Mid- to Late-Holocene coastal morphological evolution, vegetation history and land-use changes of the Porto Gulf UNESCO World Heritage site and its surroundings (NW Corsica Island, Western Mediterranean)

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Abstract

Two coastal areas located on the North-Western side of Corsica Island have been investigated to reconstruct their Mid- to Late Holocene landscape evolution together with the history of human occupation. Particular attention has been paid to the study of shoreline migration and vegetation history alongside land-use. Three boreholes were drilled to a maximum depth of 4.20 m and laboratory work comprised the identification of molluscs and pollen/NPPs as well as sedimentological analyses. Chronostratigraphy is based on a series of 18 radiocarbon datings and enabled to reconstruct the environments in the Fangu Estuary to the north of the World Heritage site over the last six millennia, and over the last four millennia on the Girolata coastal plain to the south. Palaeogeographic reconstructions of shoreline mobility are established for each site based on borehole chronostratigraphy analysis. In addition, two original pollen and NPPs diagrams were established for the Girolata and Fangu sites. These reveal that anthropogenic activities began to significantly impact local vegetation cover ca. 2500 years BP at Girolata, and ca. 2000 years BP at Fangu. Of particular interest, our work records the first complete pollen sequence in Corsica for Roman times at Girolata: first, the exploitation of cereals, grapevines and the development of husbandry is observed during the Roman Republic (500 BCE-0), followed by the almost exclusive cultivation of *Olea* sp. during the Roman Empire (0-500 CE). Following this, and using other regional pollen studies obtained for NW Corsica, we propose a regional evolution of the complex human-environment interactions for the last six millennia. Our results reveal a peak of regional forest decline (the most intense event recorded for the Late Holocene) from the 11th to the 16thcenturies CE which can be attributed to the exploitation of wood resources during the Pisan and Genoese dominations of the island.

Keywords : Palaeoenvironments, Vegetation history, land-use, UNESCO World heritage site, Coastal landscape, Corsica

1. Introduction

The coastal wetlands of the Mediterranean are of particular interest when reconstructing short- to long-term human-environment interactions, mainly at a local scale, as is attested by the abundant

[1]CEREGE – AMU-CNRS-IRD-Collège de France-INRAE, Europôle de l'Arbois BP 80 13545 Aix-en-Provence CEDEX 04, France. matthieu.ghilardi@cnrs.fr
[2]Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA),Zona Educacional 4, Campus Sescelades URV(Edifici W3), 43007 Tarragona,Spain.
[3]UniversitatRovira i Virgili, Departament d'Història i Història de l'Art,Avinguda de Catalunya 35, 43002 Tarragona, Spain
[4]University of Lyon 2, Hisoma, Collectivité de Corse
[5]University of Roma La Sapienza
[6]University of Nice – CEPAM CNRS
[7]SIGOSPHERE, Chazay d'Azergues, France

literature treating this topic over the last decade (Di Rita and Magri, 2012; Fontana et al., 2017; Melis et al., 2017; Poher et al., 2017; Brisset et al., 2018; Pascucci et al., 2018; Marco-Barba et al., 2019; Revelles et al., 2019).The general calm conditions accompanying sediment vertical accretion allow the acquisition of continuous sedimentary series, making coastal wetlands suitable places to reconstruct Early- to Late Holocene environmental changes, using a series of sedimentological, geochemical and palaeoecological proxies (Sabatier et al., 2010; Marco-Barba et al., 2013; Brisset et al., 2018; Lopez-Belzunce et al., 2020; Giaime et al., 2022). Along Corsica's shoreline (~1050 km long) where human occupation is well attested and documented, two hundred brackish (mostly lagoons and swamps) to freshwater ponds are found (Ghilardi, 2020 and 2021). These latter could potentially be cored in order to improve our understanding of landscape configuration over the last six to eight millennia. Indeed, over the last decade, Corsica, the fourth largest Mediterranean island (area of ca. 8720 km²), has been studied in an attempt to reconstruct human-environment interplays with robust chronostratigraphies on the coastal zone (Currás et al., 2017; Ghilardi et al., 2017a; Revelles et al., 2019 ; Vella et al., 2019; Di Rita et al., 2022a). All these studies are based on pollen analyses and have focused on human-environment interactions since Neolithic times (Currás et al., 2017; Ghilardi et al., 2017a; Poher et al., 2017; Revelles et al., 2019 ; Vella et al., 2019; Di Rita et al., 2022a). Some of these studies have also revealed that most of the coastal plains formed during the Late Holocene due to a general mechanism of deltaic progradation of the river mouths (Currás et al., 2017; Ghilardi et al., 2017a) following a period of maximum sea incursion that can be dated slightly before the Mid-Holocene (Vacchi et al., 2016 and 2018; Revelles et al., 2019). The Porto Gulf UNESCO World Heritage site (listed in 1983) in NW Corsica covers an area of ca. 120 km² that includes the Girolata Gulf, the Scandola Peninsula and the Fangu River (Figure 1), where a small number of coastal wetlands can be identified on the coastal plains. Until now, no geoarchaeological studies have attempted to reconstruct the human-environment interplays during the Holocene for the entire UNESCO site. However, extensive archaeological surveys conducted since the mid- 2010s attest to the presence of humans over the last ca. 2500 years at least, corresponding to the Roman (Cibecchini and Dieulefet, 2014) and Medieval periods (Huser et al., 2017; Mary, 2021 and 2022). Nonetheless, there are few known remains that reveal the complete history of the human occupation and land-use practices during Protohistory, Antiquity, and the Middle Ages. Based on archaeological findings, the Girolata and Fangu coastal plains may possibly have served as natural harbours (protected bays) since Early Roman times when the seashore was probably located further inland. In order to elucidate these geoarchaeological questions and to locally reconstruct past morphological changes and vegetation dynamics as well as land-use, the two main coastal areas (Girolata Plain and Fangu Estuary) were investigated. The aim of the present paper is to provide additional pollen sequences in the NW area of Corsica in order to obtain a full view of the vegetation history at the regional scale and over the last millennia, as influenced by human activities and other factors determining landscape changes, in particular during Protohistory, Roman and medieval times.

2. Site presentation and archaeological settings

2.1. The Girolata Plain

2.1.1. Topography and geology of the area

The Girolata Plain is situated south of the Scandola nature reserve (Figure 1) and covers an area of ca. 4 ha. Until recently, swamplands were present in the westernmost part of the plain which is drained by two intermittent streams: Girolata Stream (Fig. 2A) to the east and Novalla Stream (Fig. 2A) to the west. Both rivers drain primarily Upper Carboniferous/Lower Permian rhyodacitic rocks of volcanic origin in the upper part of the drainage basins, and monzogranite in the lowermost part of the river valleys (Vellutini et al., 1985 and 1996; Huser et al., 2017; Figure 2A). Locally, Palaeozoic micaschists

outcrops are identified to the west of the catchment (Figure 2A). The Girolata coastal plain is limited to the South East by a coastal barrier formed by well-rounded pebbles embedded within a matrix of gravels and coarse sands, turning the flat plain into a back-ridge depression (Figure 2B).

2.2.2. Previous geomorphological studies

In the late 2010s, geomorphological investigations (Huser et al., 2017) carried out in the north-eastern part of the Girolata Plain revealed a succession of different environments, starting from marine to shallow marine during the Middle Bronze Age (1800-1350 BCE), followed by mainly terrestrial environments, potentially dated after Antiquity. However, the rather low number of sedimentary sequences obtained and dated by only two radiocarbon datings were insufficient to enable a full reconstruction of the palaeogeography of the plain over the last four millennia. In addition, no information concerning past land-use and human-environment interactions was gained for this period.

2.2.3. Archaeological settings

There are no trace remains of human occupation for the Prehistoric and Protohistoric periods throughout the catchment areas of Novalla and Girolata Streams nor in the vicinity of the Girolata Plain. For the subsequent cultural periods, recent archaeological surveys have revealed an important phase of human occupation during Roman times, ranging from the late 3rdcentury BCE until the early 7th century CE (Cibecchini and Dieulefet, 2014; Mary, 2014a; 2014b; 2014c; 2018; 2021 and 2022; Huser et al., 2017). The site of Chjesaccia, located on a smooth granitic outcrop and situated a short distance from the present day shoreline of the Girolata Plain (Figs. 2A and 2B) yielded important findings. This site is also situated a very short distance from the stratigraphic profile studied in 2017 (Huser et al., 2017). In particular, tegulae (flat roofing tiles) and different building structures (apses) have been discovered and can probably be associated to an important coastal site dating roughly from the 3rd century BCE to the 2nd to 3rd centuries CE (Mary, 2014a, 2014b, 2020). Recent archaeological excavations have revealed a building probably dated from the 1st century CE (Mary, 2020) located to the west of the plain, in the modern village of Girolata. Beyond the coastal plain and its immediate surroundings, the Novalla River valley evidences (surface surveys) the presence of material dated from the 2nd and 3rd centuries CE at two sites (Figure 2A) named Novalla (mid- main stream) and Calanchelle (upper stream; Mary, 2014a, 2014b).

Traces of modern nautical activity have been dated to the 16th-18th centuries CE (Cibecchini and Dieulefet, 2014) and remarkable buildings located primarily in the westernmost part of the Girolata Plain have been identified. The aim of these structures was both to protect the coastline from invaders (mainly the Ottomans, following the fall of Constantinople in 1453 CE) and to aid the development of agriculture. The configuration of Girolata Bay offers a protected coastline that may have served as a natural harbour. The construction of the nearby Girolata fort during the Genoese administration of the island is certainly related to the presence of such a harbour, as is revealed by recent submarine surveys (Cibecchini and Dieulefet, 2014).

The continuous occupation of the Girolata area over approximately two millennia (from the 3rd century BCE until the 18thcentury CE) confirms the important geostrategic position of the protected Bay on the western coast of the island and its role as a layover on the western Mediterranean maritime routes.

2.2. The Fangu coastal plain

2.2.1. Present-day topography and geology of the surroundings

The Fangu drainage basin covers an area of ca. 235 km² for a length of 24 km (Figure 1) and marks the northern limit of both the UNESCO world heritage site and the Corsican regional park. The catchment topography is characterised by steep slopes, with upper reaches situated at an elevation of 2335 m amsl (Capu Tafunatu; Figure 1) with the highest summit culminating at 2556 m (Punta Minuta; Figure 1). The geology of the drainage basin can be divided into four main groups (Vellutini et al., 1985 and 1996): 1/ the metamorphic and sedimentary complex which is located on the northern bank of the lower Fangu River valley. This complex dates from the Palaeozoic and is older than the volcanic complex of Monte Cintu (Vellutini et al., 1985 and 1996). The metamorphic complex includes pre-Devonian shales and schists (Figure 3A) while the sedimentary complex is made up of conglomerates and sandstones dating to the Devonian (Figure 3A); 2/ the volcanic complex of Monte Cintu dates from the onset of the Permian and composes half of the geology of the Fangu catchment. This complex consists of rhyolites of different colours (Figure 3A); 3/ To the east, rhyolites with ignimbritic facies form the eastern limit of the catchment where the higher summits are situated; 4/ The lower river valley is characterised by an abundant alluvial sedimentation due to multiple migrations of the Fangu River main course during the Quaternary. The river mouth does not connect with the sea at any time of the year but forms a large coastal swamp, situated in the former river estuary behind a thick and wide coastal barrier (Figure 3B), itself composed of rounded pebbles and a matrix of sands and gravels.

2.2.2. Archaeological settings

Human occupation of the area remains largely unknown due to the paucity of archaeological surveys conducted. However, the modern period is well represented with the identification of two towers built during the Genoese administration of the island. The first one was built in 1541 (Figs 3A and 3B) while the second was built in the same location in 1574. The construction of these towers supports the strategic position of the Fangu Estuary which, like Girolata Bay, probably served as a natural harbour on the road from Calvi to Girolata on the north-western coast of Corsica. Forest exploitation can be related to this coastal settlement, where wood trunks were transported from the uplands of the Fangu drainage basin to the estuary before being loaded onto boats. Sawmills located at Pozzona on the lower Fangu River were active between 1596 and 1608 CE (Graziani, 2004), and confirm this forest activity. Other than this, little is known in terms of human presence, in particular during Roman times. Many unanswered geoarchaeological questions remain concerning land use in the area, possibly linked to the Girolata sector.

3. Methods

3.1. Core sampling

Three 50-mm diameter vibracores were drilled reaching a maximum depth of 4.20 m (Figs. 2A, 2B, 3A and 3B). Each borehole was precisely mapped and subsequently levelled with topographic information derived from a LIDAR survey (Table 1).

3.2. Grain-size analyses

Samples were taken at 5 cm intervals. Many samples exhibited coarse particles (gravels to pebbles) above 2 mm. Wet-sieving by hand was then used to isolate the total fractions of coarse (>2 mm) and fine sediments (<2 mm). For the layers which contained fine particles only (less than 2 mm), laser diffraction grain-size analyses were undertaken. The grain-size distribution was measured using a Beckman Coulter LS 13 320 laser granulometer with a range of 0.04 to 2000 µm, in 116 fractions detected from 132 detectors (126 detectors for the scattering pattern and 6 detectors for the PIDS

(Polarization Intensity Differential Scattering) technology which is sensitive to sub-micron sized particles). The calculation model (software version 5.01) uses the Fraunhöfer and Mie theory. For the calculation model we used water as the medium (RI = 1.33 at 20 °C) and a refractive index in the range of that of kaolinite for the solid phase (RI = 1.56; Buurman et al., 1996). Samples containing fine particles were diluted, enabling to measure between 8 and 12% of obscuration and between 45 and 70% PIDS obscuration.

3.3. Organic matter/carbonate content

Loss-on-ignition (LOI) measurements were conducted at CEREGE on cores Girolata 2 and Fangu following Dean (1974) and Bengtsson and Enell (1986). Sediment samples of approximately 10 to 20 g were taken at 5 cm intervals throughout the sequences. After drying at 105°C to constant weight, the samples were heated to 550°C for 7 h to estimate the organic content. A second heating phase to 950°C for a further 7 h was undertaken to assess the proportion of carbonate.

3.4. AMS dating

The chronostratigraphy of the cores was established using a series of 18 AMS radiocarbon determinations from charcoal, organic matter and plant remains (*Posidonia oceanica*) (Table 2). The analyses were conducted in the Poznan (Poland) Radiocarbon Dating Laboratory. ^{14}C ages were calibrated using Calib Software Version 8.2 (Stuiver and Reimer, 1993) and the IntCal20 calibration curve for terrestrial samples (Reimer et al., 2020). Marine samples (*Posidonia oceanica*) were corrected for the local marine reservoir effect according to Siani et al. (2000) and Reimer and McCormac (2002) where regional ΔR is -109 (±40) in the area of Bastia (situated 75 km east of the study area). Finally, the age-depth models were built in Clam.r 2.2. (Blaauw, 2010) using best fitting methods, smoothing spline for Fangu and linear interpolation for Girolata 2 (Figure 4).

3.5. Mollusc identification

Cores Girolata 1, Elbu and Fangu were devoid of molluscs, while Girolata 2 was rich in fossils. All samples were wet-sieved through a wire screen (0.40 mm mesh) and air dried at room temperature. The residue was examined under a binocular microscope (magnification: ×10) and all identifiable shells and characteristic fragments were selected and placed in separate plastic tubes. Based on the molluscan classification system which assigns Mediterranean species to well-defined ecological groups (Péres and Picard, 1964; Péres, 1982), bio-sedimentary units were then established for the present study.

3.6. Pollen identification

Pollen analysis was focused on 20 samples from the shallow marine sequence of the Girolata 2 core and 24 from the Fangu core.

All (44) samples were processed following standard methods (Goeury and Beaulieu, 1979; Girard and Renault-Miskovsky, 1969) using treatment with HCL, NaOH, flotation in dense Thoulet liquor, HF and final mounting in glycerine. Around 300-350 pollen grains of terrestrial taxa were counted using an Olympus Bx43 microscope fitted with ×10 ocular lenses and ×40/60 objectives. Hygrophyte and aquatic plants (Cyperaceae, *Typha*/*Sparganium, Myriophyllum,* Ranunculaceae) and Amaranthaceae-Chenopodioideae were excluded from the pollen sum to avoid over-representation by local taxa. All pollen types are defined according to Reille (1992b). Cerealia-type was defined according to the

morphometric criteria of Faegri and Iversen (1989) (>40 µm pollen grain, >8 µm pore). *Alnus* spp. refers to some alder species, in particular *Alnus glutinosa* and *Alnus alnobetula var. suaveolens* (Req.) Regel. Non-pollen palynomorphs (NPP) identification followed van Geel (1978, 2001), van Geel et al. (2003), Revelles et al. (2016) and Revelles and Van Geel (2016). A percentage pollen diagram was created using Tilia software (Grimm, 1991-2011), and pollen zonation was defined using CONISS (Grimm, 1987); NPPs are described in the context of the pollen zones.

4. Results

4.1. General stratigraphy

4.1.1. Girolata 1 core

This core is 3.15 m long and is characterized by the presence of very coarse material, mainly gravels and pebbles along most the sequence. However, four sedimentary units can be distinguished (Figure 5):

- Sedimentary Unit 1 is found between 3.15 and 1.30 m deep and is characterized by an alternation between layers of grey sands containing balls of the Mediterranean seagrass *Posidonia oceanica* (depths of 2.95, 2.80, 1.92, 1.89, 1.82 and 1.66 m) and layers composed of gravels and a mixture of well-rounded and angular pebbles of dacites/rhyodacites. Unit 1 contains no molluscs, and with the exception of the layers containing *Posidonia oceanica*, the organic matter content is poor. Two radiocarbon datings were performed on fibers of *Posidonia oceanica* : in the lowermost part of Unit 1, at a depth of 2.96 m, an age of 1424-1047 cal. BCE was obtained, while in the uppermost part of the unit, at a depth of 1.66 m, an age of 1317-917 cal. BCE was recorded. Unit 1 is characteristic of marine environments with high energy of deposition, possibly in the supra tidal zone since no molluscs or shell debris were found. It is noteworthy that the lithology of the detrital material composed of gravels and pebbles is exclusively composed of dacites, the dominant rock of the Girolata catchment (Fig. 2).
- Sedimentary Unit 2 is identified from 1.30 to 0.80 m and its deposition began roughly in the early 1st millennium BCE, based on the radiocarbon dating results obtained for the top of the underlying Unit 1. Sedimentological features clearly exhibit a generally calm environment of deposition (clays), such as a coastal wetland where frequent terrestrial inputs are observed. The texture is a mixture of coarse materials, mainly gravels and angular pebbles (dacites), deposited within a sandy/clayey matrix. The lack of marine fauna and organic remains such as fibers of *Posidonia ocenanica* may reflect a full terrestrial sedimentation rather than a marine origin of deposition inside the wetland.
- Sedimentary Unit 3 is found from 0.80 to 0.38 m. It consists of black organic clays with abundant organic remains and sharp pebbles of dacyte within the clayey matrix, thus indicating local detrital input into a swampland.
- Sedimentary Unit 4 is found between 0.38 m and the present day surface topography. It is composed of light orange to brown silts indicative of the modern soil plough.

Any palaeoecological (pollen based vegetation reconstruction) interest in these sedimentary units appeared to be very limited and was therefore not studied.

4.1.2. Girolata 2 core

This core is 4.20 m long and encompasses the last 4.2 kyr according to chronostratigraphy based on the radiocarbon dating results (Table 2). Five main biosedimentary units (Figure 6) can be defined from the bottom to the top, as follows:

- Unit I is found between 4.20 and 2.95 m in depth and contains both marine molluscs and an abundance of fibers of *Posidonia oceanica*. This sedimentary unit is composed of silty clays and fine sands with mean grain size generally ranging between 50 and 150 µm. Organic matter content is around 10 to 20%. The mollusc identification reveals strong representation of two main species: *Bittium reticulatum* (a marine gastropod) and *Loripes lacteus* (a shallow marine bivalve that lives on a sandy substratum), as well as *Cerastoderma glaucum*, *Clelandella miliaris*, *Tricolia pullus* and *Rissoa ventricosa* (not exceeding 5% in total). The mollusc assemblage clearly indicates the presence of a marine- to shallow marine environment dominated by a sandy sea bottom with development of the typical seagrass *P. oceanica*. It is noteworthy that this unit contains well preserved and identifiable pollen grains (see section 5.2.1). Radiocarbon dating was performed on the lowermost part of Unit I and reveals an age of 1921-1696 cal. BCE at a depth of 4.1 m. Towards the top of the unit at a depth of 3 m below the surface, an age of 1447-1286 cal. BCE was obtained. The above-described palaeoenvironmental proxies help to identify Unit I as a marine- to shallow marine environment (protected bay) with a sandy sea floor associated with calm dynamics of sedimentation. However, at the top of the unit, from 3.10 to 3 m deep, a thin layer of black organic sandy clays containing shell debris and some intact small specimens (juvenile) of *Bittium reticulatum* together with rare and intact *Cerastoderma glaucum* bivalves (of centimetric size) can be found. Also observed embedded within the clayey fraction were *P. oceanica* fibers. The top of Unit I (dated 1447-1286 cal. BCE) exhibits a clear transition to a more confined environment, still connected with the sea, and appears to correspond to a short phase of lagoonal development with very low energy of deposition.
- Unit II overlies Unit I and is found from 3 to 1.50 m below the surface. In general, it is composed of coarse material made up of sharp pebbles (dacites), angular gravels and medium to coarse sands. The radiocarbon dating performed at its transitions with Units I (below) and III (above) reveals that Unit II was deposited from ca. 1447-1286 cal. BCE to 650 cal. BCE, according to the estimation of the depth/age profile for this latter date. However, two sub-units can be distinguished and are described as follows: Unit IIA consists of grey medium to coarse sands with rare small fragments of marine molluscs (*Bittium reticulatum*) in its lowermost part. Several layers containing fibers of *Posidonia oceanica* are identified at the depths of 2.66, 2.55 and 2.20m: these fibers are abundant in the lowermost part of the unit. Unit IIB extends from 2.85 to 2.57 m and is composed of two layers of orange to red oxidized coarse sands (mean grain size ca. 400-600 µm) and sharp gravels, separated only by a thin layer (10 cm) of *Posidonia oceanica* and pebbles of dacite, dated to 1119-769 cal. BCE. No molluscs were identified in either of Unit IIB's oxidized layers, which may be indicative of terrestrial dynamics of deposition. In general, sedimentological results exhibit a higher energy of deposition in Unit II than in Unit I. The presence of rare debris of marine molluscs and balls of *P. oceanica* helps to characterize Unit II as part of a marine environment with high energy of deposition and where occasional terrestrial input can be observed at roughly the midpoint of the Final Bronze Age. Unit II can therefore be interpreted as a record of marine environments (intertidal to supratidal zone) with two isolated fluvial inputs (Unit IIB); it shows similar features and a date close to that of Unit 1 in Girolata 1 core.
- Unit III occurs between 1.50 and 0.40 m in depth. Age of deposition is well constrained and can be dated from ca. 650 cal. BCE to 1650 cal. CE, based on the dating of three samples of rich organic sediment (Table 2; Figure 6). It is composed of rich organic black clays (mean grain-size is around 5 to 10 µm) with generally high organic matter content, comprised between 10 and 32% and decreasing towards the top of the unit. The highest values are recorded in the lowermost part of the unit with peaks situated above 25%. Unit III does not attest the presence of marine molluscs, but plant remains

and large pieces of wood are identified. Pollen content is high and well preserved grains were identified for reconstructing the past vegetation from the 7thcentury BCE to the 17th century CE (see section 5.2.2.). Unit III shows similar sedimentological features to Unit 3 in Girolata 1 core.

- Unit IV is found in the uppermost section of the core, from a depth of 0.40 m to the surface. It consists of modern soils with the presence of light orange to brown silts.

4.1.3. Fangu core

The Fangu core is 4.20 m long and was drilled in the Fangu River estuary (Figs. 3A and 3B), which is disconnected from the sea during summer. Three main sedimentary units have been identified (Fig. 7) and no molluscs were identified along the sequence:

- Unit a is found from 4.20 and 3.50 m depth. It shows a transition from deeper layers of coarse material, mainly composed of very coarse sands and angular gravels, to higher homogeneous marine grey sands containing typical marine plant debris of *Posidonia oceanica* (top of the unit). A radiocarbon dating was performed at 4.12 m deep and gave an age of 3945-3653 cal. BCE (Table 2), while the uppermost part of the unit was dated to approximately 3 500 cal. BCE according to the depth/age modelling (Figure 7).
- Unit b is situated from 3.50 to 3.15 m depth. It consists of coarse material with low organic matter content (less than 5% on average), which increases towards the top. Sands and sharp gravels of rhyolite suggest a continental input since this rock forms half of the geological formations of the Fangu River. Age of deposition for Unit b is comprised between 3500 and 3100 cal. BCE (Figure 7).
- Unit c is located from a depth of 3.15 m to the surface and is relatively homogeneous (except for the sandy/gravelly layer identified between 1.15 and 0.85 m in depth), with organic clayey sand and peat layers. As a consequence, Unit c was studied for pollen identification (see below) which helps to characterize the environment of deposition. Radiocarbon dating performed in the lowermost part of Unit c (transition with Unit b) reveals an age of 3092-2907 cal. BCE (Table 2), which means that Unit c has been deposited over the last five millennia. Organic matter content shows the higher values (> 10%) situated in the lowermost part of the unit: radiocarbon dating of these peaks reveals ages ranging from 3092-2907 to 2925-2692 cal. BCE. Between 1.15 and 0.85m, a layer of coarse material can be identified (Unit c1) which decreases gradually in terms of granulometry towards the top: the lowermost part of this layer (1.15-1 m) is composed of rounded gravels and small pebbles embedded within a clayey matrix, while the uppermost part (1-0.85 m) is characterized by coarse grey sands and intercalated beds of small gravels. The age of Unit c1 cannot be directly obtained with ^{14}C dating: the depth/age model provides an estimated age from the 4th century BCE to the 4th century CE., roughly corresponding to Roman times. In the upper part of the core (0.85 m deep to the surface), and corresponding to the return to the homogeneous grey clays of Unit c, numerous micro- and macro-charcoals are identified between 0.50 and 0.35 m, indicating a sustained fire activity: radiocarbon dating performed at 0.48 m deep reveals an age of 1179-1277 cal. CE, corresponding to the Pisan occupation of the island. It is likely that this rich charcoal content layer dates to the first half of the second millennium CE.

4.2. Pollen results

4.2.1. The Girolata pollen record

Two main pollen zones and two sub-zones were defined using CONISS (Grimm, 1987; Fig. 8):

- Sub-zone A1 (417-125 cm; 1845-406 cal. BCE) shows moderate values of AP (ca.50%), predominated by *Quercus ilex* and *Pinus*. In contrast, low values of *Quercus* deciduous, occurrences of *Fagus*, low values of *Alnus* and *Olea* are reported. High values of *Erica* (up to 40%), showing a decreasing trend,

high values of *Vitis* to the end of this sub-zone. A peak of Poaceae and occurrences of Cerealia-t at 1.40 m (625cal. BCE). Low values of Cyperaceae and Amaranthaceae (Fig. 8). Among the NPP, a high abundance of Foraminifera remains at 4.12-2.98m and an increase in monolete spores, *Spirogyra*, *Glomus*, *Coniochaeta* cf. *Ligniaria* and occurrences of coprophilous fungi (*Sporormiella*, *Sordaria*-t, *Cercophora*-t) at 125-140cm (Fig. 8).

- Sub-zone A2 (120-90 cm; 290 cal.BCE-482 cal. CE) reveals a decreasing trend in AP where *Quercus ilex* remains the predominant tree. At the same time, we observe a decrease in *Pinus,* an increase in *Quercus* deciduous (Fig. 8) and an increase in riparian trees, mainly *Alnus*; high values of *Olea* are also reported. Peaks of Poaceae and Cerealia-t are identified at the beginning and at the end of the sub-zone, with an increasing trend in Asteraceae, Apiaceae, Cyperaceae and Amaranthaceae at the end of the sub-zone. Among the NPP, we note high values in monolete spores, a continuous curve of *Spirogyra*, a decrease in *Glomus* and the lack of coprophilous and lignicolous/carbonicolous fungi (Fig. 8).

- Zone B (80-50cm; 839-1461 cal. CE): there is a sharp decrease in AP (ca. 20%), *Quercus ilex* and *Olea*, and very low values of *Quercus* deciduous and *Alnus*. At the same time, a decreasing trend in *Erica* is reported with an expansion of Cistaceae along with high values of Poaceae and occurrences of Cerealia-t. High values in Asteraceae, Apiaceae, Cyperaceae and Amaranthaceae (Fig. 8). Among the NPP, high values in monolete spores, a decrease in *Spirogyra*, an expansion of *Zygnema*-t, *Rivularia* and *Pseudoschizaea*, occurrences of lignicolous-carbonicolous fungi (*Coniochaeta*, *Kretzschmaria*, HdV-6, *Chaetomium*, UAB-4, 9, 11, 38) and coprophilous fungi (*Sordaria*-t, *Sporormiella*). (Fig. 8).

4.2.2. The Fangu pollen record

Two main pollen zones and four sub-zones were defined using CONISS (Grimm, 1987; Fig. 9):

- Sub-zone A1 (200-190 cm; 2216-2082cal.BCE): high values of arboreal pollen (AP), predominated by *Pinus*, evergreen *Quercus* and riparian trees (*Alnus* spp., *Fraxinus*, *Salix*). This zone also shows low values of *Erica* and a remarkable peak of Cistaceae (Fig. 9).

- Sub-zone A2 (182-115 cm; 1962-507cal.BCE): we observe a slight regression in AP and *Pinus* and an expansion of *Erica*. High values of *Quercus ilex* and a slight decline in *Alnus* spp. are reported together with an increase in herb values (Poaceae, Asteraceae tubuliflorae, *Aster*-t) and a slight expansion in ferns (monolete spores, *Pteridium*, *Osmunda*-t and other trilete spores) (Fig. 9).

- Sub-zone B1 (83-66 cm; 316-740 cal. CE), a sharp decrease in *Pinus* values and later recovery (ca. 1500-1300 cal. BP) and opposite dynamics in *Erica*, expanding at *Pinus* regression.

- Sub-zone B2 (60-23 cm; 883-1632 cal. CE): minimum values of AP and *Pinus*, and a slight expansion of Erica. The expansion of NAP is predominated by Mediterranean shrubs (Cistaceae, *Helianthemum*-t, *Ephedra*, Lamiaceae) and grasses (Poaceae, Asteraceae, *Plantago*, *Artemisia*, Apiaceae). Occurrences of Cerealia-t at 28 and 34 cm (1435-1545 cal. CE). Occurrences of Amaranthaceae and Chenopodioideae and high values of Cyperaceae. Maximum values in monolete spores, *Polypodium*, *Isoetes*, *Pteridium* and *Osmunda*-t. Occurrences of *Pseudoschizaea* and type UAB-47 and maximum values of type HdV-36C.

5. Discussion

5.1. Palaeogeographic reconstruction of the coastal environments

5.1.1. *Shoreline reconstruction of the Girolata Gulf for the Late Holocene (Middle Bronze Age-Medieval Period/2200 cal. BCE-1800 cal. CE)*

Mid- to Final Bronze Age (1800-800 BCE) - Based on the sedimentological analyses and the mollusc and pollen identifications derived from Girolata cores 1 and 2, results indicate that the present day coastal plain remained under shallow marine conditions during the Middle Bronze Age (from ca. 1800 to 1400/1350 cal. BCE; Fig. 10A). Indeed, a shallow and protected bay with a sandy-clayey bottom with *Posidonia oceanica* seagrass was present. Our results confirm the previous chronostratigraphic results obtained for the easternmost part of the area (Huser et al., 2017). During the whole period, for the westernmost part of the present day coastal plain, the shoreline position was located approximately 150-175 m inland, while in the eastern part the coast was situated only 50 to 100 m further north, thus creating a deeper marine incursion to the west.

Following this, during the Late Bronze Age (1400-1250 cal. BCE), only the westernmost part of the study area was briefly occupied by a brackish lagoon (Fig. 10B), probably for less than a century in duration while landscape configuration in the easternmost part remains uncertain due to the paucity of chronostratigraphic data.

The Final Bronze Age (1200-800 cal. BCE) is characterised by generally higher energy of deposition than was previously observed during the Mid- to Late Bronze Age. The influence of the local streams on the coastal sedimentation is obvious and is confirmed by the presence of layers consisting of a mixture of angular pebbles and gravels of both monzogranite and dacites with *Posidonia oceanica* remains. Of note is the observation of a terrestrial input in the lower Novalla Stream valley only (Fig. 10C) at the onset of the Final Bronze Age. However, this detrital input is not homogeneous and two distinct phases of deposition composed of angular gravels of monzogranite embedded within an orange sandy matrix (rich in quartz) are observed, separated by a brief phase of marine sedimentation dating to the 1119-769 cal. BCE (median probability: 930 cal. BCE; Figure 6). The first phase of detritism, dated from ca. 1250-1150 BCE, can be related to a local phase of erosion that affected the monzogranitic bedrock, situated primarily in the lowermost part of the Novalla catchment basin and in particular, on the western hills where the small village of Girolata is located today. Similar high continental input, dated to ca. 1200-1100 BCE, has been reported for the western coast of Corsica only, at the Canniccia pond situated in SW Corsica (Ghilardi et al., 2017b; Vella et al., 2019) and at Crovani for the period 1250-1150 BCE (Ghilardi, 2020; Di Rita et al., 2022a). Regional studies conducted around the Gulf of Lion in the western Mediterranean also evidenced a phase of strong alluviation centred around 1200-1000 BCE, as is also the case in the Pyrenees (Galop et al., 2007) and in the lower Rhone River catchment (Berger et al., 2007).The existence of the so-called 3.2 kyr cal. BP Rapid Climate Change (RCC) event is suggested in the western Mediterranean with particular arid climate conditions (Mayewski et al., 2004; Magny, 2004; Magny et al., 2007; Fletcher et al., 2013). The origins of this brief period of heavy run off on the western coast of Corsica remain undetermined, but this area of the Mediterranean clearly experienced episodes of intense precipitations during a phase of prolonged aridity, in particular at the onset of the Final Bronze Age, ca. 1200-1100 cal. BCE.

Following a short return to marine conditions dated ca. 1000-900 BCE, at ca. 900-800 BCE, the Novalla stream underwent a second brief alluvial crisis, mainly affecting the granitic bedrock, as is revealed by the presence of an oxidized sandy layer. To the east, a large terrestrial input of the Girolata River is also attested, flowing into the shallow marine bay and triggering a mechanism of southward shoreline migration. Identification of this last phase of high continental detritism is based on the deposition of

sharp pebbles of rhyodacites and dacites that compose the upper reaches of the Girolata catchment. However, the exact dating of this detrital input remains unknown, even if its early phase of deposition can be dated approximately to the end of the Final Bronze Age/Early Iron Age, as suggested by the chronostratigraphy of the Girolata 1 core (Fig. 5). Following this and as a direct consequence, a lowland composed of coarse material deposited at the transition between the Final Bronze Age and the Early Iron Age formed, situated inland of a large coastal barrier system that primarily formed to the east and that advanced southwards. For the period 900-800 BCE, a mechanism of delta progradation based on a migrating coastal barrier system has also been reported for the same period for the Sagone River (Ghilardi et al., 2017a), situated approximately 30 km southwards. This morphological evolution of river mouths has been also observed along the coast of Tuscany for the Ombrone River (Pranzini, 2001; Bellotti et al., 2004; Biserni et van Geel, 2005) and in the Latium region for the Tiber River (Giraudi et al., 2009; Giraudi, 2011).Possible direct consequences of the 2.8 kyr cal. BP Bond event 2 (Iron Age/Homeric minimum; Bond et al., 1997),a period recognized for its sustained hydrological activity in the Western Mediterranean (Basetti et al., 2016), have been put forward to explain such deltaic advances. For the moment, there is no palaeoclimate reconstruction established for Corsica, so this question remains challenging, in particular along the western coast of the island.

Iron Age, Roman and Medieval periods (800 BCE- 1800 CE) - During the Iron Age and Roman times (Fig. 10D), shoreline migration decelerated and enabled the formation of a large coastal barrier that extended along the entire paleo Bay of Girolata. To the west, a large coastal swampland developed with no significant detrital input from the Novalla Stream, from the Early Iron Age until modern times. The pollen record points to a freshwater environment, which was testified from 700 cal. BCE by high values of freshwater algae and riparian trees such as *Salix* and *Tamarix*. Then, a change towards a sub-aerial brackish marshland dominated by Cyperaceae and Amaranthaceae, with remarkable amounts of Apiaceae and ferns began around 550 cal. CE. This local environment persisted until the reclamation works of the plain in the 20thcentury CE (Fig. 10E). The regression of arboreal taxa and the high dominance of Asteraceae at 0.70-0.50 m at Girolata suggests soil formation (transition to a terrestrial environment) edaphisation for the last millennium according to the chronostratigraphy (Figure 6). In conclusion, the Roman period coincides with a more humid phase attested by the existence of a freshwater wetland, suggesting that wetter conditions and the availability of freshwater favoured the establishment of human populations in coastal areas of western Corsica during the Iron Age and the Roman period.

5.1.2. The Fangu Estuary: evolution over the last six millennia

The sedimentary sequence collected in the Fangu Estuary reveals the presence of two main environments with contrasted energy of deposition. From ca. 4200 to 3500 cal. BCE, a marine environment prevailed in the western part of the present-day estuary (coring site). The presence of balls of *Posidonia oceanica* embedded within coarse sands and gravels indicates a high energy of deposition, probably related to an open marine bay. In the Mediterranean, the Mid-Holocene corresponds to a period of maximum sea incursion inland (Vacchi et al., 2016; 2018). Elsewhere in Corsica, this Mid-Holocene maximum marine incursion has been dated to 4000-3500 cal. BCE on the eastern coast, in the Aleria-Del Sale area (Currás et al., 2017) and on the North-West coast at Saint-Florent (Revelles et al., 2019). At both the Aleria and Saint Florent sites, the marine incursion was followed by a deceleration in sea-level rise that favoured the formation of coastal wetlands, mainly

lagoonal environments. Similar observations have also been reported in the Eastern Mediterranean with the onset of delta formations dated around 3500 cal. BCE (Brückner et al., 2005).

In the Fangu Estuary, the marine environment was followed by a phase of detrital input, probably linked to a deltaic advance of the Fangu River from ca. 3500 to 3100 cal. BCE. Isolation of brackish water behind a coastal spit favoured the formation of coastal wetlands shortly after that date.

From ca. 3000 BCE until the present day, generally calm environments of deposition related to the formation of coastal wetlands have been recorded. However, a brief interruption in wetland deposition occurred from ca. 400 cal. BCE to 400 cal. CE marked by a fluvial input that persisted roughly throughout Roman times. The literature contains little evidence for such detrital input from Corsican rivers during Roman times, however an anthropogenic destabilization of the soils in the upper reaches of the Fangu River cannot be ruled out as a possible influence of this process. Climate conditions during the Roman period in the Mediterranean are recognised as being warm and wet, which possibly induced reinforced runoff in a context of diminished forest cover. As a result, the Fangu catchment may have experienced reinforced alluviation. Since the end of Roman times, landscape configuration has remained stable with the presence of coastal wetlands with salt intrusions. Our pollen record suggests that the Fangu lagoon may have been surrounded by riparian forests dominated by *Alnus*, *Fraxinus*, and *Salix* species, with prevailing freshwater conditions. Companion hygrophilous species of these riparian trees also seen to increase during this time interval are Cyperaceae and ferns (e.g. *Pteridium, Osmunda-t*, and other ferns with monolete spores (Figure 9). During the Middle Ages (750 cal. CE onwards), the development of Cyperaceae (Figure 9) reflects the expansion of shore environments leading to a regression of the lagoon and the expansion of sedges. Finally, the decline of sedge vegetation and the development of fern-dominated environments suggest drier conditions at local scale.

In general, prevailing freshwater conditions throughout the Late Holocene are also testified by the continuous record of freshwater algae, accompanied by low values of Amaranthaceae.

5.2. Vegetation history of the UNESCO protected site (Fangu and Girolata coastal plains) and the influence of rapid climate changes during the Late Holocene

The palynological study of cores Girolata 2 and Fangu enables the reconstruction of landscape for NW Corsica over the last 4200 years, from the Early Bronze Age to the Middle Ages. This helps to complete previous research conducted in the 1990s in the Fangu Estuary (Reille, 1992a) and in the 2020s in the Crovani pond (Di Rita et al., 2022a), respectively.

Bronze Age (4150-2750 cal. BP/2200-800 BCE) - For the Porto Gulf UNESCO site, the vegetation has always been predominated by Mediterranean maquis, configuring an open landscape with *Erica* and Cistaceae, especially in Fangu, where *Erica* reaches 40-50% values (Figure 9). Pine and sclerophyllous forests played a secondary role in Girolata 2, while *Pinus* shows an important role in the area of Fangu, especially during the first half of the sequence (4200-2400 cal. BP/2250-450 cal. BCE). Mesic forests (*Quercus* deciduous, *Betula*, *Corylus*, *Tilia*, *Carpinus*) had a limited role in the landscape during the Late Holocene in this area, suggesting that climate conditions were more favourable to sclerophyllous vegetation in the lowlands. Of note is the limited presence of *Alnus* spp. riparian forests in this area compared with other Corsican areas, such as Saint Florent in the north (Revelles et al., 2019), Del Sale and Palo on the eastern coast (Currás et al., 2017; Revelles et al., 2019) and Sagone on the western coast (Ghilardi et al., 2017a). This may be due to the predominance of *Pinus pinaster* and *Pinus laricio*, accompanied by a maquis understory in granitic substrates at lower altitudes, as also occurs today in this area of Corsica. This would explain higher values in *Pinus* than *Quercus ilex* in Fangu, and the

limited presence of *Alnus* in both records. In this sense, during the period ca. 4200-2750 cal. BP (2250-800 cal. BCE/Bronze Age), pine forests played a significant role in the landscape in Fangu (Fig. 9), accompanied by *Erica*-dominated maquis.

Interestingly, from 4200 to 3900 cal. BP (2250-1950 cal. BCE) Pinus forest and Erica maquis declined, favouring the development of a Cistaceae-dominated shrubland. This forest dynamic may have been triggered either by land clearing practices of anthropogenic origin or by a climate change linked to the 4.2 kyr BP event, corresponding to the Bond event 3 (Bond et al., 1997; Figure 11), but the evidence is too scanty to be attributable to one cause or the other. As there are no known Early Bronze Age sites in this area of Corsica, an anthropogenic origin for this sudden change in vegetation cover is therefore highly hypothetical. As for the 4.2 kyr BP event, this climate change does not appear to be associated to any general deforestation patterns in Corsica (Di Rita et al., 2022a, b). Conversely, several pollen sites show forest development (refs). We can therefore only speculate that an arid climate event, if one occurred, had only a limited impact on intermittent coastal ecosystems.

Roman times to the end of the Genoese period (2450-150 cal. BP/500 BCE-1800 CE) - Mixed forests of *Pinus* and *Quercus ilex*, accompanied by maquis of *Erica* were the predominant component of the landscape until the change of era, when forest decline led to the expansion of maquis, predominated by *Erica* and with an increasing role of Cistaceae (Figs. 8 and 9). Until Roman times, human impact was limited in the evolution of forest cover in terms of short-term deforestation episodes and rapid recovery, consistent with previous studies in the area (Di Rita et al., 2022a). Only at Girolata can we report two brief episodes of forest decline dated at ca. 450 and 200 cal. BCE, mainly affecting the *Q. ilex* cover.

During Roman times (250 cal. BCE-400 cal. CE), the high values of *Quercus* suggest an expansion of oak forests in NW Corsica, possibly triggered by an increase in summer rainfall during the Roman Warm Period (RWP). These climate conditions also led to the development of freshwater swamps in the Girolata coastal plain (Figures 6 and 10). Subsequently, and following Roman Empire, deforestation processes and major changes in vegetation composition occurred. Indeed, from 500 CE onwards, regression of *Quercus* spp. values is evident in Girolata 2 and Fangu records, as is the decline of oak woods that began at the change of era in the area of Crovani and which is consolidated during this period. The Early Medieval cooling episode (500-900 cal. CE), also known as the Dark Ages or Migration Period Cooling (Ljungqvist, 2010) may be linked with this decline in oak woodland. This episode is clearly evidenced by minimum δ18O in GISP2 (Figure 13) and coincides with the 1.4 kyr cal. BP Bond event 1 (ca. 550 cal. CE; Bond et al., 1997), with RCC 1 (1.2-1.0 kyr cal. BP/750-950 cal. CE) defined in Mayewski et al. (2004). This period marked the transition from Late Antiquity to the Early Middle Ages when a strong human migration occurred in Europe between 300-700 cal. CE (Wanner et al., 2011). Finally, the strong human impact in the four pollen records during the first half of the second millennium CE (1000-1500 CE) leading to forest decline prevented from contrasting *Quercus* spp. curves with climate conditions from this phase onwards. Consequently, evidence from the NPPs record shows high concentrations of carbonicolous-lignicolous fungal spores in these chronologies in the Girolata pollen diagram (Figure 8) and numerous charcoals for Fangu core. These fires, associated to peaks in anthropogenic indicators, are interpreted as human-induced in other records (Lestienne et al., 2020; di Rita et al., 2022a), and explain the important role of fire in vegetation dynamics in the Mediterranean.

5.3. Human impact on coastal landscape evolution of North-Western Corsica

Figure 11 summarizes the recent pollen results acquired for four sites from the north western area of Corsica: published data from the Saint Florent and Crovani sites (Revelles et al., 2019; Di Rita et al.,

2022a) are combined with results obtained for the present study from the Fangu and Girolata sites. Arboreal pollens are associated with anthropogenic markers in order to evaluate the timing of human impact on the vegetation composition with a possible identification of climate control during Bond events.

5.3.1. For the UNESCO site (Fangu and Girolata coastal plains)

Protohistory (Bronze Age: ca. 2200-800 cal. BCE) – Evidence of human impact during the Bronze Age is scarce and is restricted to the southern part of the UNESCO site only, in the region of Girolata (Fig. 11). This site evidences agriculture during the Middle Bronze Age (1600-1350 cal. BCE, Phase 2; Figure 11), a period when the sites of human occupation (*I Casteddi*/Castles) were located primarily on the top of hill mounds or rocky outcrops (Pêche-Quilichini, 2015a and 2015b). Until now, no archaeological surveys confirming the presence of such a Middle Bronze Age site have been conducted in the UNESCO area, but in the near future archaeological prospections could include this cultural period and not only Medieval times. Cereal cultivation, though scarce, is attested during the Middle Bronze Age in the surroundings of the present day Girolata coastal plain. No indication of land-use is available for the Final Bronze Age (1200-800 cal. BCE) due to poor pollen preservation in the Girolata sequence, and to a lack of anthropogenic markers in the Fangu estuary area.

Early Iron Age - Roman times (800 cal. BCE-500 cal. CE) – Pollen results of both coastal sites clearly indicate that human activities have affected the vegetation composition for the previous 2000 years, and locally for the last 2500 years, with a significant and continuous impact on the forest cover starting from ca. 1650 cal. BP (300 cal. CE) and affecting both areas simultaneously. In addition, the Girolata 2 core shows evidence of agriculture during the whole Roman period (Phase 3; Figure 11), starting from ca. 450 cal. BCE to the 6th century CE with two intermittent phases of forest retreat dated ca. 450 and 200 cal. BCE. Two main agricultural phases can be distinguished (Figures 8 and 11): the first one dates from the 5th century BCE to the onset of the common era and combines both cereal cultivation and husbandry, as indicated by the presence of coprophilous fungi. The strong presence of *Vitis* during a short period of time over the Roman Republic (from ca. 500 to 350 cal. BCE; Figure 8) can be reasonably associated with grapevine cultivation on the hills surrounding the Girolata coastal wetland. The second phase ranges from the onset of the common era to the 6th century CE (Roman Empire) and is marked by a near- exclusive agricultural activity based on olive tree cultivation (*Olea* in Figure 8). At the onset of the common era, the sudden change in terms of land use around the Girolata coastal plain can be related to the major political changes that occurred in Rome during the transition from the Roman Republic to the start of the Roman Empire. The Roman Empire established a distinct specialisation concerning the type of agriculture undertaken in each province, a practice which can be inferred for Corsica, as well as in Northern Africa (Leveau, 1990). A clear and continuous agricultural activity is evidenced for the first time in Corsica in the Girolata sequence and in the vicinity of archaeological remains dating from throughout the Roman period (almost one millennium in duration). This confirms the geostrategic importance of both Girolata Bay and its coastal plain under the Roman domination of the Mediterranean. The Fangu site shows no clear human impact prior to the onset of the common era. The regression of pine forests and the progressive expansion of *Erica* maquis from 1600 cal. BP onwards (Figure 9) is best interpreted in the light of increasing human impact during Roman times, thus confirming Reille's vegetation pollen-based reconstruction (Reille, 1992a). However, the low resolution of the sequence pertaining to that period as well as the deposition of sands at 1.15-0.85m for the Fangu core make it difficult to study the socio-environmental dynamics during the Roman period.

Late Antiquity, Medieval times, Pisan, and Genoese administrations of the island (500 cal. CE-Late 18thcentury CE) - At Fangu, Late Antiquity and the Medieval period correspond to phases of strong human impact on forest ecosystems of the island. The lowest values of arboreal pollen date to ca. 1150 cal. CE and 1400 cal. CE, respectively (Figure 9), and reflect intense human activities during both the Pisan and Genoese administrations of the island. Forest decline during the Middle Ages was also reported at Crovani (Di Rita et al., 2022a; Fig. 1), situated only 6 km to the north, and at Saint Florent (Revelles et al., 2019). Reille's investigations at Fangu (Reille, 1992a) suggested that *Q. ilex* in the high Fangu valley probably replaced a burnt *P. laricio* forest around 1500 cal. BP. This anthropogenic disturbance mainly affected pine forests and *Erica* maquis, indicating deforestation processes both in the lowlands and uplands of the region. The presence of Cistaceae over the last 1500 years at Girolata (Figure 8) and over the last 1000 years at the Fangu site (Figure 9), combined with a high abundance of charcoal particles as observed and described during sedimentological analyses (no quantitative charcoal data are available at the moment) from ca. 1000 to 1500 cal. CE at the Fangu site reinforces the regular occurrence of fires within and in the vicinity of the UNESCO site. At Fangu, evidence of cereal cultivation is recorded solely during the Genoese administration of the island (Phase 4; Figure 11), coeval with the building of the defensive towers during the 16thcentury CE in the vicinity of the Fangu estuary (Figs. 3A and 3B). Human disturbance probably explains the expansion of Mediterranean shrublands (*Erica*, Cistaceae, *Helianthemum*-t, *Ephedra*) and grasslands and ruderals (Poaceae, Asteraceae, *Plantago;* Fig. 9). The fact that no cereal cultivation is observed in the vicinity of the Fangu estuary prior the Genoese period reinforces the idea that this area was not of strategic interest for agricultural purposes, unlike the Girolata Plain which was certainly a major site in Corsica throughout Roman times.

5.3.2. In NW Corsica: Nebbiu, Balagne and Filosorma areas

Prehistory (Late to Final Neolithic times, 3900-2200 cal. BCE) - Figure 11 shows evidence for agriculture and husbandry that points to an episode of human impact at the onset of the Late Neolithic (ca. 3900 cal. BCE) in both Crovani and Saint Florent, with a limited impact on the forest cover (Human Impact (HI) episode 1; Figure 11). Following this, the Final Neolithic (2800-2200 cal. BCE) was a period of important agricultural development in NW Corsica, notably at Crovani (Di Rita et al., 2022a) and at Saint Florent (Revelles et al., 2019). Both of these sites record cereal cultivation and husbandry along the coastal zone within an environmental context of swampland, with a generally moderate impact of human activity on the forest cover (AP decline; Figure 11). It is noteworthy that a moderate forest decline is simultaneously observed at the onset of the Final Neolithic at Crovani and at Saint-Florent (ca. 2800-2600 cal. BCE, Phase 1; Figure 11), corresponding to a phase of agricultural development along the shoreline (Phase 1; Figure 11).

Protohistory (Bronze Age, 2200-800 cal. BCE) - Following the Neolithic period, the Early Bronze Age shows little evidence of anthropogenic activities for NW Corsica, and this period is also largely marked by a paucity of sites of human occupation. In contrast, the period covering the Middle to Final Bronze Age (Phase 2, Figure 11) reveals a return to agricultural practices in the coastal areas at Girolata, Crovani and Saint Florent. A second phase of forest decline of moderate importance, consisting of short-term forest decline episodes followed by a rapid recovery, is observed during the Middle Bronze Age (Phase 2; Figure 12) which is a cultural period marked by the development of fortified castles (*I Casteddi*; Pêche-Quilichini, 2015b) on inland hilltops overhanging alluvial valleys (Ghilardi et al., 2017b). This type of site was clearly linked to isolated forest clearings and agricultural development, with grain storage inside the structures behind defensive walls. However, only low levels of cereal cultivation and scarce occurrences of husbandry are evidenced at Girolata (Phase 2, Figure 11), mainly

during the Middle Bronze Age. It seems that Fangu estuary was less favoured for agriculture at that time. The presence of the Fangu River associated with a flooding exposition of the area provides a reasonable explanation for such low agricultural activity in the lowlands

Early Iron Age - Roman times (800 cal. BCE-500 cal. CE) – For the later Iron Age to Roman period, a major regional change with clear human impacts on the vegetation composition can be observed. During the Iron Age, evidence of cereal agriculture at Girolata and at Crovani, and probable *Vitis* cultivation around Girolata, are associated with moderate impact on forest cover (HI episode 2; Figure 11). Agricultural development can thus be linked to a third phase of forest decline starting around the onset of the 5thcentury BCE at Girolata, Fangu and Crovani (Phase 3; Fig. 11), while forest decline in the area of Saint Florent appears approximately one millennium later (Figure 12). Similar observations of forest decline have also been reported for SW Corsica (Vella et al., 2019) and slightly earlier (2500 years BP), on the Eastern coast (Currás et al., 2017), thus confirming Reille's conclusions concerning dating of the first important anthropogenic impacts on Corsican vegetation composition since the onset of Roman times (Reille, 1992a). Different dynamics are observed in Saint Florent and Girolata 2: human impact affected mainly *Alnus* spp. forests and to a lesser extent secondary pine forests (Revelles et al., 2019) in Saint Florent, but predominantly pine forests in Girolata (Figure 8). The Crovani record provides evidence of probable cultivation of olives during the Roman period (Di Rita et al., 2022a), a suggestion that may also be valid in the case of Girolata, where a peak of *Olea* led to a peak in the OVJC Index (Phase 3; Figure 11) during the Roman period. Anthropogenic activities during Roman times (Roman Republican) did not significantly affect forest cover or vegetation composition in general, whereas during the Roman Empire (at the onset of the common era) forest cover substantially declined.

Late Antiquity, Medieval times, Pisan and Genoese administrations of the island (500 cal. CE-Late 18thcentury CE) - From the pre-Christian era until the end of the Genoese administration of the island, human activities deeply impacted the pine forest (Phase 4; Figure 12). Reille (1992a) suggests that frequent fires burnt the *Pinus laricio*, a finding supported by our record from Fangu which reveals a large number of micro- and macro charcoals (not identified for the present study) in the 0.50-0.35 m depth range, roughly corresponding to the first half of the second millennium CE. To explain this decline, forest exploitation must also be examined through literary sources. Indeed, manuscripts dating from the Genoese administration of the island reveal that Corsican forests were exploited for their wood (see section 5.3.3. below). In addition, due to incursions of vandalism in the Corsican coastal areas and lowlands, the inhabitants were forced to migrate away from the coast and in doing so, the need for wood to build villages was substantial. The combination of forest exploitation and repeated fires provoked a rapid and strong reduction in forest cover during a period of political instability following Roman times.

At the scale of the large Western Mediterranean islands, our results are consistent with palynological studies conducted on Minorca (Balearic Islands), where the Iron Age was a period of intense human activity and where landscape transformation during Roman times is evident in numerous records, such as at Algendar and Es Grau in Minorca (Yll et al., 1997; Burjachs et al., 2017).This is evidenced by the regression of AP, the expansion of maquis and the occurrence of Cerealia-t; and Prat de Vila (Ibiza; Burjachs et al., 2017), and also by the regression of pine forest, the expansion of maquis and grasslands, and the occurrence of Cerealia-t. In addition, on the Iberian Peninsula during the Roman period, large-scale deforestation resulted in open landscapes characterising lowland areas as a consequence of the intensification of human activities such as cropping, grazing, mining or forestry. Nevertheless, the decline of western Mediterranean forests, although initiated during the Roman

period, really began from the 10th century CE onwards (López-Sáez et al., 2015). Finally, the pollen record of the Tirso coastal plain in Western Sardinia points to a clear open vegetation rich in synanthropic herbs during the last millennium (Melis et al., 2017).

5.3.3. On the question of the exploitation of Corsican wood resources from Roman times onwards

Whereas archaeology has revealed little evidence regarding the exploitation of the forests of Corsica during the historical period, the scrutiny of historical sources can provide precious information about the exploitation of wood on the island (Rotta and Cancellieri, 2001). Indeed, the vegetation reconstruction carried out in the UNESCO site for the present study has confirmed descriptions recorded by ancient writers in documents spanning the last 2500 years.

The first event (Figure 12) of wood exploitation dates back to Early Roman times. The oldest literary source to record this event can be found in descriptions made by Theophrastus (371-288 BCE), who mentions an expedition for the recovery of wood. An attempt to build a city specialized in the intermittent exploitation of the resource between 377 and 311 BCE was planned. Activities there undoubtedly concerned the Laricio pine, defined by Teophrastus as “the largest of all” (Historia Plantarum: V.8). This text reports the presence of many gulfs and shelters testifying to a high likelihood that the later Roman expeditions most certainly took place on the western coast. During a short period of time, the Romans deforested a large amount of wood in a "small area" a short distance from the coast. The estimated date of the expedition fits tightly with the palynological results obtained for the present study, which indicate significant human impact on forest cover, particularly in the area of Girolata where pine forests regressed around 400 BCE (Figures 8, 11 and 12). It appears that this exploitation was tied to the provisioning of materials for shipbuilding.

The second event also took place during the Roman Republic at around 200 BCE in the area of Girolata, but no known ancient documents mention forest exploitation at that date.

The third event took place around the 4th-5thcenturies CE (Figure 12). Victor de Vita writes in about 486 CE (History of the persecution of the Vandals: V. 5) that a small number of Catholic bishops from Africa were deported to the island for the exploitation of the forest. Despite the low number of deportees mentioned, the pollen results agree with this historical fact and show the onset of a deforestation process in the Fangu-Girolata area which also impacted oak forests (Figures 8, 9 and 11).

The fourth attested event of forest opening (Figure 12) took place during the first Muslim invasions in the Mediterranean in around 717 CE when the Constantinople expedition was organized in the quest for raw materials necessary for the construction of their fleets (Lombard, 1959 and 1972). The search for sources of wood was persistent throughout the 9thand 10thcenturies CE, and due to clashes between the naval powers of the Caliphate and the Byzantine Empire, resources dwindled and became the object of smuggling. As a direct consequence, Muslim invaders began to attack the coasts of Anatolia, Dalmatia, Sardinia and Corsica (Lombard, 1972) in their search for wood. Strong evidence of deforestation during this period is attested around Girolata, where the lowest AP values in the Late Holocene in NW Corsica can be seen where human impact led to the abrupt regression of oak woodlands and prevented the recovery of pine forests (Figure 8). In the case of Fangu, the decline of arboreal pollen from 700 CE onwards coincides with the Muslim invasions, during which the majority of wood exploitation focussed on pine forests (Figure 9). The Crovani area also experienced strong forest decline during this period (Di Rita et al., 2022a), suggesting that the Girolata-Fangu-Crovani area was regionally affected by forest clearance beginning in the 7th-8th centuries CE.

The fifth event can be observed during the Pisan and Genoese dominations of the island between the 11th and 16th centuries CE (Figure 12). Archaeological data attest to changes in population rhythms and settlement dynamics accompanied by a new colonization of spaces at the onset of the

2nd millennium CE (Mary, 2011, 2012, and 2020) when the demand for wooden constructions such as scaffolding, planks, beams and frames became significant. The Pisan colonization of the island (1070-1284 CE) required that certain areas be cleared to permit cultivation of the land: the forest cover therefore underwent a strong decline. This is revealed by the pollen diagrams from both Girolata Plain (Figure 8) and the Fangu estuary (Figure 9), with additional forest regression attested in Crovani and Saint Florent in the same chronologies (Phase 4, Figure 11). During this period, strong evidence of farming activities is documented in the area of Girolata, with high values of cereal pollen and coprophilous fungi suggesting the practice of animal husbandry in the surrounding areas (Figures 8 and 11). At the beginning of the 16th century CE (1510 CE), the Republic of Genoa took full possession of the island and the generalised exploitation of the island's forests began. This supports the fourth phase of human impact and deforestation as defined by pollen analysis (Figures 11 and 12). The impact of farming activities during this period is also attested in the Fangu area (Figure 9), suggesting demographic growth or expansion of human communities in the territory. The Office of Saint Georges of the Genoese Republic established the first project (Della Grossa et Montegiani, 2016), including the western coast of Corsica which was the most popular region according to descriptions recorded by Monsignor Giustiniani (Giustiniani, 1993), who also mentions that the wood from the mountain sector surrounding Galeria was transported to the coast and that the inhabitants of Calvi traded it both domestically and off-island. The full development of wood exploitation was set up in the 17thcentury CE with the development of inland exploitation at Aïtone or Guagno where the trees were older, straighter, taller, and of a higher quality, according to the Dutch captain Cornelius de Witt who was dispatched there by the Genoese in 1639 (Archivio di stato di Genova, 1639). This development towards the exploitation of the island's interior woodlands is a clear example of landscape degradation through the intensive exploitation of NW Corsican coastal forests which took place during the Middle Ages and early Modern Age. Similarly, this shift toward inland resources may also explain the coastal forest recovery attested in pollen diagrams for the area of Fangu and Crovani from 1600 CE onwards (Figure 12).

6. Conclusions

The multidisciplinary dataset obtained for both the UNESCO site of Scandola-Galeria and the NW area of the Corsican regional park helps to reconstruct past human-environment interactions over the last six millennia for the first time. The main outcomes of the present work are summarized as follows:

1. The coastal plains of Girolata and Fangu formed at different times: formation of the Fangu deltaic plain began around 3500 cal. BCE following the "classical" scenario observed for most of the large Mediterranean deltas. The Girolata coastal plain is much younger and mainly formed from the mid-second millennium BCE to the mid-first millennium BCE. The Girolata plain formation shows similar features with nearby deltaic plains such as at Sagone, situated ca. 25 km southwards (Figure 12) and the coastal plains of Tuscany (Ombrone and Magra Rivers) and Latium (Tiber River).
2. The northern part of the UNESCO site (Fangu estuary) is scarcely affected by anthropogenic activities until the mid-first millennium CE, while the southern part (Girolata coastal plain) records human impacts on the vegetation composition beginning in approximately the Mid-first millennium BCE, corresponding to the onset of the Roman Republic. Before any human impact, forest vegetation composition was characterised by the predominance of a dense maquis with predominance of *Erica* sp. in the coastal area, as was recorded by Maurice Reille, and which has also recently been confirmed by the pollen-based vegetation reconstructions for the nearby Crovani (Di Rita et al., 2022a) and Saint Florent (Revelles et al., 2019) areas.

3. The Girolata Plain and its surroundings was an important site of human occupation during Roman times from the 5th century BCE until the 6th century CE, and benefitted from favourable environmental conditions for the development of agriculture, with the presence of a freshwater swamp throughout Roman times. It is clear that the sheltered bay of Girolata served as a natural harbour for the importation of goods for approximately one millennium. Evidence of land use in the environs of the Girolata Plain reveals the presence of agricultural communities who first practiced cereal cultivation and viticulture alongside livestock breeding during the first phase of Roman times (5thcentury BCE-1st century CE, Roman Republic), and who then developed a dominant *Olea* cultivation which superseded cereal cultivation and livestock breeding during the second phase (1st-6th centuries CE, Imperial Period). The Girolata pollen sequence is one of the rare Corsican, and even western Mediterranean sequences, to fully reconstruct human impacts (including land-use practices) on the vegetation composition throughout Roman times. To the north, in the Fangu catchment, a period of reinforced alluvial activity is observed throughout Roman times and may be explained by changes in land-use in the uplands related to the Girolata inland forest exploitation. Further palynological investigations will undoubtedly provide more accurate documentation of vegetation composition in the northern area of the UNESCO site during Roman times.
4. The UNESCO site began to be affected by the strong impact of human activities from the mid-1st millennium CE, with significant and widespread clearing of upland pine forests and lowland maquis starting in Roman times. Potential upland forest clearance may have provoked reinforced alluvial activity of the Fangu River during the Roman Warm Period (RWP), characterized by regionally wet climate conditions. The substantial reductions of forest cover were greatest during the Middle Ages, when pollen records indicate the lowest cover over the past four millennia, and throughout the Pisan-Genoese administration of the island, confirming regional observations made to the north and northeast in the Crovani and Saint Florent areas, respectively. Wood resources were intensely exploited during the Pisan-Genoese colonization of Corsica leading to minimum expansion of the woodland during the Late Holocene.
5. Vegetation changes represented by the replacement of *Erica*-dominated maquis by Cistaceae-dominated shrubland is recorded in the Fangu pollen record and may be linked either to human activities or to local effects of the 4.2 kyr cal. BP climate event (Bond event 3).
6. Detrital input is recorded at ca. 3.2 kyr cal. BP and reveals a possible climate control on the sediment dynamics of the local streams, related to the 3.2 kyr cal. BP RCC event. This event is also evidenced for several coastal plains situated on the western coast of Corsica and around the Gulf of Lion.
7. The 2.8 kyr cal. BP event (Bond event 2, Homeric Minimum) has been hypothesised as a driving factor of a phase of major fluvial input recorded in the Girolata area, and is also probably linked to a shoreline progradation pattern at regional scale.

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Figure captions

Figure 1 : Location map of the study area. Locator map: SF: Saint Florent. Digital Elevation Model is derived from BDAlti data from IGN. Red stars indicate the location of the studied sites ; Green circle : core drilled at Crovani pond (Di Rita et al., 2022a)

Figure 2 : Geology, topography and archaeology of the Girolata-Novalla catchment. A : Geological background and core location (geological data are derived from the 1 :50 000 scale map of Osani ; Vellutini et al., 1985 and 1996). 1: Girolata ; 2 : A Chjesaccia ; 3 : Calanchelle ; 4 : Novalla ; 5 : Girolata Fort ; 6 : modern shipwrecks (16th-18th centuries CE). B : View to the south of the Girolata Plain and Gulf (source : J.B. Mary) with coring location and main archaeological site.

Figure 3 : Geology, topography and archaeology of the lower reaches of the Fangu catchment. A : Geological background and core location (geological data are derived from the 1 :50 000 scale map of Osani ; Vellutini et al., 1985 and 1996). Yellow circle : site from the First phase (1541-1553 cal. CE) of the Genoese administration of Corsica ; 1 : Galeria tower. B : Aerial view to the south of the Fangu Estuary with coring and main archaeological site locations.

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Figure 5 :Chronostratigraphy of Girolata 1core

Figure 6 :Chronostratigraphy of Girolata 2core

Figure 7 :Chronostratigraphy of Fangu core

Figure 8 : Pollen and NPP percentage diagrams for Girolata 2 core. White curves with depth bars show exaggerated curves x2; white curves, exaggeration x5; dots represent occurrences of <1%.

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Figure 10 : Palaeogeographic reconstruction for the Girolata coastal plain for the last four millennia.

Figure 11 : Diagram showing the evolution of arboreal pollen and anthropogenic indicators in Fangu, Girolata 2, Crovani and Saint Florent cores for the last six millennia. Chronology of the cultural periods for Prehistory and Protohistory is derived from Tramoni and D'Anna (2016). Categories: OVJC (*Olea*, *Vitis*, *Juglans*, *Castanea*), Ruderals (*Rumex*, Brassicaceae, *Polygonum*, *Plantago*, *Urtica*), Coprophilous fungi (*Sordaria*-t, *Sporormiella*, *Cercophora*-t, *Podospora*-t, *Delitschia*). Colour frames indicate the four main phases of forest decline and grey frames indicate episodes of human impact without clear forest decline. Bond events (Bond et al., 1997) and RCC events (Mayewski et al., 2004) are reported on the graph.

Figure 12 : Arboreal pollen (AP) evolution from the Iron Age onwards according to chronocultural periods for the sites of Saint-Florent (Nebbiu) ; Crovani (Balagne) ; Fangu and Girolata (Filosorma). The five major forest declines identified with palynology are highlighted with dashed grey bands; Event 2 alone is not documented in any known literary source. In the locator map : SF : Saint-Florent ; Cr. : Crovani ; Fa. : Fangu ; Gi. : Girolata; Sa. : Sagone.

Table 1 : Borehole information.

Table 2 : Radiocarbon dating results. Samples indicated by an * were rejected by the depth/age model calculation.

Authors' contributions

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

Declaration of competing interest

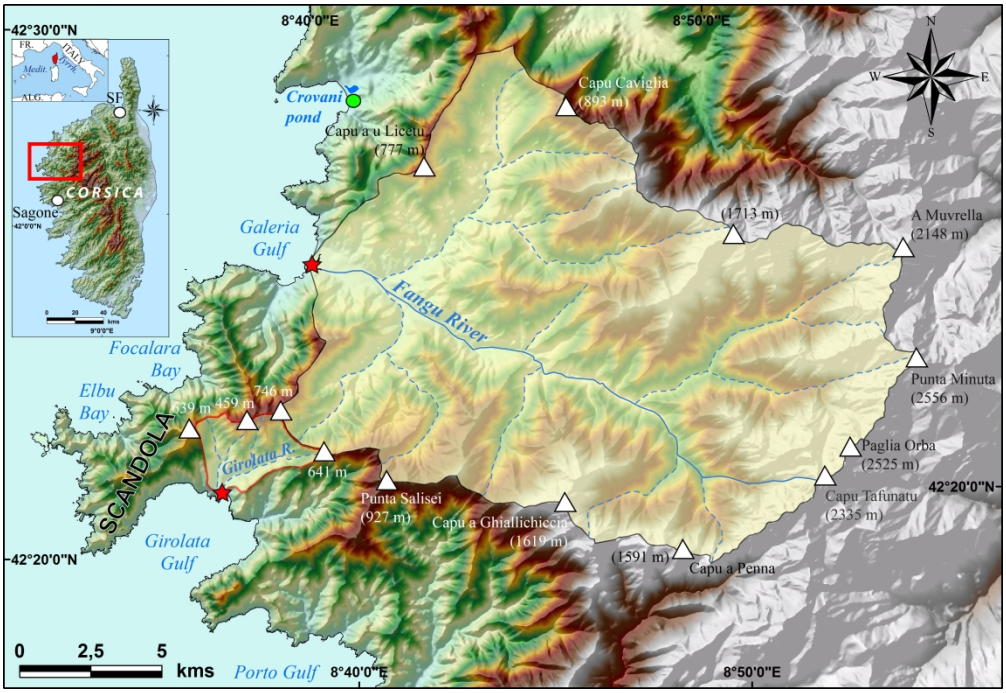
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Site	Core id	Elevation amsl (in m, error : ± 0.1 m)	Length (in m)	X (WGS 84)	Y (WGS 84)	Easting (RGF/Lambert 93)	Northing (RGF/Lambert 93)
Girolata	Girolata 1	+ 0,88	3.15	8°36'51.95"E	42°21'2.67"N	1162962,28	6155430,50
	Girolata 2	+ 0,85	4.20	8°36'44.17"E	42°21'0.03"N	1162791,59	6155337,24
Fangu	Fangu	+ 0,70	4.20	8°39'34.07"E	42°25'7.83"N	1166123,87	6163257,70

Table 1 : Boreholes location. Elevation is derived from Litto3D survey (SHOM-Collectivité de Corse-DREAL, 2020)

Core id	Depth (in m)	Elevation amsl (in m)	Material	BP	Error ±	Cal ages	Lab. code
Girolata 1	1,66	-0,78	*Posidonia oceanica*	3280	30	1317-917 BCE	Poz-129246
	2,96	-2,08	*Posidonia oceanica*	3375	35	1424-1047 BCE	Poz-128585
Girolata 2	0,68	+0,17	Organic sediment	740	30	1226-1297 CE	Poz-129251
	0,96	-0,11	Organic sediment	1770	30	222-375 CE	Poz-129248
	1,33	-0,48	Charcoal	2455	30	754-415 BCE	Poz-129249
	2,66	-1,81	*Posidonia oceanica*	3125	30	1119-769 BCE	Poz-128586
	2,98	-2,13	Organic sediment	3115	30	1447-1286 BCE	Poz-129250
	4,1	-3,25	Charcoal	3495	35	1921-1696 BCE	Poz-128587
Fangu	0,48	+0,22	Charcoal	805	30	1179-1277 CE	Poz-141492
	0,6	+0,1	Charcoal	1215	30	689-889 CE	Poz-141286
	0,79	-0,09	Plant remains	130	30	1673-1942 CE*	Poz-145856
	1,74	-1,04	Charcoal	3550	30	2013-1772 BCE	Poz-145857
	1,87	-1,17	Charcoal	3655	35	2140-1929 BCE	Poz-141287
	2,35	-1,65	Charcoal	4050	35	2925-2693 BCE	Poz-144578
	2,71	-2 ,01	Charcoal	4755	35	3640-3376 BCE*	Poz-145858
	3,05	-2,35	Plant remains	4375	35	3092-2907 BCE	Poz-144494
	3,75	-3,05	Wood (*Pinus nigra*/*sylvestris*)	5000	40	3945-3653 BCE	Poz-145859
	4,12	-3,42	Plant remains	4250	40	2672-2470 BCE*	Poz-144493

Table 2 : Radiocarbon dating results



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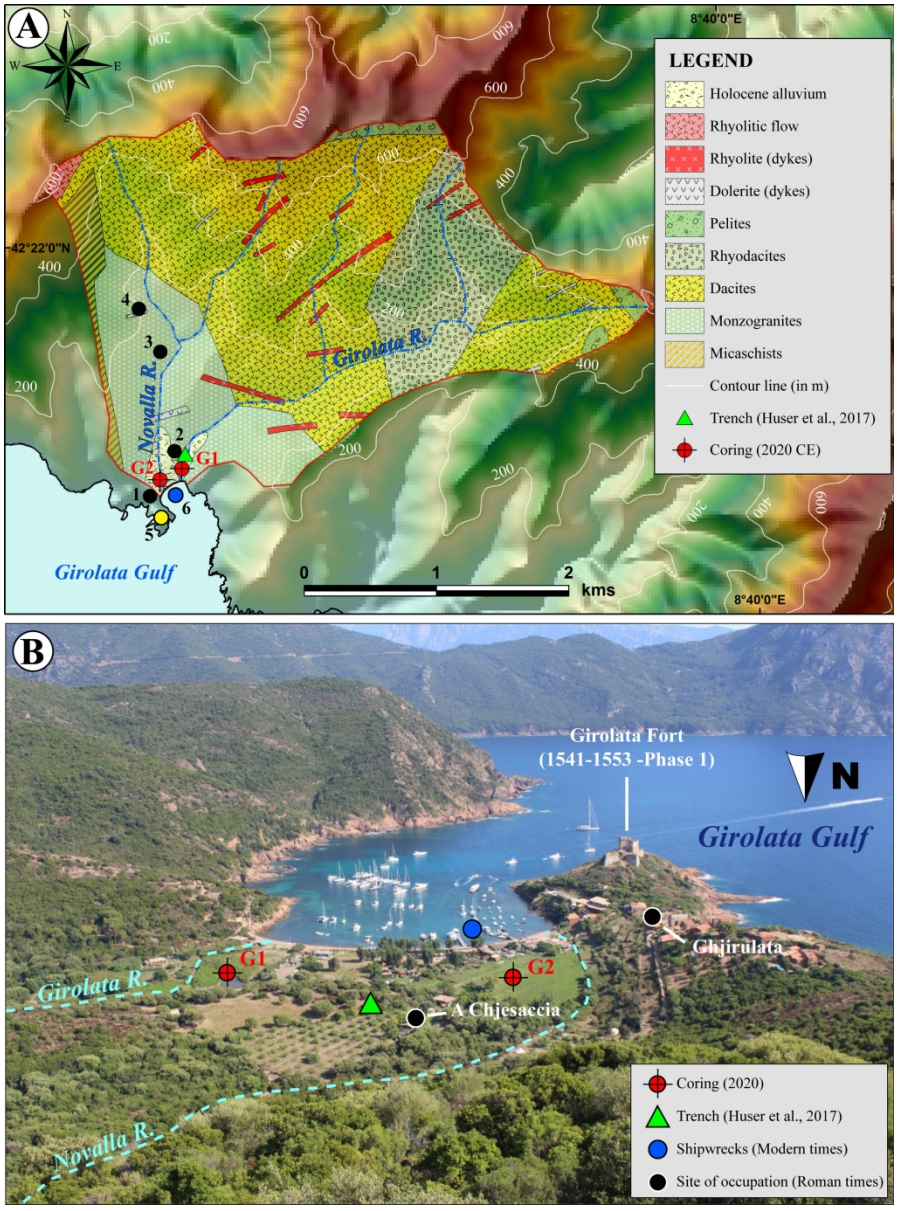

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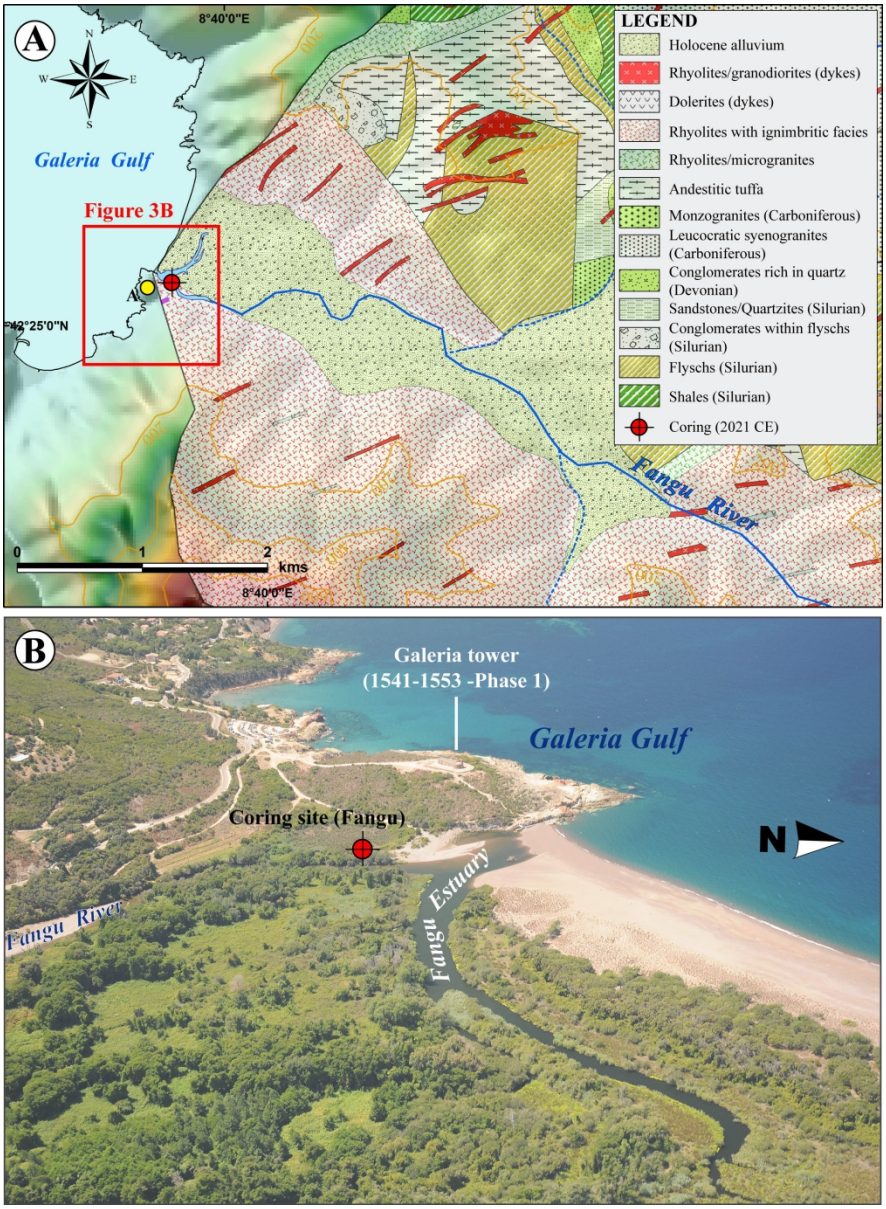

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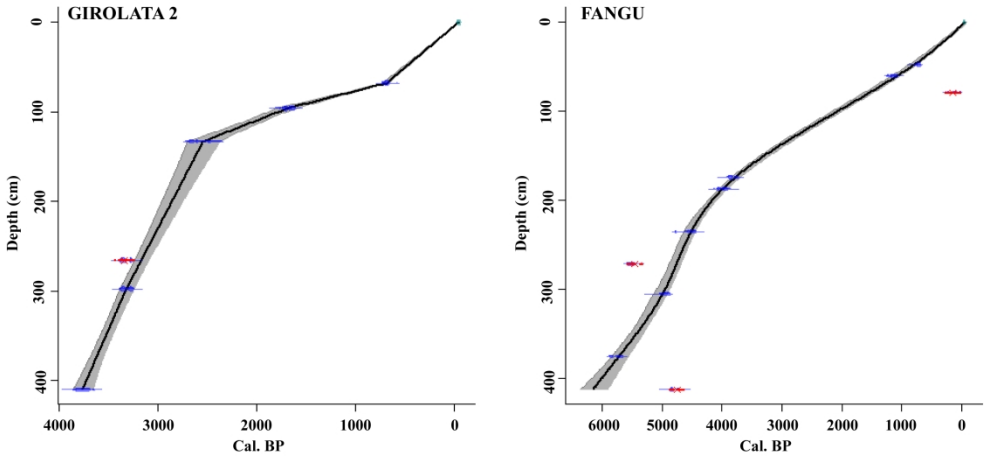
205x279mm (300 x 300 DPI)



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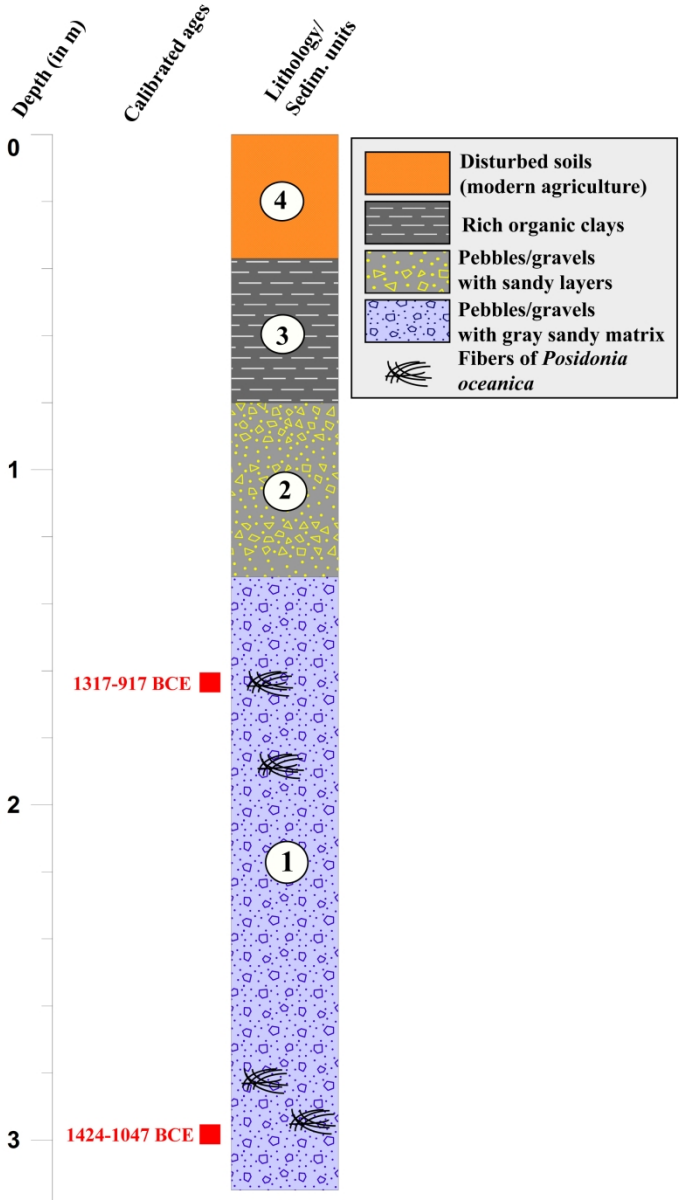

Figure 5 : Chronostratigraphy of Girolata 1 core

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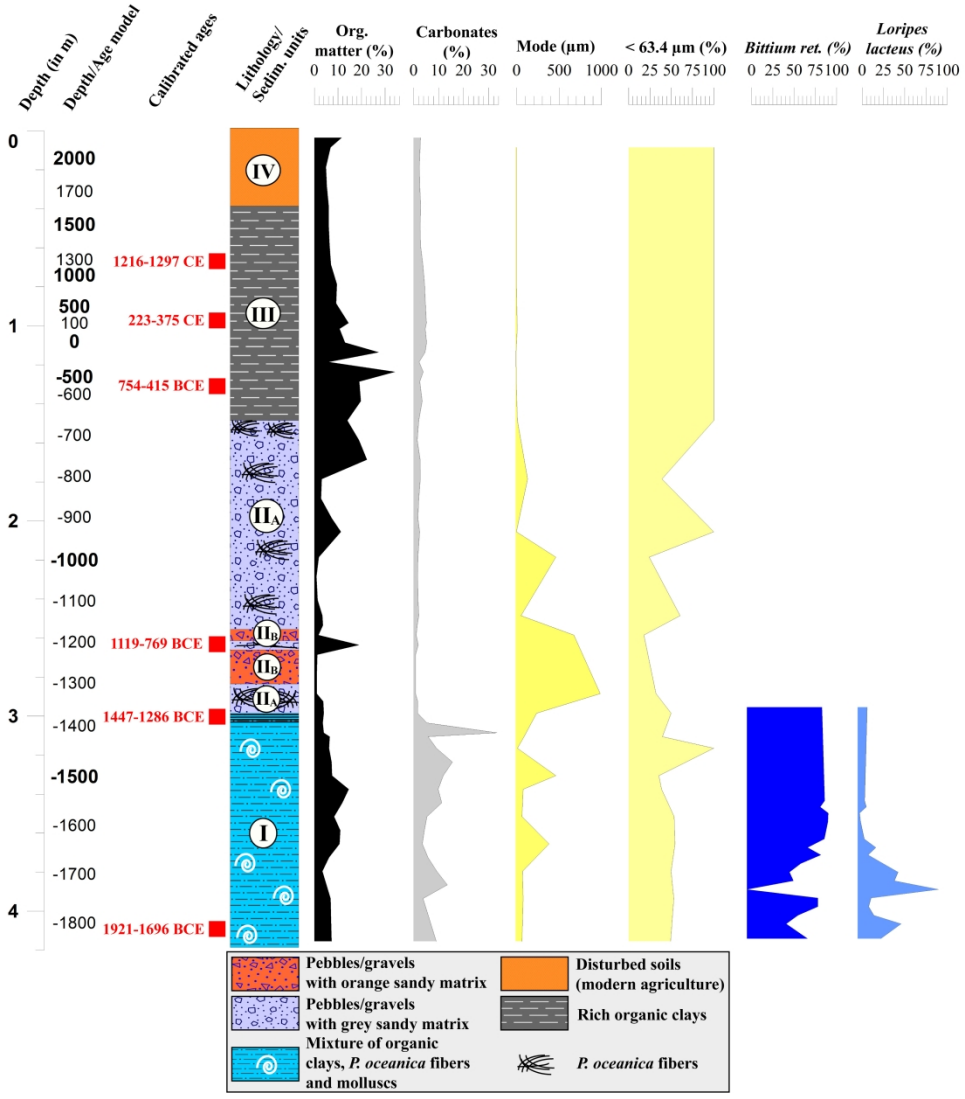

Figure 6 : Chronostratigraphy of Girolata 2core

298x325mm (300 x 300 DPI)

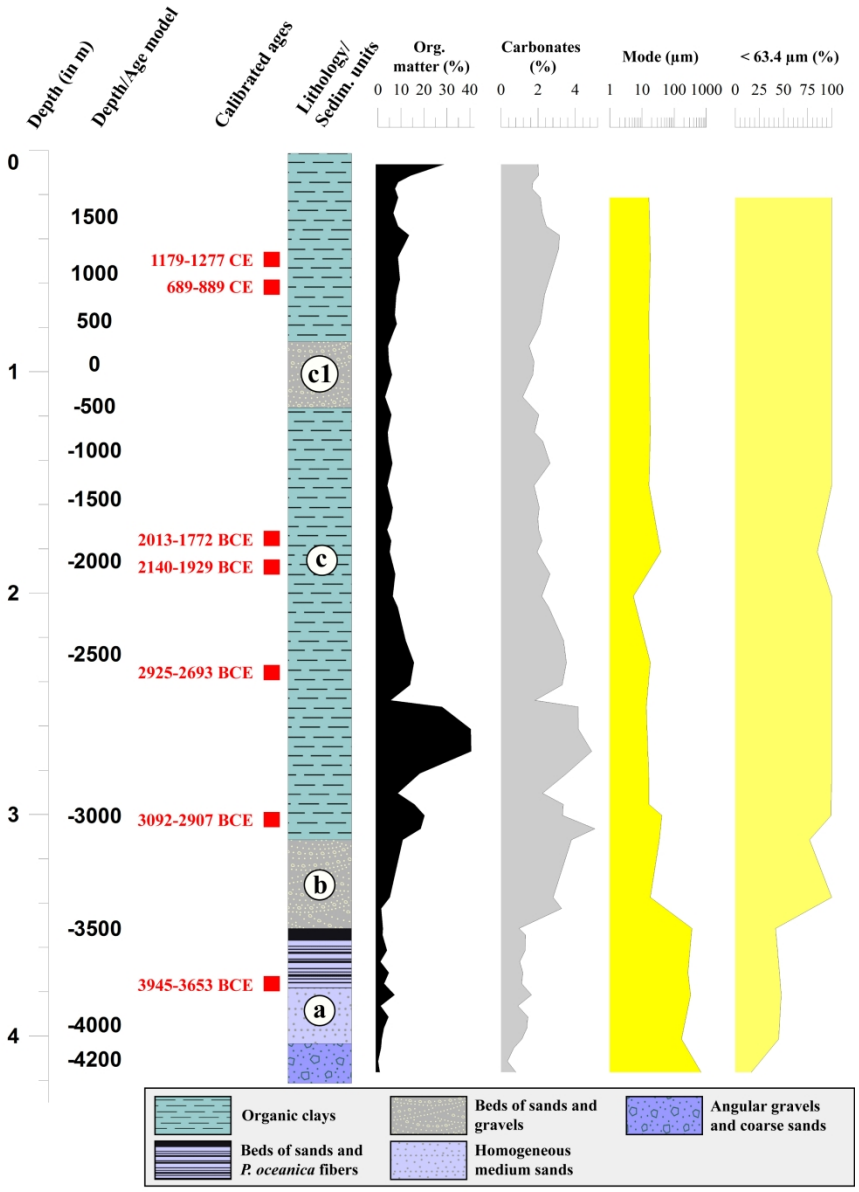

Figure 7 : Chronostratigraphy of Fangu core

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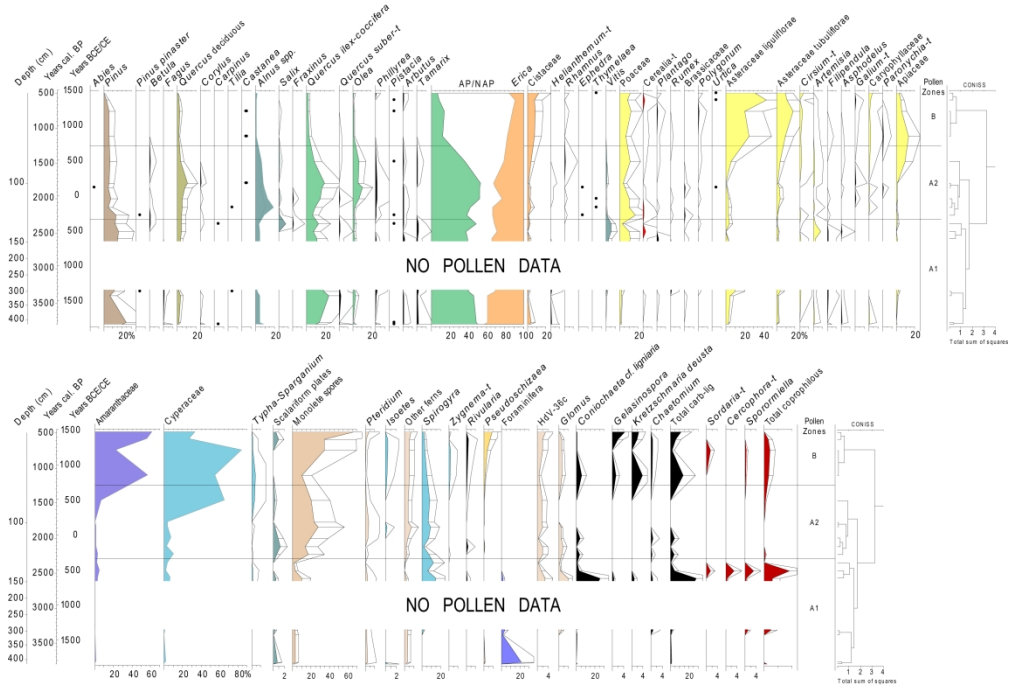

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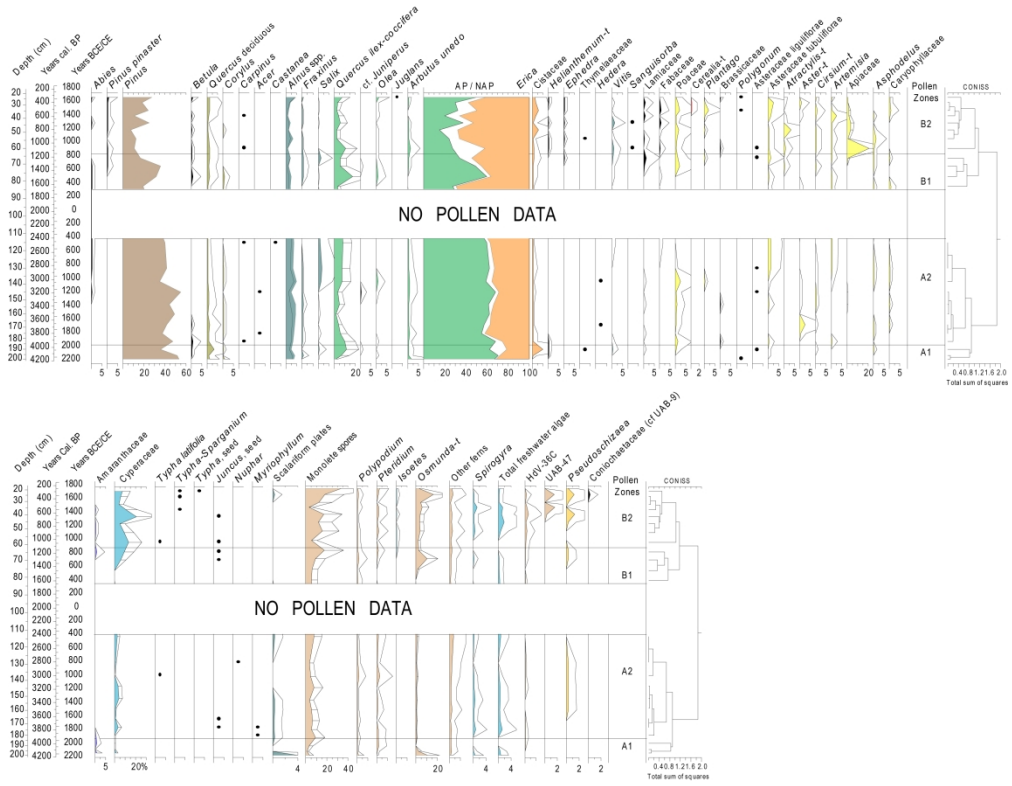

Figure 9 : Pollen and NPP percentage diagrams for Fangu core. White curves with depth bars show exaggerated curves x2; white curves, exaggeration x5; dots represent occurrences of <1%.

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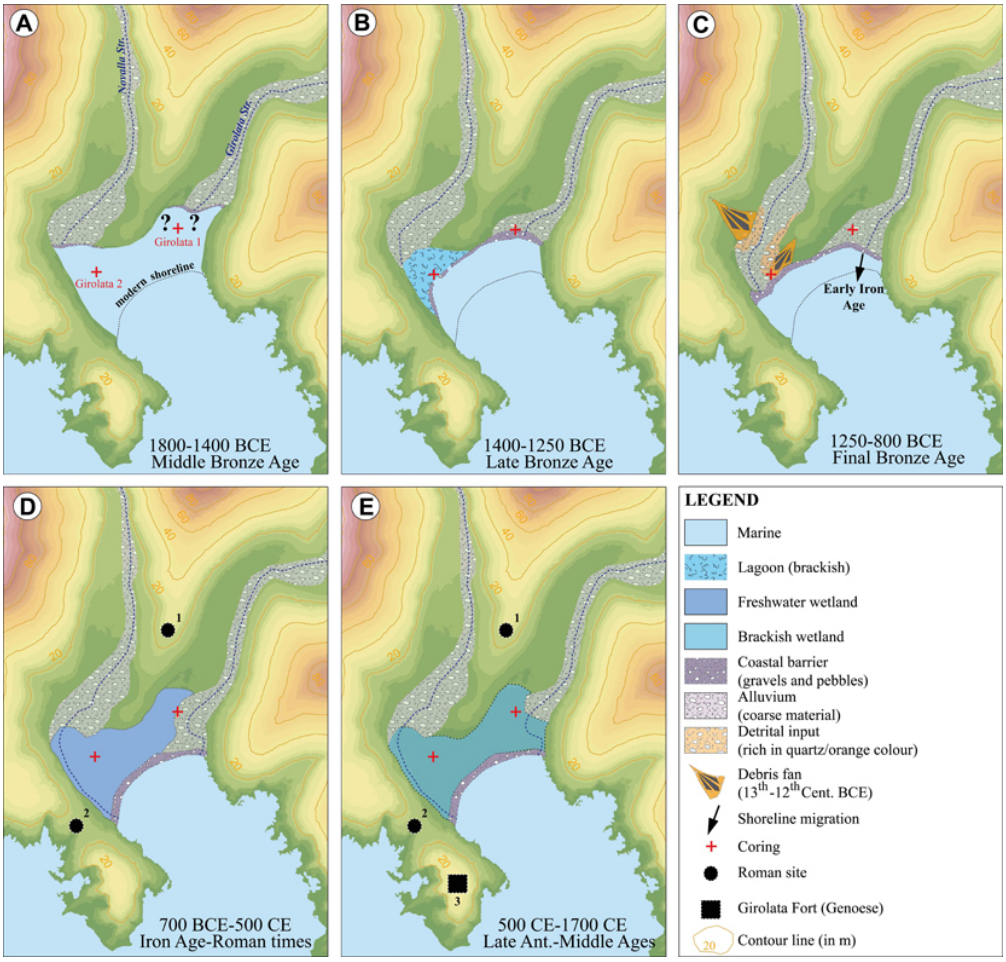

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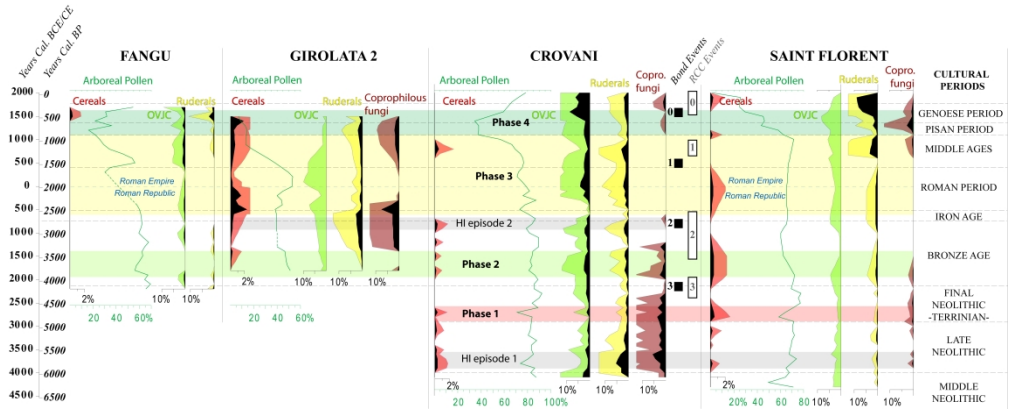

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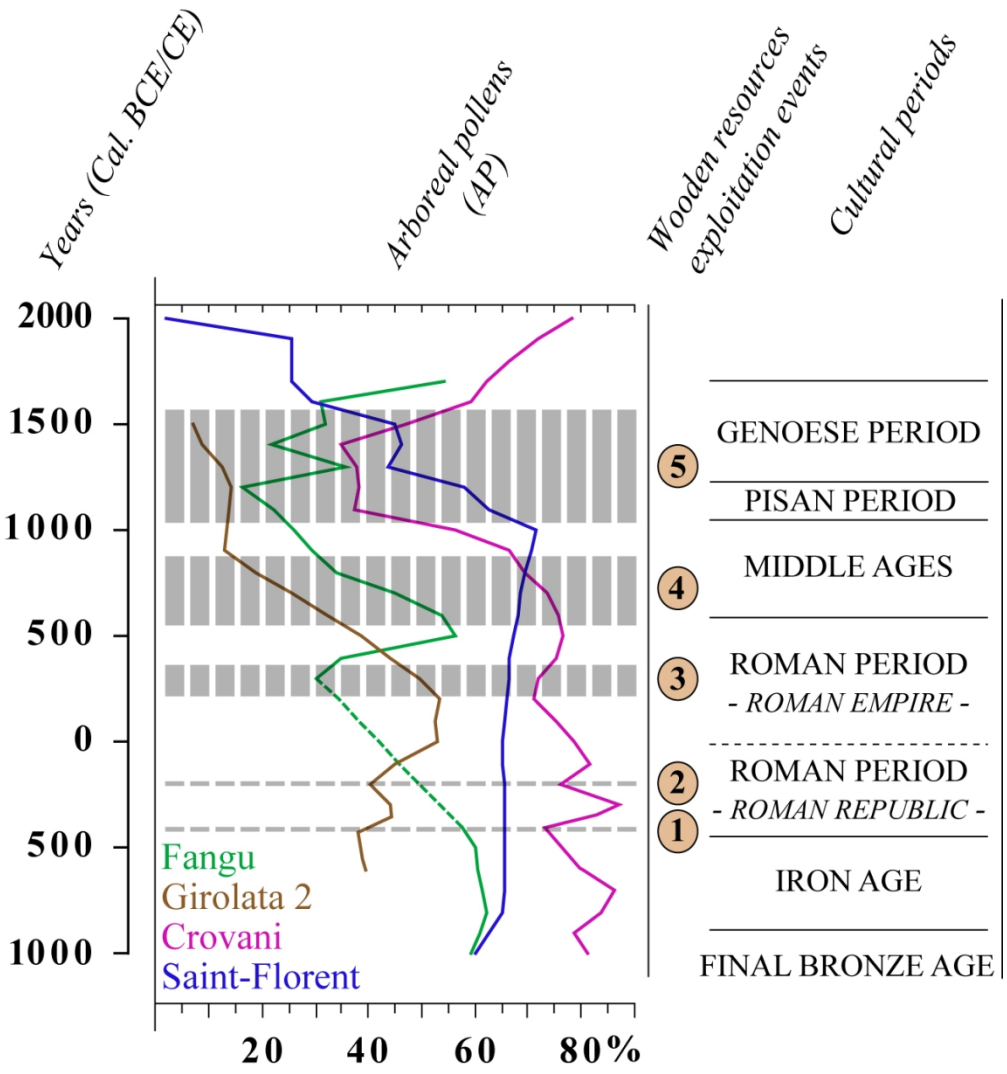
386x156mm (300 x 300 DPI)



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112x120mm (300 x 300 DPI)