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International Continental Scientific Drilling Program (ICDP) workshop on the Fucino paleolake project: the longest continuous terrestrial archive in the MEditerranean recording the last 5 Million years of Earth system history (MEME)

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Abstract. During the last 5 million years (Pliocene–Holocene), the Earth climate system has undergone a series of marked changes, including (i) the shift from the Pliocene warm state to the Pleistocene cold state with the intensification of Northern Hemisphere glaciation; (ii) the evolution of the frequency, magnitude, and shape of glacial–interglacial cycles at the Early Middle Pleistocene Transition (∼ 1.25–0.65 Ma); and (iii) the appearance of millennial-scale climate variability. While much of this paleoclimate narrative has been reconstructed from marine records, relatively little is known about the impact of these major changes on terrestrial environments and biodiversity, resulting in a significant gap in the knowledge of a fundamental component of the Earth system. Long, continuous, highly resolved, and chronologically well-constrained terrestrial records are needed to fill this gap, but they are extremely rare. To evaluate the potential of the Fucino Basin, central Italy, for a deep-drilling project in the framework of the International Continental Scientific Drilling Program (ICDP), 42 scientists from 14 countries and 32 institutions met in Gioia dei Marsi, central Italy, on 24–27 October 2023 for the ICDP-supported MEME (the longest continuous terrestrial archive in the MEditerranean recording the last 5 Million years of Earth system history) workshop. The existing information and unpublished data presented and reviewed during the workshop confirmed that the Fucino Basin fulfils all the main requisites for improving our understanding of the mode and tempo of the Plio-Quaternary climatic–environmental evolution in a terrestrial setting at different spatial and temporal scales. Specifically, the combination of the seismic line evidence with geochronological and multi-proxy data for multiple sediment cores consolidated the notion that the Fucino Basin infill (i) is constituted by a sedimentary lacustrine succession continuously spanning at least 3.5 Myr; (ii) has a high sensitivity as a paleo-environmental–paleoclimatic proxy; and (iii) contains a rich tephra record that allows us to obtain an independent, high-resolution timescale based on tephrochronology. Considering the typical half-graben, wedge-shaped geometry of the basin, four different potential drilling targets were identified: MEME-1, located in the middle of the basin, should reach the base of the Quaternary infill at ∼ 500 m depth; MEME-2, located west of MEME-1, has sedimentation rates that are lower, with the base of the Pliocene–Quaternary at ∼ 600 m depth; MEME-3b has the same target as MEME-2 but is located further west, where the base of the Pliocene–Quaternary should be reached at ∼ 300 m; and MEME-3a (∼ 200–300 m depth) is located, for tectonic purposes, on the footwall of the basin master fault. Overall, the MEME workshop sets the basis for widening the research team and defining the scientific perspectives and methodological approaches of the project, from geophysical exploration to the development of an independent chronology and to the acquisition of multi-proxy records, which will contribute to the preparation of the full MEME proposal.

1 Introduction

During the last 5 million years, from the Early Pliocene to the Holocene, the Earth system has undergone a series of prominent changes in its abiotic and biotic components. Overall, global climate shifted from the Pliocene warm state to the Pleistocene cold state (Filippelli and Flores, 2009; Haywood et al., 2009; Lisiecki and Raymo, 2007; Westerhold et al., 2020) with changes in global ice volume and atmospheric greenhouse gas concentrations (Fig. 1). Global mean temperatures during the Pliocene were ∼ 2–3 °C higher than during the pre-industrial Holocene (Haywood et al., 2009), peaking at temperatures up to 4 °C higher (e.g. Haywood et al., 2016) during the so-called mid-Pliocene Warm Period (mPWP; 3.26–3.02 Ma), with atmospheric carbon dioxide values ranging between 350–550 ppm (Stap et al., 2016; de la Vega et al., 2020; Guillermic et al., 2022) (Fig. 1) and a global sea level that was likely to be 12–20 m higher than today (Miller et al., 2020). In light of these climatic features, the Pliocene (and, in particular, the mPWP) represents a potential analogue for current and future anthropogenic global warming scenarios (Haywood et al., 2020; Allan et al., 2021; Burke et al., 2018).

Later, during the Pliocene–Pleistocene transition (PPT), the Northern Hemisphere glaciation intensified (Ravelo et al., 2004; Westerhold et al., 2020) (Fig. 1), and Earth's climate entered a new stage dominated by the quasi-periodic expansion and contraction of the major Northern Hemisphere ice sheets, driven by variations in the Earth's axial inclination and orbital geometry (Milankovitch, 1941) that affect the seasonal and latitudinal distribution of incoming solar radiation. However, the frequency, amplitude, and shape of the glacial–interglacial cycles were not uniform, and the ∼ 41 kyr periodicity that dominated the first part of the Early Pleistocene gradually turned into the longer ∼ 100 kyr high-amplitude and strongly saw-toothed cycles seen during the Early Middle Pleistocene Transition (EMPT; Head and Gibbard, 2015) between ca. 1.25 and 0.65 Ma (e.g. Berends et al., 2021) (Fig. 1). In addition to orbital-scale variability, North Atlantic and polar records revealed the extreme and pervasive nature of millennial-scale climate variability over the last 1.5 Myr (McManus et al., 1999; Jouzel et al., 2007; Barker et al., 2011; Raymo et al., 1998; Hodell et al., 2008, 2023b; Naafs et al., 2013; Hodell et al., 2023a).

The most relevant information and data for many of these events and processes that have marked the overall evolution of the Earth's climatic system during the last 5 Myr are derived from marine records (Ronge et al., 2020; Westerhold et al., 2020). However, the knowledge that can be gained from these records is reliant on astronomical tun-

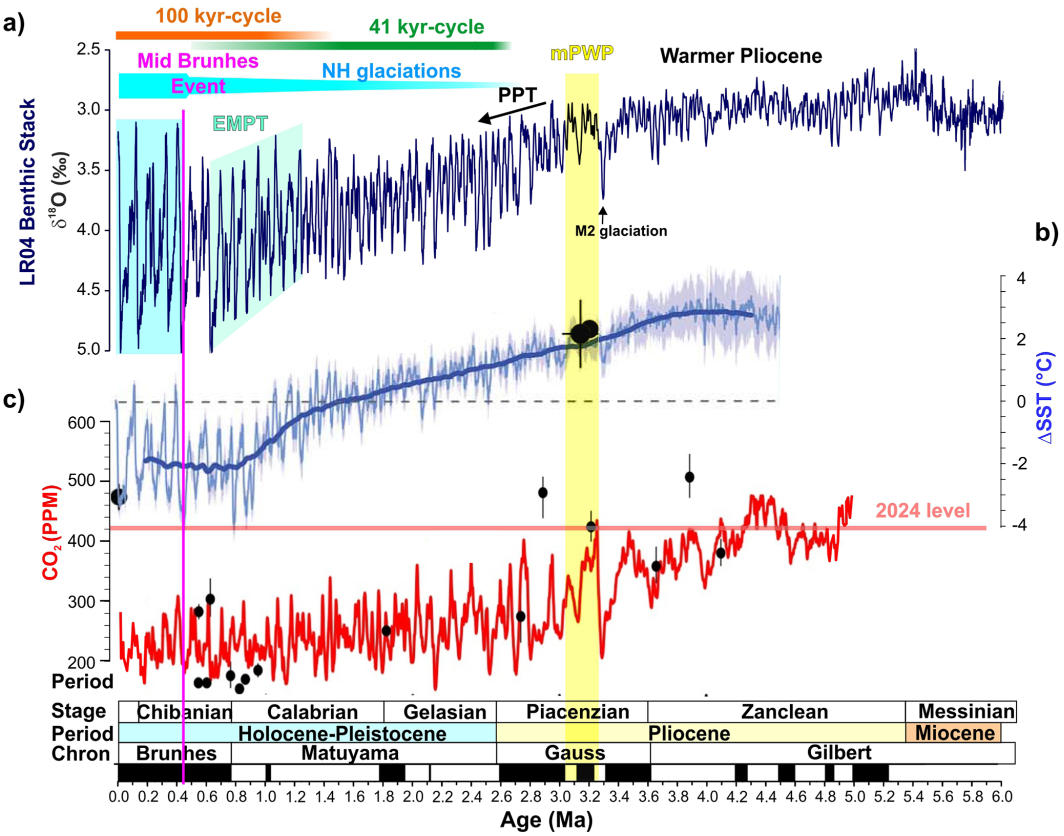

Figure 1. Main features and evolutionary processes of the last 5 million years of climate history. **(a)** LR04 benthic $\delta^{18}O$ stack from Lisiecki and Raimo (2005). **(b)** Global sea surface temperature change (ΔSST) from Clark et al. (2024) (light blue represents 1σ uncertainty, while the long-term average is in dark blue). Black circles represent ΔSSTs for the Pliocene KM5c interglaciation, the mid-Piacenzian stage (36), and the Last Glacial Maximum. **(c)** Simulated (red line) and δ11B-based (black dots) atmospheric CO_2 concentrations from Stap et al. (2016). Abbreviations: PPT – Pliocene–Pleistocene transition, M2 glaciation – Marine Isotope Stage (MIS) M2 (3.312–3.264 Ma) glaciation, mPWP – mid-Pliocene Warm Period, EMPT – Early Middle Pleistocene Transition.

ing for its chronological framework, largely lacking independent radiometric constraints and, apart from a few exceptions, missing the terrestrial dimension. Some of the knowledge gaps are targeted by recent or proposed IODP (International Ocean Discovery Program) projects, such as IODP Expedition 397 to the Iberian Margin; Expedition 401, which is constituted by the study of the Mediterranean–Atlantic Gateway Exchange since the Late Miocene; or IODP Proposal 1006, which focuses on the Mediterranean–Black Sea Gateway Exchange (see https://www.iodp.org/proposals/active-proposals, last access: 18 October 2024). Ice core records, on the other hand, provide high-resolution chronological and environmental information from the terrestrial realm, but they are limited to the last ∼ 800 kyr and to polar regions (Jouzel et al., 2007).

From the terrestrial realm, lake sediments have shown the potential to provide long, highly resolved, and precisely dated records, shedding light on climate-driven ecosystem and biodiversity changes. Outstanding examples of lake sediment records from Eurasia are the Pliocene–Pleistocene records of Baikal and El'gygytgyn (Williams et al., 1997; Melles et al., 2012; Fig. 3). Lake Baikal was the first record drilled within the framework of the ICDP (International Continental Scientific Drilling Program) in the mid-1990s, and research on this material is still ongoing (Alexander Prokopenkov, personal communication, 2023). On the other hand, the record from Lake El'gygytgyn nicely demonstrated a polar amplification of climate extremes that has not otherwise been documented in marine records so far (Melles et al., 2012). From the Mediterranean region, which is characterized by high biodiversity and a high human population today, ICDP drilling targets have included the Dead Sea, Lake Van, and Lake Ohrid (Fig. 3a). Although these records have broadened our general understanding of changes in ecosystems (Sadori et al., 2016; Donders et al., 2021), biodiversity, and endemism (Wilke et al., 2020), they are limited to ∼ 1.4 Ma and do not cover the PPT and, in particular, the mPWP.

In the framework of western Eurasia, the Pliocene–Quaternary lacustrine successions hosted in the central

Apennine intermountain tectonic depressions (e.g. Galadini et al., 2003) are among the few sedimentary archives that can fill these knowledge gaps back to the mPWP, or even beyond, in an unprecedented way. Indeed, the high sensitivity of these archives to climatic change and the occurrence of a rich record of ^{40}Ar/^{39}Ar dated tephras from the adjacent ultra-potassic peri-Tyrrhenian volcanic centres (Figs. 2, 3) are well documented (e.g. Giaccio et al., 2015a; Regattieri et al., 2015, 2016, 2019; Mannella et al., 2019; Bertini et al., 2023). However, many of the central Apennine Pliocene–Quaternary successions are discontinuous and often cover only relatively short intervals.

The Fucino Basin, which is the largest basin in the core of the central Apennine (Figs. 2, 3), is an exception. According to our present knowledge, it is the only central Apennine basin hosting a continuous and well-resolved lacustrine succession from the Early Pliocene to historical times (e.g. Cavinato et al., 2002), unique in the European realm. New (unpublished) tephrochronological paleomagnetic and pollen data of a 270 m long sediment core from the marginal part of the basin, coupled with high-resolution seismic data, suggest that the sediment succession in the lake may reach back to ∼ 3.0–3.5 Ma. Furthermore, recent investigations reported the presence of ∼ 130 volcanic ash layers in a composite ∼ 98 m long sediment core (Fig. 3c–d) from the Fucino Basin spanning the last 430 kyr (Giaccio et al., 2017, 2019; Monaco et al., 2021, 2022; Leicher et al., 2023, 2024). They confirmed the outstanding potential of this sedimentary succession to provide us with the most intensely and independently dated record of the entire Mediterranean region, setting benchmarks in the regional tephrostratigraphic framework, as well as in dating global climato-stratigraphic and paleomagnetic event boundaries (Fig. 4). Although high-resolution investigations of the Fucino Basin are limited at present to the last 430 kyr, evidence from the discontinuous successions of the adjacent basins of Sulmona and L'Aquila (Figs. 1, 3) indicate that the occurrence of tephra layers extends to as far back as at least 2 Ma (Bertini et al., 2023); volcanological records from Pontine Island (Fig. 3b) indicate that explosive activity in the region can extend back to 4.2 Ma (Conte et al., 2016). Therefore, its long and continuous geological history and its proximity to peri-Tyrrhenian volcanic centres (distance: 100 to 150 km; Fig. 3b) indicate that the Fucino Basin is ideally located to provide an exceptional record of Pliocene–Quaternary environmental changes underpinned by a precisely dated ^{40}Ar/^{39}Ar-based chronological framework.

Ultimately, the aim of MEME is to gain insights into the mode and tempo of Pliocene–Quaternary climatic–environmental changes at different spatial (e.g. from global climate variability to regional tectonics and explosive volcanism) and temporal (long-term, orbital, and millennial–centennial climate variability) scales by extending the independently dated ^{40}Ar/^{39}Ar chronology of the Fucino lacustrine record back into the Pliocene. In particular, the Fucino chronology can eventually provide a template for key marine sequences such as the new IODP Expedition 397 Site U1385 on the Iberian Margin, extending to ∼ 5.3 Ma (http://publications.iodp.org/proceedings/397/397title.html, last access: 22 September 2024). In addition, the Fucino record has the potential to form a bridge between IODP initiatives focusing on the Mediterranean–Atlantic Gateway Exchange (IODP Expedition 401) and the Mediterranean–Black Sea Gateway Exchange (IODP Proposal 1006; see https://www.iodp.org/proposals/active-proposals, last access: 14 September 2024) while offering a continental perspective on changes in climate and biodiversity. By using suitable paleoclimatic proxies and/or globally synchronous events (e.g. cosmogenic nuclide peaks related to the geomagnetic field reversal), the tephrochronology from Fucino Basin can eventually also be transferred to the Antarctic ice core records, potentially providing a radioistopically based timescale for investigating the EMPT at this iconic site (e.g. https://www.beyondepica.eu/en/publications/beyond-epica-publications/, last access: 8 August 2024). Finally, the project will offer basic new data on the tectonic evolution of the Apennine, where Fucino represents a pivotal area, being of the largest and most tectonically continuous active Quaternary basins. In order to explore the suitability of the Fucino sedimentary succession for a deep-drilling project in the framework of the ICDP and, thus, to unlock its full potential, an ICDP-supported workshop took place in Gioia dei Marsi (Fig. 3c) on 24–27 October 2023.

2 Current knowledge and potential of the Fucino sedimentary succession

2.1 Geological and climatic setting of the Fucino Basin

The Fucino Basin is a morpho-tectonic extensional basin located in central Italy at ∼ 650 m a.s.l. It is surrounded by Mesozoic to Cenozoic carbonate platform rocks that constitute the highest peaks of the central Apennine (Fig. 2), which hosted mountain glaciers during glacial periods (e.g. Giraudi and Giaccio, 2015). In historical times, the Fucino Basin hosted Lake Fucinus, which covered a surface area of ∼ 150 km^2 until the first partial drainage took place during the 1st–2nd century CE. At the end of the 19th century, the drainage of the basin was completed.

At present, the Fucino Basin is characterized by a Mediterranean climate with warm and dry summers, a mean annual temperature of ∼ 12.5 °C, and an average annual precipitation from 600 to 750 mm in the plains to 900 to 1200 mm in the piedmont zone (e.g. Lionello et al., 2006). From middle spring to early autumn, monthly average temperatures are over 10 °C, peaking in July and August (18 to 21 °C). From early autumn to middle spring, monthly average temperatures are below 10 °C, with January being the coldest month (−5 to −2 °C; e.g. Mannella et al., 2019).

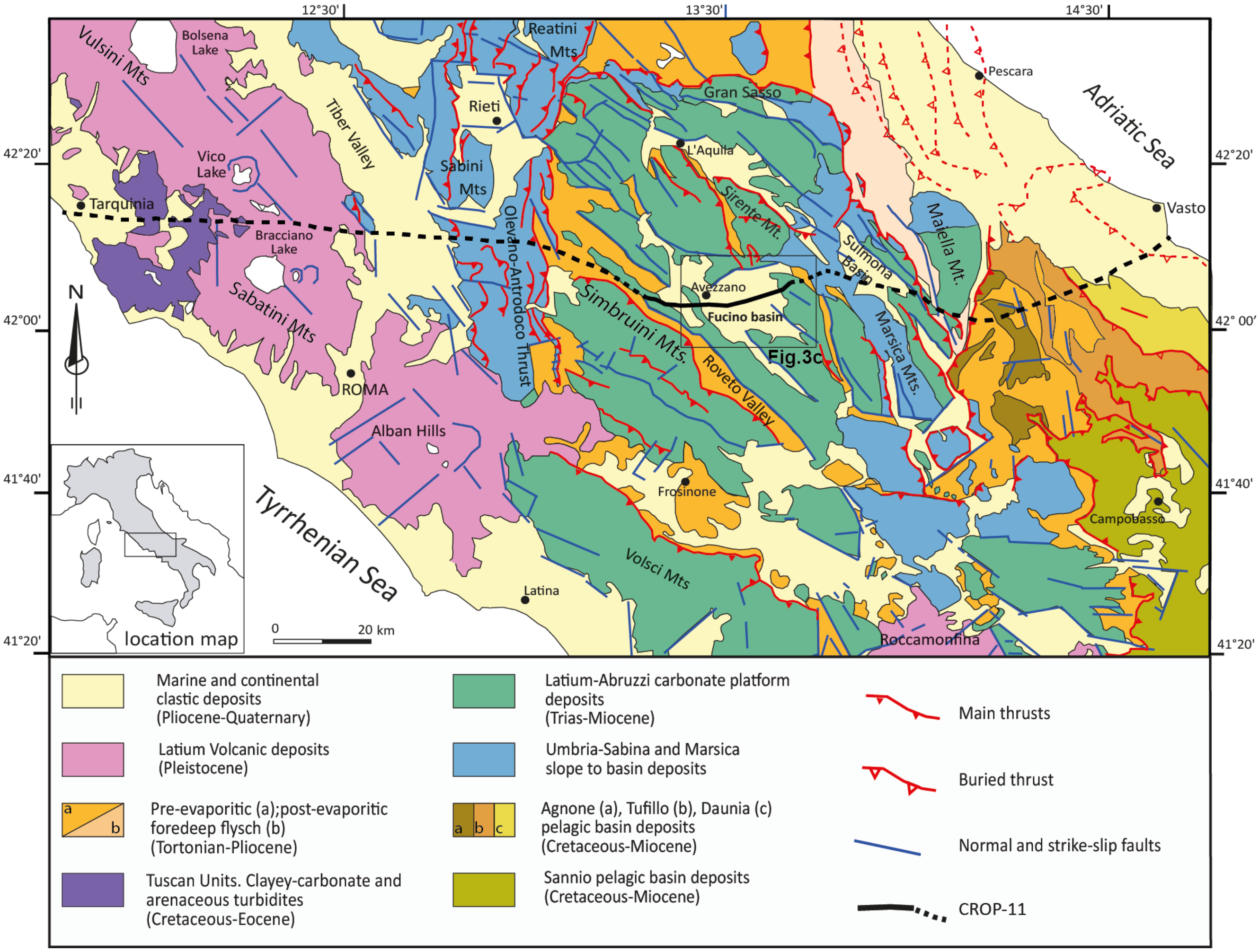

Figure 2. Geological map of central Italy, with the location of the Fucino Basin (from Caielli et al., 2023).

The opening and the Pliocene–Pleistocene evolution of the Fucino Basin were driven by the two main transversal normal fault systems of the Tremonti fault and the San Benedetto-Gioia dei Marsi (SB-GdM) fault system (Fig. 3a; Cavinato et al., 2002). The SB-GdM fault system is composed of three 110–140° N primary segments subtended in relation to their 130–140° N hanging-wall synthetic and antithetic splays (Fig. 3c; Galadini and Galli, 2000). The SB-GdM fault is currently active and was responsible for the most devastating central Italian earthquake that occurred on 13 January 1915 (M_w 7.0, Io 11 MCS grade; ∼ 33 000 fatalities; e.g. Galli et al., 2016).

The subsurface architecture of the Fucino Basin is well defined by 11 commercial and scientific seismic lines that cross the basin, both longitudinally and transversely with respect to the NW–SE trends of the tectonic structures composing the SB-GdM fault (Fig. 3c; Cavinato et al., 2002; Patacca et al., 2008; Patruno and Scisciani, 2021; Mancinelli et al., 2021; Caielli et al., 2023). The seismic lines depict a half-graben geometry with increasing thickness of the Pliocene–Quaternary sedimentary infilling from the west to the east (i.e. toward the SB-GdM) and from the northwestern and southwestern tips of the SB-GdM fault to its central part, which is the depocentre of the basin, located a few kilometres northwest of San Benedetto village (Fig. 3c). Specifically, Cavinato et al. (2002) distinguished four unconformity-bounded seismic facies: Meso-Cenozoic substratum (Seq. 1), Messinian flysch deposits (Seq. 2), Pliocene continental deposits (Seq. 3), and Quaternary continental deposits (Seq. 4), separated by the major unconformities A, B, and C (Fig. 3d). In the depocentre, Seq. 4 forms a well-defined and regularly stratified sedimentary wedge that will be targeted within the MEME deep-drilling project. In particular, the E–W-trending line 1, crossing the depocentre of the basin, shows that no significant tectonic deformations or sedimentary unconformities affect Seq. 4, which, in this sector of the basin, reaches a maximum two-way travel time of ∼ 700 ms, equivalent to a thickness of ∼ 700 m (Cavinato et al., 2002) (Fig. 3d). More

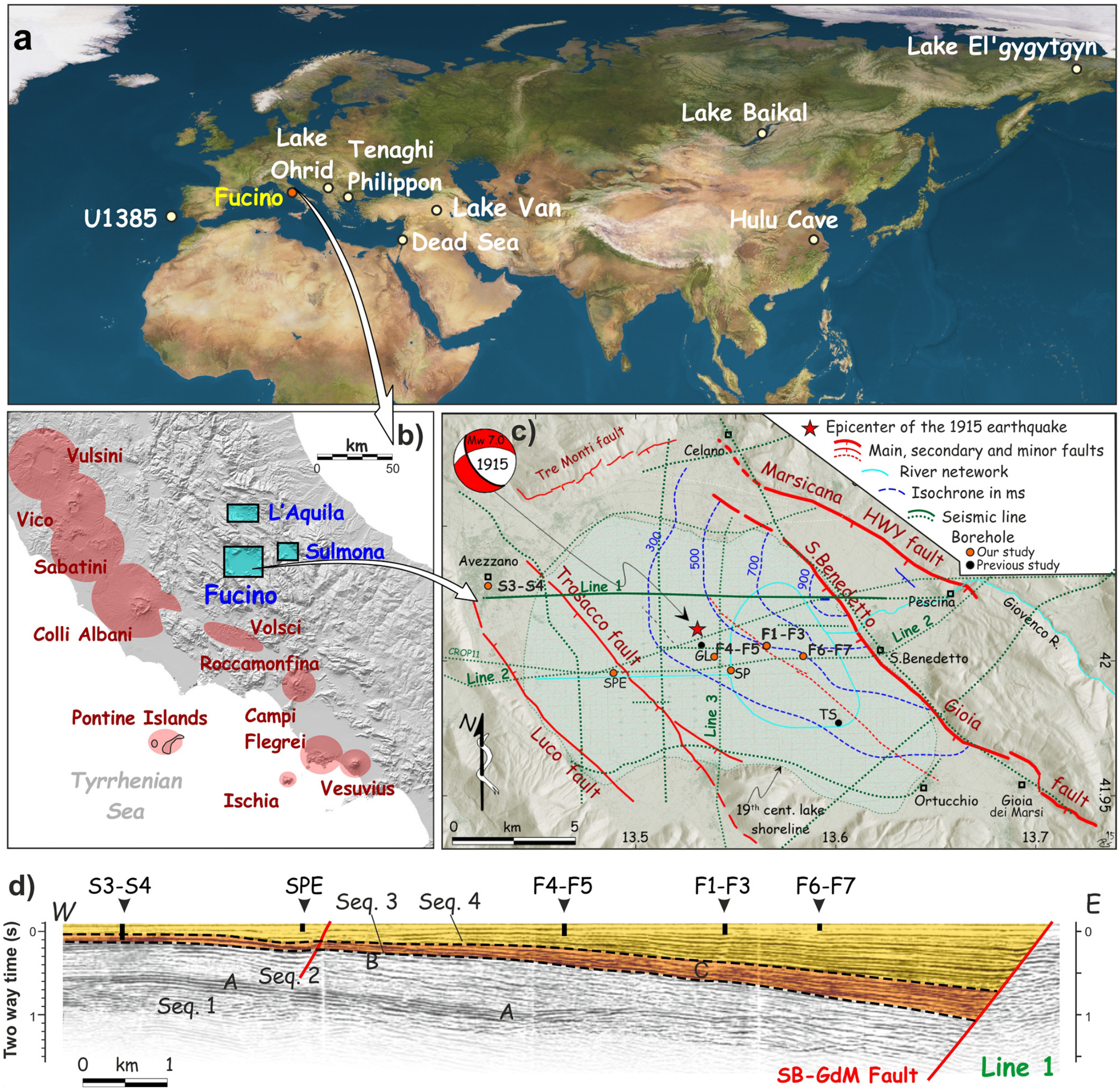

Figure 3. Reference map of the Fucino Plain with a representative seismic line crossing the basin. **(a)** The Fucino Basin in the context of some relevant Northern Hemisphere ICDP and IODP sites and other reference Quaternary paleoclimatic records, including the quoted U1385 core, Lake Ohrid, Tenaghi Philippon, L'Aquila Basin, Sulmona Basin, Lake Baikal, and Lake El'gygytgyn. **(b)** Details of the location of the Fucino Basin relative to the peri-Tyrrhenian volcanic systems of central-southern Italy. **(c)** Fucino Basin with locations of recently investigated sediment cores F1–F3 , F4–F5, F6–F7, SP, SPE, and Avezzano S3–S4 (Giaccio et al., 2015b, 2017, 2019, and unpublished data) and of previously investigated sediment cores. Isochrones of the Plio-Quaternary basin infill, traces of seismic lines (the solid one is that shown in panel **d**), Quaternary master faults responsible for the asymmetrical (half-graben) geometry of the basin, and the epicentre of the last strong earthquake (1915 CE) are also shown. The continuous green line represents the traces of the seismic profiles shown in panel **(c)**. The village of Gioia dei Marsi, where the workshop took place, is located in the southeastern corner. **(d)** Seismic line 1 showing the internal architecture of the Pliocene–Quaternary continental deposits of the Fucino Basin along a W–E profile. The projected locations of the S3–S4, SPE, F3–F4, F1–F3, and F6–F7 boreholes are marked. Seq. 1: Meso-Cenozoic marine carbonate; Seq. 2: Messinian foredeep sediments; Seq. 3: Pliocene lacustrine–fluvial deposits; Seq. 4: Quaternary lacustrine–fluvial deposits A, B, C (main unconformities). This figure and its information were compiled with modifications from Cavinato et al. (2002), Galli et al. (2012), Patacca et al. (2008), Giaccio et al. (2019), and Monaco et al. (2021).

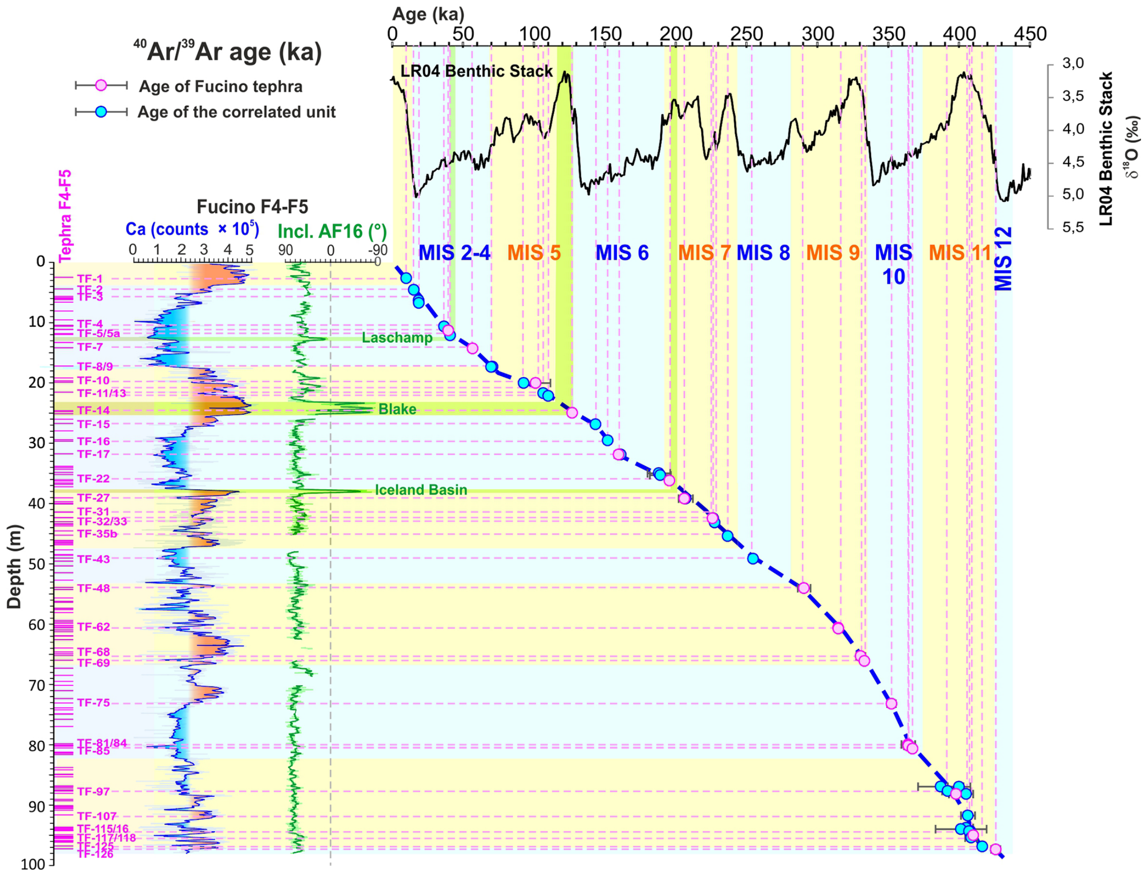

Figure 4. Tephrochronology, selected proxy data, and general chronological framework for the F1–F3 and F4–F5 (see location in Fig. 3c) composite records (from Giaccio et al., 2017, 2019; Mannella et al., 2019; Monaco et al., 2021, 2022; Leicher et al., 2023, 2024) in relation to the LR04 (Lisiecki and Raymo, 2004).

details of the existing high-resolution seismic lines are provided in Sec. 3.2.2. Several holes have been drilled in the Fucino half-graben basin for scientific and geotechnical purposes in the past decades (Fig. 3a). The longest of these boreholes is the 200 m long GeoLazio core (GL in Fig. 3c), for which only sparse geochronological and stratigraphic data exist (e.g. Follieri et al., 1986, 1991; Narcisi, 1994). More recently, four new sediment cores (F1–F3, F4–F5, F6–F7, and Avezzano S3–S4) were retrieved from the Fucino Basin, allowing more detailed insights into the stratigraphic and chronologic framework of its sedimentary infill.

2.2 Results from the deep-drilling pre-siting investigations: F1–F3, F4–F5, and F6–F7 sediment cores

In the framework of an international consortium, a ∼ 82 m long sediment succession from the eastern-central area of the Fucino Basin (F1–F3 in Fig. 3c) was recovered in June 2015. The aims of the consortium were as follows: (i) assess the lithology and continuity of the lacustrine sedimentary succession; (ii) document the presence of widespread tephra layers mandatory for regional to extra-regional correlations and their suitability for ^{40}Ar/^{39}Ar dating; (iii) evaluate the mean sedimentation rate and, thus, the potential temporal extent of the Fucino lacustrine succession; and (iv) explore the sensitivity of different paleoclimatic proxies for this site. With the same aims, but on a longer time interval, a second, 98 m long sediment succession was retrieved in 2017 from a different area of the basin within the project FUTURE, funded by the Italian Research Ministry (MUR, PRIN 2017, grant no. 20177TKBXZ_003, coordinator Giovanni Zanchetta). Here, based on seismic line evidence, the sedimentation rate was expected to be lower than at the F1–F3 drill site (Fig. 3c). Collected sediments from both drillings were all fine-grained lacustrine sediments (Giaccio et al., 2017, 2019).

Multi-proxy investigations, including tephrochronology (geochemical analyses and ^{40}Ar/^{39}Ar dating); paleomagnetic analyses; scanning XRF (X-ray fluorescence) element geochemistry; $CaCO_3$ content analyses; carbon, nitrogen, and sulfur (CNS) analyses; $\delta^{18}O_{calcite}$ analyses; and pollen analyses, have been carried out and are ongoing on both sediment successions. Tephrochronological results, based on ^{40}Ar/^{39}Ar dating of K-rich crystals extracted from Fucino tephras and robust geochemical correlation with the well-dated proximal counterparts, indicate that the F1–F3 and F4–F5 successions span the last ~ 190 and ~ 430 kyr, respectively. Mean sedimentation rates are on the order of $\sim 0.43\,\mathrm{mm\,yr^{-1}}$ for F1–F3 and $\sim 0.23\,\mathrm{mm\,yr^{-1}}$ for F4–F5 (Giaccio et al., 2017, 2019). Detailed information on MIS 12-11, MIS 10-9, MIS 8-7, and MIS 7-1 tephrostratigraphy is reported by Monaco et al. (2021), Leicher et al. (2023, 2024), Monaco et al. (2022), and Giaccio et al. (2017). Overall, ~ 130 tephra layers have been detected for both successions, 40 of which were either directly dated or correlated to their respective proximal, dated units, resulting in the richest and most intensely dated Middle–Upper Pleistocene Mediterranean tephra record (Fig. 4). Preliminary paleomagnetic data documented Laschamp, Blake, and Iceland basin geomagnetic excursions (Giaccio et al., 2019, Fig. 4). Published proxy data, e.g. scanning XRF element geochemistry and CNS data, show the high sensitivity of the Fucino sediment in providing high-resolution paleoenvironmental records as a regional expression of the orbital- and millennial- to centennial-scale climate variability (Mannella et al., 2019; Monaco et al., 2022). Ongoing pollen analyses of the interglacials documented in the Fucino succession, carried out as part of PhD projects at La Sapienza Università di Roma (MIS 12-11c, Vera-Polo et al., 2024) and the University College of London (MIS 5e-MIS 1) and as part of the NERC project VARING (Polychronis C. Tzedakis, coordinator) (MIS 9e and MIS 7e-a), reveal a close correspondence with climate changes recorded in deep-sea cores from the Iberian Margin (e.g. see Tzedakis et al., 2018).

In early 2022, two additional overlapping and ca. 33 m long cores (F6–F7) were retrieved to the east of the F1–F3 drilling site, where a higher sedimentation rate was expected. Preliminary results of the ongoing investigation confirmed that the depths of some marker tephras recognized in cores F6–F7 are deposited 2 times and 4 times deeper than the equivalent layers recognized in F1–F3 and F4–F5, respectively.

Overall, the results of the multi-proxy investigation on the F1–F3 and F4–F5 sediment successions confirm the great potential of the Fucino succession in providing us with detailed proxy records of the last 430 kyr supported by a robust chronology based on high-precision $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ dating, which enables an exploration of the role of climate drivers, avoiding any circularity that may arise from astronomical tuning. Moreover, the independent Fucino chronology can eventually be transferred to sediment sequences from the Iberian Margin on the basis of paleoclimatic alignments using homologue terrestrial proxies (e.g. pollen), documenting the vegetation response to abrupt climate change (see, for example, Tzedakis et al., 2018; Regattieri et al., 2019; Bajo et al., 2020).

3 The MEME workshop

3.1 Participants and motivation

The MEME workshop was attended by 42 scientists (Fig. 5) from 14 countries and 32 institutions, as summarized in Table 1.

The main aims of the MEME workshop were as follows:

i. evaluate the existing seismic data and discuss the potential to extend the seismic information with new profiles to better define the basin architecture, ensuring the feasibility of an ICDP drilling project;

ii. discuss the existing stratigraphic, dating, and paleoclimatic–environmental data of the Fucino sediment succession and their potential for reaching the aims of the MEME project;

iii. based on (i) and (ii), determine overarching scientific objectives and establish and plan for further investigations in preparation for a full ICDP drilling proposal;

iv. discuss drilling logistics and cost estimates mandatory for the full proposal;

v. based on (ii), identify scientific aspects not yet covered by the current team and propose invitations to additional selected experts;

vi. establish a well-coordinated interdisciplinary ICDP research group.

3.2 Programme and discussion

3.2.1 Sessions 1 and 2: state of the art

During the afternoon of 24 October, the research teams involved in past and ongoing studies on the Fucino Basin provided short presentations about the current results and methods relevant to a potential deep-drilling campaign. These included (i) a summary of the state of the art with regard to previous and ongoing investigations in the Fucino Basin (Biagio Giaccio); (ii) a general overview on the Italian Pliocene–Quaternary volcanism in the framework of the complex Mediterranean geodynamic setting (Sandro Conticelli); (iii) a discussion regarding the tectonic architecture of the sedimentary infill of the Fucino Basin (Gian Paolo Cavinato); and (iv) a general overview of the FUTURE (FUcino uniTes QUaternary REcords) project (Giovanni Zanchetta), including the main results of $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ geochronology (Sebastien Nomade), tephrostratigraphy (Niklas Leicher), pollen (Chronis Tzedakis, Alessia Masi), and mitochondrial DNA and lipid (Cindy De Jonge) investigations performed during the project.

Finally, Fabio Florindo and Adele Bertini presented the unpublished lithostratigraphical, $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$, paleomagnetic, and pollen data from the Avezzano S3–S4 sediment core,

Table 1. Participants of the MEME ICDP workshop.

ICDP-supported	Affiliation	Country
Adele Bertini	University of Florence	Italy
Gian Paolo Cavinato	National Research Council	
Giulia Cheli	University of Pisa	
Fabio Florindo	Istituto Nazionale di Geofisica e Vulcanologia	
Biagio Giaccio	National Research Council	
Luigi Improta	Istituto Nazionale di Geofisica e Vulcanologia	
Alessia Masi	Sapienza University of Rome	
Eleonora Regattieri	National Research Council	
Laura Sadori	Sapienza University of Rome	
Giovanni Zanchetta	University of Pisa	
Christine Heim*	University of Cologne	Germany
Niklas Leicher	University of Cologne	
Mathias Vinnepand	Leibniz Institute for Applied Geophysics	
Bernd Wagner	University of Cologne	
Leon Clarke	Manchester Metropolitan University	UK
Alice Paine	Oxford University	
Helen Roberts	Aberystwyth University	
Chronis Tzedakis	University College London	
Dustin White	University of York	
Paul Albert	Swansea University	
Alison Pereira*	Paris-Saclay University	France
Sebastien Nomade	CEA-CNRS-UVSQ	
Cindy De Jonge	ETH Zurich	Switzerland
Camille Thomas	University of Bern	
Marta Marchegiano	University of Granada	Spain
Jose Eugenio Ortiz Menendez	Universidad Politécnica de Madrid	
Sofia Pechlivanidou	University of Bergen	Norway
Grisha Fedorov	National Academy of Sciences of the Republic of Armenia	Armenia
Ivan Razum	Croatian Natural History Museum	Croatia
Vitor Azevedo	Trinity College Dublin	Ireland
Julieta Massaferro	National Scientific and Technical Research Council	Argentina
Alexander Franke*	University of Adelaide	Australia
Martin Danisik	Curtin University	
Anders Noren	University of Minnesota	USA
Elizabeth Niespolo*	Princeton University	
Deniz Cukur	Korea Institute of Geoscience and Mineral Resources	South Korea
Other participants		
Paolo Boncio	University "G. D'Annunzio" of Chieti–Pescara	Italy
Edi Chiarini	Istituto Superiore per la Protezione e Ricerca Ambientale	
Angelo Cipriani	Istituto Superiore per la Protezione e Ricerca Ambientale	
Sandro Conticelli	University of Florence – National Research Council	
Roberto De Franco	National Research Council	
Roberto Martini	Private company – Drilling engineering design	

* Unable to attend, contribution presented by colleagues.

Figure 5. MEME workshop participants at the panoramic-view stop during the short field trip on 26 October. The Fucino paleolake basin can be seen in the background. All participants gave their consent for the publication of the group photo.

continuously cored until a depth of ∼ 185 m and discontinuously reaching ∼ 270 m. This core was recovered from the western margin of the basin in 2019 as part of a project concerning seismic microzonation led by the University of Chieti–Pescara (Paolo Boncio coordinator) (for location, see Fig. 3). These preliminary data consistently provided evidence for a very long, though discontinuous, terrestrial record, likely extending back to ∼ 3.0–3.5 Ma.

3.2.2 Combining geophysical, stratigraphic, and chronological information to estimate the integrity and temporal extent of the Plio-Quaternary lacustrine succession

The interpretation of the available seismic reflection profile across the Fucino Basin allowed us to highlight a wedge-shaped basin fill architecture and stratigraphy. The best image of the wedge-shaped architecture of the Fucino Pliocene–Quaternary continental infill is shown in a high-resolution E–W seismic line (line 1, Figs. 3d, 5). Line 1 highlights the Pliocene–Quaternary growth geometry of the strata characterized by continuous eastward-divergent reflectors across the SB-GdM fault plane, indicating a Pliocene–Quaternary sedimentary accumulation in a fault-controlled basin (Fig. 6). In the eastern part of seismic line 1, the total thickness of Pliocene–Quaternary deposits along the hanging wall of the SB-GdM fault can be estimated to be 0.9–1.0 s two-way time (TWT), corresponding to ∼ 900–1000 m sediment thickness (Fig. 6).

According to the seismic stratigraphy and tectonic setting of the basin, the tectonic subsidence has been very low at the Avezzano drilling site. Specifically, seismic line 1 reveals that the town of Avezzano coincides with the thinner part of the sedimentary wedge that characterizes the architecture of the Fucino sedimentary infilling (Fig. 6). The Avezzano S3–S4 drilling site is, in fact, far from the Tremonti and SB-GdM fault systems (Fig. 6), which were and are responsible, at different times and in different ways, for the opening and evolution of the Fucino Basin (Cavinato et al., 2002), thus resulting in limited accommodation space and highly condensed, as well as possibly discontinuous, sedimentary succession. In agreement with this tectonic–sedimentary framework, the tephrochronological, paleomagnetic, and pollen evidence indicates that the 270 m long Avezzano sediment core could span the last 3.5 Myr, with a resulting mean sedimentation rate of 0.08 $\mathrm{mm\,yr^{-1}}$, i.e. a rate much lower than the accumulation rates in the cores drilled closer to the SB-GdM fault (Fig. 6).

While the Avezzano core has provided an opportunity to explore the temporal extent of the Fucino sediment succession within a short stratigraphic interval, confirming the extraordinarily long history of sediment accumulation in the basin, its marginal setting and lithology, also including intervals of relatively coarse sediments, contradict a complete and continuous sediment succession that is stratigraphically and lithologically suitable for high-resolution investigation. Nevertheless, the Avezzano S3–S4 sediment core can be used to calibrate seismic line 1 by translating the chronological information from this succession towards the depocentre (Fig. 6). Accordingly, at the sites F6–F7, F4–5, and F1–F3, the same stratigraphic time interval recorded in the Avezzano S3–S4 core should be represented by ∼ 800, ∼ 700 and ∼ 500 m thick successions, respectively, reaching ∼ 1000 m or more in the depocentre (SRmax. in Fig. 6). Therefore, at these sites, the Plio-Quaternary sedimentary successions should be more expanded (up to 1 order of magnitude), more highly re-

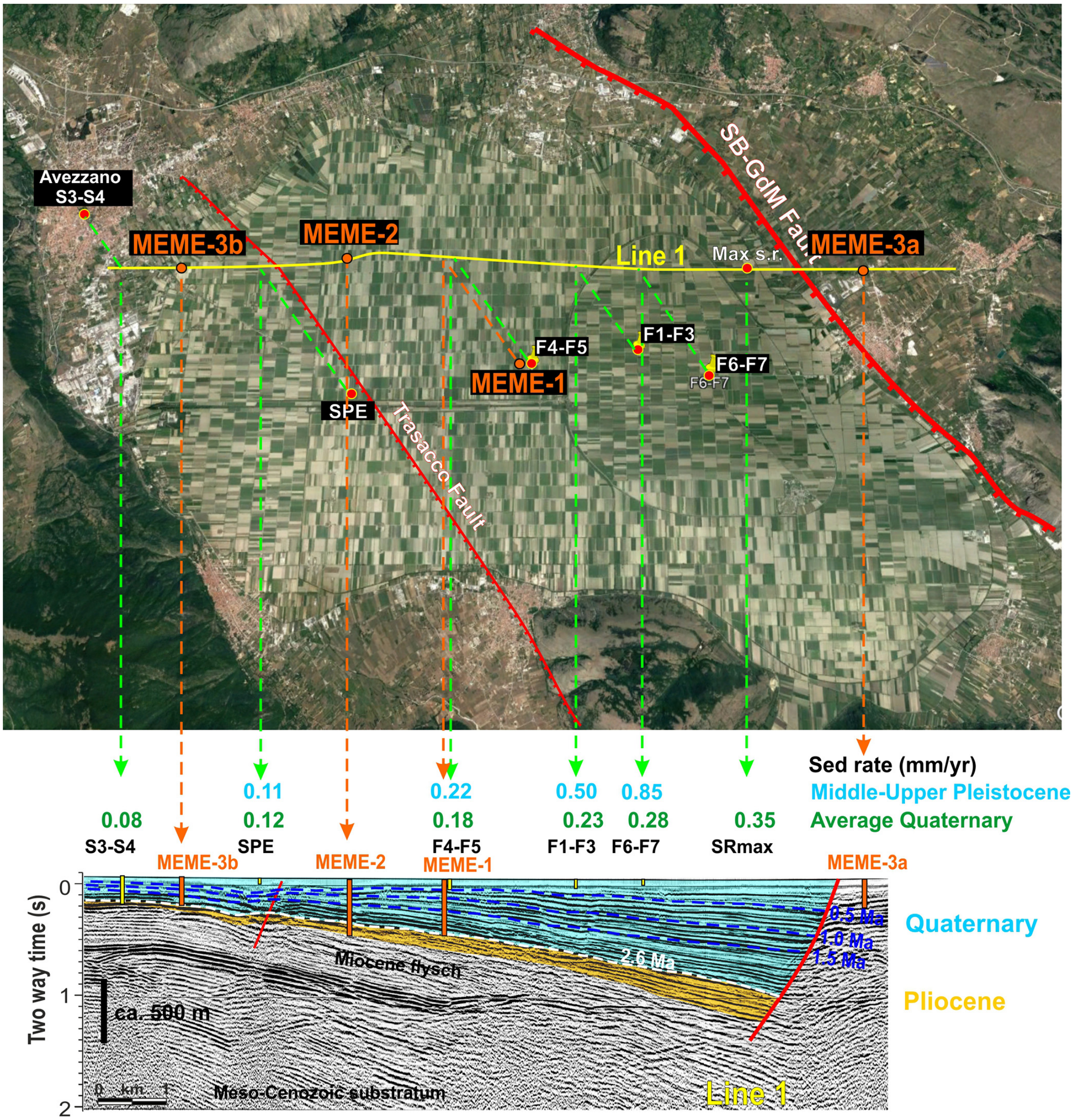

Figure 6. Aerial view of the Fucino Basin (© Google Maps), with the locations of the investigated Fucino sediment cores F1–F3, F4–F5, F6–F7, SPE, and S3–S4 (Giaccio et al., 2015b, 2017, 2019, author's unpublished data) and stratigraphical–chronological calibration of the seismic line 1 using the constraints provided by the Avezzano S3–S4 core.

solved, and characterized by finer sediments with respect to the Avezzano S3–S4 core. Thus, it should be ideally suited to recovering a complete succession for detailed and high-resolution multi-proxy investigations.

3.2.3 Concluding remarks for sessions 1 and 2

In summary, the evidence presented in sessions 1 and 2 shows that the Fucino Basin fulfils all the main requisites for achieving the aims of the MEME project to improve our understanding of the mode and tempo of the Plio-Quaternary climatic–environmental evolution at different spatial and temporal scales. This evidence includes the following:

1. long and continuous sedimentation of fine lacustrine sediments since at least 3.5 Ma;
2. high sensitivity of the paleo-environmental–paleoclimatic multi-proxies, with regional and extra-regional relevance;
3. an independent, high-resolution timescale based on tephrochronology.

3.3 Session 3: participant self-presentation

A total of 20 contributions were presented during session 3, with topics ranging from geophysical exploration, drilling operations, and geochronological methods to physical and bio-geochemical proxies (Table 2).

3.4 Field trip

On the morning of 26 October, a short field trip headed by Paolo Boncio and Gian Paolo Cavinato took place. During the field trip, the main morpho-tectonic features of the eastern side of the Fucino Basin (Fig. 6), some outcrops of the SB-GdM fault system affecting recent deposits, and the co-seismic fault scarp related to the 1915 earthquake were shown.

3.5 General discussion

Based on current insights into the subsurface of the Fucino paleolake and the paleo-environmental information recorded, the general discussion included the following topics:

1. overarching scientific and societal objectives of the MEME project;
2. location, depth(s) of the borehole(s), and technical and management aspects, reflecting the constraints of scientific and societal needs;
3. involvement of the public and private companies;
4. matching funds and compositions of the Co-PI and Co-I teams.

3.5.1 Objectives

Recovering and investigating a long continuous succession from Fucino Basin will provide unprecedented insights into the evolution of the Earth system during the Pliocene–Quaternary, i.e. the last 3.0–3.5 Myr.

Our proposed multi-method dating approach, including direct ^{40}Ar/^{39}Ar, tephrochronology, zircon double-dating, luminescence and amino acids, and a multi-proxy analysis of sediment physical and bio-geochemical properties, has the potential to provide a detailed radiometric chronology for reconstructing the timing and dynamics of the Pliocene–Quaternary geo-bio-environmental and climatic processes independently of any a priori assumptions regarding response times to climate forcing and feedbacks. By studying the interaction between climate and environmental changes, these insights will allow a better understanding of the impact of ongoing and future climatic–environmental changes in the highly populated Mediterranean area. Eventually, the Fucino record will be linked to reference marine records by constructing a tephro-stratigraphic and pollen stratigraphic lattice.

The specific objectives of the deep drilling into the Fucino Basin are outlined below.

A. Stratigraphy, paleoclimate, and biodiversity

A1. Event stratigraphy

We assemble a regional to global stratigraphic reference record deep into the Pliocene, including and combining a unique time series of orbital- to millennial-scale climate events and cycles and tephrostratigraphic and magnetostratigraphic cosmogenic nuclide events.

A2. Sequence, timing, duration, and dynamics of Pliocene–Quaternary climatic events

i. We reconstruct climate conditions during the warm Pliocene and during the transition to the colder Pleistocene.

ii. We evaluate the timing and differences of the terminations of glacial periods;

iii. We assess interglacial structures, namely their internal variability, initiation, development, and demise.

iv. We constrain hydrological changes in the central Mediterranean at times of sapropel formation, specifically their links to low- and high-latitudes climate.

v. We explore millennial-scale variability during glacial times within the central Mediterranean.

vi. We evaluate the longitudinal influence of changes in North Atlantic circulation patterns by means a west–east transect including the records of U1385; Fucino; Lake Ohrid; Tenaghi Philippon; and, potentially, other records across the Eurasian continent, including the Lake Baikal record.

A3. Changes in terrestrial ecosystems and biodiversity across main climatic transitions and events since the late Pliocene

i. We reconstruct the response of Mediterranean environments and biomes to global changes during the warm Pliocene, including the mPWP; the progressive expansion of the Northern Hemisphere ice sheets during the Plio-Pleistocene transition; and the change in periodicity, magnitude, and shape (symmetrical vs. asymmetrical) of the glacial–interglacial cycles during the EMPT and after the Mid-Brunhes Event.

ii. We establish the timing and causes of the progressive extinction of forest species in the Mediterranean.

iii. We consider the intra-lacustrine diversity dynamics of different biological groups through time.

Table 2. List of the participant presentations in session 3.

Name	Presentation title
Luigi Improta	A new high-resolution seismic reflection experiment in the Fucino Basin acquisition geometry and data quality
Sofia Pechlivanidou	From surface processes modeling to high-resolution drilling record resolving key controls on sediment production and stratigraphic development in active rifts
Deniz Cukur	Geophysics
Anders Noren	Drilling operations
Elizabeth Niespolo[1]	^{40}Ar/^{39}Ar geochronology
Paul Albert	Tephra (cryptotephra) studies
Vitor Azevedo	Tephrochronology – machine learning models
Ivan Razum	Statistical treatment of tephra data
Martin Danisik	Zircon double-dating applied to tephras
Helen Roberts	Luminescence dating of calcite
Dustin White	Malacology and amino acid dating
Alice Pine	New geochemical proxies
Alexander Franke[2]	Novel (trace metal) isotope methods to infer Quaternary environmental change
Leoan Clarke	Bio-geochemistry
Eleonora Regattieri	Stable isotope and other geochemical proxies
Marta Marchegiano	Carbonate clumped isotope (Δ47) paleothermometry
Jose E. Ortiz Menendez	Organic molecules, amino acid geochronology, and lipid biomarkers
Grisha Fedorov	Sedimentology
Mathias Vinnepand	Sediment physical properties
Julieta Massaferro	Paleoecology, insects

[1] Not attending, presented by Biagio Giaccio. [2] Not attending, presented by Bernd Wagner.

iv. We generate a reference site of a vegetation-based record to assess the paleo-environmental background for early hominin migration and occupation in western Eurasia.

B. Geodynamics

B1. Volcanology and magmatic evolution

i. We reconstruct the history and recurrence time of explosive volcanism in the peri-Tyrrhenian region.

ii. We define the chronology and timing of the transition between the calc-alkaline and ultra-potassic (late Pliocene–earliest Pleistocene) peri-Tyrrhenian volcanism.

iii. We explore the possible relation between glacio-eustatic sea level change and explosive peri-Tyrrhenian volcanism.

iv. We evaluate the evolutionary petrological processes as related to the mantle–crust magma source dynamics.

v. We assess the impact of the large explosive eruptions on local- and regional-scale ecosystems.

B2. Tectonics

i. We consider the tempo and dynamics of the opening and development of the Fucino Basin in relation to the surrounding fault systems in the framework of the Mediterranean geodynamic field.

ii. We conduct an assessment of seismic hazards in relation to seismic amplification phenomena.

3.5.2 Location and depth of drilling(s) and technical and management aspects

Parallel drilling is needed and envisaged to obtain a continuous sediment succession. Drilling in the area of the maximum sedimentation rate would be the best location to obtain a full, expanded (~ 1000 m deep drill hole; SRmax in Fig. 6), and continuous succession of the Fucino lacustrine infill, providing the ideal setting for very high-resolution investigations. Despite these eligible conditions, this option was noted to be challenging to the drilling engineers because of the necessary casing strings, the mud composition for pressure control, the borehole stability, and the management of swelling clays. Altogether, much higher costs and risks are associated with this approach. However, the basin fill architecture (Figs. 3d and 6) offers an alternative option with multiple shallower drill holes drilled along an east–west transect, each of which recovers a section of the basin fill.

In order to overcome drilling-related risks and to provide a cost-efficient drilling operation, the participants discussed three drilling sites with different targets and maximum drill depths of < 500 m. The first selected drilling site, MEME-1, is in the central part of the basin, not far from F4–F5 site. Here, according to the seismic reflection data, the base of the lacustrine succession should be around 500 m depth (Fig. 6).

The second site, MEME-2, is further to the west, where sedimentation rates are lower (Fig. 6). Here, a drilling of ~ 500 m would allow us to recover almost the entire sediment succession down to the bedrock and to provide the full Pliocene–Quaternary history of the Fucino Basin, although this would be at a lower resolution compared to MEME-1. A further site was considered for tectonic purposes. It could be shallower (200–300 m) and located on the footwall of the SB-GdM fault system, where relatively low sedimentation rates are expected (MEME-3a; Fig. 6).

Depending on the outcomes of MEME-1 and MEME-2, as a contingency plan, the third shallower drilling could be also placed further toward the MEME-2 site, where, according to seismic data, the whole Quaternary or Pliocene–Quaternary succession should be recovered in 200–300 m (MEME-3b, Fig. 6). This option is relevant in terms of the strategy and success of the MEME project as, in case of technical problems at MEME-1 and MEME-2, MEME-3b would warrant recovering the whole lacustrine succession and would thus reach the target of the MEME project, although this would be with a shorter sediment core, which, theoretically, is technically easier to recover.

Based on the experience from past drilling campaigns in the Fucino Basin, the optimal approach will include the use of soft-sediment coring tools deployed in numerous ICDP lake-drilling campaigns for the upper ~ 200 m at each site, with standard industry tools used for the remainder of each profile. Budget estimates produced by local drilling contractors provide the basis for this plan, with additional costs to be added for soft sediment coring.

3.5.3 Societal, economic, and industrial aims

Scientific deep drilling has not only scientific and economic relevance but also a great educational potential.

A local professional photographer and videographer participated in the workshop to discuss the best strategies for engaging the local community and identifying effective communication channels for spreading the news. Workshop participants were interviewed to create a video explaining the importance of the Fucino Basin and the MEME research project in layperson's terms, which was then sent to the local press; uploaded to YouTube; and shared on social media platforms such as X, Instagram, and Facebook. A short report of the workshop, including the future research plan, was shared with the Italian National Research Center that published it on their website.

In the future, we plan to involve both the local community and the general public in our research. This will be done at different levels. For the local community, preliminary meetings will be planned in cooperation with local authorities and organizations to illustrate the aims and the methods of the research.

During the drilling operation, visits to the drilling site will be organized for local schools and committees. To involve the general public, we also plan to have a media release for every step of the project, both through local and national press avenues and through the use of social networks. In addition, as many of the PIs are enrolled in universities, specific field trips and training involving university students from bachelor level to PhD level will be planned prior to, during, and after the drilling.

MEME drilling will also give the opportunity to measure the local geothermal gradient and to evaluate the potential for low-enthalpy geothermal resources, eventually with the use of the holes for pivotal heat exchanger systems. Moreover, after drilling, the borehole(s) will be equipped with specific probes to measure geochemical parameters such as conductivity, pH, Eh, dissolved CO_2, and temperature in addition to facilitating water sampling. These geochemical parameters may indeed constitute indicators of seismic cycles or even earthquake precursors (Skelton et al., 2014).

3.5.4 Time frame, Co-PI and Co-I team, and matching funds

The workshop included small-group and whole-group discussions regarding potential sources of funding available to supplement the costs of scientific drilling and also of funding to support post-drilling science. The steps and timeline involved in preparing a full proposal for submission to the ICDP for deep drilling in the Fucino paleolake were considered. In order to develop a well-coordinated research programme and to prepare an ICDP full proposal, the participants committed themselves to providing all the information required to support more detailed project planning, including (i) a detailed budget plan; (ii) a detailed operations plan, including a permission plan with a list of authorities to be contacted; (iii) a project management plan; (iv) a plan for data and sample management and long-term core curation; and (v) an education and outreach plan.

The constitution of the Co-PI and Co-I teams was discussed with regard to the proposers of the workshop, as well as with the participants as a whole, considering the contributions and the interests of the workshop participants. All participants agreed on modifications to the PI- and Co-PI teams to meet the ICDP balance requirements and to support equality, diversity, and inclusion (e.g. gender, age, nationality, expertise).

4 Concluding remarks

The ICDP-supported MEME workshop provided the opportunity to enlarge the spectrum of expertise, opening new research perspectives for the geophysical exploration needed for the drilling site location and for the development of a multi-method and independent chronology, consisting of ^{40}Ar/^{39}Ar; tephrostratigraphy; paleomagnetism; U series; luminescence and amino acid dating methods; and multiproxy records, such as sediment physical properties, stable isotopes, clumped isotopes, inorganic and organic biogeochemistry, pollen, and insects. As a matter of fact, the Fucino sedimentary archive brought into focus the broad interests expressed by participants, who enthusiastically expressed their commitment to continue collaborating, either as Co-PIs or Co-Is or as external collaborators. Therefore, the next steps will be the constitution of the Co-PI and Co-I teams together with collecting the data and information needed for the writing of a full MEME proposal.

Data availability. No data sets were used in this article.

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Author contributions. Conceptualization: BG, BW, GZ, LS, and PCT. Methodology, validation, formal analysis, investigation, data curation, and writing (original draft preparation): BG, BW, GZ, AB, GPC, RdF, FF, SN, AP, LS, SS, and PCT. Writing (review and editing) and visualization: BG, BW, GZ, AB, GPC, RdF, FF, DAH, TAN, SN, AP, LS, SS, PCT, PA, PB, CDJ, AF, CH, AM, MM, HMR, and AN. All the authors have read and agreed to the published version of the paper. In addition to the named co-authors of this paper, the MEME team includes all the people mentioned in the Team list, whose participation in the workshop contributed to the generation of ideas presented in this report.

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