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The recent evolution of the salt marsh 'Pantano Grande' (NE Sicily, Italy): interplay between natural and human activity over the last 3700 years

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ABSTRACT: Combined natural processes and human activities shaped the late Holocene landscape history in many Mediterranean regions. This is especially true with areas subjected to specific human interest, such as coastal areas morphologically suitable to the establishment of harbours. Here, we test the hypothesis on the location of the Roman harbour *Portus Trajectus* in Peloro Cape (NE Sicily, Italy) and describe the evolution of the area over the last 3700 years through lithostratigraphic, geochemical, meiofauna and microfossil analyses performed on a new sediment core recovered from the coastal salt marsh *Pantano Grande* (aka *Lago di Ganzirri*). The age–depth model was developed on radiocarbon dates and geochemical fingerprinting of two tephra layers. Results indicate that the area underwent dramatic changes *ca.* 650 BCE. The anthropogenic impact of Greek colonies may have contributed to modifying the coastal environment of Peloro Cape due to their widespread impact on natural resources. This happened at many localities in the Mediterranean, indicating the magnitude of impact of the Greek colonies over the landscape. According to our results, it is unlikely that the current *Pantano Grande* basin was used as a harbour in Roman times, although the presence of a harbour in the nearby *Pantano Piccolo* marsh cannot be excluded. *Pantano Grande* had been isolated from the sea for more than 2000 years. Human intervention in the 19th century halted that isolation and provided the background for the ecological, economic and social functions the salt marsh performs today.
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KEYWORDS: coastal landscape history; dinocysts; FL tephra; meiofauna; Pompeii tephra

Introduction

Coastal environments are extremely vulnerable to the combined effects of several natural and anthropogenic factors and are thus particularly threatened by global changes (Bini & Rossi, 2021; Pepe et al., 2013; Turner et al., 1996). They perform multiple natural, socioeconomic and cultural functions and are subject to specific management and conservation measures aimed at safeguarding their functioning (Doody, 2001). Coastal systems are also geological archives that can provide insights into combined natural and human-induced environmental changes, allowing future trends to be hypothesised (Anthony et al., 2014). This especially applies to areas characterised by a long-lasting interplay between natural and human activity.

In this context, the study of ancient harbours is of paramount importance. Ancient harbours are affected by relative sea-level changes, sedimentary supply, coastal marine currents and human intervention (Giaime et al., 2019; Marriner & Morhange, 2007). The study of ancient harbours can provide valuable archaeological, palaeoecological and geomorphological information on the evolution of coastal environments and have the potential to describe the development and decline of ancient societies as well as past environmental features at the local and extra-local scale (e.g. Kaniewski et al., 2018; Mazzini et al., 2011; Sadori et al., 2015). On the Italian peninsula, case studies include the *Altinum* in Venice (Ninfo et al., 2009), *Portus Lunae* in Luni (Bini et al., 2012), *Portus Pisanus* in Pisa (Kaniewski et al., 2018), the *Claudius* and *Trajan* basins (Mazzini et al., 2011; Sadori et al., 2010), the *Ostia* harbour in the Tiber delta near Rome (Goiran et al., 2014; Pepe et al., 2013) and the harbour of *Neapolis* in Naples (Di Donato et al., 2018). However, many ancient harbours described in classical historical sources no longer exist, and

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their position has never been precisely identified. This amounts to a substantial loss of information about the evolution of the coastal landscape and the human–environment relationships in place.

A specific case is the ancient harbour at Peloro Cape (NE Sicily), which is mentioned as *Portus Trajectus* in the *Tabula Peutingeriana* (Uggeri, 1969) and as *Trajectus* in the *Itinerarium Antonini* (Uggeri, 1968). In the absence of detailed historical information on the harbour location, Bottari & Carveni (2009) inferred the geographical position of the harbour through geomorphological reconstructions of the Peloro Cape based on sea-level changes, uplift data and cartographic information. Supported by historical and archaeological evidence, the two authors argued that the ancient harbour was probably located in the salt marsh called *Pantano Piccolo*, located at the NE extremity of the Peloro Cape. The current coastline does not show any landing or inlet that could offer protection for ancient ships. According to palaeotopographic models, the area was suitable to serve as a harbour in the fifth century BCE, when the local sea level was hypothesised to be 1.5 m higher than today (Bottari & Carveni, 2009). In the Peloro Cape area, there are two salt marshes, *Pantano Piccolo* (also known as *Lago di Faro*) and *Pantano Grande* (also known as *Lago di Ganzirri*), roughly oriented NE–SW. The marshes could have constituted an interconnected system until their progressive separation and partial reclamation during historical time (see Fig. 8c in Bottari & Carveni, 2009). The area between the two marshes (called the *Margi* area) underwent land reclamation in the 19th century and its palaeotopography was not investigated. It is thus not clear whether the two marshes actually constituted an interconnected system capable of hosting several ancient ships during the Greek and Roman occupation of Sicily. Furthermore, there are relevant uncertainties on the recent evolution of Peloro Cape and changes in the morphology, ecology and function of the two salt marshes.

In this work we present lithological, geochemical, meiofauna and microfossil analyses obtained from a sediment core retrieved in *Pantano Grande*. We developed an age–depth model of the sediment profile through combined radiocarbon and tephrochronological data, giving new insights into the evolution of the marsh system and the Peloro Cape area over the last 3700 years. The objective of this paper is to describe changes in the geomorphology and ecology of *Pantano Grande* over time using a multidisciplinary approach, and specifically investigate changes in its connections to the Mediterranean Sea.

Our results provide new information on the location and extension of *Portus Trajectus* and the interplay between anthropogenic and natural processes in the evolution of the coastal environment of the Peloro Cape area since the late Bronze Age.

Study site

Pantano Grande (literally the 'big marsh') is a coastal salt marsh located in NE Sicily (southern Italy), in the municipality of Messina (Fig. 1). The water body is approximately 1.7 km long and 0.25 km wide (surface area 0.34 km^2); has a maximum water depth of *ca.* 7 m and runs parallel to the Sicilian coast of the Strait of Messina, between the districts of Ganzirri and Margi. The marsh lies in the plain bordering the Ionian coastline of Sicily, 850 m from the salt marsh of *Pantano Piccolo* (Fig. 1).

Four water bodies were historically documented in the area. The extension of *Pantano Grande* is the result of the union of two adjacent smaller marshes. Between *Pantano Grande* and *Pantano Piccolo*, in the area called Margi, there was another small independent marsh and a temple dedicated to Neptune, which was presumably destroyed in Roman times (Biddittu et al., 1979). According to Maurolico (1543), two marshes were present in the Peloro Cape area in the 16th century CE. *Pantano Piccolo* was connected to the Ionian Sea in 1794 CE, and *Pantano Grande* was connected to *Pantano Piccolo* in 1810 CE. Finally, *Pantano Grande* was connected to the Mediterranean Sea through two further artificial channels in 1830 CE (Fig. 1).

Two normal faults surround the coastal plain of Peloro Cape. *Pantano Grande* probably originated due to the differential subsidence of the plain coupled with the Late Quaternary uplift of the Messina area and relative changes in sea level during the Holocene (Bottari et al., 2005). The marsh is separated from the sea by outcropping Holocene alluvial silt and conglomerate of the Messina Formation (Pleistocene), that are overlaid by Holocene aeolian deposits (Bottari et al., 2005; Gargano, 1994). There are no stream inlets. Water exchange is today mediated by the Due Torri and Margi channels (Fig. 1). Occasionally, the underground Catuso channel is also opened (Fig. 1). *Pantano Grande* is currently used for the cultivation of clams.

Materials and methods

Sediment sampling

In the summer of 2019, two parallel overlapping sediment cores (GPG-1A and GPG-2A) were recovered from the approximate depocenter of *Pantano Grande* at 6.65 m water depth (Fig. 1). The coring spot was located in the area displaying the maximum water depth. Sediment cores were taken through a modified square-rod Livingstone corer. The upper 140 cm (GPG-1P) were sampled with a modified Bolivia-type corer, which provided the undisturbed sediment–water interface. Overlapping sections were spliced according to optical and lithostratigraphic information, in order to avoid analysis of sediment disturbances associated with sections top and bottom. The composite core was 731.5 cm long (decompressed depth).

Age–depth model

The sediment succession was initially dated through four radiocarbon dates (Table 1). During core-opening operations, two volcanic ash layers (hereafter tephra) were identified at 399.6 cm and 631.7 cm depth. After geochemical fingerprinting and tephrostratigraphic correlation, the tephra ages were used as additional chronological tie points for the age model. Radiocarbon analyses were performed with accelerator mass spectrometry (AMS) at the Center for Isotopic Research on the Cultural and Environmental Heritage (CIRCE) of the University of Campania Luigi Vanvitelli and the INNOVA Center. The age–depth model was developed through the R package 'RBacon' (Blaauw & Christen, 2018). Raw radiocarbon ages were calibrated through the IntCal20 calibration curve for the Northern Hemisphere (Reimer et al., 2020).

Tephra layer analysis

Samples from the two tephra were labelled as T1 (399.6 cm depth) and T2 (631.7 cm depth) and processed by geochemical analysis. Major and minor element compositions were determined on micropumices with a Jeol Superprobe JXA-8230, equipped with five WDS wavelength dispersive spectrometers (WDS) and installed at the Istituto di Geoscienze e

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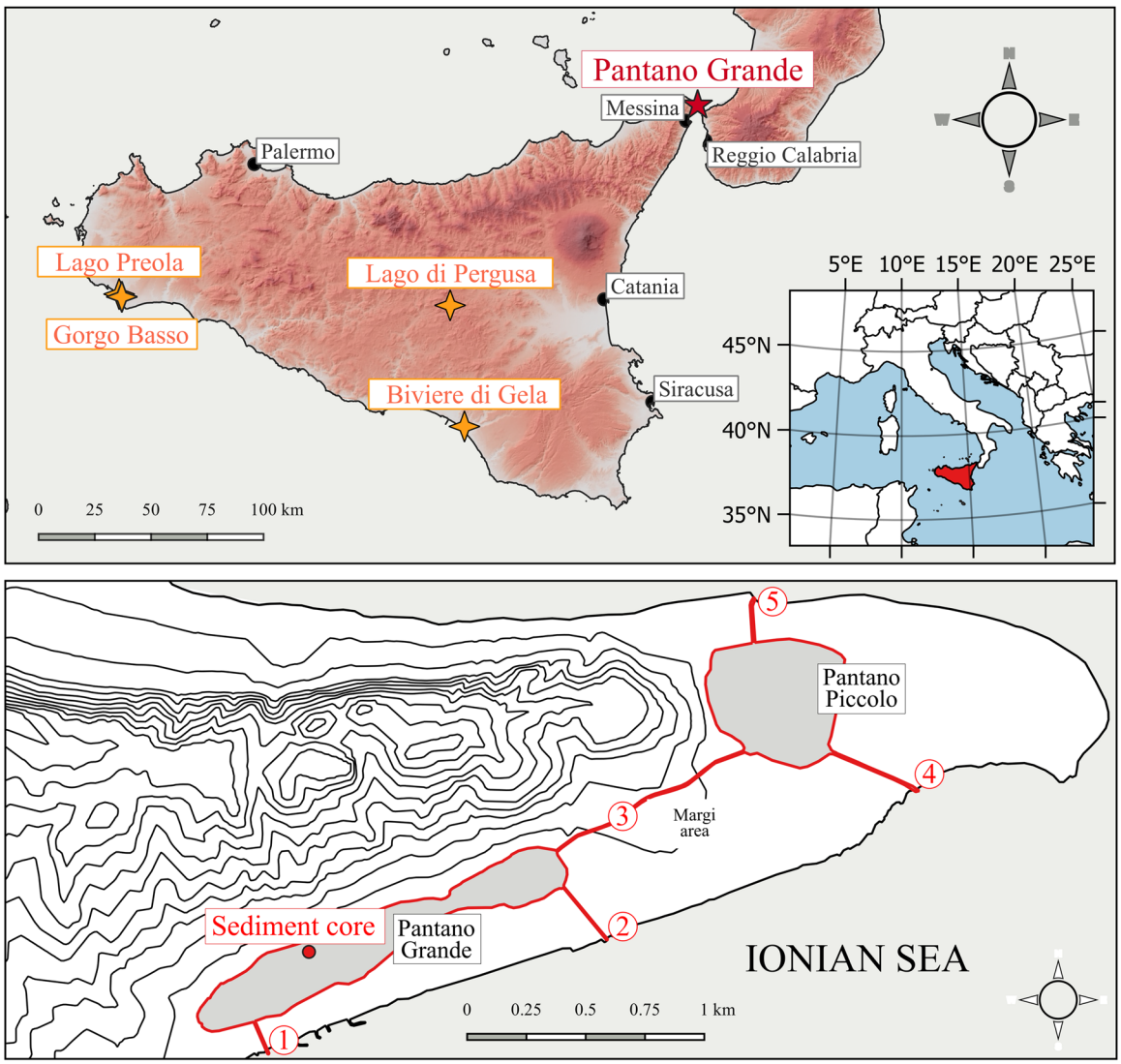

Figure 1. Map of the location of the study site. Upper panel: the study site '*Pantano Grande*' in NE Sicily (red star) and the location of other sediment records cited in the text (yellow stars) and principal modern cities in Sicily and Calabria (black dots). Lower panel: Capo Peloro area and the location of the sediment core discussed in this paper (red dot). Artificial channels (highlighted in red) were built between 1794 and 1830 CE: (1) Catuso channel; (2) Due Torri (or Carmine) channel; (3) Margi channel; (4) Faro channel; (5) English's channel. [Color figure can be viewed at wileyonlinelibrary.com]

Table 1. Uncalibrated (raw) radiocarbon ages from the *Pantano Grande* sediment core. Depth values refer to the running depth of the composite core. Ages are expressed in years BP, which is conventionally years before 1950 CE.

Depth (cm)	Material	Radiocarbon age (years BP)	±
114	Plant remains	425	25
302	Wood	1724	27
730.6	Bulk	3827	34
740	Bulk	3409	23

Georisorse of the Italian National Research Country (IGG-CNR) laboratory in Florence (Italy). Operating conditions were set to 15 kV accelerating voltage, 10 nA beam current and 10 μm defocused beam diameter to limit Na mobilisation and loss. Element counting times were 15 s for all elements except for Na (10 s), F (20 s), S (30 s), Mn, P and Cl (40 s). Albite (Si and Na), ilmenite (Ti and Fe), plagioclase (Al), bustamite (Mn), olivine (Mg), diopside (Ca), sanidine (K), apatite (P), fluorite (F), tugtupite (Cl) and celestine (S) were used as internal standards. Lipari ID3506 (Kuehn et al., 2011), CFA47 (Marianelli & Sbrana, 1998), Scapolite NMNH R6600 and MPI-DING glass standards of Jochum et al. (2006) were measured prior to the analytical session to evaluate the accuracy of the electron-microprobe analysis. Data reduction was carried out using the ZAF correction, while data processing was performed in Microsoft Excel. All compositional data are shown as oxide weight percentages (wt%), with total iron (FeOtot) calculated as FeO, and normalised to 100% on a volatile-free basis (i.e. excluding Cl, SO_3 and F volatiles) for correlation purposes. We adopted 93 wt% as a threshold of the measured total. The glass geochemical composition of the T1 and T2 tephras is shown in the total alkali vs silica (TAS; Le Maitre et al., 2002) diagram.

X-ray fluorescence analysis

High resolution (1 mm) elemental analyses were performed on the core-half surface by energy dispersive X-ray fluorescence (XRF) scanning at the Institute of Geology and Mineralogy in Cologne (University of Cologne, Germany) using an Itrax XRF scanner (Cox Analytical Systems, Sweden). XRF scans were made using a Chromium tube set at 55 kV and 30 mA with a dwell time of 10 s and a step-size of 1 mm. Data are expressed in counts per second for incremental steps of 1 mm. For this manuscript, we selected K (potassium) as a potential indicator

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of clastic matter input into the lake (e.g. Francke et al., 2016; Mannella et al., 2019) and Ca (calcium) as an indicator of biogenic or authigenic calcite and/or input from volcanic Ca-rich ashes.

Meiofauna analysis

We performed a quantitative analysis of benthic foraminifers and ostracods on 15 selected samples collected at regular intervals along the composite core, paying special attention to sedimentary facies. For each sample, approximately 1.5–2 g of dry sediment was treated following the methodology reported in Amorosi et al. (2014). The fraction >63 μm was analysed under an optical microscope. Foraminifer tests and ostracod valves were identified to species level. *Taxa* identification and autecological data were based on reference papers (Athersuch et al., 1989; Barbieri & Vaiani, 2018). Changes in community structure and composition of meiofauna were used to describe subtle palaeoenvironmental oscillations within transitional successions (e.g. Barbieri & Vaiani, 2018; Pint & Frenzel, 2017; Rossi et al., 2021; Triantaphyllou et al., 2021).

Dinocyst analysis

A total of 85 levels were subsampled at regular intervals along the sediment succession for microfossil analyses. Dry sediment samples were weighed and processed through acid-base-acid reactions at the University of Rome La Sapienza (Italy). Standard palynological methods were used to process the sediment samples (Faegri & Iversen, 1964). Lycopodium spores were added during the chemical treatment to calculate microfossil concentration (Stockmarr, 1971). Processed samples were mounted on microscope slides and analysed through an optical microscope at 400× and 600× magnification. Microfossil analyses involved pollen and palynomorphs. Pollen data will be published in a separate paper; here we present the data for the dinoflagellate cysts (dinocysts) to support the interpretation of changes in sedimentary facies (Zonneveld et al., 2013).

Results

Geochemistry of tephra layers

T1 – 399.6 cm depth

T1 is mainly characterised by sub-rounded 150–250 μm-sized micropumices with clean exposed sections. The majority of the micropumices are high-vesicular, and most of them are associated with abundant phenocrysts of leucite and other mineral phases, such as feldspar. T1 is characterised by a SiO_2 content ranging from 50.63 to 55.17 wt% and an alkali sum varying between 13.06 and 15.50 wt% with a mean K_2O/Na_2O ratio of 1.46 (up to 1.98). The Al_2O_3 and Cl contents are high, being >20 wt% and >0.6–0.7 wt%, respectively, while the MgO content is low (0.53 wt% on average and down to 0.37 wt%). It can be classified as a phonolite–tephriphonolite according to the TAS classification diagram (Fig. 2). The high Cl content (>0.6 wt%) indicates a Campanian origin consistent with Somma-Vesuvius. A comparison with glass-WDS chemical analysis from Santacroce et al. (2008) indicates correlation with the 79 CE Pompeii eruption (Fig. 3). The Avellino eruption, although showing geochemical similarities with the Pompeii eruption, is characterised by CaO generally <2 wt%, which is inconsistent with the composition of our tephra, which has a mean CaO content of 4.92 wt%. Other differences between the Avellino pumice and tephra T1 are the higher Al_2O_3 and Na_2O, and lower Na_2O/K_2O ratio, TiO_2, FeO and MgO (Santacroce et al., 2008; Turney et al., 2008). These potential correlatives can also be excluded on the basis of the stratigraphic position and the radiocarbon ages (Table 1). Furthermore, the other eruptive episodes of Somma-Vesuvius had a dominant dispersion towards the E or NE (Gurioli et al., 2005; Santacroce et al., 2008; R. et al., 2014) while the Pompeii eruption had a S–SE dispersion, which explains its occurrence in *Pantano Grande*.

T2 – 631.7 cm depth

T2 consists of large (hundreds of μm) poor-vesicular micropumices, which are, however, characterised by the extensive presence of microlites that could potentially contaminate the analysis. Nevertheless, the presence of some pumice with clean and (almost) mineral-uncontaminated sections allowed a sufficient number of analytical points to geochemically characterise the sample's composition. In this case, the pumice is associated with mafic minerals, such as olivine, pyroxene and Fe-Ti microlites. In the TAS diagram (Fig. 2), T2 occupies various fields, i.e. those of basaltic-trachyandesites, trachyandesites, phonotephrites and tephriphonolites. T2 has a measured SiO_2 content varying between 52.36 and 54 wt%, an alkali sum ranging from 8.48 to 9.55 wt% and a K_2O/Na_2O ratio of 0.48–0.64. It is characterised by a mafic composition, with high amounts of FeO (8.77 wt% in average) and MgO (up to 3.57 wt%). T2 is characterised by a Na-enriched

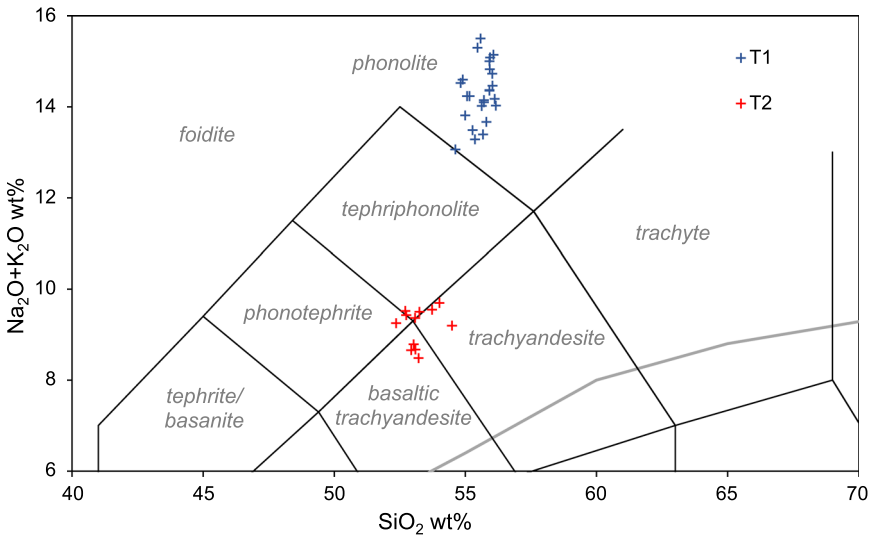

Figure 2. Total alkali vs silica (TAS) classification diagram (Le Maitre et al., 2002) displaying the composition of T1 (red crosses) and T2 (green crosses) tephras. [Color figure can be viewed at wileyonlinelibrary.com]

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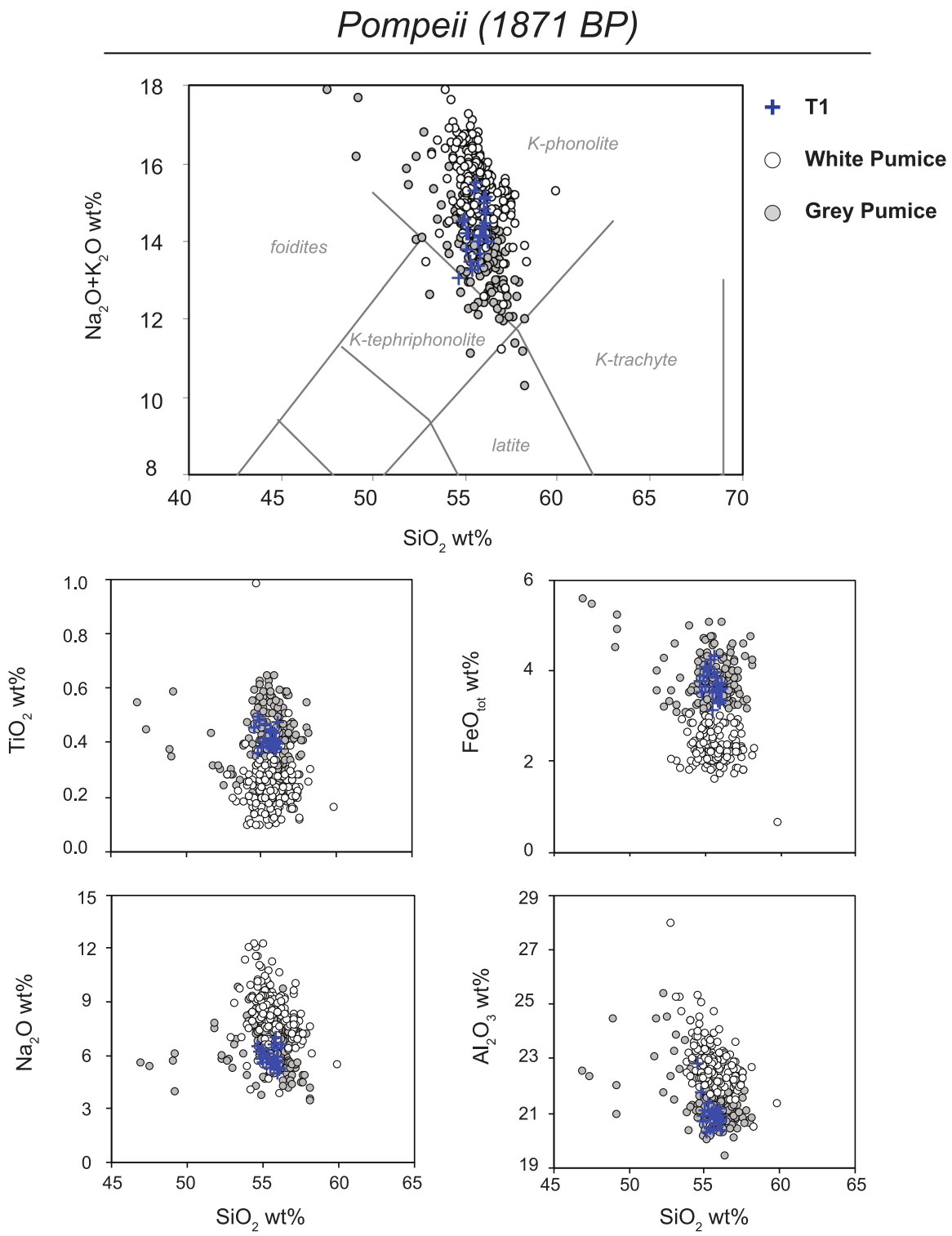

Figure 3. Total alkali vs silica (TAS; Le Maitre et al., 2002) and major element biplot diagrams of T1 tephra in comparison with white and grey pumice glass-WDS data from Santacroce et al. (2008). [Color figure can be viewed at wileyonlinelibrary.com]

composition that can be attributed to the sodic alkaline sequence. Na-alkaline rocks are peculiar to the Mount Etna volcano (e.g. Peccerillo, 2017). Currently Mount Etna is characterised by a dominant quasi-persistent effusive activity, consisting of frequent eruptions of trachybasaltic lavas (Peccerillo, 2017). Nevertheless, the last 15 ka of activity have been characterised by several violent strombolian to sub-Plinian to Plinian explosive events (Coltelli et al., 2000) that produced widespread tephra layers (e.g. Y-1/Et-1; Paterne et al., 1988) in both the eastern Mediterranean and central-southern Italy (e.g. Del Carlo et al., 2020; Giaccio et al., 2017; Wulf et al., 2008). Coltelli et al. (2000) identified in mid-proximal settings five periods of activity or Units, from A to E, where E refers to the last 15 ka following the Biancavilla-Montalto caldera-forming eruption (which corresponds to Unit D). Unit E includes at least one Plinian and 24 sub-Plinian events during the last 13 ka, which produced several regional markers. Among these markers, the FL unit, mugearitic in composition, has a NE dispersal and has been recognised as far as the Balkans, ≥600 km distant, in Lake Ohrid (Albania and Macedonia; Francke et al., 2019; Sulpizio et al., 2010b; Vogel et al., 2010; Wagner et al., 2008), Lake Prespa (North Macedonia, Albania

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and Macedonia; Sulpizio et al., 2010b); and Lake Shkodra (Albania and Montenegro; Sulpizio et al., 2010a). In mid-proximal settings, it has also been recognised in Lago di Pergusa (Sicily, Italy), *ca.* 100 km W–SW from Mount Etna, where it was radiocarbon-dated to 3055 ± 75 BP (Sadori et al., 2013; Sadori & Narcisi, 2001). A comparison between tephra T1 and the FL tephra can be made only with energy-dispersive-spectrometry (EDS) data from glass shards, as other published data are not available. We employed EDS data from Lake Ohrid (FYROM, Albania), Lake Shkodra (Albania, Montenegro) and Lago di Pergusa (Sicily) (Francke et al., 2019; Sadori et al., 2013; Sadori & Narcisi, 2001; Sulpizio et al., 2010a) (Fig. 4). FL tephra has a dominant mugearitic–benmoreitic composition, which is displayed by all tephra except for SK13-514 from Lake Shkodra, which lacks the mugearitic component and displays a more evolved benmoreitic–Na–trachytic composition (Fig. 4).

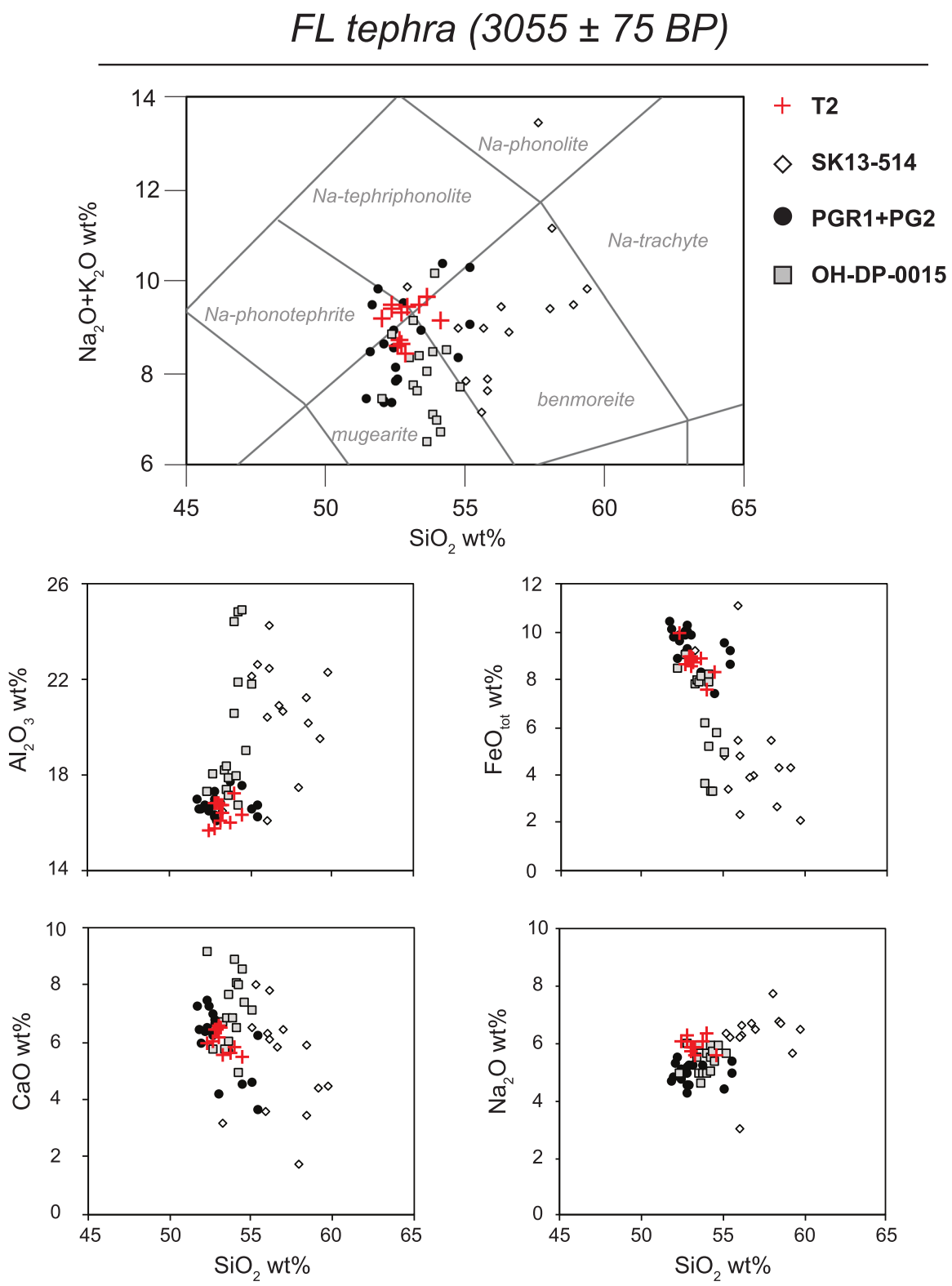

Figure 4. Total alkali vs silica (TAS; Le Maitre et al., 2002) and major element biplot diagrams of T2 tephra in comparison with literature data for FL tephra. EDS-data source: SK13-514 (Lake Shkodra) (Sulpizio et al., 2010a); PGR1 and PG2 (Lago di Pergusa): (Sadori et al., 2013; Sadori & Narcisi, 2001); OH-DP-0015 (Lake Ohrid) (Francke et al., 2019). [Color figure can be viewed at wileyonlinelibrary.com]

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Nevertheless, biplot diagrams highlighted a good agreement between SK13-514 and the other FL tephra, as well as with our data, confirming the attribution of T2 tephra to the FL regional marker.

Chronology

The age–depth model spans from *ca.* 1770 BCE (3720 BP) to 2019 CE (69 AP) (Fig. 5). The surface age was set at 2019 – the year of the coring campaign, and the two tephra ages were included in the model as further tie points. The bulk age from 730.6 cm was rejected because it provided a reversal and an apparently too old age (Table 1). The age–depth model displays a fairly constant sedimentation rate (average 5 yrs cm^{-1}) over the last 3700 years. The mean age uncertainty is ±123 years (min ±6 yrs, max ±178.5 yrs).

Late Holocene stratigraphy of Pantano Grande

The sediment succession from Pantano Grande was mainly composed of fine sands and silty sands. Benthic foraminifers showed highly variable abundances (from 1 to 300 specimens g^{-1}) and were represented by small-sized individuals belonging to few taxa (*Ammonia tepida*, *Ammonia parkinsoniana* and *Aubignyna perlucida*) (Fig. 6). Very scarce valves (up to three valves) of the ostracod species *Cyprideis torosa* were locally encountered. Dinoflagellate cysts were mainly represented by *Lingulodinium machaerophorum* and *Spiniferites* spp. The latter were identified at genus level due to taxonomical ambiguities and convergent morphologies between different species (de Vernal et al., 2018). Dinocysts that were not determined are grouped in the 'not identified' category (Fig. 6).

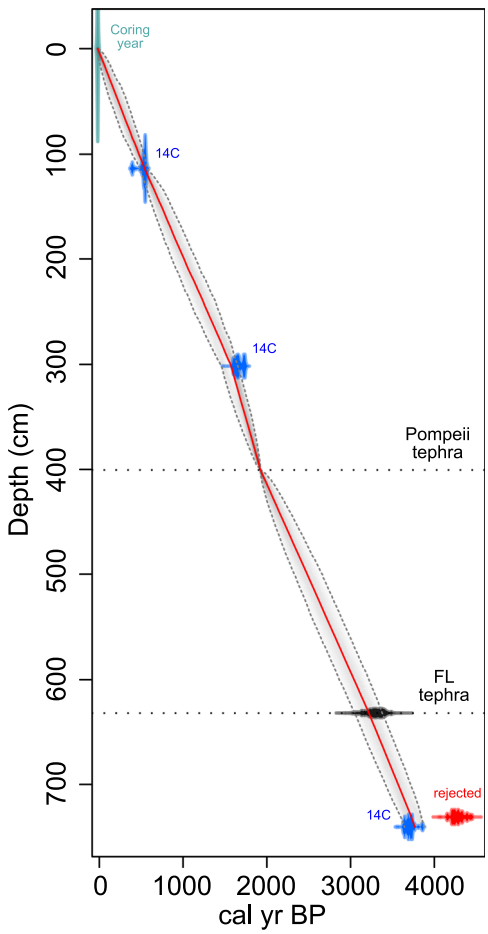

Figure 5. Age–depth model of the 740 cm composite core from *Pantano Grande* developed through the R package 'RBacon' (Blaauw & Christen, 2018). The IntCal20 calibration curve for the Northern Hemisphere (Reimer et al., 2020) was used to calibrate the raw radiocarbon ages. [Color figure can be viewed at wileyonlinelibrary.com]

Three main facies associations (FA1, FA2, FA3) were identified by the integration of features deriving from the visual inspection of the sediment core (e.g. mean grain size, sedimentary structures, molluscs) with geochemical (Ca and K), meiofauna and microfossil data (Fig. 6).

The lowermost facies association (FA1) was deposited between *ca.* 1770 BCE (3720 BP) and 650 BCE (2600 BP) and is composed of ~2 m-thick massive or mostly massive sands enriched in organic matter containing thin layers of intact and fragmented mollusc shells (Fig. 6). Highly fluctuating values of K and Ca may indicate the presence of K-rich clastic mineral and abundant biogenic fragments (e.g. shell remains, foraminifera, ostracods). The foraminiferal abundance shows a similar pattern to Ca and K (Fig. 6). The foraminiferal fauna is almost entirely composed of *A. tepida* and *A. parkinsoniana* morphotypes, accompanied by scattered remains of *A. perlucida*. Few valves of the ostracod *C. torosa* were also encountered (Fig. 6). *L. machaerophorum* dominated the fossilised dinoflagellate community in FA1, showing considerably high concentrations until about 800 BCE (2750 BP) (Fig. 6). Of note, only 10–20% of the dinoflagellate species produce cysts that can be fossilised (Vernal & Marret, 2007). Subsequently, dinocyst records abruptly dropped to near zero and never recovered such a high concentration value in the upper portion of the sediment core (Fig. 6).

FA2 spans from 650 BCE (2600 BP) to 1800 CE (150 BP). FA2 shows a ~4.80 m-thick succession of silty sands with a well-defined, thin (mm-thick) lamination and variable organic matter (Fig. 6). Few mollusc fragments or shells occur, with the exception of two sandy intervals enriched in malacofauna remains (Fig. 6). Ca and K values show overall opposite trends. Ca is relatively low but has two maxima between 800 and 950 CE (1150–1000 BP) and between 1300 and 1500 CE (650–450 BP), which are probably related to the occurrence of occasional and dispersed shell fragments. Variations in K are probably related to changes in grain-size composition of the sediments, as K is often correlated with more fine-grained material. However, it is also diluted by organic matter. Meiofauna is almost totally absent, while dinocysts are recorded in very low concentrations (Fig. 6). *L. machaerophorum* show an isolated peak around 350 CE (1600 BP).

The topmost facies association (FA3) is ~0.5 m-thick and encompasses the last approximately 200 years. It is characterised by medium sands rich in bivalve shells. High values of Ca and K typify the lower boundary of FA3 and decrease sharply towards the sediment surface (Fig. 6). Of the meiofauna, a relatively abundant foraminiferal fauna exclusively composed of *A. tepida*, *A. parkinsoniana* morphotypes was found along with very few *C. torosa* valves. Dinocysts are poorly recorded (Fig. 6).

Discussion

Facies associations in the *Pantano Grande* sediment profile indicate that substantial changes in the morphology and ecology of the marsh occurred at *ca.* 650 BCE (2600 BP). In FA1, between *ca.* 1770 BCE (3720 BP) and 650 BCE (2600 BP), the presence of euryhaline opportunistic foraminifera, ostracods and dinoflagellate species suggested connections between *Pantano Grande* and the Mediterranean Sea, which presumably developed through *Pantano Piccolo* (Fig. 1). The ecology of the benthic

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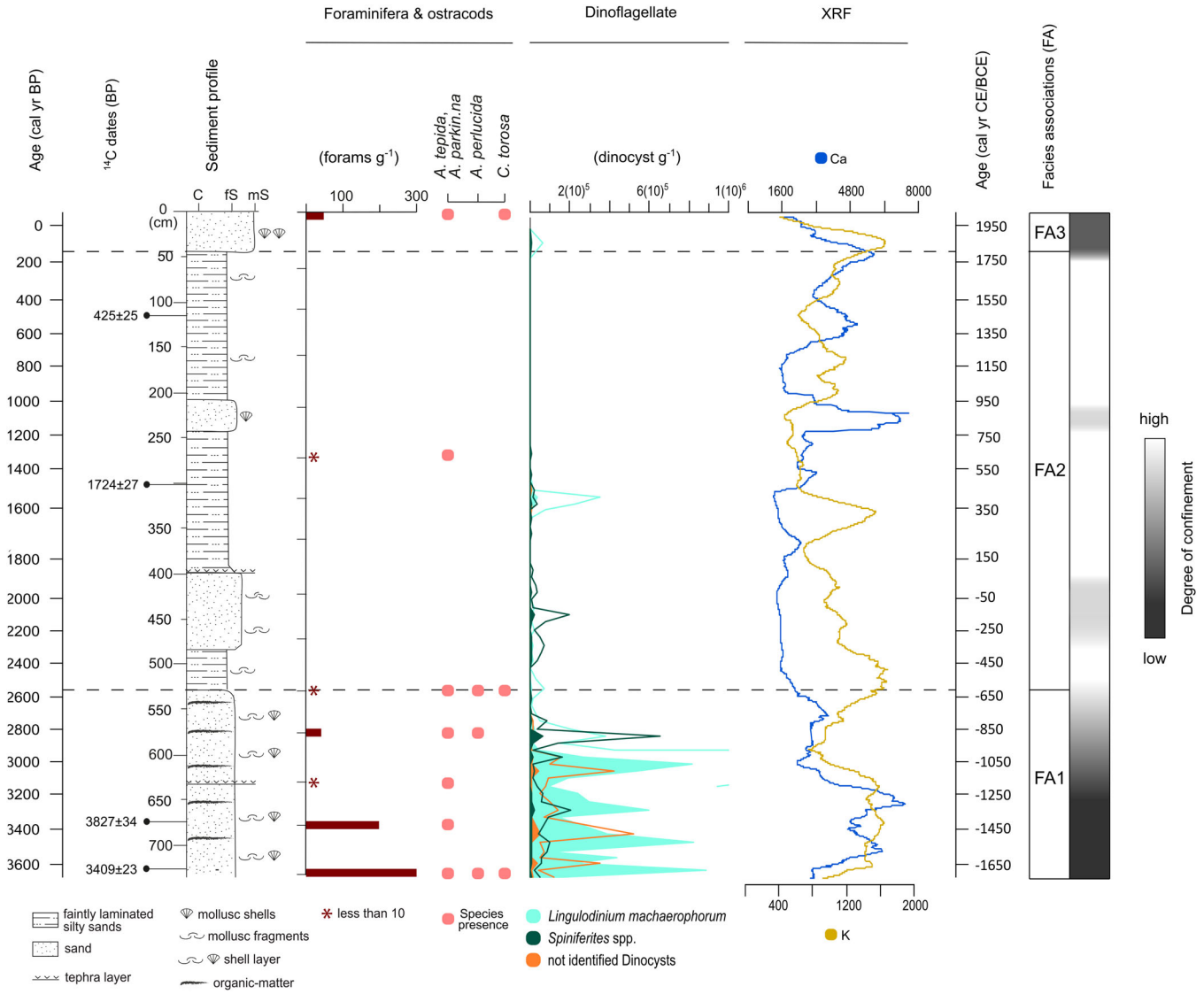

Figure 6. Characterisation of the *Pantano Grande* sediment profile. Facies associations are based on meiofauna and dinocyst content and stratigraphy. Ca and K counts from XRF analyses are displayed. Ages are shown as raw ^{14}C ages and calibrated ages extracted from the age–depth model. On the right side, the degree of confinement of the marsh from 'open to the sea' to 'closed basin' is inferred from the biosedimentary data. [Color figure can be viewed at wileyonlinelibrary.com]

and planktonic communities identified in the sediment core precludes the possibility that *Pantano Grande* was directly connected to the sea. *A. tepida* and *A. parkinsoniana* morphotypes commonly thrive in restricted environments characterised by variable salinity and organic matter enrichment (Debenay & Guillou, 2002; Murray, 2006). *A. perlucida* is a shallow-marine taxon tolerant of remarkable amounts of organic matter (Jorissen et al., 2018), while *C. torosa* is characterised by an euryhaline and opportunistic ecology (Mazzini et al., 2017). The small size and low diversity of foraminifer and ostracod species indicated stressing conditions that are consistent with restricted environments (*sensu* Debenay & Guillou, 2002). Apart from metal pollution, modern datasets from transitional environments (e.g. lagoons, bays) document the occurrence of benthic foraminifer (mainly *Ammonia tepida*) dwarf tests under eutrophic and stagnant conditions, which typically affect highly confined bottoms (Martins et al., 2016; Vilela et al., 2011). Accordingly, high concentrations of *L. machaerophorum* and *Spiniferites* spp. (dinocysts) can occur in eutrophic and hypoxic environments (Zonneveld & Pospelova, 2015). In FA1, the area between *Pantano Grande* and *Pantano Piccolo* (Margi area, Fig. 1) was probably a place of other smaller marshes which altogether constituted an interconnected system open to the sea towards the NE. This scenario matches the palaeotopographic reconstruction proposed by Bottari & Carveni (2009, Fig. 8c therein).

Since 1250 BCE (3200 BP) meiofauna occurrences started decreasing and *Pantano Grande* gradually moved from stressing to inhospitable conditions for meiofauna and dinoflagellate algae (Fig. 6). This change started right after the FL eruption, which was identified by Vezzoli et al. (1997) as the 'Sicanian Event' described by the Roman writer Diodonis Siculus (first century BCE). This massive Etna eruption would have largely and abruptly changed the environment in eastern Sicily and caused the migration of Sicanians towards western Sicily. The sediment succession of *Pantano Grande* recorded ecological changes after the FL eruption, although the lithology showed no remarkable changes (Fig. 6).

The passage from FA1 to FA2 (*ca.* 650 BCE, 2600 BP) consisted of a sharp transition from massive sands to laminated silty sands (Fig. 6) characterised by a strong reduction in sediment bioturbation. During FA2, *Pantano Grande* was characterised by conditions that prevented the presence of meiofauna and fossilised dinocysts. The stratigraphic and biotic evidence featuring FA2 agreed with a scenario of stagnation and anoxia that changed *Pantano Grande* into a sterile water body. This new pattern could be the result of

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isolation and absence of connections between *Pantano Grande* and the sea. Considering sea-level and land-uplift reconstructions, Bottari and Carveni (2009) argued that the current configuration of Peloro Cape was the result of progressive geological processes. Our results suggested the timespan in which the isolation of *Pantano Grande* from its marine inlet occurred. The process started at 1250 BCE (3200 BP) during the final part of the deposition of FA1 and culminated in 650 BCE (2600 BP) with a sharp transition to FA2.

Some lines of evidence may suggest that anthropogenic impacts could have contributed to the marine water inflow interruption in *Pantano Grande*. Greek colonists arrived in Sicily in the 8th century BCE (*ca.* 2700 BCE) and soon began modifying the landscape through the use of natural resources (Calò et al., 2012; Sadori et al., 2013; Tinner et al., 2009; Zanchetta et al., 2022). In that period, the area near *Pantano Grande* was hosting the Greek settlement of Zancle (i.e. the modern Messina). Human activities in pre-Roman times in the Capo Peloro area are attested to by historical and archaeological evidence indicating the presence of an ancient temple dedicated to Neptune, which was presumably destroyed in Roman times (Bidditu et al., 1979). Archaeological excavations in the Messina area uncovered locally produced potteries and other archaeological findings of the Hellenistic period (Barone et al., 2002; Cucinotta & Burgio, 2003; Spigo, 1992). The presence of modern buildings makes it difficult to perform archaeological excavations in the town area. In fact, despite the presence of several potential archaeological sites in the subsoil of Messina, archaeological excavations are still limited (Imposa et al., 2018). Archaeobotanical remains dated to the Bronze Age were found during archaeological excavations in the Aeolian Archipelago (NE Sicily), testify to the early occupation of the islands near the Peloro Cape, while on mainland Sicily such evidence is still scarce (Mercuri et al., 2015).

The impact of Greek colonies over Sicily was argued in pollen-based landscape reconstructions from lacustrine sediment records. A strong reduction in AP% (arboreal pollen) is visible after the eighth century BCE in four lakes across Sicily (Figs. 1 and 7a–d). Impacts on forests have occurred in a period of wet climate – inferred by the oxygen isotope composition of lacustrine carbonate (δ^{18}Oc) in Lago di Pergusa (Fig. 7e) – which would not support forest decline due to dry climate conditions (Zanchetta et al., 2022).

One hypothesis is that the combination of deforestation and increasing rainfall led to increased soil erosion and debris supply and may have accelerated the development of a barrier between the marsh system and the sea. The development of a barrier would also be facilitated by decreased sea-level change rates in the same period (Fig. 7f). The area around Messina is also subjected to flash floods and debris flow events caused by intense rainfall (Aronica et al., 2012), as likely occurred during

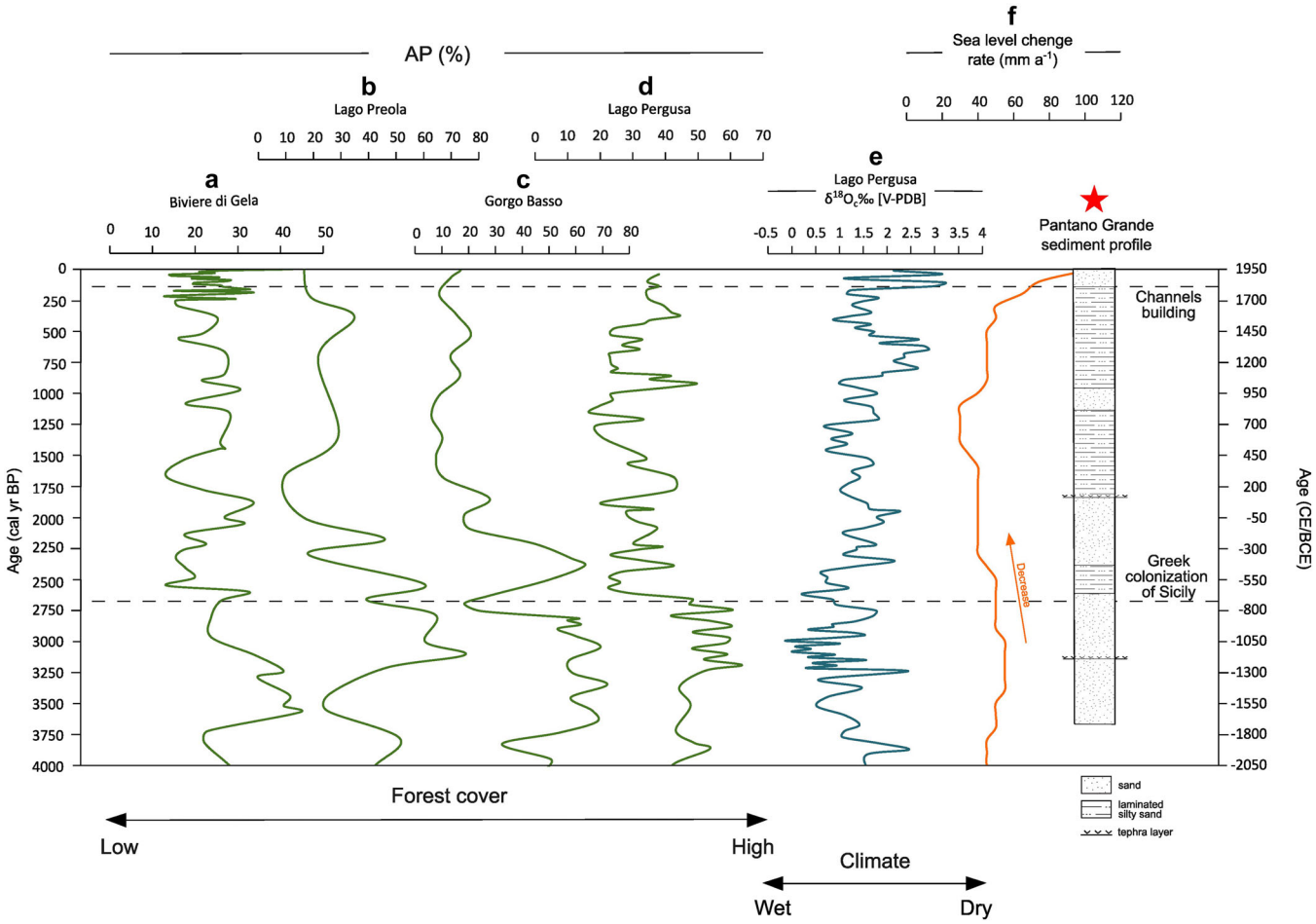

Figure 7. Forest cover, climate and sea level change during the last 4000 years in Sicily. Green curves represent the arboreal pollen percentages (AP %), calculated by excluding *Pistacia* from the pollen sum due to overrepresentation of this taxon. a) Biviere di Gela (Noti et al., 2009), b) Lago Preola (Calò et al., 2012), c) Gorgo Basso (Tinner et al., 2009) and Lago Pergusa (Sadori et al., 2013). The locations of the sites are shown in Fig. 1. The blue curve (e) indicates the $\delta^{18}O_c$ ‰ from Lago di Pergusa from Zanchetta et al. (2022). The orange curve (f) displays rates of sea-level change in the central and western Mediterranean from Vacchi et al. (2021). On the right side is the sediment profile from *Pantano Grande*. Dashed lines indicate the Greek arrival in Sicily, and the opening of the artificial channels that connect *Pantano Grande* and *Pantano Piccolo* to the sea. [Color figure can be viewed at wileyonlinelibrary.com]

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the wet climate period described in central Sicily between 900 and 500 BCE (Zanchetta et al., 2022). This scenario would explain the sharp change in the facies association of *Pantano Grande* between FA1 and FA2, and its isolation from the sea. A similar pattern of combined natural and human-induced changes over a coastal hydrological system was observed in Lake Butrint (southern Albania), which underwent progressive isolation from the Ionian Sea starting *ca.* 1620 BCE (Morellón et al., 2016). Such as at *Pantano Grande*, since *ca.* 650 BCE the sediment succession turned into finely laminated facies in Lake Butrint, reflecting reducing bottom-water conditions caused by human impact (Morellón et al., 2016). Other similar sites include the Marseilles harbour (southern France), where major coastline changes after 600 BCE were attributed to Greek land-use and the related increased erosion and large deposit supply (Morhange et al., 2003); and the harbour of Ephesus (western Turkey) where significant human-induced soil erosion since the 8th century BCE has been recorded (Stock et al., 2016). The similarity in the morphological evolution of Peloro Cape and other coastal systems in the Mediterranean indicates that combined natural processes (i.e. increased precipitation) and anthropogenic impact (i.e. increased agricultural activity, forest cutting, development of human settlements) have affected the evolution of many coastal areas in the Mediterranean in the same period. In these cases, relative sea-level changes can be excluded as the trigger.

According to our results, it is unlikely that *Pantano Grande* served as a harbour in Roman times. However, our results do not exclude the possibility that *Portus Trajectus* was placed in the current *Pantano Piccolo* basin.

Massive sands, rare fossil fragments (even with no evidence of meiofauna) and increased records of *Spiniferites* spp. (dinocyst) typify a short period between *ca.* 250 BCE and the 1st century CE (Fig. 6). The heterogeneous ecological significance displayed by different species of *Spiniferites* does not permit palaeoecological inferences to be made based on the presence of the genus alone (de Vernal et al., 2018). However, the above-mentioned changes in lithology and dinocyst content may indicate renewed connections between *Pantano Grande* and *Pantano Piccolo*. This interval coincides with the Roman domination of Sicily, and interestingly it ends after the deposition of the Pompeii eruption ashes in 79 CE (Fig. 6). Massive sands appeared again in late Byzantine times in an even shorter interval (Fig. 6). Both periods were characterised by intense human activity and sociopolitical stability across Sicily (Sadori et al., 2016). Assuming the presence of a harbour at *Pantano Piccolo*, it would be reasonable for local people to try to keep the marsh system interconnected. Even limited water exchanges would limit the health issues related to stagnant waters. The two sandy intervals in FA2 may thus indicate short time periods in which *Pantano Grande* was connected to *Pantano Piccolo* or the sea through, probably, artificial channels.

Despite these two intervals, sterile conditions characterised FA2 until about 1800 CE (150 BP), when the sediment turned into massive sands and meiofauna, fossilised dinocysts and malacofauna were recorded again (Fig. 6). This change marked the onset of FA3 (Fig. 6). In the 1800s CE the Bourbons began the reclamation of the area and the excavation of the channels that connect *Pantano Grande* to *Pantano Piccolo* and the sea (e.g. Manganaro et al., 2012) (Fig. 1). The two channels that connect *Pantano Grande* to the sea allow only limited water exchange (average water renewal time 71 days; Ferrarin et al., 2013). The sediment succession discussed in this paper was taken from the western part of *Pantano Grande*, which is characterised by more pronounced chlorophyll concentration, meso-eutrophic conditions and lower water renewal capacity than the eastern part (Ferrarin et al., 2013). Despite that, the opening of the channels led to radical changes in the marsh's ecology, strengthening the hypothesis that *Pantano Grande* has been completely isolated from the sea during FA2. FA1 displayed a higher abundance and diversity in benthic meiofauna and fossilised dinocysts than FA3 (Fig. 6), indicating that connections between *Pantano Grande* and the Mediterranean Sea allowed for a greater marine water inflow in pre-Hellenistic times compared with the last two centuries.

Conclusion

The chronological and environmental data obtained by the sediment core collected from *Pantano Grande* indicate that the marsh was distantly connected to the sea between 1750 and 1250 BCE (3700–3200 BP). The coastal morphology of Peloro Cape was significantly different from today. After the FL eruption, also known as the 'Sicanian Event', the sediment succession of *Pantano Grande* recorded changes in meiofauna and fossilised dinocyst composition and abundance, which are interpreted as changes in the water body morphology and ecology. Since *ca.* 650 BCE *Pantano Grande* became completely isolated and sterile due to the lack of connection to the adjacent marshes and the sea. This phase of marsh closure is chronologically close to the onset of the Greek colonisation of Sicily. The comparison of our results with independent published data may indicate that human activity played a role in the progressive closure of the salt marsh. The synergy between natural processes (i.e. climate shifts) and anthropogenic landscape modifications (i.e. deforestation, increased agricultural activity) may have generated substantial changes in the coastal morphology of the Peloro Cape after the Greek colonisation. This process occurred similarly in other localities of the Mediterranean that hosted Greek settlements. Changes in the flood frequency, erosion rate and space accommodation could also have contributed.

A possible short reopening of *Pantano Grande* through connections with *Pantano Piccolo* (even if extremely reduced) may have occurred between the 3rd century BCE and the 1st century CE, and between the 8th and 9th centuries CE, according to changes in the sediment lithology and dinocyst presence. Despite that, there is evidence of isolation and sterility of *Pantano Grande* which lasted over 2000 years, until the 19th century CE when artificial channels were built.

Our data do not support the presence of a Roman harbour located in *Pantano Grande* but we cannot rule out the possibility that *Portus Trajectus* was located in the nearby *Pantano Piccolo*. Lithological variations, the presence/absence and community composition of meiofauna and fossilised dinoflagellate cysts indicate that changes in the morphology, ecology and functioning of *Pantano Grande* have mostly been the direct or indirect consequences of human activity over the last 3700 years.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Abbreviations. AP, Arboreal pollen; BCE, Before Common Era; BP, Before Present; CE, Common Era; EDS, Energy-dispersive-spectrometry; FA, Facies associations; NE, Northeast; SW, Southwest; TAS, Total alkali vs silica; WDS, Wavelength Dispersive Spectrometers; XRF, X-Ray Fluorescence.

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