Quaternary International 671 (2023) 1–14

Contents lists available at ScienceDirect

Quaternary International

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

Setting the basis for a high-resolution record of the late Quaternary to present climate variability from Castiglione maar, central Italy: First results from AMUSED project

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ARTICLE INFO

Keywords:
Paleolake succession
Drilling core
Paleoclimate changes
Tephrochronology
Electrical resistivity tomography

ABSTRACT

The AMUSED (A MUltidisciplinary Study of past global climatE changes from continental and marine archives in the MeDiterranean region) project aims at improving knowledge of late Quaternary climate variability and its expressions in different geological settings of the Mediterranean region. In this framework, the Castiglione maar, in the Colli Albani Volcanic District, central Italy, was selected for acquiring a high-resolution and geochronologically well-constrained multi-proxy record by drilling the entire lacustrine succession. Electrical Resistivity Tomography (ERT) profiles were acquired across the central portion and the SW crater edge to depict the geometry of the sedimentary infilling and select the best drilling site. Two parallel cores (C1 and C2), 116 m- and 126.5 m-depth respectively, were recovered from the central sector of the Castiglione basin, where, according to ERT profiles, the sedimentary succession reaches the maximum thickness. The sedimentary infilling consists of fine-grained sediments: mainly fine sand, silt and clay, with minor gravel intervals and numerous tephra layers and volcaniclastic lenses. Specifically, more than 60 tephras were identified and used, alongside other lithostratigraphic features, to correlate the C1 and C2 cores and to assemble a composite section. The variability in magnetic susceptibility, led by glacial-interglacial cycles, and the geochemical fingerprinting of key tephra layers allowed to establish a preliminary chronological framework for the Castiglione succession which certainly spans the last 365 ka, with a mean sedimentation rate of 0.33 mm/yr. The relatively long time span of the Castiglione maar succession arises as a new potentially meaningful node of the network of Mediterranean records for better reconstructing the late Quaternary climate dynamics on a regional and extra-regional scale.

1. Introduction

Lake sediments hosted in volcanic craters provide continuous sedimentary successions ideal for multi-proxy paleoclimatic and paleoenvironmental studies (e.g., Mingram et al., 2004; Brauer et al., 2007; White and Ross, 2011; Marchetto et al., 2015; Lacey et al., 2015; Chu et al., 2014; Wu et al., 2019 for review). Lacustrine successions are strongly sensitive to climatic variations and are often characterised by the presence of varves and/or other materials (macrofossils, charcoals, organic carbon) suitable for isotopic and AMS radiocarbon chronology (e.g., Zolitschka et al., 2015; Sirocko, 2016).

In the last decades, the lacustrine successions from central-southern Italy volcanic and tectonics basins proved to be valuable records for reconstructing and understanding at regional to a global scale the climatic variability at different, from decennial to millennial, time scales (e.g. Allen et al., 1999; Brauer et al., 2007; Giaccio et al., 2019; Regattieri et al., 2016, 2019; Vigliotti et al., 2010). One of the features that make the central-southern Italy lacustrine successions particularly relevant for the paleoclimate reconstructions, is the possibility of anchoring the proxy series to an independent, radioisotopic chronology

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https://doi.org/10.1016/j.quaint.2023.09.016

Available online 6 October 2023

based on the high-precision $^{40}Ar/^{39}Ar$ dating of tephra layers, which are frequently found in the lake sediments (e.g., Creer and Morris, 1996; Tomlinson et al., 2015). In fact, during the Quaternary volcanoes of central-southern Italy were characterised by intense and continuous explosive volcanic activity (Branca et al., 2023).

Despite this potential, the central-southern Italy lacustrine successions are still poorly exploited. A paleoclimatic investigation has been carried out at Lago Grande di Monticchio, which hosts a sediment record of the last 135 ka, providing important marker layers for correlation with other Mediterranean palaeoclimate records (Ramrath et al., 1999; Brauer et al., 2007; Wulf et al., 2004, Wulf et al., 2012). A longer succession, spanning the last 430 ka, was retrieved in the Fucino basin (Giaccio et al., 2017, 2019; Mannella et al., 2019; Monaco et al., 2021, 2022), but proxies analysis is still in progress. Again, the Sulmona basin yielded important, yet fragmentary, paleohydrological records spanning the last 800 kyr (e.g., Giaccio et al., 2017; Regattieri et al., 2016, 2019). Furthermore, in the broader framework of the Mediterranean region, only a few studies of lacustrine successions extend back beyond the Holocene or the Last Glacial, with most of them providing low-resolution proxy series, geochronologically poorly constrained or stratigraphically discontinuous. In the Balkan Peninsula, the Lake Ohrid sedimentary succession provided a very long and continuous paleoenvironmental and paleoclimatic archive for the last 1.3 Ma (Francke et al., 2016; Wagner et al., 2019), but only a few proxy and/or key intervals are investigated at very high resolution. The iconic record of Tenaghi Philippon, in Greece, yielded another 1.35 Ma long pollen record (Tzedakis et al., 2006), yet high-resolution investigations and robust chronological constraints are limited to the last 135 kyr (e.g., Pross et al., 2015). Therefore, acquiring long and high-resolution proxy records holding robust and independent chronologies remains a challenge.

To extend the network of Mediterranean records having the fundamental requisites of high-resolution and good geochronological constraints, we focused on the lacustrine sequence of the Castiglione maar, in the Colli Albani Volcanic District, central Italy (Figs. 1 and 2). Previous low-resolution investigations of an 88 m-long core indicated that the basin hosts a lacustrine succession spanning at least the last 270 kyr (e.g., Alessio et al., 1986; Follieri et al., 1989; Narcisi et al., 1992). Different portions of this core were subject to multidisciplinary studies such as lithostratigraphy, palynology, paleoecology, geochronology, geochemistry, and stable isotopes (Follieri et al., 1989; Magri and Sadori, 1999; Zanchetta et al., 1999; Anadón et al., 2012). However, these studies were carried out at a resolution and with chronological constraints that are inadequate for the modern paleoclimate investigation.

To get a new high-resolved and chronologically well-constrained record from the Castiglione maar succession, a new drilling campaign was conducted in the framework of the AMUSED project (A MUltidisciplinary Study of past global climatE changes from continental and marine archives in the MeDiterranean region). Here we present the overall results of geophysical investigations, the lithostratigraphic description of a 126 m-long Castiglione Composite section and provide a preliminary chronological framework of the sequence. These data are critical for setting the basis for further multiproxy studies and point out that the lacustrine sequence of the Castiglione maar could be relevant for reconstructing the variability of the climate since the late Quaternary in the central Tyrrhenian area and in the entire Mediterranean.

2. Geological and volcanological setting

2.1. The AMUSED project and the Castiglione maar

The AMUSED project (https://progetti.ingv.it/index.php/it/amused), funded by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), aims to improve the knowledge of paleoenvironmental and paleoclimatic variability in the central Mediterranean region since the Late Quaternary. The project intends to obtain this main target through a series of specific investigations that include the acquisition of new

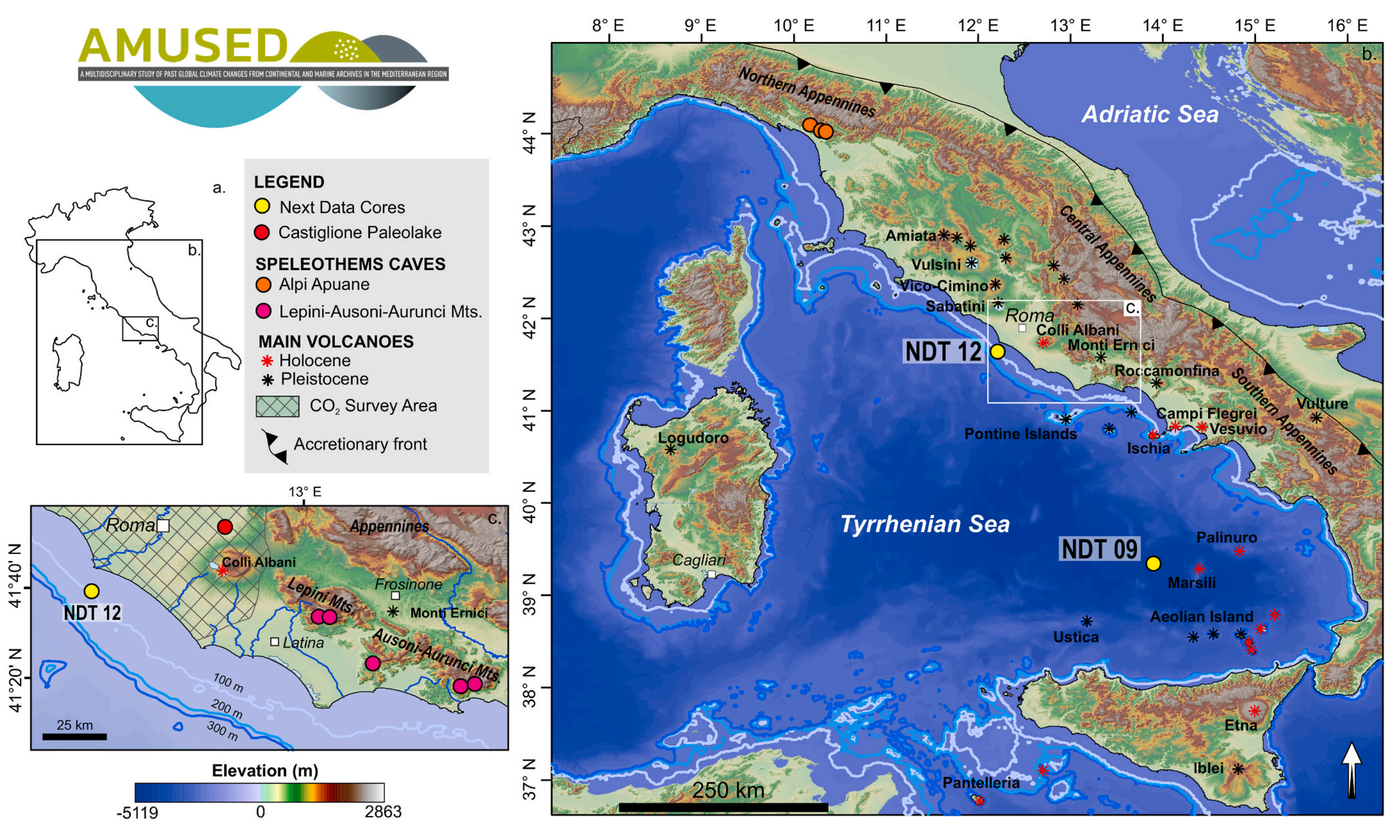

Fig. 1. Sites location of all the Amused Project investigations in the central Mediterranean region.

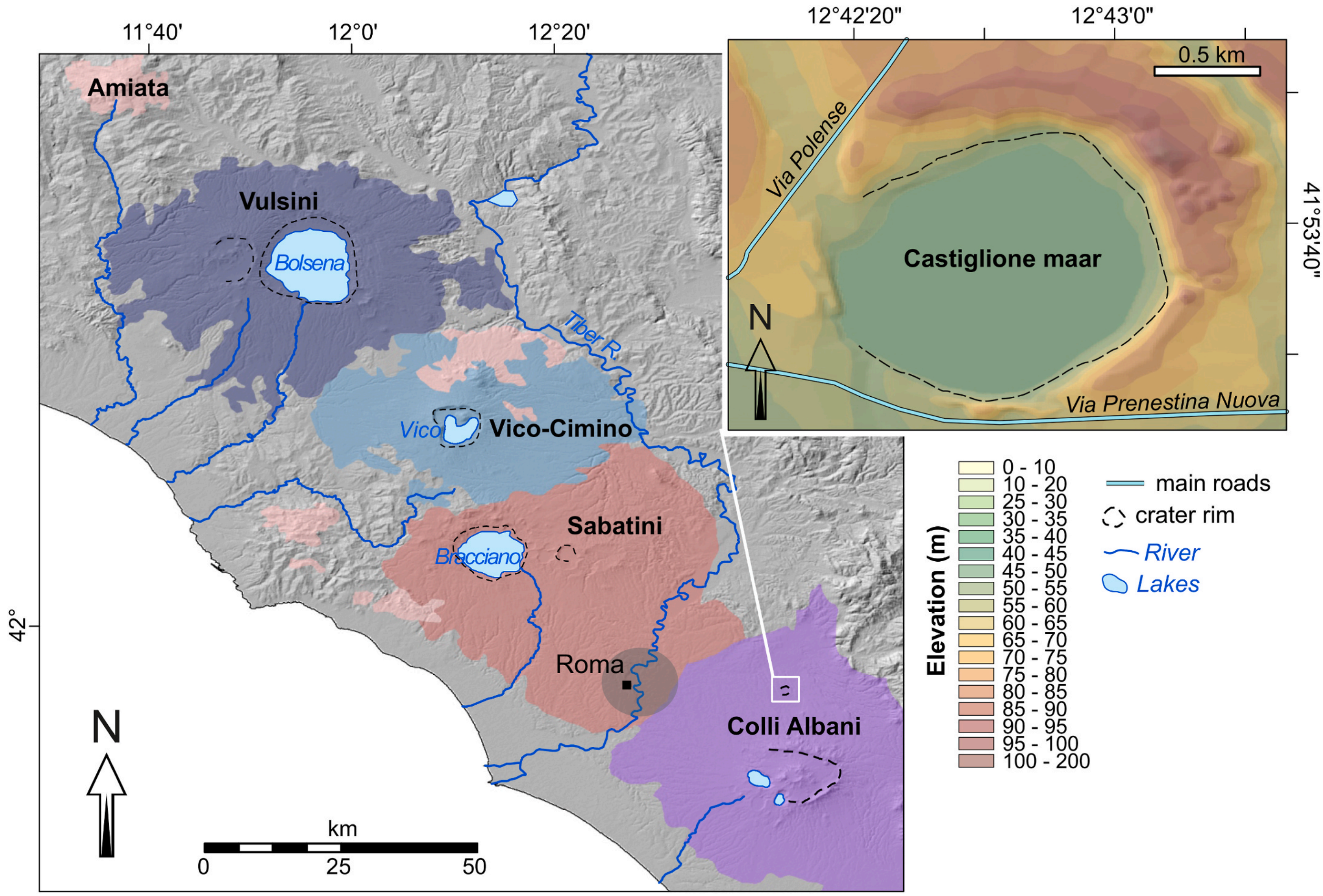

Fig. 2. Geologic map of the main volcanic complexes in central Italy (a.) and topography of the Castiglione maar (b.).

integrated multi-proxies data from terrestrial and marine environments. Great attention is paid in the AMUSED project to the development of robust and independent age model, crucial for comparing the different sedimentary archives of past climate changes in a coherent and reliable chronological framework.

The project carries out scientific activities in different geological settings which comprise the Italian continental margin (Castiglione maar drilling site and speleothems analyses from Lepini-Ausoni-Aurunci and Apuane Alps karst area) and the Tyrrhenian Sea (Marsili basin and Tiber river mouth sediment cores collected during the NextData2016 cruise) (Fig. 1). The high-resolution and geochronological well-constrained multi-proxy records will be further compared to the available regional and extra-regional data, to evaluate paleoclimatic connections, possible interhemispheric time lags/leads and unveiling processes underlying the overall climate dynamics. Another main task of the AMUSED project is to estimate the natural soil CO_2 emission in the Colli Albani volcanic area and the metropolitan city of Rome and try to mitigate the environmental effects of natural CO_2 emissions through the planting of high-absorbing vegetation (Fig. 1).

In this study, we focus on the Castiglione maar lacustrine succession, a continuous sediment record suitable for high-resolution paleoclimatic multi-proxy analyses and where tephrochronology is expected to allow the assemblage of a robust age-model and reliable correlations with other paleoenvironmental and paleoclimatic proxies series via tephra synchronisation.

The Castiglione crater is an eccentric explosive centre, located on the northern flank of the Colli Albani volcanic complex, about 20 km east of Rome and about 35 km far from the Tyrrhenian Sea (Figs. 1–2). Its phreatomagmatic activity is related to the post-caldera volcanic activity of Colli Albani (Locardi et al., 1976; Karner et al., 2001). Geochronological and stratigraphical data pointed out that the crater-forming event occurred before 250 ka, likely around 285 ka (Marra et al., 2003 and references therein). A lake established into the crater, after its freato-magmatic eruptive phase, but it was artificially drained during the Renaissance era (Giordano and the CARG Team, 2010). The Castiglione maar succession is thus expected to host tephra layers from the above-described active and relatively close volcanoes, providing an abundance of possible temporal constraints.

The sediment cores recovered, under the auspices of the Project, being subjected to ongoing physical, bio-geochemical, and paleontological multi-proxy analysis, which includes: lithofacies characterization, X-ray fluorescence (XRF) core scanning, paleomagnetic and rock magnetic measurements, pollens and ostracods determinations on selected intervals, $\delta^{18}O$-$\delta^{13}C$ on bulk carbonates, carbon content (TC/TIC/TOC), and geochronology, including radiocarbon dating and tephrochronology (major and trace element compositions, isotopes analysis and $^{40}Ar/^{39}Ar$ dating).

2.2. Regional volcanism and tephrochronological potential

The Quaternary volcanic activity in the central Italy area, surrounding the drilling site, was dominated by explosive eruptions with a broad spectrum of intensity and magnitude and fed by magmas differing in composition. In the time window approximately covered by the Castiglione maar sedimentary sequence, the volcanic complexes of Monti Vulsini, Monti Sabatini, Vico, Colli Albani and Roccamonfina were repeatedly active with very large, energetic explosive eruptions (often caldera-forming) capable of spreading relevant tephra deposits in the drilling site area (e.g., Brauer et al., 2007, Figs. 1–2).

Nearest to the sampling site, the volcanic activity of the Colli Albani relevant to our study is divided into two main phases: i) the Monte Faete or Tuscolano-Artemisio-Faete Period (355–180 ka; Giordano and the CARG Team, 2010) and ii) the Via dei Laghi Period (200 ka to 36 ka). The Tuscolano-Artemisio-Faete period saw the formation of several peri-caldera and extra-caldera centres along with the growth of the intra-caldera Faete cone. The following Via dei Laghi period is mainly characterised by moderately energetic hydromagmatic explosions from the Ariccia, Nemi, Valle Marciana and Albano maars at c. 200 ka, 150 ka, 102 ka and 73–36 ka, respectively (e.g., Freda et al., 2006; Giaccio et al., 2009; Marra et al., 2016; Di Roberto et al., 2018).

The Sabatini volcanic district, which is located north of the Castiglione site (Fig. 2), comprises two main volcanic complexes, i.e., the Sacrofano (~300–200 ka) and Bracciano (~325–200 ka) calderas. These were active in the time interval here considered (Sottili et al., 2019) and produced large Plinian eruptions like the Magliano Romano eruption (312 ± 2 ka; Sottili et al., 2010) and caldera-forming events of Bracciano, Sacrofano and Pizzo Prato. These eruptions emplaced extensive pyroclastic flow deposits like the Tufo di Bracciano (323 ± 2 ka), the Tufo Giallo di Sacrofano (285 ± 6 ka), and the Tufo di Pizzo Prato (Sottili et al., 2010, 2019). The final phase of volcanic activity of the Sabatini volcanic district, took place between 250 and 90 ka, in the area between the Bracciano and Baccano calderas and consisted of strombolian eruptions, lava effusions and hydromagmatic activity from monogenetic cones and maars.

The Monti Vulsini district (Fig. 2) was probably the most active volcanic complex of the Roman Volcanic Province in the studied period. The activity of the Bolsena-Orvieto complex lasted until 300 ka and was characterised by strong explosive activity emplacing fallout, surge and pyroclastic-flow deposits. The more energetic event is represented by the Orvieto-Bagnoregio caldera-forming eruption, between 333 and 294 ka (Turbeville, 1992; Nappi et al., 1994; Marra et al., 2020) that occurred in the northeastern part of the present Bolsena caldera. At the same time, between 200 and 300 ka, the Montefiascone volcano was active on the southeastern edge of the caldera. Its activity comprises moderately explosive eruptions, often characterised by hydromagmatic character. The largest eruption of the Montefiascone basal ignimbrite created the Montefiascone caldera. The Latera volcanic complex developed in the western part of the Vulsini district was the site of the acme of volcanic activity between 250 ka and 160 ka ago (Palladino and Valentine, 1995; Palladino and Agosta, 1997). Here a series of caldera-forming eruptions with associated pyroclastic flow and plinian fallout deposits were emplaced during the Canino, Stenzano, Farnese, Sovana, Sorano, Grotte di Castro, Onano and Pitigliano eruptions.

The Vico complex is located further north of the Castiglione site (Fig. 2) and comprises three main periods of activity (Peccerillo, 2005). The second period spanning between 300 ka and 140 ka was initially characterised by effusive eruptions (300–250 ka; Perini et al., 2004). Successively, four major explosive eruptions occurred and emplaced the so-called ignimbrites A, B, C, and D, each accompanied by large caldera collapses that shaped the morphology of the present edifice (Bear et al., 2009). Post-caldera activity between 138 ka and 95 ka included moderately explosive eruptions (sometimes hydromagmatic) and effusive eruptions whose products were dispersed close to the caldera rim.

At Roccamonfina, south of Castiglione (Fig. 1), two main caldera-forming eruptions occurred in the period covered by the Castiglione maar sequence, namely the Upper White Trachytic Tuff eruption at c. 230 ka (Giannetti and De Casa, 2000) and the Yellow Trachytic Tuff eruption at 227 ka (Giannetti, 1996). This activity was followed by the construction of Monte Lattani and Monte Santa Croce scoria cones approximately between 170 ka and 150 ka (Ruchon et al., 2008).

More distally strong explosive activity potentially producing tephra able to disperse in the study site, occurred also at volcanoes in the Naples area from Campi Flegrei, Vesuvio and Ischia complexes (Fig. 1). Ignimbrite-like deposits with composition compatible with Campanian origin such those of Seiano, Moschiano and Taurano are recognised in proximal and distal occurrence and are dated between 290 ka and 157 ka (De Vivo et al., 2001; Rolandi et al., 2003; Petrosino et al., 2015; Giaccio et al., 2017a). At Campi Flegrei caldera, an intense pre-Campanian Ignimbrite (CI, 40 ka, Giaccio et al., 2017b) explosive activity, dated between 109 ka and 92 ka, took place, generating widely dispersed tephra (Monaco et al., 2022). During the last 90 ka, the Campi Flegrei was the site an intense and continuous explosive activity including the large CI eruption, and two other major events of the Masseria del Monte Tuff (MdMT; 29.3 ± 0.7 ka; Albert et al., 2019), and the Neapolitan Yellow Tuff (NYT; 14.9 ± 0.4 ka) and a series of relatively minor events following (e.g., Smith et al., 2011) and preceding either NYT or CI (e.g., Orsi et al., 1995; Pappalardo et al., 1999).

Volcanic activity at Ischia Island, off the Gulf of Naples, is documented as far back as 150 ka, which is the age of the oldest exposed deposits, and up to historical times. The activity of Ischia is subdivided into five stages, with the thirty-one (55–33 ka) characterised by the occurrence of the largest recognised eruption the 55 ka Monte Epomeo Green Tuff eruption (MEGT; Poli et al., 1987), widely spread in Mediterranean area (e.g., Tomlinson et al., 2014; D'Antonio et al., 2021).

3. Methods

3.1. Geophysical exploration

The geophysical exploration aimed to define the three-dimensional geometry of the lacustrine basin, including tectonics features, thickness, structure and extent of the sediment packages, to determine their depocenter and to identify the best sites for drilling purposes.

We use Electrical Resistivity Tomography (ERT) which is an active geoelectrical method widely applied to (provide) evaluate 2D and 3D images of the distribution of subsurface resistivity variations. The Castiglione maar is particularly adequate for this kind of investigation due to the high electrical resistivity contrast between fine-grained lacustrine sediments and volcanic materials. The geophysical survey in the basin consisted of four electrical resistivity tomography profiles acquired using a Syscal Pro resistivity-meter, equipped with 72 and 48 electrodes (IRIS Instruments).

The ERT profiles were carried out across the maar (ERT 1–2) and radial to it (ERT 3 and ERT 4) along its south-western border (Fig. 3). All profiles were acquired with both Wenner and dipole-dipole electrode arrays to provide vertical and horizontal resolution of the subsurface resistivity contrasts. The apparent resistivity measured in the field was inverted using the Res2DInv software (Loke and Barker, 1996) to obtain true resistivity values of the subsurface lithologies. The ERT 1–2 are partly overlapping profiles acquired along the meridian part of the maar in a roll-along mode with an electrode spacing of 10 m. The overall length of the profile is ca. 950 m providing an investigation depth of approximately 120 m. The ERT 3 and ERT 4 are shorter profiles, acquired along the SW rim crater, with a length of 48 m each and an electrode spacing of 1 m. Both profiles have an exploration depth of ca. 8–10 m and have been useful to detect the subsurface geometry of the maar's borders.

3.2. Fieldwork and core composite section construction

3.2.1. Drilling operations

The drilling sites were identified after the interpretation of the resistivity profile described above. The selection of the ideal drilling location involved both scientific (i.e., the possibility of recovering the longer and continuous sedimentary succession); and logistic (i.e., accessibility for the drilling machines, availability of water charge and discharge lanes). Following the above criteria, we identified the best drilling site in the paleolake central area (Fig. 3; 41.890° N, 12.709° E). To recover a sedimentary succession as much complete as possible, two parallel cores were recovered at the same drilling site in two boreholes,

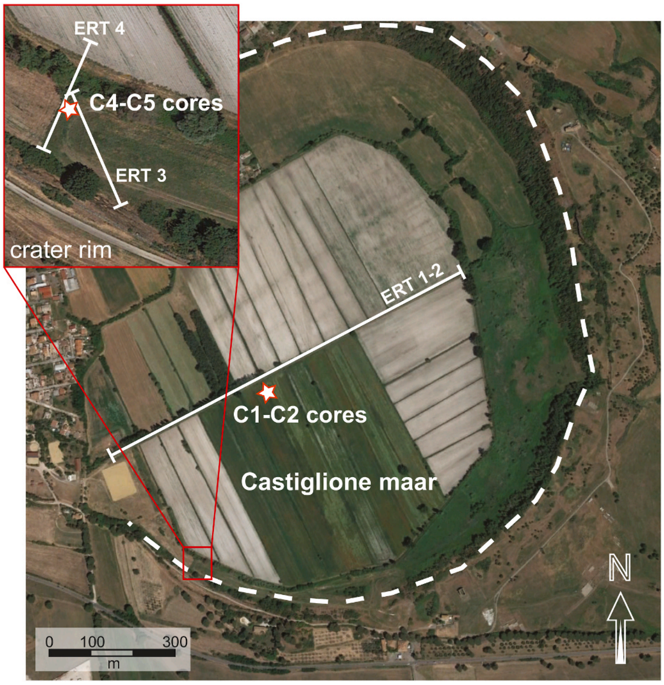

Fig. 3. Location of the drilling sites (C1–C3 and C4–C5) and the ERT geo-electrical profiles (1–2 and 3, 4) in the Castiglione ring. White dashed line indicates the crater rim.

C1 and C2, 5 m apart from each other. An additional core C3 has been located between the two boreholes to maximise the recovery of the upper 15 m of succession. Afterwards, two cores, C4 and C5, with a length of ca. 12 m and 3 m, respectively, were located at the side of the lake, at 41.887° N and 12.708° E coordinates. This location has been defined after the interpretation of two additional shorter ERT resistivity profiles along the SW rim of the crater.

In March–April 2021 the drilling campaign was successfully conducted. The core barrel was 3-m long and in C1 and C2 boreholes the drilling started at 0 m and 1.5 m below ground level, respectively. In this way, the 3 m-long C1 and C2 core sections were offset and overlapped by ca. 1.5 m. This allowed to maximise the amount of recover as a lost interval in between two subsequent sections of the core C1 (e.g., sections C1-1 and C1-2) would be recovered in the middle part of the corresponding cores section C2 (i.e., C2-1), and vice versa. This approach was successfully used in other continental drilling campaign (e.g. Nakagawa et al., 2012). Once drilled, the material was extruded to 1.5 m long PVC core holders and packed after length measurements and a brief visual description. Monitoring of the drilling progress was carried out following a simple table, hereafter referred to as field log, where the length of each drilling manoeuvre, the length of recovered material, and how it has been split in the 1.5 m long PVC core holders were constantly tracked. This helped to track the amount of recovered/lost material and to place the main stratigraphic gaps. The comparison of the two field logs provided an immediate raw composite section. A main gap in the recovered material occurred at 90–110 m depth in both cores due to the intersection with the water table. The volcanic basement has been reached at 116 m and 126.5 m for C1 and C2, respectively. The final amount of recovered material amounts to 81%, 85% and 90% for C1, C2 and C3 cores, respectively. Boreholes C4 and C5, recovered 90% and 66% of the material. The sediment cores were stored in a +5 °C cold room repository at INGV.

3.2.2. *Cores description, magnetic susceptibility measurement and sampling*

The core sections opening took place in the laboratories of the INGV from May to October 2021. Each core section was lengthwise split into two halves, one to be archived and one to be analysed and sampled (working). Careful lithostratigraphic descriptions and high-resolution pictures were performed for each core section. This allows us to identify the main lithological boundaries. During the cores description phase, a 3-cm spacing magnetic susceptibility measurement was also acquired, on each core section, using a Bartigton MS2E Surface Scanning Sensor instrument coupled with the Bartsoft software. Tephra layers, identified during description or revealed by high magnetic susceptibility values were sampled, as well as u-channel for paleomagnetic analysis. In total 156 tephra/volcaniclastic layers were collected and preliminarily observed under the stereomicroscope to define their lithological characteristics. Of these, 60 tephra units were identified and selected for further analysis.

3.2.3. *Castiglione Composite section compilation and sampling*

To play down the sediment gaps, which are unavoidable between two subsequent core sections of the same drilling, we built a Composite section for the Castiglione maar succession using the sediment cores C1 and C2, which overlap each other by 1.5 m (see section 4.3). To do this, we first identified robust tie points between the two cores using unambiguous lithostratigraphic features, such as tephra layers and other distinctive horizons. The correlation and the build of the Composite section were carried out using the Corelyzer software (https://cse.umn.edu/csd/corelyzer). When homologous stratigraphic intervals in C1 and C2 cores showed remarkable length differences, we systematically selected the more expanded one.

The main sampling for multi-proxy analysis was conducted, and completed by May 2022, directly on the Composite section. Sediments were collected for inorganic/organic carbon (TIC/TOC/TC), ostracods, pollen and isotopic analysis. In the first 18 m, the carbon content samples were sampled every 5 cm while a resolution of 25 cm was used below 18 m until the bottom of the succession was reached. The ostracod samples were selected every 50 cm until 91 m and every 25 cm in the lower portion of the succession. In this first phase of analyses, pollen samples were every 4 cm in the interval 37–45 m. We gathered 450 samples for TIC/TOC/TC, 280 samples for ostracods and 197 samples for pollen analysis.

3.2.4. *Preliminary tephra analysis*

Incoming X-ray fluorescence (CS-XRF) core scanning allows us to analyse the chemical composition of the sediments and to identify cryptotephra that will be helpful to further determine the age model. For this paper we have performed the analysis of the uppermost and the deepest tephra found in the succession, to have a first indication of the period covered by the Castiglione sequence. Major and minor element glass composition was determined using a JEOL JXA-8200 electron microprobe (EPMA) equipped with five wavelength-dispersive spectrometers at the High-Pressure High-Temperature (HPHT) Laboratory of the INGV. Operating conditions were 15 kV accelerating voltage, 8 nA beam current, 5 mm probe diameter, and 10 and 5s acquisition time for peak and background, respectively). Standards of glass were analysed to test the accuracy of data during the EPMA analyses.

4. Results

4.1. *Geophysics*

The electrical resistivity tomography profiles acquired both in the middle and along the border of the Castiglione maar clearly show the presence of a thick sedimentary infilling of the basin (Fig. 4). The low resistivity values (<50 Ohm*m) shown in the ERT 1–2 indicate fine-grained clayey, silty, and sandy sediments of the drilled lacustrine succession. As shown in Fig. 4, the southwestern crater border is very sharp and the thickness of the continental infilling rapidly increases to reach a maximum value of more than 110 m in the centre of the paleolake, unlike the eastern border of the crater was not investigated by this

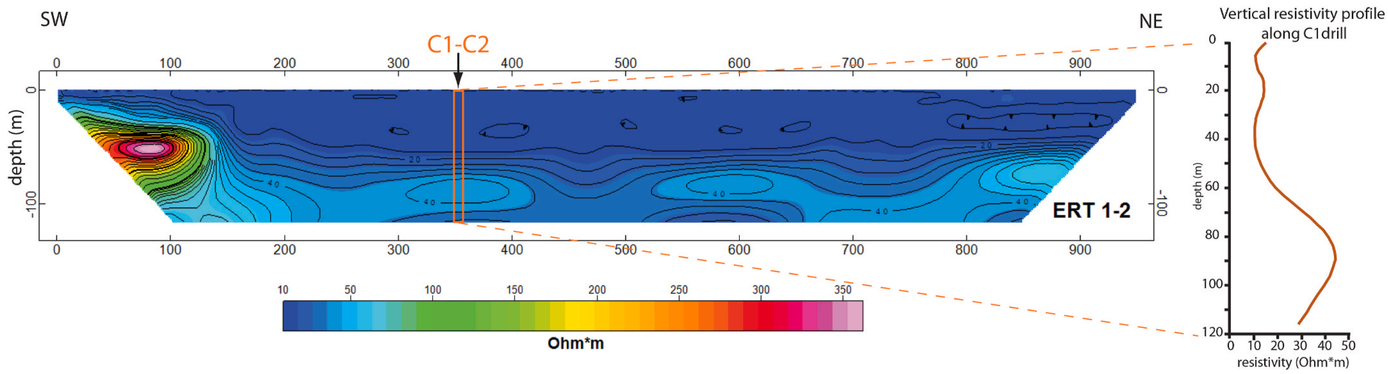

Fig. 4. Electrical resistivity tomography profile ERT 1–2.

profile due to logistic difficulties. In addition, the ERT 1–2 profile indicates that the lacustrine sediment thickness varies a little inside the crater.

In the lacustrine sequence, two distinct intervals can be distinguished according to the resistivity change with the depth. The first 60 m are characterised by a constant value of ca. 10–15 Ohm*m, whereas the deeper portion of the sequence displays higher values with a maximum of 45 Ohm*m at 85 m of depth. This vertical increase in the resistivity profiles, according to the stratigraphy shown in Fig. 6 could be related to lithological changes and/or to the increasing number of tephra layers.

Volcanic rocks, characterised by high resistivity values > 100 Ohm*m, have been highlighted in the western edge of the ERT 1–2. Confirming this, an outcrop of lava flow, belonging to the Pantano Borghese succession (Giordano and the CARG Team, 2010), is visible in correspondence to the beginning of the profile, Unfortunately, the volcanic basement has not been highlighted along the ERT 1–2 profile being located at a depth greater than 110 m, as confirmed by the C1 and C2 drillings (Fig. 4).

Both shorter profiles ERT 3 and ERT 4, acquired along the SW border of the paleolake, show very low resistivity sediments (<50 Ohm*m), possibly related to the same lacustrine succession found in the ERT 1–2 profile, with intercalated at shallow depth volcanic blocks characterised by higher resistivity values (Fig. 5). This configuration is probably due to erosion of the rim crater whereas the high resistivity volcanic basement should be deeper than 10 m, the maximum investigation depth of ERT profiles. The vertical electrical resistivity profile computed along the ERT 4 profile in correspondence with the C4–C5 drillings is in good agreement with the cores; a maximum value of 35 Ohm*m coincides with an interval of reworked Castiglione maar surge deposits (Fig. 5).

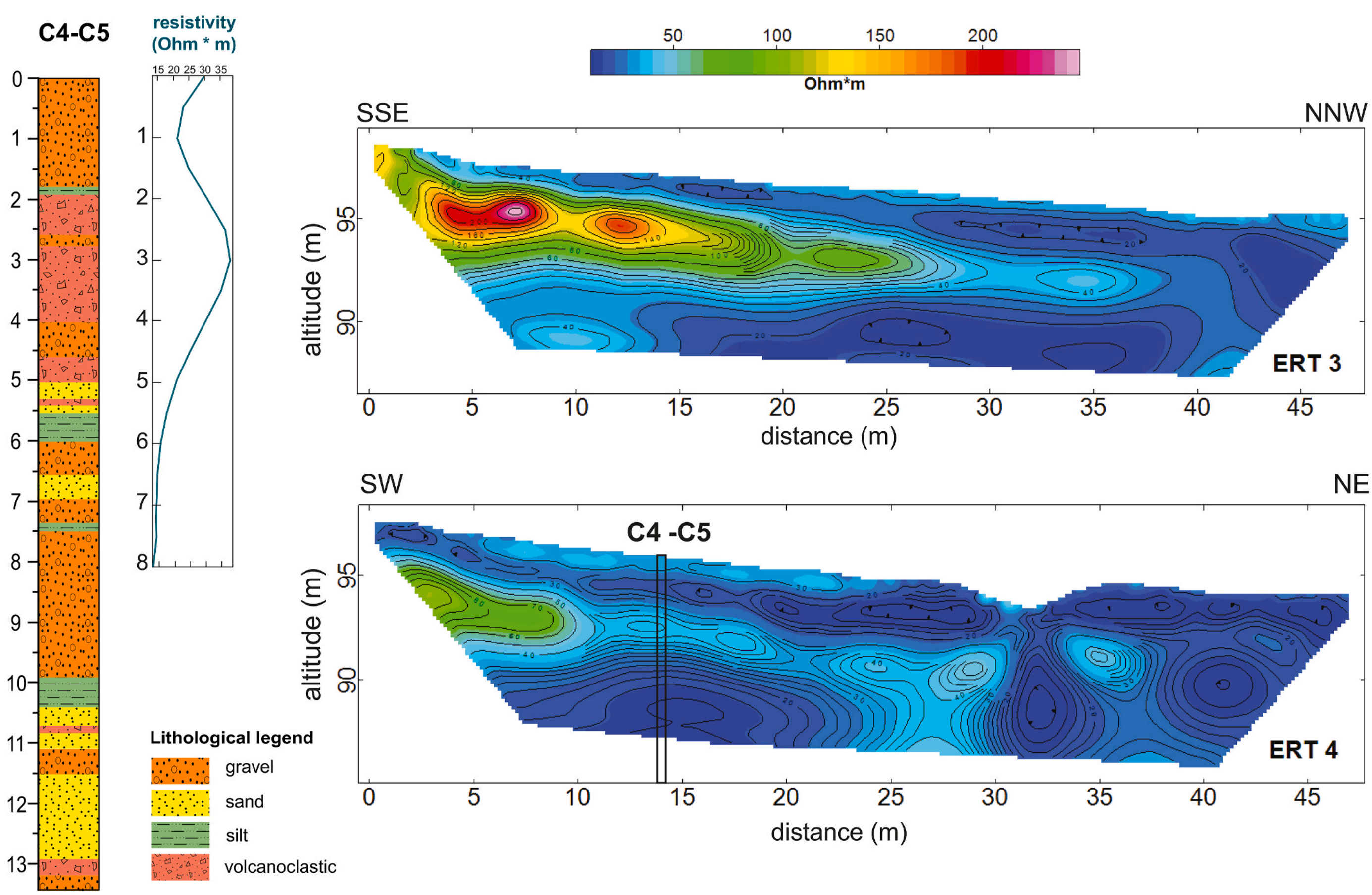

Fig. 5. Simplified C4–C5 stratigraphic log, with its resistivity profile, and the ERT 3 and ERT 4 profiles.

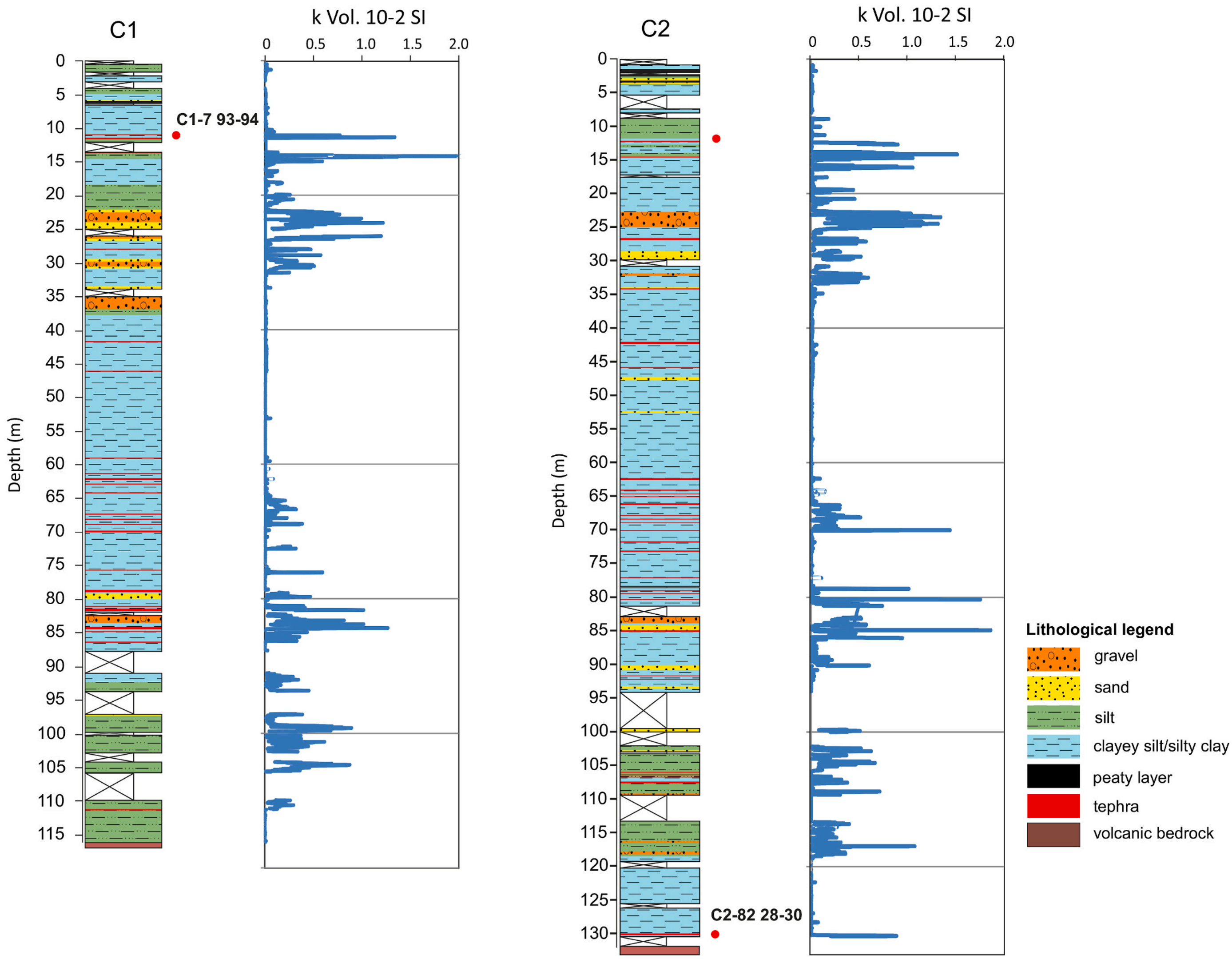

Fig. 6. C1 and C2 stratigraphic logs and magnetic susceptibility record with the highlighted position of the TC3 and TC2-79 tephra layers (red dots).

4.2. Lithotratigraphy and magnetic susceptibility data

4.2.1. Lithostratigraphic features in sediment cores C1–C2 and C4–C5

The two boreholes (C4 and C5) were drilled on the SW paleolake border down to 13 m and 3 m of depth, respectively (see the stratigraphic column in Fig. 5). The uppermost 1.9 m sequence in cores C4 and C5 is characterised by a 1.8 m thick fine to coarse gravel in a poor silty matrix laying on a 10 cm thick sandy silt layer. From 1.9 m down to 5 m (core C5 stops at 3 m) the stratigraphy is dominated by volcaniclastic deposits composed of volcanic clasts in a sandy matrix alternating to two layers of gravel. Below 5 m and down to the core bottom, the C4 core stratigraphy turns to gravel alternating with thick sandy intervals and silt within mm pebbles.

The overall sedimentary succession recovered in the boreholes C1 and C2, collected in the paleolake depocenter, is composed of fine-grained sediments: mainly fine sand, silt and clay alternated with volcanic layers and thick volcaniclastic intervals (Fig. 6). The whole succession is characterised by alternate massive intervals and laminated silty clay and clayey silt (see section 4.4 for a detailed description). Furthermore, core C2 showed deformed layers and convoluted silty intervals from −113 m downwards. In both cores, the volcanic basement was reached and samples of coarse-grained pyroclastic rocks (volcanic breccia) were drilled at a depth of 116 m and 126.5 m for drills C1 and C2, respectively.

4.2.2. Magnetic susceptibility

Magnetic Susceptibility measurements conducted in continuous along the C1 and C2 cores indicate a mean value of 7.24×10^{-4} SI and 5.38×10^{-4} SI, respectively, with sparse peak until $1.5–2.0 \times 10^{-2}$ SI in correspondence of the main tephra levels detected in the cores. Increasing mean values, ca. 2.5×10^{-3} were observed in the ca. 10–33 m and ca. 65–118 m depth intervals for both cores. These intervals are generally characterised by an increase of sandy and silty levels and by the presence of dark and light mm-to cm-thick laminations that probably led mineralogical changes (Fig. 6).

4.3. Lithostratigraphy and tephrostratigraphy of the Castiglione Composite section

The Castiglione Composite section compilation resulted in a 131.37 m long sedimentary succession, with 87% recovery, which is higher than the recovery of both C1 (81%) and C2 (85%) cores. Core C1 and C2 contributed 43.3% and 42.7%, respectively, to the construction of the Composite section. Although both cores contributed more or less equally to the construction of the composite, below 90 m only core C2 was used, which had higher sediment recovery.

The sedimentary stratigraphy of the Composite section is represented as follows (Fig. 7). The uppermost 10 m are characterised by dark brown-greenish silt and silty clay rich in organic matter and shell

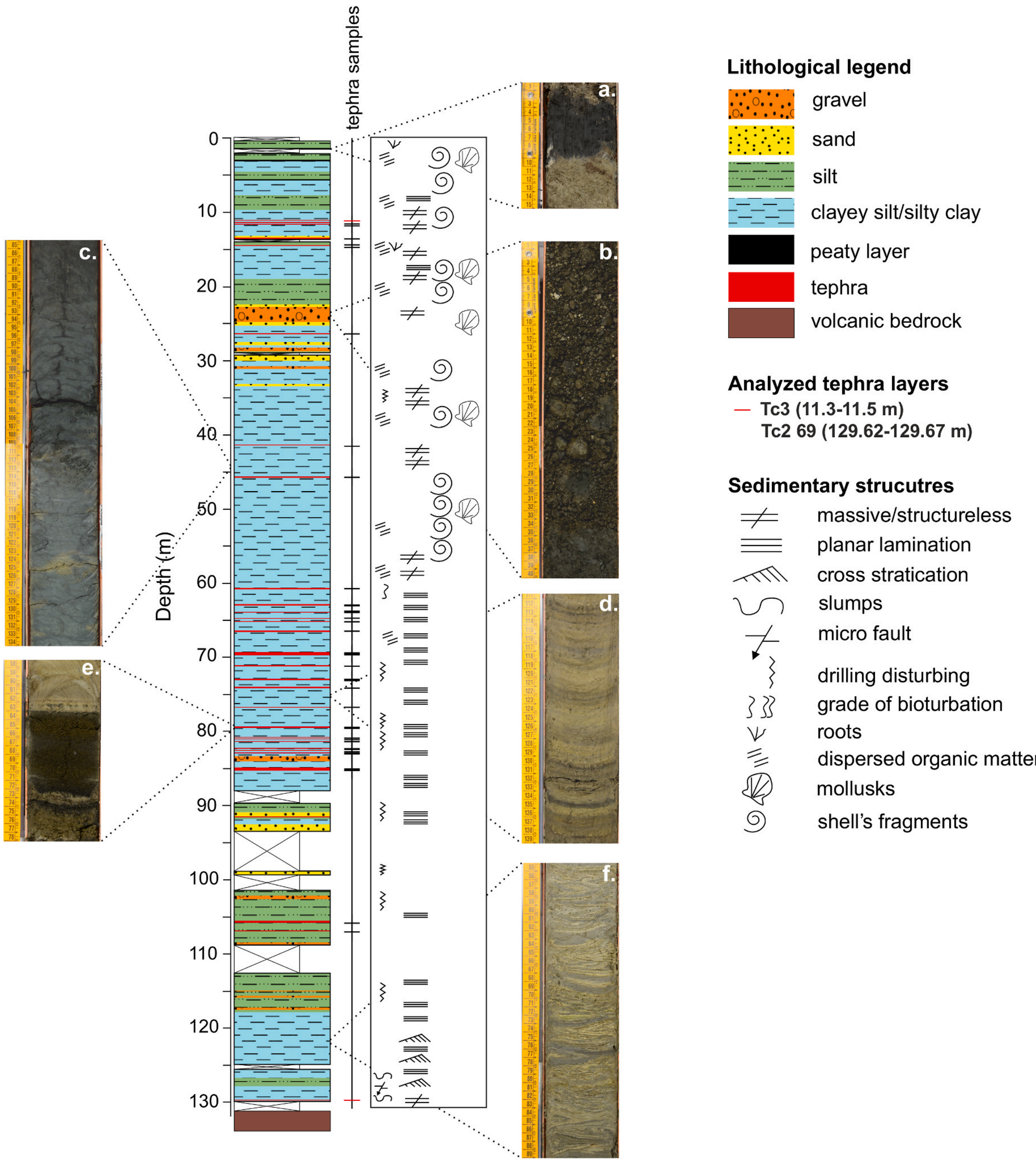

Fig. 7. Castiglione composite section. The column shows the sedimentary stratigraphy of the Castiglione Paleolake. a.: peat layer found at 2.10 m; b.: gravel layer found at ca. 24–25 m; c.: transitional stratigraphic limit observed at ca. 44 m; d.: parallel lamination in clayey silt observed at ca. 75 m. e.: detail of tephra layer observed at 79 m; f.: convolute layering observed in clayey silt at 123 m.

fragments. Two peaty layers 30 cm thick occur at 1.43 m and 3.15 m, respectively. From 10 m to 22.50 m, the succession is made of quite massive sediments that only locally show a faint lamination (around 17–18 m), rich in organic matter and shell fragments and a few whole molluscs. In detail, between 10 and 12 m, the sediments consist of grey silty clay tuning to green-olive to brown clayey silt and silts from 12 to 22.50 m. Conversely, between 22.50 m and 30 m, the succession is characterised by alternating coarser sediments (oxidised gravel and sand) and grey to dark grey clayey silt. Here the passages from coarse to fine lithologies are generally sharp. From 30 m to 60 m, the lithology becomes quite monotonous displaying silty clay with abundant shell fragments and whole shells, often massive with sparse organic matter. The colour of sediments is mainly brown to dark brown that between 43 m and 53 m turns to grey-dark grey shades. Moving down, from ca. 60 m–87 m, lithology remains the same but massive sediments were replaced by thinly laminated silty clay with regular bedding of dark and light mm-to cm-thick laminae.

Unfortunately, below 70 m several intervals showed drilling disturbances likely due to the occurrence of laminated sediments with high water content. In the depth interval 60 m–87 m sediments colour change to different tones. Brown to dark brown silty clay is shown in the depth intervals 60–69 m and 71–78 m replaced by grey and olive grey sediments in the leftover intervals. Between 87 m and 120 m, the stratigraphic succession shows a strong loss in sediment recovery accompanied by an increase in grain size. This interval is characterised by grey silt alternating with a few gravel levels likely of volcaniclastic origin. Silts, although often laminated, are sometimes disturbed by drilling and contain a fair amount of scattered clasts of volcanic origin.

Below 120 m the Composite succession displays mainly grey-olive clayey silt showing planar lamination and cross-stratified sediments in the lower part of the sequence. Moreover, from 127 m to 129 m, convoluted structures and slumping, likely related to a general tectonic instability phase of the site, characterise the lithostratigraphy of the lowermost part of the succession. The deepest sediments recovered before reaching the volcanic bedrock, corresponding to 131.2 m depth in the Composite section, consist of 20 cm of massive dark grey silty clay.

In the Composite section, more than 60 tephra units were identified ranging from a few millimetres-thick, fine-grained, ash layers to decimetres thick bed sets of alternate fine ash to fine lapilli. Visible tephra layers are scarce in the first part of the core with only eight layers in the first 40 m of the succession. Tephra became more frequent between 41.5 m and 85 m depth in the section, where 35 tephra layers were identified. Only four layers are present in the deeper part of the succession, between 85 m to the core bottom. The uppermost and the deepest tephra found in the succession were further analysed in order to obtain a first estimate of chronology and sedimentation rate (see Figs. 7 and 8).

4.4. Lithology and chemical composition of the uppermost and lowermost tephra

The C1-7-93-94 tephra is the uppermost visible tephra found in the Castiglione sequence at 11.15–11.18 m of depth in the Castiglione Composite section (Fig. 8). It is a 3 cm thick medium ash made of dense clasts to poorly vesicular porphyritic scoria bearing abundant microphenocrysts and microlites of leucite (some altered in analcime), clinopyroxene, Fe-spinel, and apatite set in a glassy to cryptocrystalline groundmass (Fig. 8). The major element of glass composition is foidite (Fig. 8c).

C2-82-28-30 tephra is the lowermost visible layer found in the Castiglione sequence at 129.62–129.67 m depth in the Castiglione Composite section (Fig. 8). It is a 5 cm-thick fine ash prevalently made of poorly vesicular porphyritic scoria bearing abundant microphenocrysts and microlites of leucite, clinopyroxenes, spinels and amphiboles set in a glassy to cryptocrystalline groundmass. A second particle population occurs made of vesicular pumice fragments (Fig. 8). The major element composition of glass is bimodal with porphyritic scoria having a foiditic composition and pumice a phonolite composition (Fig. 8e).

5. Discussion

5.1. Correlation between the ERT results and core stratigraphy

The lacustrine stratigraphy revealed by drilling cores and synthesized in the Composite section is in good agreement to the resistivity profiles shown in Figs. 4 and 5. The electrical resistivity tomography (ERT) values and lithological features are highly consistent, clearly revealing the presence of ca. 120 m thick lacustrine sediments, directly underlain by a volcanic basement reached at 116 m and 126.5 m for C1 and C2, respectively. Generally, the lacustrine succession recovered in the Castiglione maar is characterised by very small resistivity values (<50 Ohm*m), typical of clayey silt and silty clay sedimentary sequences. Similar values were found in other post-eruptive lacustrine sediments (Oms et al., 2015; Chen et al., 2021).

In particular, the highest conductive sediments are found in the first 60 m of depth of the ERT 1–2 profile, while downward we observe a slightly increase in the resistivity values that also corresponds to an increase in the magnetic susceptibility (see section 4.2.2). In the cores stratigraphy this transition corresponds to a passage from massive to

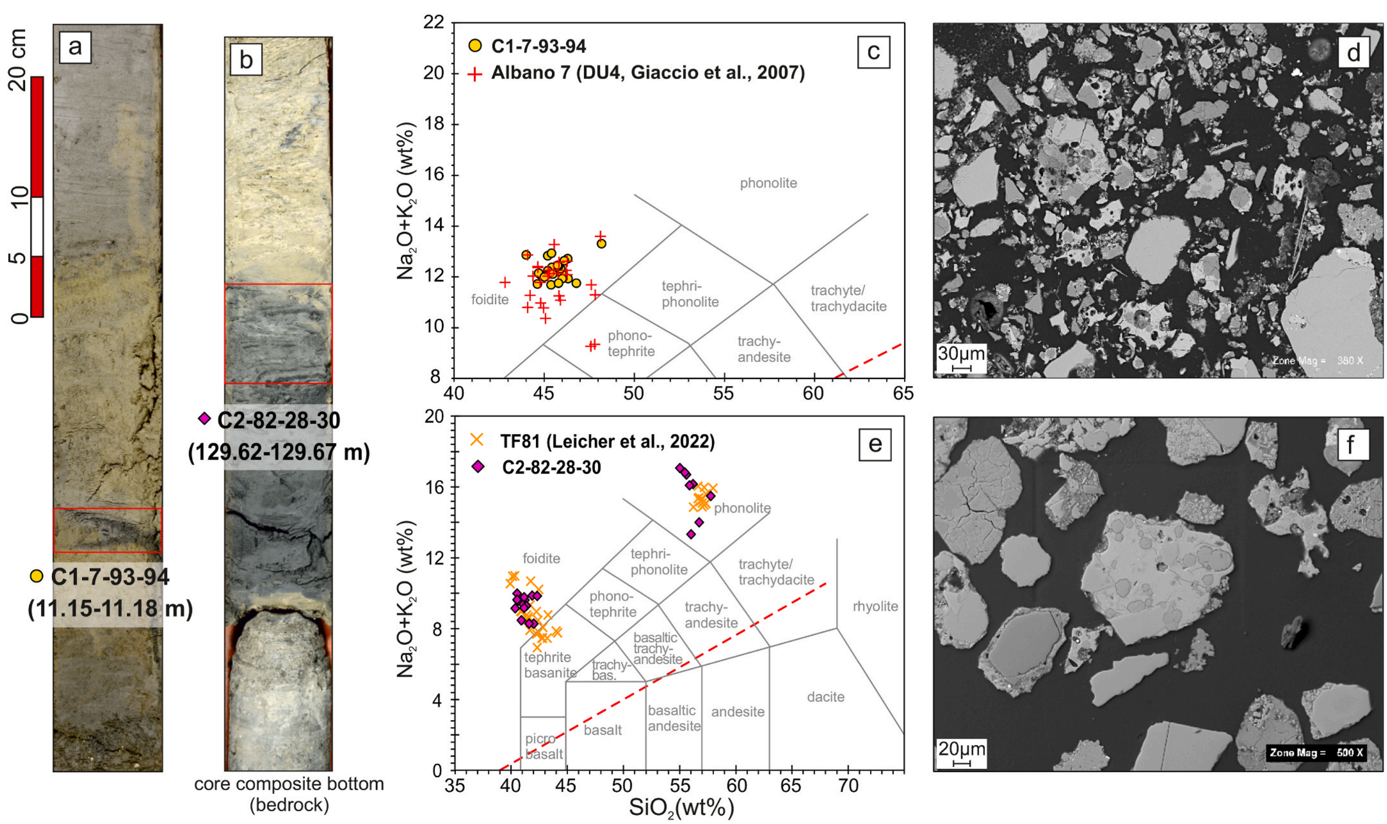

Fig. 8. Total Alkali Silica diagram (TAS; LeMaitre et al., 1989) and scanning electron microscope (SEM) backscattered images of the uppermost C1-7-93-94 and lowermost C2-82-28-30 tephra layers, visible in the Castiglione sedimentary sequence. a) Glass composition of C1-7-93-94 glass compared with the composition of proximal and distal deposits of Albano Maar recent cycle (grey field; data from Cross et al., 2014; Di Roberto et al., 2018; Giaccio et al., 2007, 2017; Freda et al., 2006; Narcisi et al., 1992, 1999). c) Glass composition of C2-82-28-30 tephra compared with the composition of TF-81 tephra of Leicher et al. (2022) dated at 362.7 ± 5.0 ka by $^{40}Ar/^{39}Ar$.

thinly laminated silty clay sediments and to an increase in tephra layers. These lithological changes could be the cause of the increase in both resistivity and magnetic susceptibility values. Further planned analyses on the cores will confirm and better clarify this lithological passage.

The volcanic basement, drilled in both cores, has been highlighted in the southwestern edge of the ERT 1–2 profile where it is characterised by resistivity values higher than 100 Ohm*m.

5.2. Chronological indications from previous investigations

While the acquisition of direct, ^{14}C and $^{40}Ar/^{39}Ar$ dating are ongoing, a preliminary estimation of the chronological interval spanned by the newly recovered Castiglione cores was proposed, according to the previous stratigraphic, paleoenvironmental (e.g., Alessio et al., 1986; Follieri et al., 1989; Narcisi et al., 1992) and volcanological investigations (e.g., Marra et al., 2003) available in the basin (Fig. 9). In fact, the new 131.37 m-long Castiglione Composite section was obtained

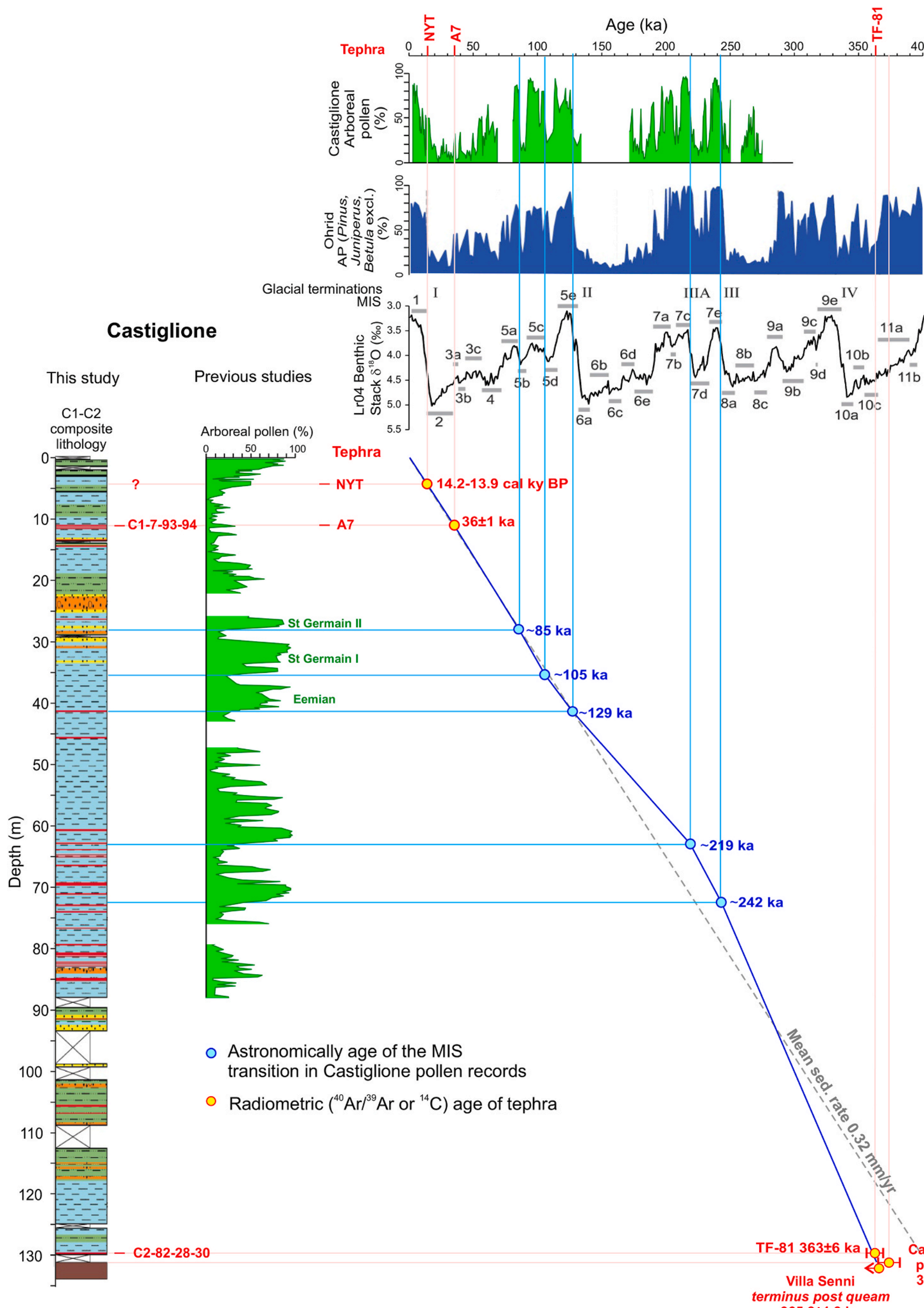

Fig. 9. Preliminary age-depth model for the 132 m-long Castiglione lacustrine successions, based on a combination of chronological data from literature and vulcanological data available from a previously investigated 88 m-long sediment core (e.g., Follieri et al., 1989). Source: overall sedimentation rate of 0.32 mm/yr (dashed grey line) from Magri (1989); pollen profile of Follieri et al. (1989); $^{40}Ar/^{39}Ar$ age of Castiglione pyroclastic products from Marra et al. (2003); $^{40}Ar/^{39}Ar$ age of the Villa Senni Ignimbrite and distal tephra from Marra et al. (2009) and Monaco et al. (2021); $^{40}Ar/^{39}Ar$ age of the Fucino tephra TF-81 from Leicher et al. (2022); position of the Albano 7 tephra in the previously investigated core from Giaccio et al. (2007); $^{40}Ar/^{39}Ar$ age of the Albano 7 tephra from Freda et al. (2006); position of the Neapolitan Yellow Tuff (NYT) in the previously investigated core from Narcisi, 1999); ^{14}C age of the NYT fromBlockley et al. (2008)); LR04 Benthic Stack of Lisiecki and Raymo (2005), the marine isotope stage (MIS) and sub-stage subdivision is according to Railsback et al. (2015); Lake Ohrid pollen record from Sadori et al. (2016).

in the central part of the maar, where a previously investigated 88 m-long core was retrieved (e.g., Alessio et al., 1986; Narcisi et al., 1992). The previous pollen interpretations indicate the first 88 m of the lacustrine succession spans the last 270 ka (Follieri et al., 1989; Magri, 1989) and the available radiocarbon dating and pollen evidence, consistently indicated that the lacustrine sediments accumulate with a rather constant rate of ~0.32 mm/yr (Magri, 1989).

The base of the Last Interglacial period (129–116 ka), the Eemian, roughly matching the marine isotope stage (MIS 5e; e.g. Shackleton et al., 2003), and the base of the MIS 7e Interglacial period (~242 ka; e.g. Railsback et al., 2015), can be placed at ~42 m and ~73 m depth, respectively (Fig. 9). Considering these tie points a sedimentation rate of 0.33 mm/yr and 0.28 mm/yr, can be estimated for the interval Present-129 ka and 129–242 ka, respectively (Fig. 9). As much as straightforward, the base of the MIS 7c and of the sub-stages MIS 5c and MIS 5a, corresponding to the St Germain I and St Germain II, is recognising and defining a roughly constant sedimentation rate. The recognition of the Albano 7 (36 ± 1 ka) and of the Neapolitan Yellow Tuff (14.320–13.900 ka BP; Blockley et al., 2008) tephra markers at the depths of 11.4–11.2 m (Giaccio et al., 2007) and 4.00–4.10 m (Narcisi, 1999), again imply a roughly constant sedimentation rate of ~0.32 mm/yr (Fig. 9). Noteworthy, using these chronological tie points, the resulting time series of the Castiglione pollen record replicates quite well the orbital- and suborbital-scale variability documented in Lake Ohrid pollen record (Sadori et al., 2016) (Fig. 9), thus supporting the soundness of the proposed preliminary chronology.

A further chronological point control for the Castiglione lacustrine succession can be provided by the age of the maar formation itself, which has to match the age of the onset of lake sedimentation. According to Marra et al. (2003), the Castiglione crater formed around 285 ka proposed by estimating the age of the base of the lacustrine succession, which at that date was considered to be 88 m-thick, i.e., strongly underestimated with respect to the actual thickness of ~131 m documented in this study. On the other hand, Marra et al. (2003) obtained an $^{40}Ar/^{39}Ar$ age of 373 ± 8 ka for the Castiglione maar pyroclastic products that the authors interpreted as affected by xenocrysts contamination, deriving from the deposits of the large Villa Senni eruption, dated to 365 ± 4 ka (Marra et al., 2009), laying immediately beneath the Castiglione maar deposits. However, the new stratigraphic data, showing that the Castiglione succession is significantly thicker than previously believed, would suggest instead that the age of 373 ± 8 ka is likely derived from the juvenile crystals from Castiglione products and thus that the Castiglione maar belongs to the cluster of maars – also including Pantano Secco and Prata Porci – that developed immediately after the Villa Senni caldera-forming eruption (Marra et al., 2003, 2016; Gaeta et al., 2016).

As matter of fact the age of 373 ± 8 ka implies a mean sedimentation rate of ~0.35 mm/yr for the last 373 ka and a slightly higher sedimentation rate of 0.44 mm/yr for the interval 242–373 ka, that are fully consistent with the rate of the sediment accumulation determined in different intervals of the Castiglione succession (Fig. 9). This age appears thus as the most likely and coherent chronological constraint for dating the formation of the Castiglione maar and the bottom of the paleolake succession. The accuracy and precision of this dating can be further improved by using the age of the underlying Villa Senni ignimbrite at 365 ± 4 ka as *terminus post quem* for the maar formation, the distal counterpart of which in Fucino succession was even more precisely dated at 365.8 ± 1.8 ka (Monaco et al., 2021). Therefore, the age of 365.8 ± 1.8 ka represents the best current available *terminus post quem* for both the formation of the Castiglione maar and the start of the lacustrine sedimentation.

5.3. New tephrochronological constraints

The high-resolution age model for the Castiglione maar sequence is under construction and will be based on the direct and indirect dating of the numerous tephra interspersed with lake sediments and magnetostratigraphic analyses and correlations. The glass chemical composition of the two, lowermost and topmost, tephra layers analysed in this study, alongside the chronological indications provided in sub-section 5.2, were used for recognising potential correlatives and thus strengthening the chronology of the Castiglione succession.

From a textural and compositional point of view, the tephra C1-7-93-94 matches the recent products of the Albano maar (Freda et al., 2006; Giaccio et al., 2009b; De Benedetti et al., 2008; Sottili et al., 2009; Giordano et al., 2006; Giordano and the CARG Team, 2010; Marra et al., 2016). This tephra occurs at the Castiglione Composite depth of 11.15–11.18 m, which is almost the same depth of the tephra found in the previously investigated sediment core attributed to Albano 7 (11.4–11.2 m, Giaccio et al., 2007). The tephra C1-7-93-94 can be thus reliably correlated to the Albano 7 unit, dated at ~36 ± 1 ka (Freda et al., 2006; Giaccio et al., 2009b; 2017; Marra et al., 2016).

The Castiglione Composite depth of the lowermost tephra C2-82-28-30, at 129.62–129.67 m, very close to the lacustrine base, implies that it has to be slightly younger than 365.8 ± 1.8 ka, i.e., the maximum age of the Castiglione maar formation. Furthermore, within the Middle Pleistocene Italian volcanism, the bimodal composition of tephra C2-82-28-30 is a quite rare and peculiar feature that, together with the available chronological indications, allow the potential correlatives to be reliably identified. The best candidate for a correlation with C2-82-28-30, both in terms of chronology and chemical composition, is the tephra TF-81 identified in the sediments of the Fucino basin (Leicher et al., 2022). In fact, this tephra, ascribed to the Colli Albani post-Villa Senni activity or the Roccamonfina Brown Leucitic Tuff (Leicher et al., 2022), shows the same peculiar bimodal composition of C2-82-28-30 (Fig. 8e) and was directly dated by the $^{40}Ar/^{39}Ar$ method at 362.7 ± 5.0 ka or by Bayesian age modelling at 364.5 ± 3.0 ka.

The sedimentation rate of the Castiglione composite sequence studied here roughly calculated using the age of the tephra C1-7-93-94, and tephra C2-82-28-30, recognised at the base of succession and possibly dated at ~363 ka, provide strong evidence supporting the notion that the sedimentation of the two, previous and new, recovered successions accumulated with a similar sedimentation rate. In turn, this validates the assumption of utilising the chronological information of the previously investigated core to get a reliable, though preliminary, chronology for the new longer sediment core. Waiting for the ongoing $^{40}Ar/^{39}Ar$ and ^{14}C dating, as well as the chronological indications from detailed tephrochronological investigation, such preliminary ag-model can be used for orienting.

6. Conclusion

The new AMUSED drilling campaign in the Castiglione maar gave us the possibility to reach for the first time the volcanic substrate of the paleolake and permit us to recover a very long and continuous lacustrine sediment succession suitable for multidisciplinary high-resolution paleoenvironmental and paleoclimatic studies.

Combining the lithostratigraphic and tephrochronological data of the new 131.37 m-long Castiglione Composite section with literature paleoenvironmental and volcanological data, we showed that the lacustrine succession spans the last ~365 ka, so extending by ~100 ka its temporal span previously believed be no longer than 270–280 ka. Data presented here set the basis for future high-resolution multi-proxy investigations (already in-progress) and highlight that the Castiglione maar sediment succession has a great potential to represent a valuable archive of data for the study of environmental and climatic change during the last four full glacial-interglacial cycles, from the MIS 10 to the Holocene. The Castiglione maar succession candidates thus as potential new important node to add to the high-resolution paleoclimate archives network for the Mediterranean which is required for exploring the fine structure and the regional expression of the past climate system dynamics.

Data availability

The raw geophysical data for ERT 1–2, 3 and 4 profiles are included in the supplementary material. Basic data and lithological description of the drilled cores are included in this paper.

CRediT authorship contribution statement

Patrizia Macrì: Writing – original draft, Supervision, Project administration. **Alessandra Smedile:** Investigation, Visualization, Data curation, Writing – original draft. **Liliana Minelli:** Investigation, Visualization, Data curation, Writing – original draft. **Gaia Siravo:** Investigation, Visualization, Data curation. **Chiara Caricchi:** Investigation, Data curation. **Bianca Scateni:** Investigation, Data curation. **Alessio Di Roberto:** Investigation, Data curation, Writing – original draft. **Giuseppe Re:** Investigation. **Iacopo Nicolosi:** Investigation. **Francesca D'Ajello Caracciolo:** Investigation. **Biagio Giaccio:** Writing – review & editing.

Declaration of competing interest

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

Acknowledgements

This research is funded by Istituto Nazionale di Geofisica e Vulcanologia, in the frame of the AMUSED project. Special thanks to Conte Flavio Cavazza for giving us permission to drill in his ownership. Alfredo Sorice helped for the laboratory sampling activity. Many thanks to the reviewers who positively evaluated the paper and helped us to improve it.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2023.09.016.

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