concentrations of *Erica* and *Q. ilex* concur in depicting a *maquis* characterized by high biomass and decomposed organic matter, as suggested by generally high values in the loss of ignition and a significant presence of saproxylic and phytopathogenic fungi, such as *Kretzschmaria deusta*, *Asterosporium* and *Xylariaceae* (Fig. 7).

In Sardinia, Beffa et al. (2016) hypothesize that a protracted dominance of *Erica* and the absence of evergreen oak forests in the first part of the Middle Holocene (until ca. 5300 cal. BP) were related to warmer/drier summers and cooler/moister winters than today. They suggest that also in Corsica such a climate regime,

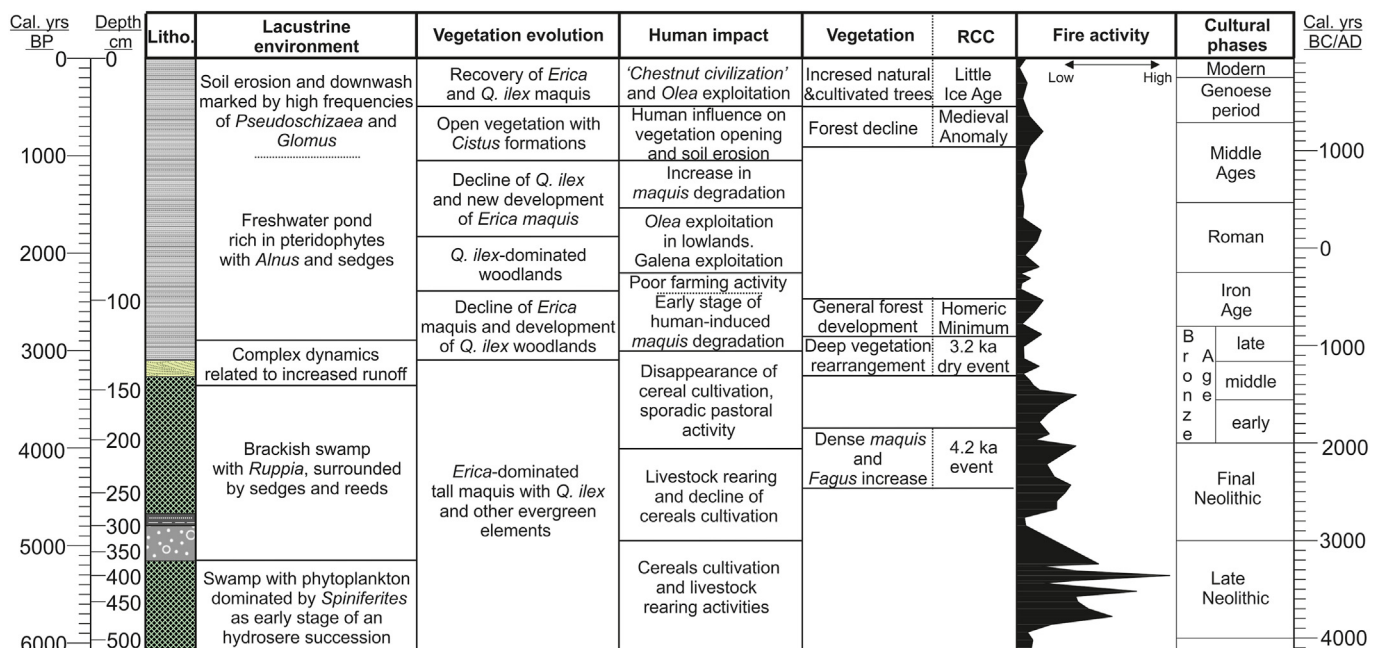


Fig. 10. Synoptic table with timing and nature of key environmental changes reconstructed from the Crovani record.

characterized by frequent and prolonged droughts during the spring and summer, may have led to frequent seasonal wildfires advantaging communities dominated by *Erica scoparia* and *Erica arborea*, which are two fire-adapted species able to quickly resprout and generate new aboveground biomass after frequent and intense fires. In contrast, *Quercus ilex* is considered to have been severely affected by natural and anthropogenic fires and favoured by a climate change leading to increased summer rainfall and decreased fire occurred at the end of the Middle Holocene (Colombaroli et al., 2009; Beffa et al., 2016; Pedrotta et al., 2021).

In contrast to this view, at Crovani, high concentrations of microcharcoal, reflecting fires, are recorded in correspondence of high values of both *Erica* and *Q. ilex*. Contemporary high values of *Q. ilex* and microcharcoal support the interpretation of Reille (1992a) and Carcaillet et al. (1997), which suggest that the development of holm oak in Corsica was triggered by anthropogenic fires. At Crovani, a substantial portion of the Mid-Holocene fires may be related to human activity, which is witnessed by a significant presence of anthropogenic indicators (Figs. 6–8). High frequencies of microcharcoal in zones CRO-1 and CRO-2 are consistent with the coeval high incidence of fires recorded in the region (Leys et al., 2014; Lestienne et al., 2020a, b), most of which are attributed to human activity. According to Lestienne et al. (2020b), since 5000 cal. BP humans have taken control of the fire regime through agro-pastoralism, favouring large and/or frequent fire events. For the same reason, the marked decrease in microcharcoal recorded at Crovani during the Late Holocene after ~3350 cal. BP, which matches a decrease in anthropogenic pollen indicators, may reflect decreased human activity, at a time of an unsuitable climate for fires.

Starting from ~2900 cal. BP, there was a general decline in *Erica*, opposed to an increase in holm oaks, which led to a turnover of the two woody taxa between 2300 and 1900 cal. BP. At this time-interval, an increase in oaks may have been influenced by the forestry practices of Roman times. All the same, in the last ~2500 years, a clear development of cork oak in Corsica (Reille, 1984, 1992a), Sardinia (Di Rita and Melis, 2013), and the western Iberian Peninsula (Carrión et al., 2000) may be related to silvicultural practices.

Between 1900 and 1000 cal. BP (pollen zone CRO-6), a new moderate increase in *Erica* at the expense of *Q. ilex* suggests a new expansion of the native *Erica*-dominated shrublands.

Between 1000 and 500 cal. BP (pollen zone CRO-7), a major degradation of the forest cover is recorded, with a massive decline of the tall *maquis* that was replaced by *Cistus*-dominated low shrubland. After ~500 BP, *Erica* and *Q. ilex* recovered, as recorded also in other sites of Corsica (e.g. Vella et al., 2019).

Modest oscillations of deciduous trees throughout the record (Figs. 6 and 8) suggest that they were scarcely involved in the environmental processes influencing the evergreen vegetation, probably because they were located at higher elevations in the island. Frequent finds of mesophilous trees such as *Fagus* and *Betula*, which require temperate and humid conditions, confirm that part of the pollen rain originated from the montane vegetation belt. The fingerprint of deciduous trees in the pollen record of Crovani, as in other coastal pollen records of Corsica (Reille, 1992a; Currás et al., 2017; Revelles et al., 2019), is clearly due the steep topography of the island, which determined a relatively low distance of montane and sub-montane vegetation belts from the coast. However, it cannot be excluded that sparse stands of mixed oak communities could also be preserved in humid areas at low elevations, especially inside floodplain and riparian woodlands, dominated by *Alnus*, accompanied by *Salix*, *Tamarix*, and possible wild *Vitis*, which are still documented in the area (Reille, 1992a).

Conifers are mostly represented by *Pinus*, substantially reflecting the persistence of *Pinus nigra* subsp. *laricio* at montane and sub-montane elevations since the late glacial period (Leys et al., 2014). The occurrence of *Pinus pinaster* since the Bronze Age is probably related to human activity (Reille, 1992a). In addition to pine, conifers include taxa distributed in both lowland/coastal areas, such as *Juniperus*, and in montane sectors, such as *Abies* and *Taxus* (Fig. 7). Rare occurrences of *Picea*, whose current natural range does not include Corsica (Caudullo et al., 2016), are of distant origin.

5.2. Environmental responses to hydrological and morphosedimentary processes

The local aquatic environment outlined by the pollen record ranged from brackish (6100–3400 cal. BP) to freshwater conditions (~3400 cal. BP–present day) (Fig. 10). This range is documented by the presence of freshwater taxa, such as *Spirogyra*, *Zygnema* and *Myriophyllum*, salt-tolerant species, such as *Ruppia maritima*, and marine organisms, represented by foraminiferal linings, pointing to inputs of salt-water into the pond (Bellotti et al., 2016). This was likely related to the morphological response of the pond to the Mediterranean sea-level rise whose average rates decreased from ~2 mm a⁻¹ at ~6100 BP to less than ~0.5 mm a⁻¹ in the last 3500 years (Vacchi et al., 2021). These major changes in the rising rates probably have an influence on the connection of the pond with the open sea as already observed in lagoonal setting both in Corsica (e.g. Vacchi et al., 2017; Revelles et al., 2019) and in Sardinia (Melis et al., 2017, 2018). However, the absence of fossil faunal associations hampered a detailed reconstruction of the nature of this backshore environment and its millennial evolution.

The lower part of the record (~6100–~4800 cal. BP) is characterized by high frequencies of *Spiniferites* sp. (Fig. 7), dinoflagellate cysts often difficult to identify at the species level by routine observation in light microscopy (de Vernal et al., 2018). The genus *Spiniferites* is characterized by marine species, but it cannot be excluded that some Mediterranean species live in freshwater environments (Kouli et al., 2001; Zonneveld et al., 2013). Based on pollen records obtained from central Mediterranean regions, the presence of *Spiniferites* is often associated to brackish water (Di Rita et al., 2018b). Irrespective of water salinity, high frequencies of *Spiniferites* in the lower part of the Crovani sequence may reflect the pioneer stages of a hydrosere succession connected to the early phases of development of the coastal pond.

From ~4800 to ~3350 cal. BP (zone CRO-2), a significant increase in *Ruppia maritima*, a submerged angiosperm with large salinity tolerance (Kantrud, 1991), coupled with occurrences of foraminiferal linings, highlights a brackish environment. It is consistent with the observed presence of halite in unit VI (Fig. 4). Beds of submerged widgeongrass plants usually occur on muddy sand and mud in brackish pools. They accumulate sediment and may be associated with terrestrial saltmarsh plants, forming a hydrosere succession in coastal wetlands (Rodwell, 2000).

Starting from ~3350 cal. BP, the abrupt decrease in *Ruppia* and the disappearance of most spores of fungi, coupled with a major increase in *Pseudoschizaea* (2%) and fern spores, are the results of complex sedimentological and ecological changes leading to a lowering of the water level and to the establishment of the present-day marshy environments. *Pseudoschizaea* suggests both desiccation (Scott, 1992) and freshwater flows accompanied by erosive processes, sometimes associated with runoff events (Pantalón-Cano et al., 2003), while the disappearance of most fungal spores, the decrease in pollen concentrations, and the high percentages of Cichorioideae (Figs. 6–8) can be interpreted as selective preservation of palynomorphs (Bottema, 1975; Haviga, 1984).

It is noteworthy that Reille (1992a) recorded a sharp drop in *Ruppia* at 150 cm depth and correlated it with a local change in sediment accumulation. This was caused by an event of forest clearance, followed by an increase in runoff, leading to the accumulation of a sandy layer and a significant development of ferns. In our record, a phase of increased terrestrial runoff is revealed by an input of organic matter of continental origin recorded by a positive excursion of C/N ratio at 1.36 m (ca. 3250 cal. BP - Fig. 4) and by a significant increase in detrital minerals (Fig. S1), but is not preceded by clear changes in AP percentages that may testify to a deforestation process, although there is a drop in AP concentrations around 3350 cal. BP. A clearance of local shrubs, represented by a sharp decline in *Erica* frequencies, was recorded only after ~3100 cal. BP (Figs. 6 and 8).

Summarizing, initially the opening of the vegetation did not change the composition of the shrubland, which was later affected by the drop of *Erica*. Sedimentological analyses indicate an increase of the granulometry within a broader context of swamp environment of deposition characterized by homogeneous clays. At ~136 cm depth (ca. 3250 cal. BP), there is an event of higher energy of deposition characterized by the punctual presence of coarse silts to fine sands. In the Canticcia pond, located in SW Corsica, Ghilardi et al. (2017b) and Vella et al. (2019) identified a high detrital input dated ca. 3350 cal. BP. At a regional scale, the southern France recorded an intense phase of alluviation within the Rhone drainage basin (Berger et al., 2007) and the Pyrenean mountains (Galop et al., 2007). This is possibly explained by the occurrence of a cooler and more arid period that resulted in deforestation on a regional scale (Ghilardi et al., 2017a), recognized in western Mediterranean pollen records (Carrión, 2002; Fletcher et al., 2013) and in speleothems from Tuscany located only ca. 200 km from Crovani (Regattieri et al., 2014). However, the eastern coast of Corsica did not record such event (Currás et al., 2017), which seems to have especially affected western Corsica.

Since ~2900 cal. BP, an expansion of ferns and other hydrophytes (Fig. 7) suggests stagnant water, which may have been produced by a lowering of the lake enhanced by runoff, sediment infilling, and a salinity change towards more freshwater conditions. This change is confirmed by the observed decrease in the halite since the final part of units VI (Fig. 4). Such pattern is consistent with a substantial sea-level stability, which occurred in the NW Mediterranean Sea in the last ~2000 years (Vacchi et al., 2021). This stabilization process significantly decreased the salinity input within the pond triggering the progressive transition in pure freshwater environment.

Overall, the sequence dinoflagellates (*Spiniferites*) → aquatic plants (*Ruppia maritima*) → ferns profiled throughout the pollen record corresponds to a hydrosere succession, whose evolution is strictly related to the sediment infilling of lakes (Fig. 6). This ecological succession typically involves reed swamp vegetation at an intermediate stage, here represented by pollen of Cyperaceae and partly of Poaceae, and *Alnus* at a mature stage. In several coastal sedimentary archives of the central Mediterranean, temporary expansions of Cyperaceae and Poaceae are followed by an increase in *Alnus* (Magri et al., 2019 and references therein). At Crovani this pattern is especially clear in the interval between ~2600 and ~1700 cal. BP, when complete hydrosere succession with a climax woodland stage occurred in marginal sectors of the basin, in relation to a lagoon reduction (Fig. 6).

5.3. Human impact on the landscape

Human activity is evident throughout the pollen record with different intensity and type of land use (Fig. 10). During the Late Neolithic, from ~3900 to ~3250 BC, the continuous curve of cereal-type pollen testifies to early cultivations (Fig. 6). Evidence for

agriculture is also observed at the Saint Florent site starting from ~4000 cal. BC (Revelles et al., 2019), but only the extreme south of the island (Bonifacio-Piantarella area) exhibits continuous agricultural practices all along the Neolithic period. At Crovani, the pollen record reveals human activity older than the archaeological finds, indicating that farming was practiced ~1000 years before the earliest trace of human occupation at the Teghja di Linu site (Sicurani and Martinet, 2019).

Cereal cultivation appears associated to livestock rearing activities, which contributed to the development of disturbed meadows, as highlighted by a significant record of *Sporormiella*, *Sordaria*, and *Podospora*, and by pollen indicators for Mediterranean pasturelands, such as *Carduus*-type, *Plantago*, *Polygonum aviculare*-type, as well as some species of the subfamilies Asteroideae and Cichorioideae (Desprat et al., 2013; Florenzano et al., 2015) (Figs. 6 and 8). The high values of microcharcoal may partly reflect the use of fire for farming purposes, such as slash-and-burn practices, which however did not affect the fire-adapted local shrubland. In general, human activity during the Late Neolithic certainly influenced the vegetation evolution of the area, but its impact did not induce a marked local deforestation. While we cannot advance any precise explanation for this pattern, we can speculate that local settlements were not populated enough to induce forest declines detectable in the pollen diagram.

During the Final Neolithic and Bronze Age (from ~3000 to ~800 BC), both cereal cultivation and livestock rearing appear less intense and discontinuous. The archaeological history of Corsica indicates that Early to Middle Bronze Age are periods of human implantation in the upper part of the hills (Casteddi) when lowlands and coastal areas were less occupied (Cesari and Pêche Quilichini, 2015). The pollen record from Crovani confirms this pattern, even if in some coastal areas the Mid-to Late Bronze Age corresponds to a phase of renewed agriculture (Ghilardi et al., 2017a).

In the Iron Age, cereals disappeared and scattered occurrences of pasture weeds (e.g., *Carduus*, *Plantago*, and *Rumex*) testify to poor farming practices addressed to livestock rearing, suggesting a scarce human frequentation in the area (Fig. 6).

Human activity at Crovani is also revealed by the record of cultivated trees (OJCV curve, Fig. 8), which also include pollen of wild individuals of *Olea* and *Vitis* that is difficult to differentiate from pollen of cultivated plants (Reille, 1992a).

In the period encompassing the Neolithic to the Bronze Age, the pollen record of Crovani shows some early occurrences of *Juglans* (ca. 3700 BC) and *Castanea* (ca. 1200 BC) (Fig. 6). Similar early finds are also recorded in pollen diagrams from recently published coastal sites (Poher et al., 2017; Currás et al., 2017; Revelles et al., 2019). Although these occurrences are generally found during phases of intense human activity, as confirmed by the presence of other anthropogenic pollen indicators, it is difficult to hypothesize that cultivation of these trees was so early, without a clear archaeobotanical evidence. Unfortunately, the palynological studies of Reille (1992a, 1999) and Lestienne (2020a) do not contribute to solve this question, since their records do not show any *Castanea* and *Juglans* before 2500 cal. BP. They interpret these finds as a result of cultivation in the island in historical times. In addition, the absence of palynological investigations from Pleistocene sediments prevents us from speculating on a possible redeposition of pollen from older deposits. We would exclude a long-distance origin, especially for *Juglans*, whose pollen dispersal occurs over short distance despite its renowned anemophily (Carrión and Sánchez-Gómez, 1992).

Phylogeographical studies demonstrate that the post-glacial distribution of chestnut and walnut in Europe and in the Mediterranean regions started from multiple glacial refugia (Mattioni et al.,

2013; Pollegioni et al., 2017). However, due to both the scarcity of palaeobotanical knowledge and incomplete genetic sampling, as in the case of Corsica and Sardinia, there is still much uncertainty in detecting glacial refugia and drawing up robust biogeographical histories of cultivated trees (Médail et al., 2019).

In historical time, the OJCV record shows two major phases of tree cultivation. The first one, between ~250 BC and ~150 AD, reflects a widespread exploitation of olive resources during the Roman Period, also documented by archaeological evidence (Terral et al., 2004). The second increase, after ~1450 AD, testifies to an intensification of *Olea* cultivation and a regional plantation of *Castanea* in the uplands. From 1548 until the 17th century, the Genoese authority introduced the compulsory cultivation of chestnut, whose fingerprint in the Crovani record is represented by a peak of *Castanea* (Fig. 6) (Michon, 2011). The consequence of this decree was a large reorganization of the food production, economy, and socio-cultural systems, as shepherds slowly became chestnut growers and settled more permanently in mid-mountain villages. The chestnut culture fully developed during the 18th and 19th centuries, providing flour for daily meals, fodder for animals, and fruits for trade. By the end of the 19th century, the development of local industries and the related outflow of rural population towards urban centres determined the collapse of the chestnut culture (Michon, 2011).

Human impact on the forest cover is recorded since ~1000 BC (Final Bronze Age), mostly by decreases in evergreen trees and shrubs staggered over time (Fig. 8), coupled with increases in both herbaceous vegetation and *Cistus* dominated low shrublands (Figs. 6 and 8). Considering the local modest farming activities during the last three millennia, this pattern may mostly reflect clearance practices of the *Erica* shrubland at a regional scale. This is consistent with the human-induced opening of the forests recorded in several other pollen sites of Corsica (Reille, 1992a; Revelles et al., 2019; Lestienne et al., 2020a), and in coastal sites of the central Mediterranean since ~1000 cal. BC (Di Rita and Magri, 2012). According to Roberts et al. (2019), after ~1000 BC human activity became the dominant causation in determining landscape openings in the Mediterranean regions.

Despite the clear changes in land use recorded, human activities at Crovani did not completely transform the structure of the vegetation in terms of forest canopy, except for a temporary dramatic drop in the *maquis* vegetation between 950 and 1450 AD (1000–500 cal. BP), for which a prominent anthropogenic causation cannot be ruled out. Pollen indicators of human activity are scarce in this period, but the reappearance of coprophilous fungi (*Sporormiella*) and the increase in *Castanea* and *Olea*, together with a slight increase in fire frequency, may reflect silvicultural practices aimed at felling shrublands to gain land available for both stock rearing and olive cultivation in the lowlands, as well as for chestnut cultivation in the uplands. A similar observation was advanced for the Saint-Florent area, where an important deforestation phase was coeval to the development of pastoral activities (Revelles et al., 2019). Between ~1000 and ~500 cal. BP, frequencies >2% of *Pseudoschizaea* and *Glomus* support soil erosion and local deforestation (Figs. 7 and 10). This was also the time when several churches were locally built (Fig. 1A).

Human activities may also be tracked from the Pb isotope signature of the Crovani sediments. Sedimentary Pb data are aligned along a linear trend in a binary $^{208}\text{Pb}/^{206}\text{Pb}$ – $^{206}\text{Pb}/^{207}\text{Pb}$ diagram (Fig. 5A and B). Such distribution indicates a mixing between two end-members, a natural end-member with higher isotope Pb ratios and a probable anthropogenic-derived end-member characterized by lower isotope ratios.

- (a) The first end-member has been defined by the average signature of 3 samples dated from the Final Neolithic period (196–260 cm). They are used to define the local detrital source with low isotope ratios (i.e., $^{208}\text{Pb}/^{204}\text{Pb} = 38.9584 \pm 0.0020$, $^{207}\text{Pb}/^{204}\text{Pb} = ^{206}\text{Pb}/^{204}\text{Pb} 15.6719 \pm 0.0008$ and $^{206}\text{Pb}/^{204}\text{Pb} = 19.0775 \pm 0.0008$) (Table S1). This end-member represents the natural background end-member. The composition of the samples corresponding to the Iron Age, only defined by 2 measurements, is slightly different from the previous Bronze Age and Final Neolithic periods, with a position closer to the sample from the Roman representative average. The Pb isotope ratios of the sediments roughly decrease upwards from the natural background end-member. The oldest pre-Roman samples (n = 19, 93–260 cm) are clustered with an average signature of 38.9667 ± 0.0235 , 15.6716 ± 0.0007 and 19.0702 ± 0.0008 for $^{208}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$, respectively.
- (b) A shift towards lower Pb isotope ratios is marked for the Roman samples (53 and 73 cm) and for the modern samples (11–23 cm). The first Roman shift may be related to some exploitation of Pb ores. The isotope composition of both regional Pb-bearing ores and modern urban airborne particles (Bollhöfer and Rosman, 2001) are reported in order to confirm any anthropogenic contribution in the sediment Pb isotope composition. The isotope Pb ratios of the Roman and modern samples become closer and closer to the Corsican Pb minerals (Fig. 5). The analysed Pb-bearing minerals display close Pb isotope signatures, with an average composition of 1.1779 for $^{206}\text{Pb}/^{207}\text{Pb}$ and 2.0894 for $^{208}\text{Pb}/^{206}\text{Pb}$. The first decrease of the Pb isotopic ratio observed in the Roman Crovani sediments is in agreement with the historical exploitation of the Pb–Ag ores from the Argentella during the Roman period (Gauthier, 2006). The linear trend defined by the modern samples does not point towards the modern urban airborne particles but rather towards the Pb signature of the Sardinian ores (Stos-Gale et al., 1995). In the Crovani sediments, Sardinia seems to be the most probable anthropogenic source of Pb among the main Pb mines exploited in the Mediterranean area, i.e. in Greece, Turkey, Italy and Spain since the Antiquity (see more details in Fagel et al., 2017). In the binary $^{206}\text{Pb}/^{207}\text{Pb}$ – $^{208}\text{Pb}/^{206}\text{Pb}$ diagram, the Crovani samples define a linear trend that, if extrapolated, points to the representative average signature of Sardinian ores (Fig. 5 B).

5.4. Effects of rapid climate changes on coastal tree-cover

In the palaeobotanical narrative of Corsica, no clear tree-cover change has ever been attributed to a “Bond event” (Bond et al., 2001) (Fig. 8) or other RCC of global interest, such as the 4.2 ka BP event (Bini et al., 2019), the Homeric minimum (2.8 ka BP) (Martin-Puertas et al., 2012) and the Little Ice Age (Trouet et al., 2009). These events caused major changes in forest cover in many sites of central and western Mediterranean regions, although with contrasting trends (Fletcher et al., 2013; Magny et al., 2013; Di Rita et al., 2018a).

The 4.2 cal. BP event, perceived in south-central Italy as an aridity crisis producing a forest decline, did not trigger a rapid response in the regional forest vegetation in Corsica and in the northern Apennines (Di Rita and Magri, 2019; Revelles et al., 2019; Di Rita et al., 2022). However, previous studies in Corsica have shown that the 4.2 event played an influence on geomorphological and sedimentological processes, due to increased storm and fluvial activities as recorded in several lagoon archives (Revelles et al.,

2019 and references therein). In our record from Crovani, rapid fluctuations of the forest cover are found, marked by maximum values of AP (92%) at ca. 4450 cal. BP (Figs. 6 and 8). Between 4700 and 3500 cal. BP, a long-lasting increase in *Fagus* suggests permanent humid conditions during the Mid-to Late Holocene transition (Fig. 6), which are recorded also in other montane sites (Reille, 1975; Reille et al., 1999) and pollen sequences from coastal Corsica (Poher et al., 2017). The development of beech corresponds to relatively wet climatic conditions in central Italy, as revealed by lake level highstands at Lake Accesa ca. 160 km far from Crovani (Magny et al., 2013). Lake level highstands reflecting humid conditions are also recorded in northern Italy (cf. Lake Ledro: Magny et al., 2012), and in west-central Europe (Magny et al., 2013 and references therein).

The development of beech also corresponds to periods of increased storm activity in southern France (Sabatier et al., 2012) (Fig. 8). Although these periods were previously interpreted as a result of southward westerly winds bringing moisture to mid-latitudes in Europe (Sabatier et al., 2012; Magny et al., 2013), they may also reflect an increase in the frequency of marine storms that are not directly interpretable as periods of regional increased precipitation (Azuara et al., 2020). An alkenone record from the Gulf of Lion suggests moisture increase in southern France since ca. 4200 cal. BP (Jalali et al., 2017; Azuara et al., 2020).

The general pattern of increased humidity in western Corsica contrasts with the drier conditions indicated by precipitation proxies from the speleothems of the Corchia and Renella caves in Tuscany (Zanchetta et al., 2016; Isola et al., 2019), and depicts a complex geographic expression of the 4.2 ka event (Bini et al., 2019; Di Rita and Magri, 2019; Di Rita et al., 2022).

The Homeric Minimum (2750–2550 cal. BP, Martin-Puertas et al., 2012) was associated to forest declines influenced by human impact and dryer climate conditions in many records of the south-central Mediterranean (Di Rita et al., 2018c). At Crovani, it corresponds to a modest peak in AP, possibly related to slightly wetter conditions. Relatively higher precipitations were recorded from lake-level highstands since 2800 cal. BP at Lake Accesa (Fig. 8), and from lake-level highstands and pollen evidence at Lake Ledro (Magny et al., 2012; Peyron et al., 2017). More humid climate conditions were also found in the western Mediterranean, possibly associated to the negative NAO index that characterizes this interval (Fletcher et al., 2013). This phase corresponds also to increased storm activity in the Gulf of Lion (Sabatier et al., 2012).

During the Little Ice Age, the record of Crovani shows a marked increase in *Erica* and *Q. ilex maquis*, accompanied by significant frequencies of cultivated trees related to orchards and conifer plantations (Figs. 6 and 8). The development of natural and cultivated woody taxa was probably favoured by relatively wet climate conditions, which were also recorded in both central and northern Italy from lake-level highstands (Magny et al., 2013), as well as in southern France from records of major flooding (Benito et al., 2015; Pichard et al., 2017), coinciding with a mostly negative NAO index (Franke et al., 2017) (Figs. 8 and 10). Climate reconstructions in Corsica are still fragmentary, however the few published studies indicate the occurrence of periods characterized by wet and cool conditions (Szymczak et al., 2012; Vella et al., 2014).

The archaeological and palaeoenvironmental literature does not provide noticeable examples of rapid and dry climate events in Corsica. As previously discussed, the complex sedimentological pattern at ~3250 cal. BP (Fig. 4) might be related to an arid climate event observed around the same age in other palaeoenvironmental records. Relatively dry and warm climate conditions may also have contributed to the major forest decline recorded between 1000 and 500 cal. BP, limiting the resprout of the natural forest vegetation affected by felling activities. In the western Mediterranean, the dry

and warm climate of the Medieval Climate Anomaly is usually associated to an overall positive NAO index (Trouet et al., 2009; Franke et al., 2017) (Fig. 8).

Sabatier et al. (2020) have found a strong relationship between the transport of Saharan dust conveyed to Corsica during the last ~3000 years and both total solar irradiance (TSI) and NAO activity. They have shown that the NAO was the main climatic forcing for centennial to decadal variations since ~1070 AD, with an increase in Saharan dust input during positive NAO phases. Before ~1070 AD, TSI was the main forcing factor, with increases in African dust input during low TSI phases.

We applied a REDFIT analysis to the total AP percentages to investigate the effects of the atmospheric circulation on the tree cover record from Crovani (Fig. 9). The prominent 230-year cycle found in our statistical elaboration by and large corresponds to the Suess-de Vries cycle of solar activity, which has been held responsible for environmental and atmospheric changes in several records around the world, including the Mediterranean (Castagnoli et al., 1992; Galloway et al., 2013; Di Rita, 2013; Degeai et al., 2014; Sabatier et al., 2020). The Suess-de Vries cycle is commonly identified as a conventional 210-year periodicity; however, an increasing number of studies demonstrates its non-stationary variability, which may have a range of ~200–300 years (Vecchio et al., 2017). Similarly, its expression in palaeoenvironment proxies shows a non-stationary periodicity (Galloway et al., 2013). A 230-year cycle was detected in direct proxies of solar magnetic activity, such as ¹⁴C time series and naked-eye observations of sunspots (Ma and Vaquero, 2020).

The REDFIT analysis from Crovani shows also two periodicities of ca. 430 and 1000 years, respectively (Fig. 9). The first one corresponds to the ca. 430-years and 450-year cycles detected by Sabatier et al. (2020) in the records of Saharan dust in Corsica, as shown by both TSI and ITCZ, although the authors attribute a low significance to this cycle. A 440-year cycle (together with a 230-year cycle) was found in $\delta^{13}\text{C}$ records of speleothems from northern Iberia and was interpreted as the result of climate forcing mechanisms related to changes in solar irradiance and North Atlantic circulation patterns (Márton-Chivelet et al., 2011). Periodicities of ~400-years were recognized in various palaeoclimate proxies from both marine (e.g., Bond et al., 2001) and lake records (e.g., Yu and Ito, 2002; Wu et al., 2009) of the Middle-Late Holocene.

The last periodicity we found at Crovani matches a prominent ~1000-year cycle of moisture supply reported in proxy records from the western Mediterranean, especially during the Early Holocene, which have been associated to solar activity (Debret et al., 2009; Fletcher et al., 2013; Jiménez Moreno et al., 2020 and references therein).

Overall, our results show that the forest oscillations at Crovani present a fundamental tempo of variability consistent with the atmospheric forcing held responsible for the transport of Saharan dust to Corsica. Although the relationship between solar activity and forest dynamics in Corsica is only sketched, our findings encourage future research in the central Mediterranean, interpreted in the light of the regional patterns of vegetation change.

5.5. Coastal landscape evolution of the Crovani area

Based on the cross combination of sedimentological, palynological and geochemical proxies, we propose a synthetic palaeogeographical reconstruction of the investigated area, even if additional cores would be necessary to evaluate in a comprehensive way both the morphological changes and the spatial evolution of the Crovani wetland since the Mid-Holocene. The bottom of the core records a detrital environment with a mixture of well-rounded

pebbles and coarse material, ranging from sands to gravels. Unfortunately, this section of the core did not contain enough organic material for obtaining a radiocarbon age. Furthermore, facies identification was difficult due to the lack of fossil fauna. However, on the basis of the sedimentological information, two types of energy of deposition can be identified. The first is controlled by terrestrial dynamics being characterized by the finest particles (grey clays). The second is conversely controlled by coastal dynamics as indicated by the presence of well-rounded pebbles that are analogue in shape and petrography to the sediments which compose the modern coastal barrier. These data suggest that the continental dynamics likely prevailed during the first half of the Holocene. This was followed by a mid-Holocene marine transgression that reached its maximum ~6500 cal. BP, when the sea-level in Corsica was ca. 3.5–4 m below its present-day position (Vacchi et al., 2018). At that time, which broadly correspond to Middle to Late Neolithic, a marine incursion occurred in the Crovani coastal pond following a pattern that was also observed in other coastal lagoons in Corsica, such as Saint Florent (Revelles et al., 2019) and Del Sale (Curras et al., 2017). As a result, the pond turned into brackish conditions after ~6100 cal. BP, as confirmed by the presence of *Spiniferites*, which substantially indicates a connection with the sea (Figs. 6 and 10). However, probably due to the presence of Late Pleistocene alluvial formations and relict coastal deposits (former coastal barriers), the marine incursion inland was spatially limited. This could explain the lack of faunal assemblages typical of coastal lagoon made by ostracods, foraminifera and molluscs faunas. After ~5100 cal. BP, during the Late to Final Neolithic characterized by the first occupation of the nearby site of Teghja di Linu, data show detrital input that suddenly modified the brackish conditions of the pond. However, our results indicate that neither a climatic event nor human impact resulted in deforestation associated with intense foothill erosion and sedimentary accumulation of coarse material, even if there was clear land use at that time (Fig. 10). A second phase of wetland development is well attested from the Final Neolithic to Middle/Late Bronze Age. Presence of salt intrusion is confirmed by both the vegetation composition and the geochemical analyses (presence of halite) but there is no clear evidence for a direct connection of the coastal pond to the sea (e.g., presence of faunal assemblages typical of coastal lagoons). A second detrital input is observed during the Late Bronze Age (Unit VII). The C/N Ratio exhibits the highest values for the entire sequence studied, thus indicating a terrestrial deposition of organic matter (see section 4.2.) (Fig. 4). This likely was a rapid event (not more than a century in duration) that could have caused the silting up of the wetland. Finally, the present-day landscape configuration was established starting from the Final Bronze Age (unit VIII) with very little morphological changes afterwards. Since ~3200 cal. BP, Crovani coastal pond has been a backshore freshwater body with probable aeolian input of salt, no permanent connection to the sea, and low sediment accumulation rate (Fig. 10).

6. Conclusions

The new multidisciplinary dataset obtained from northwest Corsica helps to reconstruct past environmental dynamics (Fig. 10) within an archaeological context, and to frame them into the wider scenario of the central Mediterranean landscape evolution. Our results contribute to the lively discussion on the vegetation response to rapid climate changes, as raising as new questions about planetary drivers of past atmospheric circulation and their possible influence on the forested ecosystems of this strategic region of the Mediterranean. In particular, the following conclusions can be drawn:

- 1) A dense *Erica*-dominated shrubland rich in many evergreen elements characterized the landscape from ~6100 to ~1000 cal. BP, being temporarily replaced by mixed woodlands dominated by *Q. ilex* between 2300 and 1900 cal. BP. A major opening of the landscape occurred only between ~1000 and ~500 cal. BP, featured by a temporary decline in *Erica*-dominated tall shrublands, paralleled by an expansion of *Cistus*-dominated low shrublands and followed by the recovery of the tall *maquis* formations.
- 2) Fires played a prominent role in the development and maintenance of the *Erica*-dominated shrublands, especially during the Middle Holocene (from ~5900 to ~5200 cal. BP), when frequent and intense wild and anthropogenic fires boosted the sprout of *Erica* species. Differently from other sites in Corsica and Sardinia, at Crovani fires did not affect *Q. ilex*, whose development cannot be univocally explained in the region and may be influenced by a long-lasting ecological legacy. The general decrease of fires after ~3300 cal. BP may reflect a combination of decreased human activity and climate unsuitable for fires.
- 3) The Crovani wetland has been little influenced by marine incursions over the last six millennia, as indicated by sedimentological data, pollen and NPPs. Moderate brackish conditions occurred only from the Late Neolithic to part of the Bronze Age, while during the last three millennia general freshwater conditions prevailed. The sequential development of diatoms, *Ruppia*, and ferns appears to reflect a hydrosere succession, whose evolution is strictly related to the infilling of the lake. After ~3300 cal. BP, this ecological process was influenced by a sudden deposition of continental organic-rich sediments, following rapid deforestation and runoff of regional extension, coeval to an arid climate event occurred around ~3200 cal. BP.
- 4) Evidence for human activity is present throughout the pollen record, with important differences through time. Between ~6000 and ~5200 cal. BP, a continuous curve of cereal-type pollen testifies to the earliest cultivations in this area. Farming activities are also confirmed by the presence of disturbed meadows for livestock rearing, indicated by coprophilous fungi and pollen indicators of plants frequently living in Mediterranean pasturelands. Starting around 3300 cal. BP, indicators of cereal cultivation and stock rearing practices become sparse, and evidence for human activity comes from cultivated trees, especially after ca. 2000 cal. BP and even more after ~500 cal. BP. The former increase reflects olive exploitation during the Roman Period, the latter points to both olive cultivation in lowland areas and chestnut culture in the uplands. A clear forest degradation dates back to the last three millennia, with a dramatic opening of the landscape only from ~1000 to ~500 cal. BP, related to human activity in the medieval times and Genoese domination.
- 5) The spectral analysis applied to total AP revealed a ~230-year cycle, in the bandwidth of the Suess-de Vries cycle, and other cyclicities attributed to the magnetic activity of the Sun, recognized also in other climate proxies from the Mediterranean. This suggests that the atmospheric modifications of solar activity and North Atlantic Oscillation had some influence on the tree cover fluctuations in Corsica. However, known rapid climate changes, such as the 4.2 ka BP event, the Homeric minimum, and the Little Ice Age, did not determine at Crovani extensive forest declines as they did in sites of the south-central Mediterranean. In contrast, in northwestern Corsica these phases correspond to a forest development consistent with the humid phases detected in southern France and northern Italy. The high-resolution record from Crovani is an important piece of information to define the spatial pattern of vegetation response to the

atmospheric arrangements produced by rapid climate changes over the Mediterranean Basin during the Holocene.

Authors' contributions

All authors have materially participated in the research project and article preparation, as follows. Conceptualization: FDR, MG, NF, and MV. Sediment collection: MG, JS and LM. Methodology: FDR, MG, NF, and MV. Formal analyses: FDR, MG, NF, MV, FW, DD, and SR. Data collection: FDR, MG, NF, MV, FW, DD, JS, LM, and SR. Results interpretation: FDR, MG, NF, and MV. Writing original draft: FDR, MG, NF, and MV. Contribution in interpreting results and writing the paper: FW, DD, JS, LM, and SR. Funding acquisition: MG.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This article is a contribution of the PCR "Approche géoarchéologique des paysages de Corse à l'Holocène, entre mer et intérieur des terres « Tra Mare è Monti » programme, funded by the DRAC Corsica and directed by Matthieu Ghilardi. It is also part of the MISTRALS-PALEOMEX programme of CNRS, France (INEE-INSU scientific departments) and was funded by the ARCHEOMED workshop (Dir. Laurent Lespez). This research was also supported by Sapienza University of Rome, Italy (grant numbers RM11715C820D1E6F, RM1181641C0CB0C7, and RM120172AE4E11D6). The authors are grateful to the Conservatoire du Littoral (branch of Corsica) and its Director, Michel Muracciole, for delivering the work permits. We thank Donatella Magri for her precious suggestions and two anonymous reviewers for helpful comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2022.107372>.

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