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Unravelling land-sea correlations during the Pliocene-Pleistocene in the Mediterranean area

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ABSTRACT - In this paper, we synthetised pollen, foraminiferal, and calcareous nannofossil data from marine and continental successions in Italy to investigate the complex dynamics of climate-induced shifts in terrestrial and marine ecosystems during the Late Pliocene and Early to Middle Pleistocene. Additionally, by focusing on three key case studies derived from interdisciplinary research of marine sedimentary successions (Semaforo, Vrica-Santa Lucia and Montalbano Jonico) we present concurrent evidence from both marine and continental proxies, offering a refined perspective on the environmental history of the Mediterranean. This integrated approach enhances the precision of reconstructing climate system interactions during critical intervals of the Quaternary, mitigating potential discrepancies arising from independent chronologies and methods of study. Overall, the synthesis and case studies contribute to a more comprehensive understanding the role of the Mediterranean in global climate variability, emphasising the sensitivity of the region to both continental and marine climatic drivers throughout the Quaternary.

INTRODUCTION

The Mediterranean region has long been recognised as a key area for investigating climate variability and environmental change, particularly from approximately 3 million years (Ma) onwards (e.g., Colleoni et al., 2015; De Boer et al., 2021; Berner et al., 2022; Mondanaro et al., 2024). This interval marks the onset of large-scale climatic oscillations driven by glacial-interglacial (G/I) cycles that shaped global climate system. The unique geographical setting of the Mediterranean, situated at the crossroads of temperate, subtropical, and arid climatic zones, makes it particularly sensitive to both regional and global climatic shifts. This sensitivity, combined with the semi-enclosed nature of the Mediterranean Basin, provides an exceptional archive for reconstructing climate dynamics and biotic responses during key phases at the Pliocene-Pleistocene transition (PPt; e.g., Petrick et al., 2018; McClymont et al., 2023) and the Early-Middle Pleistocene Transition (EMPT; Head & Gibbard, 2015). The complex interplay of G/I cycles, sea-level changes, and orbital forcing in the Mediterranean region has left behind high-resolution records in both marine and terrestrial sedimentary archives. These records capture critical responses to global cooling, changes in insolation, and variations in atmospheric and oceanic systems, offering valuable insights into the processes driving environmental and ecological transformations. Notably, marine proxies such as foraminifer and calcareous nannofossil assemblages provide reconstructions of sea-surface features (temperature, salinity, turbidity, nutrient content, stratification/mixing) (Hemleben et al., 1989; Beaufort et al., 1999; Bárcena et al., 2001; Bauman et al., 2005), while pollen records deliver an unparalleled view of land flora composition, vegetation dynamics and regional climate conditions (Suc et al., 2018; Bertini & Combourieu-Nebout, 2023 and references therein). By integrating terrestrial and marine proxy records, it is possible to trace the timing, magnitude, and mechanisms of environmental changes. This approach enables a deeper understanding of how ecosystems responded to major climatic drivers. Numerous studies have used these proxies to highlight the Mediterranean's climatic fluctuations over orbital and millennial timescales (e.g., Martrat et al., 2004; Fletcher & Sánchez-Goñi, 2008; Suc et al., 2010, 2018; Ausín et al., 2015; Bertini et al., 2015; Combourieu-Nebout et al., 2015; Rohling et al., 2015; Maiorano et al., 2016a, b; Tzedakis et al., 2017; Marino et al., 2020; Toti et al., 2020), though some have been limited by lower-resolution datasets (see references in Bertini, 2010; Bertini et al., 2010; Magri et al., 2017; Bertini & Combourieu-Nebout, 2023). Nevertheless, all previous contributions have significantly advanced our comprehension of environmental shifts in the region.

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The Mediterranean's role in deciphering Quaternary climate dynamics extends beyond regional relevance; it has broader implications for understanding global climate systems. The challenge of correlating terrestrial and marine records is magnified by the region's tectonic activity, sea-level fluctuations, and hydrological variability, all of which add layers of complexity to palaeoenvironmental reconstructions (e.g., Nomade et al., 2019; Marino et al., 2020; Dumitru et al., 2021; Lionello et al., 2023). However, the integration of these records (combining palynological data with marine micropalaeontological evidence) offers a robust framework for unravelling the intricate land-sea correlations during the Quaternary. Understanding these complex interactions is not only essential for reconstructing past environmental conditions, but also for predicting future responses to ongoing climate change in this highly vulnerable region.

In this contribution, we critically synthesised key information to reconstruct Mediterranean environments during the Pliocene and Pleistocene, by integrating data from both continental and marine sedimentary successions which were calibrated using independent time-diagnostic tools. Additionally, we aimed to emphasise, through specific case studies, the critical role that interdisciplinary studies - combining palynological data, calcareous plankton, and other biogeochemical proxies from marine successions - play in constructing comprehensive climate change assessments. Indeed, by comparing and correlating data from both terrestrial and marine contexts, we obtained insights into synchronous climatic and oceanographic-atmospheric events. This integrative approach not only highlights the intrinsic connections between these two seemingly distinct realms but also offers a more nuanced understanding of how global climate dynamics is expressed across different ecosystems concurrently.

MATERIALS AND METHODS

This study adopted a multidisciplinary approach to evaluate the effectiveness of land-sea correlations, synthesising bibliographic data from key reference sites throughout Italy (Figs 1 and 2). For each of the first three stages of the Quaternary (Gelasian, Calabrian, Chibanian) we reconstructed terrestrial environments using pollen data to analyse floristic composition and changes in vegetation. Concurrently, marine conditions are assessed through records of planktonic foraminifera and calcareous nannofossils, which provided insights into sea surface temperature, productivity, and ocean circulation patterns. When working with different natural archives, such as lacustrine versus marine deposits, we selected those that have a robust chronostratigraphic and geochronologic framework thanks to the use of temporally diagnostic tools, such as radiometric dating, magnetostratigraphy, and biostratigraphy.

A notable advantage arises when both terrestrial and marine proxies are derived from the same marine archive, as this facilitates direct correlation and enhances the precision of palaeoenvironmental reconstructions. This advantage is particularly significant due to the remarkable ability of pollen grains to be deposited and preserved within various environmental contexts, including marine settings. Pollen grains become incorporated into sediments along with marine plankton, contributing to the accumulation of deposits in marine basins. This integrated approach enabled us to capture the differing response times of terrestrial and marine systems to substantial climatic shifts in the Mediterranean region. By aligning terrestrial pollen data with marine planktonic microfossils, we can effectively bridge gaps that often arise from the independent application of chronostratigraphic and geochronologic schemes, thus resolving issues of temporal misalignment. The robustness of marine archives in this context is crucial, as they allow for the simultaneous recording of land-sea interactions, facilitating comprehensive testing and validation of these correlations. This, in turn, enhances our understanding of environmental changes. By focusing on three key case studies, including Semaforo, Vrica-Santa Lucia, and Montalbano Jonico sites, we illustrated how interdisciplinary approaches to marine successions are indispensable for detecting synchronous climatic and environmental shifts across the Mediterranean region (Figs 3-6). Furthermore, following the two preceding insights into the Italian sites, comparisons were extended to coeval continental and/or marine sites within the Mediterranean region, as well as to key sites at a broader extra-Mediterranean scale. In Fig. 2 the Astronomically Tuned Neogene Time Scale (ATNTS2004) by Lourens et al. (2004) is used as reference, integrating marine sedimentary cycles, palaeomagnetic reversals, and biostratigraphy from Mediterranean deep-sea cores (Ocean Drilling Program-ODP sites). This chronology provides a robust framework based on oxygen isotope, Milankovitch cyclicity, sapropel layers, and calcareous plankton bioevents. Sapropel stratigraphy aligns with the syntheses by Lourens et al. (1996a, 2004). The Pliocene-Pleistocene chronostratigraphy follows the International Union of Geological Sciences (IUGS) standard (June 2009; Head et al., 2008; Walker & Geissman, 2009). Additional chronostratigraphic comparison is made with Gradstein et al. (2004) and Gradstein & Ogg (2020) for clarity. Biozones of calcareous nannofossils are based on Rio et al. (1990), and planktonic foraminiferal zones on Cita (1975, amended) and Lirer et al. (2019). Astronomical ages for biozone boundaries follow Lourens et al. (2004) and Raffi et al. (2006). The pollen records from selected Italian continental and marine sites are constrained by palaeomagnetic, marine stratigraphic, and biochronological markers (e.g., mammalian biozones) (Fig. 2). Stratigraphic and geological data for each site, along with references for detailed pollen data, are from Bertini (2010), Bertini et al. (2010), Sadori et al. (2013), Combourieu-Nebout et al. (2015), Magri et al. (2017), Bertini & Combourieu-Nebout (2023), along with relevant references therein.

FROM LATEST PIACENZIAN TO CHIBANIAN: A COMPREHENSIVE SYNTHESIS OF KEY ENVIRONMENTAL CHANGES IN ITALY

This overview focuses on the first three stages of the Pleistocene, emphasising significant climate changes, including the strengthening of the Northern Hemisphere Glaciation (NHG) around 2.7 Ma (e.g., Ravelo et al., 2004; Bartoli et al., 2005, 2011; Mudelsee & Raymo, 2005; Ruggieri et al., 2009; Kabot-Bhar et al., 2021; McClymont et al., 2023) following the mid-Piacenzian Warm Period (mPWP, 3.3-3 Ma), characterised by reduced global ice volume and elevated pCO_2 (e.g., de la Vega et al., 2020). It also analyses the EMPT (1.25-0.4 Ma; Head & Gibbard, 2015), which resulted in intensified glacial phases in the Mediterranean region and at global scale, leading to increased aridity on land and more pronounced fluctuations in marine environments.

Latest Piacenzian-Gelasian (Figs 1-4)

Since the late Piacenzian, the shift from relatively warm to cooler climates paved the way for the high-magnitude G/I cycles of the Quaternary. The Gelasian (~2.58-1.8 Ma, Marine Isotope Stages, MIS 103-MIS 65/64), marking the beginning of this period, is characterised by the onset of large-scale NHG driven by obliquity (41 kyr). This transition profoundly impacted global climate patterns, leading to significant changes in both terrestrial and marine environments throughout the Mediterranean region.

Marine records - The Pliocene-Pleistocene transition marks the onset of the profound G/I fluctuations with sawtooth pattern of benthic $\delta^{18}O$, which were the main feature of Pleistocene Epoch as recorded by multiple data (e.g., Shackleton et al., 1995; Lisiecki & Raymo, 2005). The transition is well documented in the Mediterranean marine archives thanks to well exposed on land sedimentary successions, which allowed high resolution cyclostratigraphy and biostratigraphy starting from the Piacenzian (e.g., Zachariasse et al., 1989; Sprovieri et al., 2006). The $\delta^{18}O$ records, both at low (e.g., Lourens et al., 1992; Howell et al., 1998; Kroon et al., 1998; Serrano, 2020) and high resolution (Becker et al., 2005; Grant et al., 2022; Addante et al., 2024a-b, 2025; Zanola et al., 2024), evidence the high latitude climate variability but also the influence of low latitude African monsoon activity (Rohling et al., 2015), which determined the deposition of sapropel layers in marine sediments at the precession scale (Hilgen, 1991; Rohling et al., 2015). These climate conditions affected the calcareous plankton evolution in response to progressive lower sea surface temperature, variation of salinity and nutrient availability, and structure of photic waters (stratification/mixing, nutricline/thermocline depth). Related to the cooling trend through PPt and the NHG and maybe to shallowing nutricline and mixing (Schueth & Bralower, 2015; Tangunan et al., 2018) is the prominent drop of warm and oligotrophic nannofossil *Discoaster* spp. documented in many deep sea cores recovered during several ODP expeditions (e.g., ODP Legs 13, 42, 107, 160, 161; see http://www-odp.tamu.edu/publications/) and on land marine sections, such as Monte San Nicola (Driever, 1988; Channell et al., 1992; Rio et al., 1998; Addante et al., 2025), Mandorlo (Capraro et al., 2022; Zanola et al., 2024), and Punta Piccola (Castradori et al., 1998) in Sicily, Singa in Calabria (Lourens et al., 1992), along with Marecchia Valley in northern Apennines (Rio et al., 1996). They also enriched the Mediterranean calcareous plankton biostratigraphic

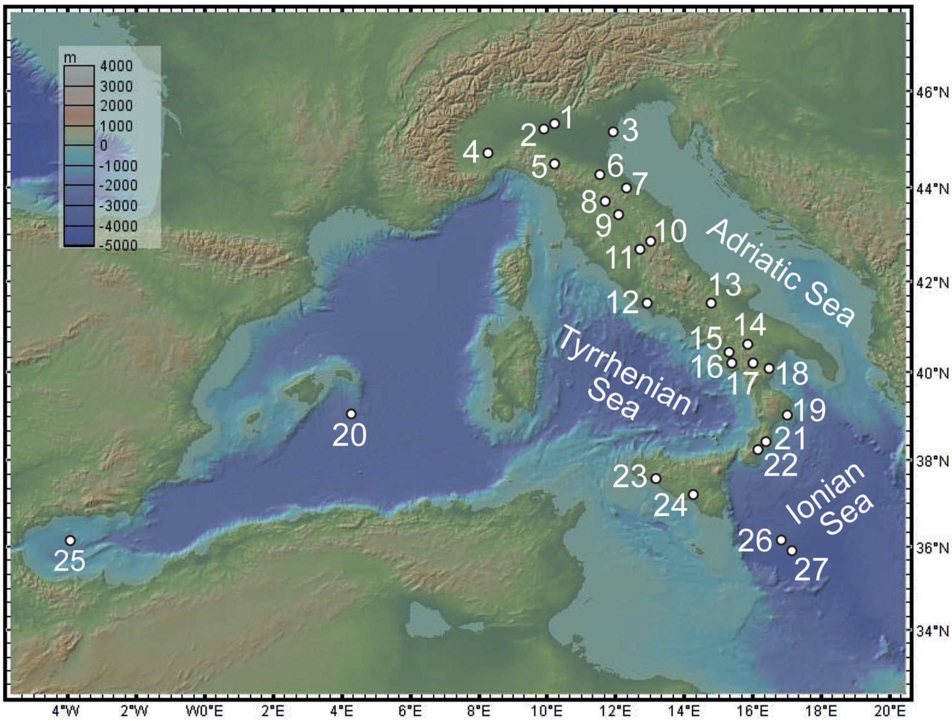
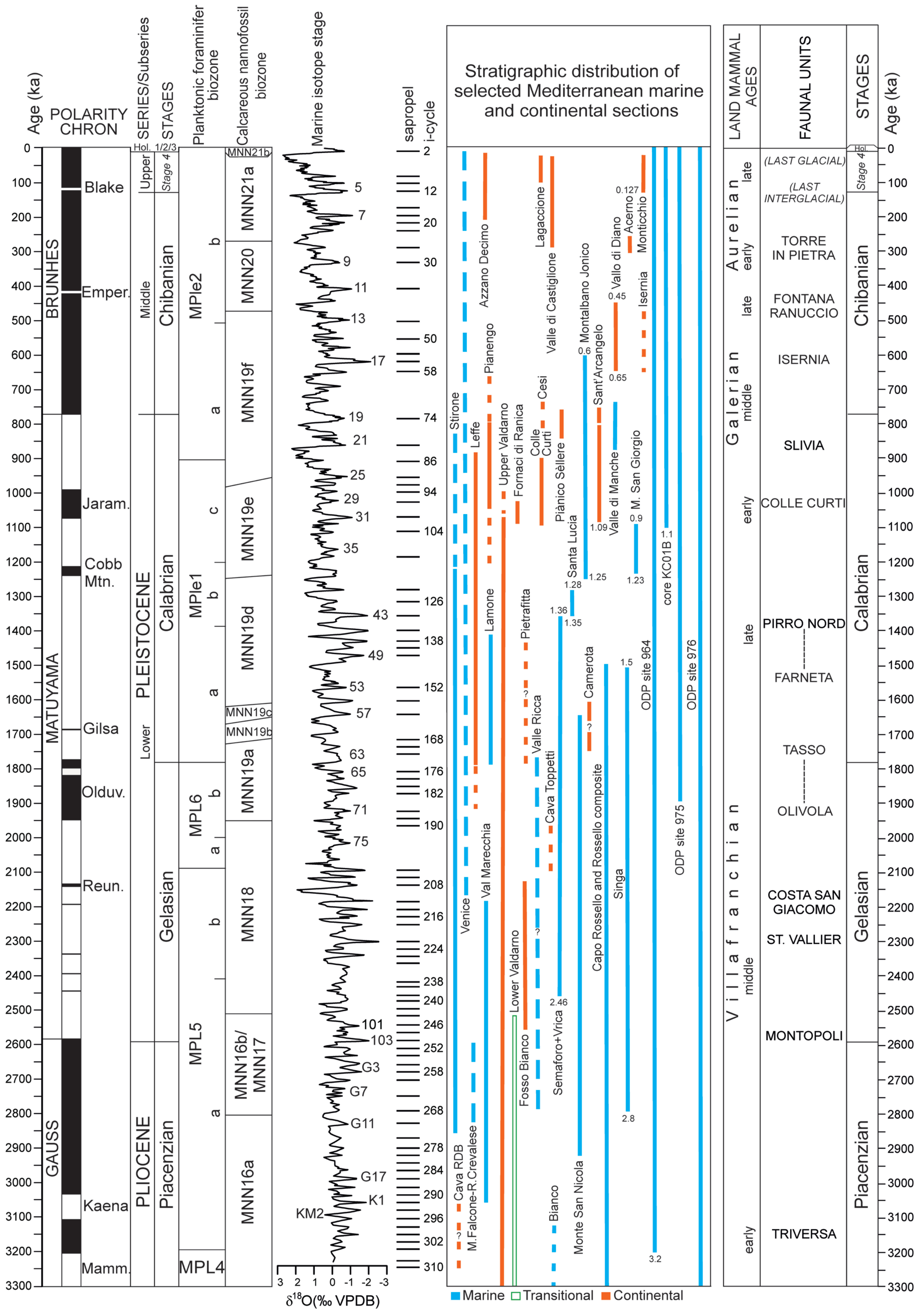


Fig. 1 - (color online) Location map of selected Pleistocene marine and continental sites (1-27). 1: Piànico-Sèllere; 2: Leffe; 3: Venice; 4: Cava RDB; 5: Castell'Arquato, Stirone; 6: Lamone, Santerno; 7: Val Marecchia; 8: Lower Valdarno; 9: Upper Valdarno; 10: Colfiorito; 11: Tiberino Basin; 12: F. Ranuccio-Costa S. Giacomo; 13: Isernia; 14: Monticchio; 15: Acerno; 16: Vallo di Diano; 17: Sant'Arcangelo; 18: Montalbano Jonico; 19: Crotone Basin; 20: ODP site 975; 21: Singa; 22: Bianco; 23: Punta Piccola-Capo Rossello; 24: Monte San Nicola; 25: ODP site 976; 26: core KC01B; 27: ODP site 964. For additional information on sites see the references in Bertini et al. (2010) and Bertini & Combourieu-Nebout (2023).


Age (ka)
POLARITY CHRON
SERIES/Subseries
STAGES
Planktonic foraminifer biozone
Calcareous nannofossil biozone
Marine isotope stage
sapropel i-cycle
Stratigraphic distribution of selected Mediterranean marine and continental sections
LAND MAMMAL AGES
FAUNAL UNITS
BRUNHES
MATUYAMA
GAUSS
Blake
Emper.
Jaram.
Cobb Mtn.
Gilsa
Olduv.
Reun.
Kaena
Mamm.
PLEISTOCENE
PLIOCENE
Upper
Middle
Lower
Hol.
Chibanian
Calabrian
Gelasian
Piacenzian
MPle2
MPle1
MPL6
MPL5
MPL4
MNN21b
MNN21a
MNN20
MNN19f
MNN19e
MNN19d
MNN19c
MNN19b
MNN19a
MNN18
MNN16b/MNN17
MNN16a
δ18O(‰ VPDB)
Stirone
Venice
Cava RDB
M.Falcone-R.Crevalese
Leffe
Azzano Decimo
Pianengo
Lamone
Val Marecchia
Upper Valdarno
Lower Valdarno
Fornaci di Ranica
Fosso Bianco
Pietrafitta
Colle Curti
Cesi
Lagaccione
Valle di Castiglione
Valle Ricca
Cava Toppetti
Piànico Sèllere
Semaforo+Vrica
Bianco
Santa Lucia
Montalbano Jonico
Monte San Nicola
Sant'Arcangelo
Camerota
Capo Rossello and Rossello composite
Vallo di Diano
Valle di Manche
Singa
Acerno
Monticchio
Isernia
M. San Giorgio
ODP site 964
core KC01B
ODP site 975
ODP site 976
Marine
Transitional
Continental
Aurelian
Galerian
Villafranchian
early
middle
late
(LAST GLACIAL)
(LAST INTERGLACIAL)
TORRE IN PIETRA
FONTANA RANUCCIO
ISERNIA
SLIVIA
COLLE CURTI
PIRRO NORD
FARNETA
TASSO
OLIVOLA
COSTA SAN GIACOMO
ST. VALLIER
MONTOPOLI
TRIVERSA

schemes (e.g., Cita, 1975; Rio et al., 1990; Lirer et al., 2019; see also synthesis in Capraro & Maiorano, 2023), the sapropel stratigraphy and the Astronomical Time Scale (Lourens et al., 1996a). In the Monte San Nicola section, where the Global Stratigraphic Section and Point (GSSP) of the Gelasian Stage was defined (Rio et al., 1998), the last occurrence of *Discoaster pentaradiatus* (Tan, 1927) has been recently assigned to an age of 2.52 Ma (Addante et al., 2024a), within MIS 100, together with a relevant abundance drop of the genus. Moreover, a first significant occurrence of the polar-subpolar foraminifer *Neogloboquadrina atlantica* (Berggren, 1972) has been recognised during MIS 104, just below the Gelasian GSSP, and in MIS 100. The influxes of this taxon in the Mediterranean Sea were previously reported through the Pliocene-Pleistocene transition (MIS 104 and MIS 100) by other authors (e.g., Lourens et al., 1996a; Caruso, 2004; Becker et al., 2005; Addante et al., 2024b). These calcareous plankton events are a clear signal of climate deterioration and cooling of sea surface temperature (SST), which also emphasise the connection between high and middle latitude climate during the NHG. The southward migration of the Subarctic Front at these times agrees with lower alkenone-SSTs at the Monte San Nicola section (Herbert et al., 2018; Addante et al., 2024a) and is contemporaneous with the occurrences of ice rafted debris (Naafs et al., 2013), lower sea surface temperature (Naafs et al., 2020) and *N. atlantica* (Bolton et al., 2010) at the mid-latitude North Atlantic Integrated Ocean Drilling Program-IODP site U1313.

Terrestrial records - Pollen data indicate a marked transition toward cooler and drier conditions. The prevalent expansion of open steppe-like vegetation and a reduction in forested areas suggest a response to the advancing glaciations. Notably, the palynological records show a decline in thermophilous arboreal taxa particularly those currently distributed in subtropical regions, and an increase in herbaceous plants, reflecting the colder, more arid climate (Bertini, 2010; Suc et al., 2018; Bertini & Combourieu-Nebout, 2023 and references therein).

After the glacial marine isotope stage M2 (~3.3 Ma), the mPWP marked a final global warm phase, characterised by a rise in sea surface temperatures of approximately 3 °C and atmospheric CO_2 levels reaching around 400 ppm, comparable to modern anthropogenic levels (e.g., Haywood & Valdes, 2004; Pagani et al., 2009; Bartoli et al., 2011). In central Italy, at Santa Barbara (Upper Valdarno), a rich subtropical-to-warm-temperate forest thrived during this warm phase (~3.0 Ma), following the cooling episodes of M2 and MG2. Dominated by *Taxodium/Glyptostrobus*-type, *Nyssa*, and other thermophilous taxa, this forest gradually transitioned to cooler species such as *Picea* and *Fagus* around 2.8 Ma, indicating a shift towards cooler conditions (Bertini, 2010, 2013). This transition aligns with isotopic evidence of intensifying glaciation and the subsequent reduction or disappearance of thermophilous taxa across central and northern Italy (Bertini, 2010 and references therein).

In southern Italy, Piacenzian pollen records, though more limited, reveal a cool, humid climate with reduced seasonality around 3.31 Ma, especially at Bianco, where forests were dominated by *Picea* and *Abies*, and Mediterranean evergreen taxa experienced a marked decline (Bertoldi et al., 1989). Between 3 and 2.92 Ma, at Punta Piccola (Sicily), high-resolution records suggest alternating warm and arid phases linked to precession cycles, with humid conditions prevalent during the deposition of laminated sediments (Combourieu-Nebout et al., 2004). By 2.5 Ma, increasingly drier conditions and the spread of Mediterranean vegetation were documented at Capo Rossello (Sicily), reflecting a progressive shift towards arid climates during the warm season (Bertoldi et al., 1989; Rio et al., 1990). Since ~3.0 Ma, the intensification of Mediterranean outflow and the onset of NHG further triggered cooler, more seasonal, and drier conditions across the Mediterranean region (Lourens et al., 1996b, 2004). This is reflected in the 41 kyr obliquity-driven G/I cycles observed in Italian pollen records, characterised by alternating forest and steppe vegetation (Bertini, 2010; Combourieu-Nebout et al., 2015). A prominent example is the Semaforo section (Crotone, Calabria) (Fig. 4a-b and c1), where pollen and oxygen isotope data provide evidence of these climatic shifts from 2.46 Ma onwards (Combourieu-Nebout & Vergnaud-Grazzini, 1991; Combourieu-Nebout, 1993, 1995). However, pollen data from other southern Italian sites, such as the Gelasian sites at Le Castella and Gela (Monte San Nicola), reveal a contrasting pattern, where forests expanded during glacials, and open vegetation dominated during interglacials, according to Bertoldi et al. (1989). More recent high-resolution studies at Monte San Nicola refine the previously described pattern, contrasting with the more typical one observed along the Mediterranean littoral (Bertini et al., 2024). Glacial and interglacial intervals are distinctly characterised by the prevalence of steppe taxa and thermophilous arboreal plants, respectively. In northern Italy, G/I cycles at sites like Castell'Arquato and Stirone (Emilia-Romagna) are characterised by subtropical-to-warm-temperate forests, contrasting with coniferous forests, with limited steppe vegetation (Bertini, 2001). In the Upper Valdarno Basin, a significant expansion of herbaceous taxa, including *Artemisia*, was recorded in aeolian deposits during the first G/I cycles (Bertini, 1994, 2010). The Piacenzian-Gelasian transition in the Tiberino Basin shows vegetation responding to G/I cycles through the competition between

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Fig. 2 - (color online) Marine and continental fossil correlation from late Piacenzian to Chibanian in Italy and the Mediterranean Sea. On the left, the Standard Biochronostratigraphy. The column Series reports the Pliocene-Pleistocene chronostratigraphy according to the IUGS statement (June 2009), Head et al. (2008), and Walker & Geissman (2009). Planktonic foraminifera biozones are from Cita (1975), emended, and Lirer et al. (2019). Calcareous nannofossil biozones are from Rio et al. (1990). In the column Stages, 1, 2, and 3 correspond to the Greenlandian, Northgrippian and Meghalayan, according to Walker et al. (2018). The Mediterranean $\delta^{18}O$ planktonic foraminifer *Globigerinoides ruber* stacked record is from Lourens (2004, and references therein). Sapropel age/stratigraphy is in agreement with the synthesis in Lourens et al. (1996b, 1998) and Lourens (2004). Land Mammal Ages are from Gliozzi et al. (1997), modified; Faunal Units are from Palombo (2004, 2007), Rook & Martínez-Navarro (2010). For additional information on Italian and Mediterranean sites see the references in Bertini et al. (2010) and Bertini & Combourieu-Nebout (2023).

Fig. 3 - (color online) a) Panoramic view of the Crotone area. b) Semaforo section with indication of sapropel layer. c) View on the five parts of the Crotone series. d) Details of the Vrica C section with indications of some sapropel layers. e-f) Details of the Vrica B section with indication of the ash layer and some sapropel layers.

coniferous and thermophilous forests (Pontini, 1997; Martinetto et al., 2014). In northern Italy, the progressive decline of "Taxodiaceae" forests (including Taxodioideae and Sequoioideae) and the rise of *Cathaya* are noted from around 2.7 Ma (Stirone), while in southern Italy, "Taxodiaceae" forests at Semaforo decline from 2.38 Ma, with *Cathaya* expanding significantly between 1.92 and 1.74 Ma (Combourieu-Nebout & Vergnaud-Grazzini, 1991; Klotz et al., 2006; Suc et al., 2010).

Climate reconstructions for the last 200 kyrs of the Piacenzian at Stirone (northern Italy) indicate warm and cold phases with temperature and precipitation values similar to those of the following Gelasian (Fauquette & Bertini, 2003). During the Gelasian, warm phases in northern Italy exhibited high mean annual temperatures (MATs) and precipitation (MAP), comparable to those of the Zanclean, with temperatures around 12-13 °C during glacials and precipitation exceeding modern values by 200-500 mm. In central Italy (Poggio Rosso, Upper Valdarno), climate amplitude reconstructions from a G/I cycle just before the Gelasian/Calabrian boundary show MATs of 12.5-14 °C and MAP of about 800 mm during glacials (with a minimum of 400 mm) and MATs of 15-19 °C and MAP of 750-1200 mm during interglacials (Bertini et al., 2010). In southern Italy, the Semaforo site reveals higher interglacial temperatures (by at least 2.8 °C annually and 2.2 °C in winter) and 500 mm more precipitation compared to today, during the period from 2.46 to 2.11 Ma (Klotz et al., 2006). Glacial conditions showed temperatures similar to present, with precipitation remaining equivalent and occurring all year along, although there was a general cooling trend over consecutive G/I cycles.

Calabrian (Figs 1-6)

As previously noted, the EMPT marked a major global climatic reorganisation that profoundly influenced oceanic and atmospheric circulation, ice sheets, and biota, including early humans (Head & Gibbard, 2015). Lasting until about 0.4 Ma, it saw a shift from 41 kyr obliquity-driven cycles of the Early Pleistocene to the 100 kyr G/I cycles of the later Pleistocene. Several severe glaciations occurred, such as MIS 36, 24, and 22, particularly impacting the Northern Hemisphere.

Marine records - The Calabrian Stage, covering MIS 65/64 to MIS 19 interval, is well represented in the Mediterranean region due to the on land marine successions well exposed mainly in the Crotone Basin (Calabria) and Sicily, and deep-sea cores (ODP sites 964 and 967, KC01B) (see a synthesis in Cita et al., 2006, 2008, and reference therein). The Vrica section, housing the Calabrian GSSP, consists of spectacularly exposed blue hemipelagic marly clays, astronomically calibrated thanks to the occurrence of several sapropel layers (Lourens et al., 1996b, 1998). It is a continuous succession with high sedimentation rate (Pasini & Colalongo, 1994; Rio et al., 1996; Suc et al., 2010) that made possible wide interdisciplinary study including marine invertebrate (molluscs, ostracods, planktonic and benthic foraminifera) and pollen (Suc et al., 2010 and references therein) as well as oxygen isotope stratigraphy and magnetostratigraphy (Lourens et al., 1996a, 1998). Among the plethora of biostratigraphic events and data, it is worth to mention the signals of climate deterioration close to the Calabrian GSSP that are the extinction of the warm nannofossil *Discoaster brouweri* (Tan, 1927, emend. Bramlette & Riedel, 1954) (the last survivor of the genus decimated during the PPt), the first increase in abundance of polar-subpolar *Neogloboquadrina pachyderma* (left-coiled) (Lourens et al., 1996a), and the first occurrence of the cold guest benthic foraminifer *Hyalinea balthica* (Schröter, 1783), the latter also recorded at the Rossello section in MIS 53 (Caruso, 2004). Other significant biostratigraphic events in the Calabrian Stage are the appearance of medium-sized *Gephyrocapsa* (4-5.5 μm) (*G. oceanica* Kamptner, 1943; *G. caribbeanica* Boudreaux & Hay in Hay et al., 1967), the last occurrence of *Calcidiscus macintyrei* (Bukry & Bramlette, 1969), the first occurrence of large *Gephyrocapsa* (> 5 μm), and the last occurrence of *Helicosphaera sellii* (Bukry & Bramlette, 1969) (e.g., Rio et al., 1990). Following a temporary disappearance/rarity of *N. pachyderma* from MIS 43 to MIS 37, a new increase of the species is recorded in the glacial MIS 36, in agreement with its distribution in the Montalbano Jonico section (MJS, Girone et al., 2013a) and ODP site 967 (Lourens et al., 1998), almost synchronously with data from North Atlantic Ocean (ODP site 607, Ruddiman et al., 1989; see synthesis in Maiorano et al., 2010). The MIS 31, considered as a super interglacial analogous of the present Holocene (Maldonado et al., 2014) and the last significant warm interglacial of the obliquity-dominated climate regime (Scherer et al., 2008), is a significant wide scale period of climate amelioration. It is recorded in the Mediterranean $\delta^{18}O$ record (Lourens et al., 1996a, 2004; Lourens, 2004) and the MJS, and is accompanied by a biostratigraphic event maybe of climate significance, the lowest common occurrence of the extinct nannofossil *Reticulofenestra asanoi* (Sato & Takayama, 1992) (Maiorano et al., 2004). A severe cold glacial during the Calabrian is represented by MIS 22 as recorded in the MJS. It marks the beginning of higher amplitude G/I oscillations and is characterised by the base of temporary disappearance of the warm nannofossil *Gephyrocapsa omega* (Bukry, 1973) (Maiorano et al., 2004) because of the cooling trend during the first major ice volume-induced sea level decrease of the Pleistocene (Shackleton & Opdyke, 1976).

Terrestrial records - In southern Italy, extensive palynological records provide evidence of climatic changes across this interval. Notable sites include Vrica (ca. 2.2-1.36 Ma; e.g., Combourieu-Nebout et al., 1990), Santa Lucia (1.356-1.24 Ma, Joannin et al., 2007), and Valle di Manche (0.87-0.73 Ma, e.g., Capraro et al., 2005, 2022) in the Crotone Basin, along with marine and continental records from the MJS (1.24-0.9 Ma, Joannin et al., 2008; 0.82-0.774 Ma, Maiorano et al., 2008; Bertini et al., 2015; Toti, 2015; Toti & Bertini, 2018; Nomade et al., 2019) and Sant'Arcangelo successions (San Lorenzo cycle: ca. 1.1-0.8 Ma, Sabato et al., 2005) in Basilicata. Pollen assemblages indicate a dynamic interplay between open vegetation and forested landscapes, characterised by steppe taxa (e.g., *Artemisia*, *Ephedra*) and warm temperate forest species (e.g., *Quercus*, *Carya*). Contrastingly, northern Italy's records (e.g., Lamone: Fusco, 2007; Leffe: Ravazzi & Rossignol Strick, 1995; Muttoni et al., 2007; Stirone: Lona & Bertoldi, 1972; Bertolani Marchetti et al., 1979) show expansions of coniferous forests during glacial phases rather than steppe vegetation, while interglacials favoured thermophilous forest types. The Lamone marine succession exhibits three forest formations, including mixed-deciduous, Juglandaceae, and mountain coniferous forests, indicating fluctuating humidity levels. The flora experienced significant depletion, particularly with the decline of key taxa (e.g., "Taxodiaceae", *Cathaya*) around 1.2 Ma, marking the transition from subtropical ecosystems to deciduous forests in the Mediterranean (Combourieu-Nebout & Vergnaud Grazzini, 1991; Combourieu-Nebout et al., 2015).

Climate reconstructions reveal a pronounced cooling trend between 1.4 and 1.3 Ma, with reductions in winter temperatures and annual precipitation during both interglacial and glacial phases (Combourieu-Nebout et al., 2015), signalling a progressive increase in aridity, particularly during glacial periods.

Chibanian (Figs 1-2 and 5-6)

During the Chianian (MIS 19-MIS 6/5), which includes the upper portion of the EMPT (Mudelsee & Schulz, 1997; Clark, 2006; Elderfield et al., 2012), the Mediterranean region continued to experience progressive floristic impoverishment, aligned with climatic gradients, marked by severe glacial episodes (e.g., MIS 16, 12 and 6). The previously dominant 41 kyr G/I cycles (Pisias & Moore, 1981) transitioned to the longer 100 kyr cycles, extending the duration of glacial stages (Tzedakis, 2005, 2007; Leroy, 2007; Tzedakis et al., 2012) and the pronounced asymmetric pattern of G/I with increasingly "sawtooth" wave form of benthic oxygen isotope stratigraphy (Lourens, 2004; Lisiecki & Raymo, 2005; see also Past Interglacials Working Group of PAGES, 2016). This is the widely studied time interval that also benefits from the high-resolution data and chronology provided by ice cores (e.g., Bazin et al., 2013) and from estimate of sea-level changes (Elderfield et al., 2012). From MIS 11 onwards, a notable rise in interglacial temperatures and CO_2 levels was recorded during the mid-Brunhes Event (MBE), as evidenced by marine, terrestrial, and ice-core data (Masson-Delmotte et al., 2010; Lang & Wolff, 2011; McClymont et al., 2013).

Marine records - Marine records from different intervals of the Chibanian are well studied in the Mediterranean area based on multiproxy studies, testifying the occurrence of very high amplitude oscillations in climate proxies. The high climate variability influenced the calcareous plankton evolution although no significant turnover occurred in both foraminifera and nannofossil assemblages. They, however, display prominent abundance fluctuations of selected key taxa in response to variations in the environmental conditions at orbital and millennial to centennial scale that were a result of high-low icesheet volume and its instability, strength of thermohaline circulation and of Mediterranean-Atlantic water exchange, and brief influx of polar-subpolar taxa into the Mediterranean. The main examples of such events are from on land marine record of MJS (Marino et al., 2020, see detail below), deep-sea cores in MIS 20-19 transition (TIX, Quivelli et al., 2020, 2021; Toti et al., 2020) and the mid-Brunhes interval (Kandiano et al., 2012; Cortina et al., 2013; Girone et al., 2013b; Maiorano et al., 2013b, 2016b; Milker et al., 2013; Regattieri et al., 2015, 2019; Capotondi et al., 2016; Marino et al., 2018; Trotta et al., 2019; Azibeiro et al., 2021). The latter includes the exceptional cold glacial MIS 12 with sea level about 125 m below present (Bintanja et al., 2005; Elderfield et al., 2012) and the warm long-lasting MIS 11, considered an analogue of the Holocene (de Abreu et al., 2005), with sea level 20 m above the mean present level (e.g., Kindler & Hearty, 2000). The last occurrence of the extinct nannofossil *Pseudoemiliania lacunosa* (Kamptner, 1963) in MIS 12 (e.g., Raffi et al., 2006; Maiorano et al., 2016b) could represent a response to the severe cooling at this time, testified by the incursion of polar calcareous plankton taxa (*N. pachyderma* left coiled and *Coccolithus pelagicus* ssp. *pelagicus* (Wallich, 1877), together with cold low saline melt waters from the Atlantic Ocean into the Mediterranean through the Gibraltar Strait during the southward migration of the Polar Front. The occurrence of these taxa in the Mediterranean Sea allowed to recognise short-term colder events referred as Heinrich-type events (Girone et al., 2013b; Marino et al., 2018; Azibeiro et al., 2021) since their chronology correlates with that of ice rafted detritus (Stein et al., 2009; Alonso-Garcia et al., 2011; Naafs et al., 2011) and lower sea surface temperature (Rodrigues et al., 2011, 2017) in the North Atlantic Ocean, and more arid condition in the Mediterranean region (Larrasoaña et al., 2003). The evolution towards increased size (> 4 µm) of nannofossil *Gephyrocapsa margereli-muellerae* (sensu Baumann & Freitag, 2004) starting from MIS 12 and MIS 10, has been also recognised as a signal of colder glacials (Girone et al., 2013b; Maiorano et al., 2015; Marino et al., 2018). Whereas the influx of extinct warm nannofossil *Helicosphaera inversa* (Gartner, 1977) distinctly marks MIS 11 in the Mediterranean Sea (Maiorano et al., 2013a), in line with the increase of sea surface temperature and warm water taxa within planktonic foraminifera assemblages (Girone et al., 2013b; Maiorano et al., 2013b, 2016b; Capotondi et al., 2016) during enhanced northward transport of tropical waters in the Atlantic Ocean, as recorded west of Portugal (Voelker et al., 2010) and its influx into the Mediterranean.

Terrestrial records - Pollen records from southern sites during the early Chibanian indicate a dominance of *Artemisia* and *Ephedra* steppes, with alternating temperate to warm-temperate deciduous forests. Significant expansions of steppe taxa were observed at MJS during glacials and stadials within MIS 19 and the base of MIS 16 (Bertini et al., 2015; Toti & Bertini, 2018; Nomade et al., 2019; Toti et al., 2020). Conversely, the Valle di Manche site features alpine-type forests during MIS 18, characterised by *Picea*, *Abies*, and *Fagus* (Capraro et al., 2005, 2015). At Piànico-Sèllere in northern Italy, evidence of a prolonged interglacial phase within MIS 19 is indicated by the expansion of broad-leaved deciduous forests, followed by a contraction of thermophilous species and the rise of coniferous forests (Ravazzi, 2003; Pini et al., 2014). The floristic assemblages reflect climatic fluctuations, with taxa such as *Hippophaë rhamnoides* (Linnaeus, 1753) expanding during colder steppe phases and thermophilous taxa like *Cistus* declining (Suc et al., 1995). Chronological distribution studies have traced the last occurrences of several key taxa, including "Taxodiaceae," *Carya*, *Pterocarya*, and *Tsuga* (e.g., Bertini, 2010; Combourieu-Nebout et al., 2015; Magri et al., 2017). In northern Italy, *Tsuga*'s presence decreased significantly during the Early-Middle Pleistocene (Piànico-Sèllere: Pini et al., 2014; Moscariello et al., 2000), while it remained in southern sites until MIS 18 (Valle di Manche: Capraro et al., 2005; Montalbano Jonico: Bertini et al., 2015; Toti & Bertini, 2018), though always in low percentages. *Tsuga*'s decline has been linked to increasing global aridity and temperature reductions associated with the shift from 41 to 100 kyr Milankovitch cycles (Bertini, 2000), as well as to potential catastrophic fires during drought periods (Ravazzi et al., 2005). Overall, pollen data indicate that drought intensified during longer glacial periods, with shorter interglacials beginning at cooler temperatures (Combourieu-Nebout et al., 2015).

LAND-SEA CORRELATIONS IN THE MEDITERRANEAN REGION: CASE STUDIES FROM THE GELASIAN, CALABRIAN AND CHIBANIAN STAGES

The Gelasian: the effects of Northern Hemisphere Glaciations (southern Italy) as recorded in the Semaforo section (Figs 1-4 and 7)

The Semaforo section together with Vrica and Santa Lucia is part of the Crotone series (southern Italy), one of the most thoroughly studied Early Pleistocene succession.

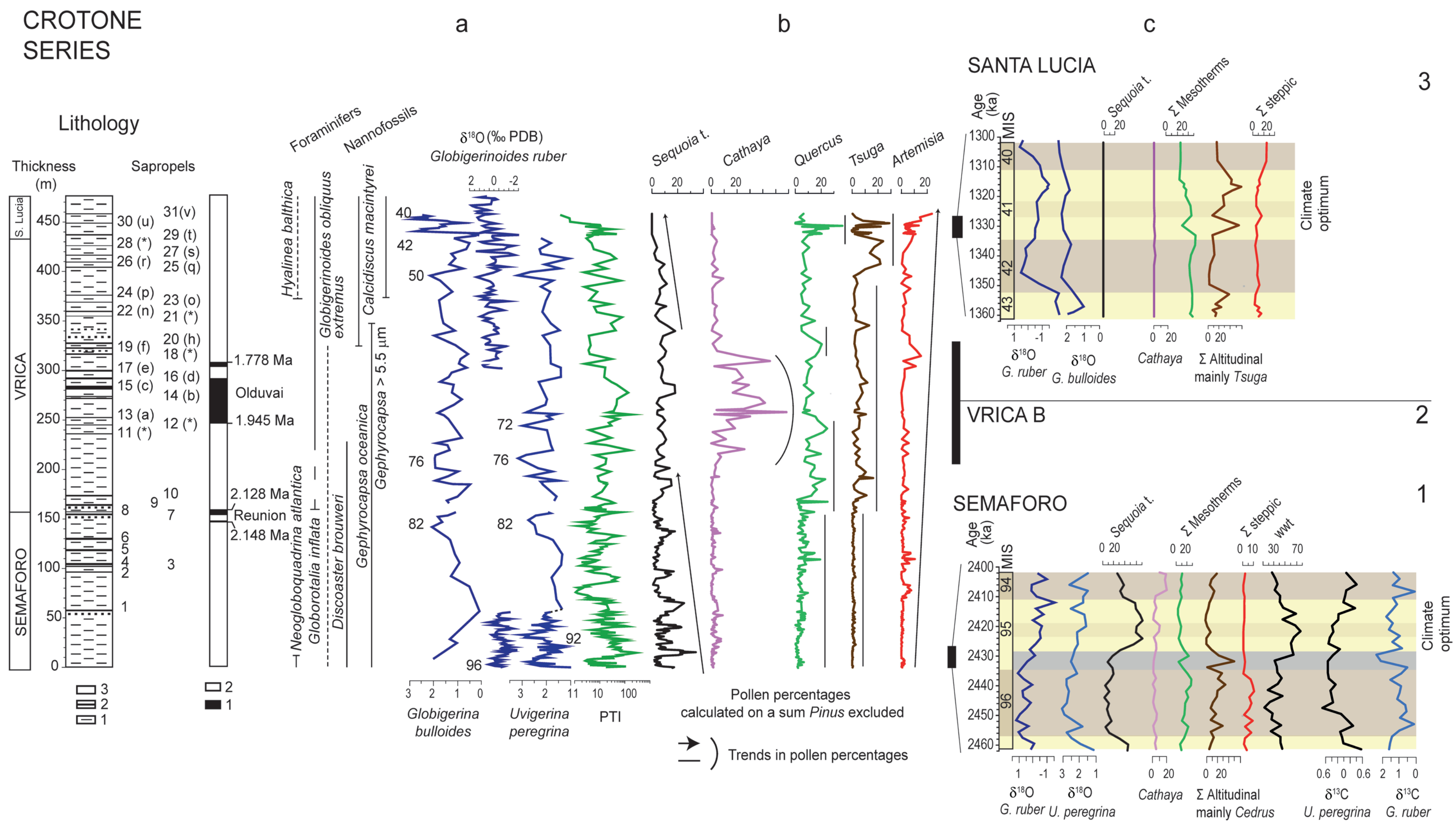


Fig. 4 - (color online) The Crotone series. a) Main sedimentary, chronological, and biostratigraphic constraints. b) Pollen curves of the main representatives of the vegetation. c) Three windows showing significant marine and terrestrial changes pertinent to palaeoenvironmental reconstructions: the Gelasian (Semaforo) (c1), the Gelasian/Calabrian transition (Vrica B) (c2), the Calabrian (Santa Lucia) (c3). Lithology: 1: clays; 2: sapropel; 3; ash. Magnetic polarity: 1: normal; 2: reverse. Wwt indicates warm water foraminifera.

Fig. 5 - (color online) a) Panoramic view of the badlands outcropping west of Montalbano Jonico town, showing the upper part of the studied succession and the V5-V9 volcaniclastic layers. b) The Ideale section with the main chronostratigraphic and palaeoenvironmental features.

Its exceptional location and depositional environment (Fig. 3) provided unparalleled opportunities for advancements in biostratigraphy, magnetostratigraphy, cyclostratigraphy, and precise chronological reconstructions (Suc et al., 2010; Cita et al., 2012, and references therein). The sedimentary succession mainly consists of grey claystones, including four main ash beds and 31 brownish sapropel layers, moderately to strongly laminated (Hilgen, 1991; Zijderveld et al., 1991; Combourieu-Nebout, 1995). The biostratigraphy of foraminifera and calcareous nannofossils within the Crotone series exhibits notable heterogeneity and some inconsistencies remain unresolved. Different approaches (e.g., Colalongo in Selli et al., 1977; Colalongo et al., 1981; D'Onofrio, 1981; Spaak, 1983; Hilgen, 1990; and unpublished data from J. Cravatte and F. Quillevére, as cited in Joannin et al., 2007) led to some taxonomic inconsistencies and discrepancies in species biostratigraphic ranges, particularly for taxa like *Neogloboquadrina atlantica*. In the case of calcareous nannofossils, early low-resolution studies (e.g., Cati & Borsetti, 1981; Nakagawa et al., 1997) were significantly expanded by Rio et al. (1997), who provided a detailed record of the Vrica section, later complemented by Lourens et al. (1998) using data from the Santa Lucia section. However, no nannofossil analyses have been conducted on the Semaforo section. Other microfossil groups, such as ostracods and diatoms, along with macrofossils like molluscs and fishes, offered limited biostratigraphic data (for more detailed discussions, refer to Pasini & Colalongo, 1997). The three main sections are stratigraphically more or less overlapping, i.e., the Semaforo section is entirely within the Gelasian Stage, the Vrica (A, B, C) section partly belongs to the Gelasian, partly to the Calabrian Stage, and the Santa Lucia section belongs to the Calabrian Stage. The Crotone series covers the time-interval from 2.47 to 1.21 Ma and displays 30 complete G/I cycles, from MIS 97 to MIS 37. Insolation cycles (i-c) are recorded from i-c236 to i-c116 by combining lithology (sapropels) and palynology (amorphous organic matter and abundance in pollen grains of riparian trees, two indices of anoxic condition development and runoff intensity, respectively). The understanding of Early Pleistocene G/I cycles pollen records was clarified as the response of vegetation to the strong interaction between precession and obliquity as analysed along several successive climatic cycles.

The Semaforo section, covering the lower part of the Crotone series, from 2.45 to 2.2 Ma, records the first climate cycles (G/I) driven by the obliquity periodicity (about 41 kyr) (Figs 3 and 4b, c1), linked to the onset of northern polar ice sheet. During interglacials, continental areas were dominated, as indicated by pollen data (Combourieu-Nebout, 1993; Fig. 4b, c1), by extensive *Sequoia* forest, and exhibit the recurrent development of subtropical forests associated to warm and yearly humid climate. In contrast, glacials were characterised by the expansion of steppe vegetation and the growth of coniferous forests at higher altitude as evidenced by increases of *Artemisia* and *Cedrus* pollen grains, respectively. These patterns indicate cyclic dry and/or cool conditions. In the marine environment, oxygen isotope curves illustrate the regular alternation between warm and cold conditions, with the earliest G/I alternations detailed in Fig. 4c1. These cycles are characterised by the last occurrence in MIS 96 of cold water *Neogloboquadrina atlantica*, following its short-term pulses in the Mediterranean Sea during colder glacials MIS 100 and MIS 98 as recorded in the Singa section (Zachariasse et al., 1990; Lourens et al., 1992) and Capo Rossello (Caruso, 2004) in agreement with colder sea surface temperature (Herbert et al., 2015, 2018), and by the extinction of *Globorotalia bononiensis* (Dondi, 1962) at the base, as well as the first occurrence of *Globorotalia inflata* (d'Orbigny, 1839a) (e.g., Spaak, 1983). At Capo Rossello, the cyclostratigraphic and micropalaeontological study of Caruso (2004) reports a rich planktonic foraminifera assemblage characterised by fluctuating abundances of warm, temperate and cold taxa in relation to the Gelasian climate cycles, e.g., *Globigerinoides ruber* (d'Orbigny, 1839b), *Trilobatus sacculifer* (Brady, 1877), *Globorotalia crassaformis* (Galloway & Wissler, 1927), *Truncorotalia truncatulinoides* (d'Orbigny, 1839a), *Globigerina bulloides* (d'Orbigny, 1826), and *Turborotalita quinqueloba* (Natland, 1938). Several peaks of *N. atlantica* are observed and correlate with *Artemisia* steppe phases. Oxygen isotope oscillations show consistent intensity, except for MIS 94, which appears less cold, and corresponds to a smaller retreat of forests on the continent (Combourieu-Nebout, 1993). The selected time slice of the base of the Semaforo (Fig. 4c1) highlights the G/I cycle corresponding to MIS 96-95 oscillations. This interval captures the peak development of *Sequoia* forest in the Semaforo section and the initial retreat of the subtropical taxa during the Early Pleistocene. In pollen record, a decrease in *Sequoia* forest is accompanied by an increase in *Artemisia* pollen, indicating steppe expansion during the glacial period (Fig. 4c). Simultaneously, the occurrence of *Neogloboquadrina atlantica* is a signal of cooling of sea surface water in the Ionian Sea during this glacial episode. The warming in the sea water (wwt) as expressed by the lower value in $\delta^{18}O_{G.\ bulloides}$ and the *Sequoia* forest pollen record show parallel patterns illustrating simultaneous temperature variations in the sea surface and terrestrial environments (Fig. 4c). However, the wwt curve from planktonic foraminifer $\delta^{18}O$ appears to rise earlier than the vegetation shift marked by the expansion of the *Sequoia* forest. The end of the MIS 96 is earlier in the Mediterranean waters suggesting that response of marine environment to climate changes was more rapid than continental ones. This is probably due to the dynamics of the vegetation that need time to get started after the glacial. During the MIS 95 climatic optimum, a slight oscillation is observed between *Sequoia* and *Cathaya* representation in the forest. This might reflect a minor cooling, as *Cathaya* is known to persist under cooler conditions.

Calabrian: Intensification of glaciations and disappearance of subtropical ecosystems in the southern Mediterranean as recorded in the Vrica and Santa Lucia sections (southern Italy) (Figs 1-4 and 7)

The Crotone series provides significant and unique stratigraphic and palaeoenvironmental insights also for the Calabrian, as demonstrated by records from the Vrica and Santa Lucia sections (Figs 3 and 4). They document the successive steps of changes in flora and vegetation. The decline and/or disappearance of all subtropical taxa such as *Sequoia*, *Engelhardia*, *Distylium*, and other Hamamelidaceae represent the most prominent event straddling the Gelasian/Calabrian transition. This shift is associated to a notable reduction in flora and ecosystem diversity in southern Italy. The cooling shift is also recorded through the Gelasian-Calabrian transition in marine realm marked by several events that could represent a turnover in calcareous plankton: the last occurrence of *Discoaster brouweri*, the first occurrences of *Globigerina cariacoensis* (Rögl & Bolli, 1973), *Globigerina calabra* (Colalongo & Sartoni, 1977) and of *Globigerinoides tenellus* (Parker, 1958), the extinction of *Globigerinoides obliquus extremus* (Bolli & Bermudez, 1965), the re-occurrence of abundant *Neogloboquadrina pachyderma* left coiled (First Common Occurrence) and the appearance of nannofossil medium-sized *Gephyrocapsa* (4-5.5 µm), followed by the disappearance of *Calcidiscus macintyrei* (Bukry & Bramlette, 1969) and the appearance of large *Gephyrocapsa* (> 5.5 µm) (see Cita et al., 2008, 2012; Lirer et al., 2019 and references therein). The increasing size in the placoliths of *Gephyrocapsa* may have been a response to a lowering trend of sea water temperature, in agreement with Kulhanek (2009), Girone et al. (2013b), Marino et al. (2014).

This is shown primarily by the consistent decline in *Sequoia* forest during interglacials, culminating in its near-complete disappearance at ~1.3 Ma in the Santa Lucia section. The concomitant expansion of *Quercus* forest between 2.1 and 1.95 Ma, followed by *Cathaya* forest between ~1.9 and ~1.7 Ma suggests a gradual cooling of interglacial maxima. Strong glacials, as depicted in the oxygen isotope record, occurred just before the expansion of *Cathaya* forest and may have been a contributing factor to the significant retreat of *Sequoia* in southern Italian forests. This decline likely reflects the combined effects of climatic cooling and competition among plant taxa. After 1.7 Ma, the forest underwent a significant restructuring, marked by the rapid retreat of *Cathaya* forest in southern Italy. This is followed by the establishment of a *Quercus* forest with *Carya* at mid-altitude and then of a coniferous forest with *Tsuga* at higher altitude, indicating further cooling of interglacial conditions. Simultaneously, marine evidence in the Vrica section shows the first occurrence of *Hyalinea balthica*, a foraminifer associated with cold waters (Selli, 1967). The oxygen isotopes record strong glacial conditions, especially in sea surface waters, as documented in the Santa Lucia section. Notably, a slight oscillation is observed during the MIS 41 (details in Fig. 4), between *Quercus* and *Tsuga*, likely reflecting a brief temperature drop, with *Tsuga* persisting under cooler conditions. In the Santa Lucia section, the MIS 41 optimum is clearly represented by the abundance of *Quercus* and *Tsuga* and correlated with warming in the sea surface. This warming appears to have commenced earlier in the last G/I cycle recorded in the Vrica section. In parallel, glacials became increasingly severe, marked by the expansion of *Artemisia* steppe, especially in the Santa Lucia section. This reflects enhanced dryness during glacials. In fact, *Artemisia* steppe reaches its maximum extent within the Crotone series at the top of the Santa Lucia section, just after 1.3 Ma, corresponding to an intense glacial period as indicated by oxygen isotope records.

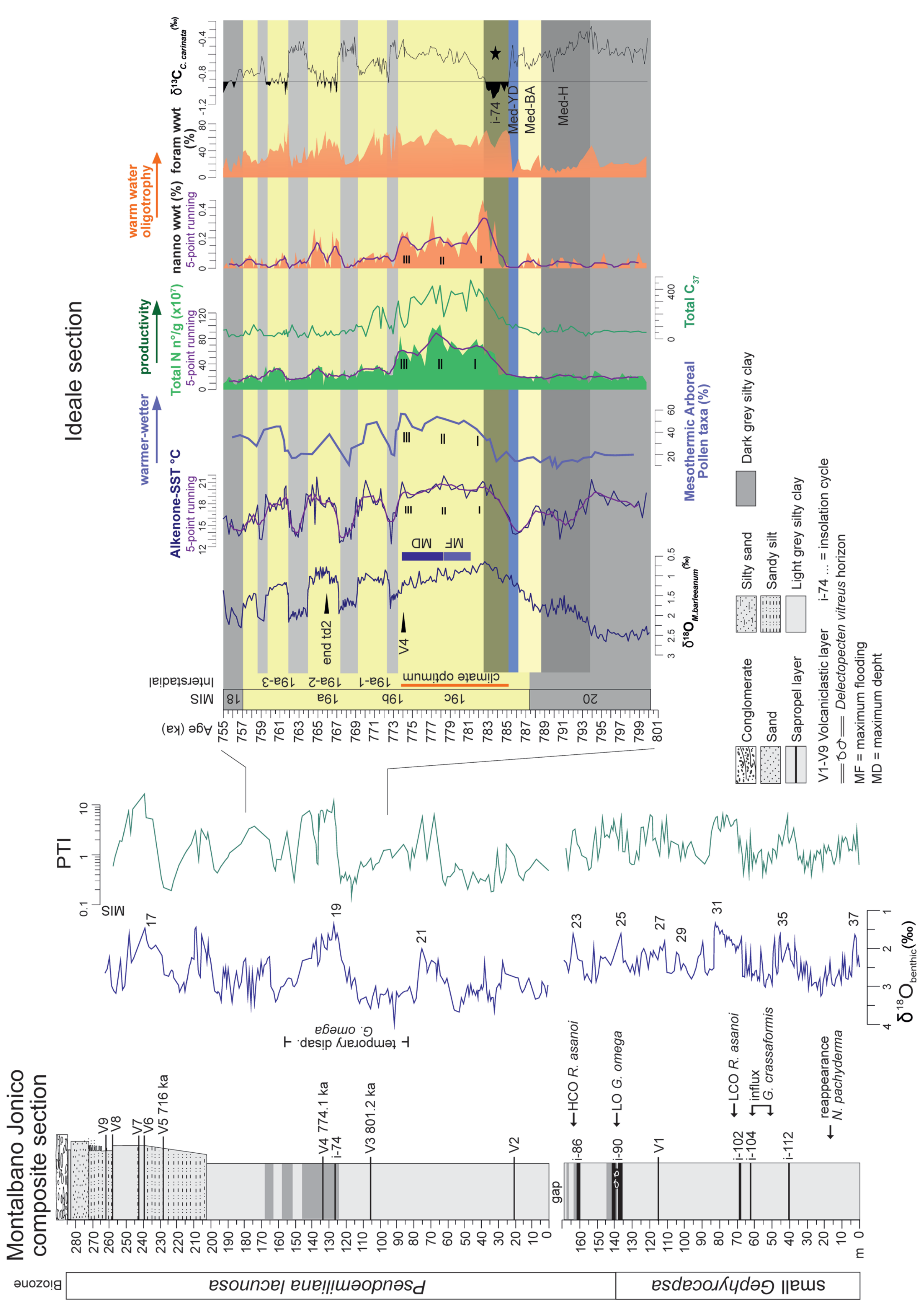
Chibanian: The climate variability as recorded in the Montalbano section towards the transition to 100,000 year glacial cycles (Figs 1-2 and 5-7)

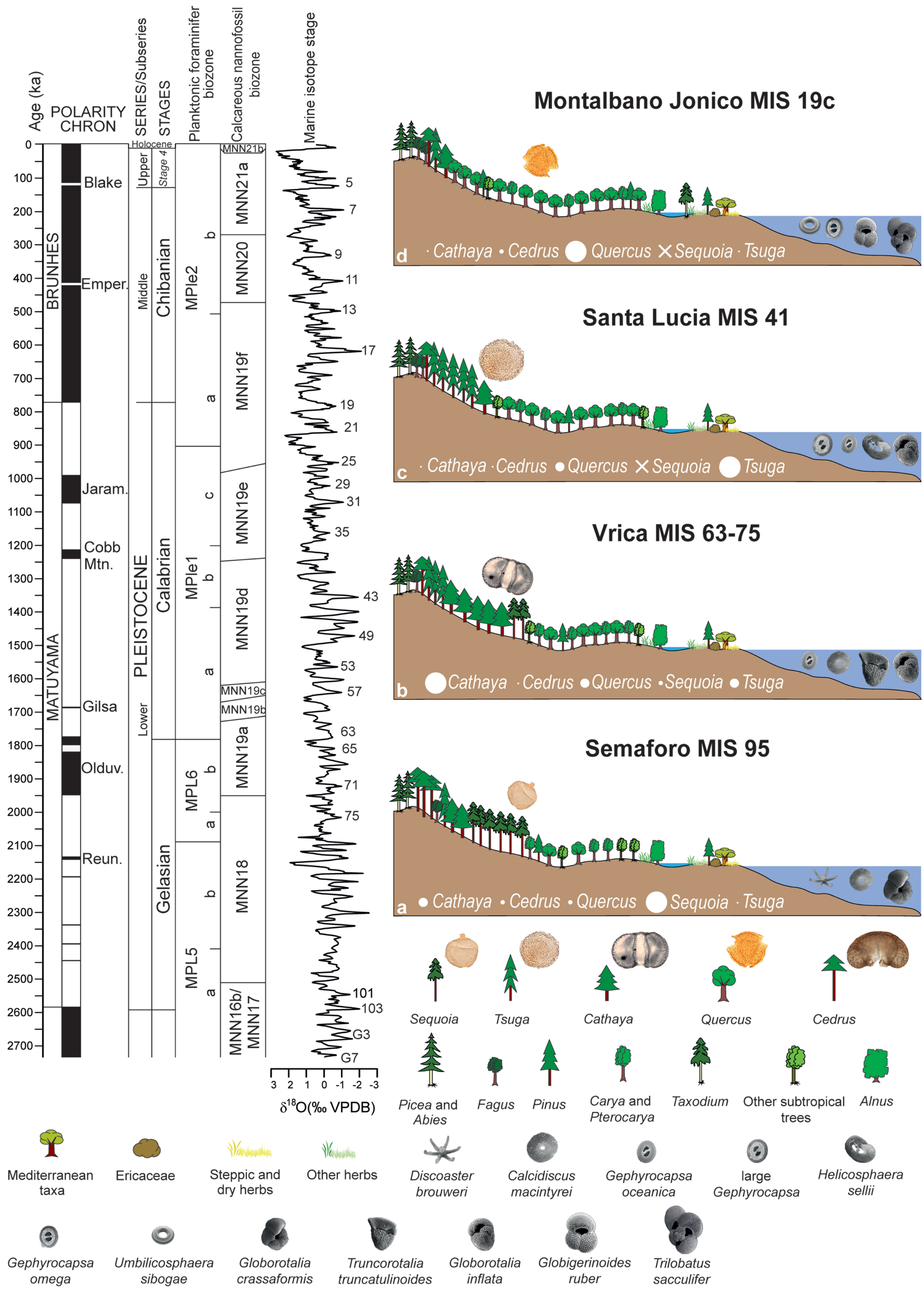
The Chibanian is well represented in the Mediterranean region by pelagic-hemipelagic sediments, which predominantly outcrop at several southern Italy sites. Among these, the Ideale section (IS), as a part of the MJS (Ciaranfi et al., 2010; Maiorano et al., 2010) (Fig. 5), holds particular significance. Recently ratified as a Standard Auxiliary Boundary Stratotype (SABS) for the GSSP of the Middle Pleistocene Subseries/Subepoch (Marino et al., 2024) (Fig. 6), it provides a key Mediterranean reference section for this interval. It is important to highlight that the primary GSSP for the Chibanian Stage was established at the Chiba section in Japan (Suganuma et al., 2021; https://stratigraphy.org/gssps/chibanian). The IS, however, complements this designation, offering a unique perspective from the Mediterranean area, where its stratigraphic features contribute to understanding regional expressions of global climatic and environmental changes during the Middle Pleistocene.

The MJS, encompassing MIS 37-16, is ca. 450 m thick and consists of a coarsening-upwards sedimentary succession ranging from silty clays to silty sands, belonging to the "Argille subappenine" informal unit (Azzaroli et al., 1968). It deposited in the southern Apennines foredeep in a lower circalittoral-upper bathyal setting, which registered even slight climatically induced modifications of local and global significance such as changes in sea level, precipitation, inorganic/organic and fresh water input from land, and tectonic and volcanic events in the Italian Peninsula (D'Alessandro et al., 2003; Stefanelli, 2003, 2004; Maiorano et al., 2008, 2010, 2016a; Ciaranfi et al., 2010; Girone et al., 2013a; Petrosino et al., 2015; Gallicchio et al., 2023). Nine tephra (V1-V9) have been identified, some of which (V3, V4, and V5) were $^{39}Ar/^{40}Ar$ dated (Fig. 5). The MJS is a prime example of multidisciplinary palaeoenvironmental and chronostratigraphic research, which took advantage from terrestrial (pollen grains) (Joannin et al., 2008; Bertini et al., 2015; Marino et al., 2015; Toti, 2015; Maiorano et al., 2016a) and marine (dinoflagellate cysts, calcareous plankton and benthos, ostracods, molluscs, otoliths) fossil proxies (D'Alessandro et al., 2003; Stefanelli, 2003, 2004; Maiorano et al., 2004, 2008, 2010, 2016a, 2021; Ciaranfi & D'Alessandro, 2005; Girone, 2005; Stefanelli et al., 2005; Girone et al., 2013a; Aiello et al., 2015), and from geochemical and biomarker analyses (stable oxygen and carbon isotopes, $^{10}Be/^{9}Be$, alkenones; Ciaranfi et al., 2010; Simon et al., 2017; Nomade et al., 2019; Marino et al., 2020; Maiorano et al., 2021). The multiproxy approach has provided accurate calcareous plankton (foraminifera and nannofossils) biostratigraphy, recognition of G/I cycles and stadial-interstadial phases, palaeodepth variation, and evidence of sapropel insolation cycles (i-c) 112-74 (Fig. 6).

The Pollen Temperature Index (PTI), defined as the ratio of thermophilous arboreal to steppe taxa, serves as a reliable indicator of regional temperature changes and, when integrated with oxygen isotope curves, enables the identification of glacial and interglacial intervals, as well as submillennial-scale fluctuations, as already observed in the Crotone series (Fig. 4a). Reconstructed for the entire MJS (Bertini et al., 2015; Toti, 2015; Vannacci, 2016),

Fig. 6 - (color online) On the left, the Montalbano Jonico composite section, with the main sedimentary, chronological, biostratigraphic and palaeoenvironmental constraints. LO: lowest occurrence; LCO: lowest common occurrence; HCO: highest common occurrence. On the right, a detail of the Ideale section showing the most important marine and terrestrial record for palaeonvironmental reconstruction. Data are from Ciaranfi et al. (2010); Maiorano et al. (2010, 2016a); Bertini et al. (2015); Marino et al. (2015, 2020); Petrosino et al. (2015); Simon et al. (2017); Nomade et al. (2019). PTI (Pollen Temperature Index) curve is according to Bertini et al. (2015); Toti et al. (2015); Vannacci et al. (2016). In the Ideale section: end td2 is the end of the temporary disappearance of *G. omega*; Total N indicates total nannofossil absolute abundance; wwt indicates warm water taxa; MF is the maximum flooding; MD is the maximum depth; I, II and III are the three warmer phases in MIS 19c; star symbol is the abundance peak of *P. zoharyi*; Med-H is the terminal stadial-like event; Med-BA is the Bølling-Allerød-like event; Med-YD is the Younger Dryas-like episode.


Montalbano Jonico composite section
Biozone
Pseudoemiliania lacunosa
small Gephyrocapsa
gap
V9
V8
V7
V6
V5 716 ka
V4 774.1 ka
i-74
V3 801.2 ka
V2
i-86
i-90
V1
i-102
i-104
i-112
HCO R. asanoi
LO G. omega
LCO R. asanoi
influx G. crassaformis
reappearance N. pachyderma
temporary disap. G. omega
MIS
δ18Obenthic(‰)
PTI
Ideale section
Age (ka)
Interstadial
climate optimum
end td2
MF
MD
Alkenone-SST °C
5-point running
warmer-wetter
Mesothermic Arboreal Pollen taxa (%)
productivity
Total N n°/g (x10⁷)
Total C37
warm water oligotrophy
nanno wwt (%)
foram wwt (%)
δ13CC. carinata (‰)
Med-YD
Med-BA
Med-H
Conglomerate
Sand
Sapropel layer
Silty sand
Sandy silt
Light grey silty clay
Dark grey silty clay
V1-V9 Volcaniclastic layer
i-74 ... = insolation cycle
Delectopecten vitreus horizon
MF = maximum flooding
MD = maximum depth


Age (ka)
POLARITY CHRON
SERIES/Subseries
STAGES
Planktonic foraminifer biozone
Calcareous nannofossil biozone
Marine isotope stage
BRUNHES
MATUYAMA
Blake
Emper.
Jaram.
Cobb Mtn.
Gilsa
Olduv.
Reun.
Holocene
Upper
Middle
Lower
PLEISTOCENE
Stage 4
Chibanian
Calabrian
Gelasian
MPle2
MPle1
MPL6
MPL5
MNN21b
MNN21a
MNN20
MNN19f
MNN19e
MNN19d
MNN19c
MNN19b
MNN19a
MNN18
MNN16b/ MNN17
δ18O(‰ VPDB)
Montalbano Jonico MIS 19c
Cathaya · Cedrus · Quercus · Sequoia · Tsuga
Santa Lucia MIS 41
Vrica MIS 63-75
Semaforo MIS 95
Sequoia
Tsuga
Cathaya
Quercus
Cedrus
Picea and Abies
Fagus
Pinus
Carya and Pterocarya
Taxodium
Other subtropical trees
Alnus
Mediterranean taxa
Ericaceae
Steppic and dry herbs
Other herbs
Discoaster brouweri
Calcidiscus macintyrei
Gephyrocapsa oceanica
large Gephyrocapsa
Helicosphaera sellii
Gephyrocapsa omega
Umbilicosphaera sibogae
Globorotalia crassaformis
Truncorotalia truncatulinoides
Globorotalia inflata
Globigerinoides ruber
Trilobatus sacculifer

the PTI reveals distinctive oscillations between warmer and colder phases that closely align with variations in palaeodepth (see fig. 2 in Marino et al., 2024) and G/I patterns (Fig. 6). Notably, the amplitude variations in the PTI curve, in conjunction with the benthic $\delta^{18}O$, are particularly striking. These covariant changes, observed between the lower and upper parts of the MJS, reflect the progressive establishment of the 100 kyr periodicity of G/I cycles, beginning from MIS 22 onward.

The IS (Figs 5-6), ca 80 m thick, covers the time interval from MIS 20 to the onset of MIS 18. The high temporal resolution study of this section (up to 200 years; Nomade et al., 2019) analysed the same samples based on pollen and calcareous plankton assemblages, carbon and oxygen isotopes together with alkenones, the latter providing the alkenone-derived sea surface temperature (alkenone-SST) and the total C_{37} as a proxy of marine palaeoproductivity (Marino et al., 2020; Maiorano et al., 2021). G/I and stadial/interstadial phases have been recognised in agreement with $\delta^{18}O$, $\delta^{13}C$, Mesothermic Arboreal Pollen Taxa (MAPT) and calcareous plankton dataset. The signature of orbital to millennial climate variability is clearly imprinted in the IS as recorded by multiproxy investigations and by the alternating dark grey and light grey sediment color exposed in the field, which correspond to the warm-wet and cold-dry climate phases, respectively (Fig. 5). In late MIS 20, between 794 and 788.5 ka, a terminal stadial-like event (Med-H_{TIX}, Med-H in Fig. 6) occurred as a result of combined atmospheric dynamics and oceanic/hydrological processes (Fig. 6) (Marino et al., 2020). The Med-H_{TIX} is characterised by: 1) an alkenone-SST 4-5 °C cooler than in the older interval, 2) higher abundances of arctic-subarctic *Coccolithus pelagicus* ssp. *pelagicus* and *Neogloboquadrina pachyderma* (Maiorano et al., 2016a) and decrease of warm-oligotrophic calcareous plankton taxa (Fig. 6), 3) a large expansion of open landscapes including prevalent (cold) dry steppe on land (Bertini et al., 2015) and a slight decrease of MAPT (Fig. 6), and 4) a lightening of 1‰ in the $\delta^{18}O_{M.barleeanum}$ (Nomade et al., 2019) reflecting the influx of lighter fresh water into the Ionian Sea (meltwaters coming from mountain glaciers of the Alpine and Apennines chains or from North Atlantic via the Gibraltar Strait) (Fig. 6). The Med-H_{TIX} at the IS is a signal of both a local and global climate episode since it correlates with a peak of $C_{37:4}$ (low salinity and colder meltwaters) at the western Mediterranean ODP Site 975 (Quivelli et al., 2021) and at the Iberian Margin Integrated Ocean Drilling Program (IODP) Site U1385 (Rodrigues et al., 2017) as well as with the deposition of ice-rafted debris (IRD) in the northern Atlantic (Wright & Flower, 2002). During MIS 20-19 deglaciation (Termination IX), millennial scale episodes before the onset of full interglacial MIS 19c have been identified and they recall the high frequency climate oscillation of Termination I (see Maiorano et al., 2016a; Marino et al., 2020). In this respect, a warm episode has been referred to a Bølling-Allerød-like event (Med-BA_{TIX}, Med-BA in Fig. 6), characterised by a climate amelioration (alkenone-SST increase of 4 °C, slight increase of warm water calcareous plankton taxa and MAPT) also documented by the increase of dinoflagellate cysts *Spiniferites mirabilis/hyperacanthus* (Rossignol, 1964; Sarjeant, 1970) and distinct patterns of *Orbulina universa* (d'Orbigny, 1839b) and *Globorotalia inflata*. Upwards, a Younger Dryas-like episode (Med-YD_{TIX}, Med-YD in Fig. 6) has been suggested based on a 2.5 °C decrease of alkenone-SST, the short-term peaks of *Coccolithus pelagicus* ssp. *pelagicus*, *Neogloboquadrina pachyderma* and *Neogloboquadrina incompta* (Cifelli, 1961), and slight decrease of warm water calcareous plankton taxa (wwt in Fig. 6) and MAPT (Fig. 6). The combined analyses were able to detect the ghost sapropel i-c74 in early MIS 19c, from 785.0 ka to 782.6 ka and its internal variability has been described in detail (Maiorano et al., 2016a; Nomade et al., 2019; Marino et al., 2020). Together with the $\delta^{13}C$ minimum (water column stratification, higher organic matter at the sea floor), an increase in the benthic foraminiferal infauna/epifauna ratio (sea bottom stress; Stefanelli, 2003) and a peak of the dinoflagellate cyst *Polysphaeridium zoharyi* (Rossignol, 1962) (less saline water; Bertini et al., 2015; Maiorano et al., 2016a) (star in Fig. 6) showed an increase during i-74. It is worth noting that the interruption of the stable and stratified surface water conditions in the middle of sapropel evidenced by calcareous plankton as a signal of a short-term increase in nutrients and mixing in sea water (Marino et al., 2020) is accompanied by a brief cooler and dryer episode on land indicated by a decrease in the MAPT curve (Fig. 6), suggesting a synchronous response of terrestrial and marine realms to even millennial climate changes. The warmer climate conditions and the climate optimum during MIS 19c lasted for ~11.5 ± 3.4 kyr (Nomade et al., 2019) similarly to the full interglacial recorded in the lacustrine Sulmona section (i.e., 11 ky; Regattieri et al., 2019) or inferred in the North Atlantic records (i.e., 12.5-10.5 kyr; Tzedakis et al., 2012; Head, 2021). This warm phase was marked by a distinct increase of calcareous plankton warm taxa, such as *Umbilicosphaera sibogae* (Weber van Bosse, 1901), *G. caribbeanica*, *G. omega*, *Oolithotus* spp., *Globigerinoides ruber*, and *Trilobatus sacculifer*. A contemporary response to marine and terrestrial environmental variation is highlighted by the three warmer phases visible during the full interglacial MIS 19c, as recorded by the patterns of total nannofossil absolute abundance (Total N in Fig. 6) and warm water calcareous nannofossil taxa, in concert with the increase of alkenone-SST and of MAPT. Three main increases of the Mediterranean Forest Pollen during Tajo phase (Sánchez-Goñi et al., 2016) were also detected on the Iberian margin at the IODP site U1385 similarly to what occurred in the MIS 19c at the IS highlighting a shared response of vegetation to atmospheric processes that, in concert to repeated tropical subtropical water influxes through the Gibraltar Strait towards the central Mediterranean Sea, also influenced the marine proxies (Marino et al., 2020). It is remarkable to observe how the

Fig. 7 - (color online) Major environmental shifts in terrestrial and marine ecosystems of southern Italy during selected time windows. Key changes in both terrestrial vegetation and marine conditions illustrate the dynamic interplay between land and sea from MIS 95 to MIS 19c. On the left is the Standard Biochronostratigraphy, see Fig. 2 for the legend and references. Micrograph images of selected taxa are not to scale.

upward stadial-interstadial oscillations in MIS 19b-MIS 19a interval toward the MIS 18 onset are synchronously recorded by both MAPT and calcareous plankton data set, which together with the $\delta^{18}O$, $\delta^{13}C$ and alkenone-SST patterns indicate short-term changeable conditions in marine and terrestrial environments. In this respect: 1) warmer and wetter on land climate corresponds to enhanced chemical on land weathering and continental fresh water input (Bertini et al., 2015; Maiorano et al., 2016a; Nomade et al., 2019), and stratified sea surface waters during higher sea level within interstadials (MIS 19a-1 and 19a-3 in Fig. 6) (D'Alessandro et al., 2003; Stefanelli, 2003; Aiello et al., 2015; Bertini et al., 2015; Marino et al., 2015; Maiorano et al., 2021), while 2) colder and drier terrestrial climate occurred when sea surface waters experienced lower temperature and mixing during lower sea level within stadials.

CONCLUDING REMARKS

This synthesis integrated Italian pollen records with marine datasets (Figs 1 and 2), providing a comprehensive view of both terrestrial and marine environments during the latest Pliocene and Pleistocene (Figs 3-7) and improving the timing of events and changes in a shared chronology. Pollen data from the Mediterranean region reveal significant shifts in vegetation, which align with glacial-interglacial cycles, stadial/interstadial phases, and rapid, short-lived events. As summarised in Bertini et al. (2010) and Bertini & Combourieu-Nebout (2023), the glacial-interglacial cycles are generally characterised by the predominance of steppe communities during glacials, marked by the expansion of *Artemisia* and *Ephedra*, indicating progressive establishment of cooler and drier conditions. In contrast, interglacial phases support broadleaf deciduous forests, reflecting favourable climatic conditions for diverse flora. The alternation between cold and warm phases during the Late Pliocene and Early Pleistocene influenced the evolution of calcareous plankton in marine environment as evidenced by appearance and extinction of climate-sensitive taxa (e.g., last occurrence of *Discoaster brouweri*) or their abundance increase and temporary disappearance (e.g., *Neogloboquadrina pachyderma* left coiling), and short-term influxes (e.g., *N. atlantica*) of polar key species in the Mediterranean Sea. The transition from 41 kyr to 100 kyr glacial cycles profoundly impacted both terrestrial and marine ecosystems determining the gradual disappearance of subtropical taxa and ecosystems (e.g., Bertini, 2010; Magri et al., 2017; Bertini & Combourieu-Nebout, 2023 and references therein). This is particularly well-documented in the sites selected in this paper (Figs 4, 6 and 7), starting with the reduction and eventual disappearance of *Sequoia* in the upper portion of Semaforo, followed by the reduction of *Cathaya* and subsequently *Tsuga*, especially evident in the sites of Vrica-Santa Lucia and MJS (Fig. 7). Previous palynological data also contributed to describing the presence of ecological and climatic gradients across the region, at least since the latest Pliocene. The calcareous plankton experienced a turnover marked by extinction and appearance of species in the Vrica series and recorded significant orbital-suborbital changes in the MJS, where variation in the abundance of warm and cold taxa with different ecological preference for nutrients and photic column water structure have been detected in line with climate-induced change in terrestrial environments. From approximately MIS 43 to MIS 16, the quite well-calibrated Italian pollen records can be compared with key reference sites across Europe, such as Lake Ohrid (Donders et al., 2021, 2024) and Tenaghi Philippon (e.g., Pross et al., 2015), as well as those from the Iberian margin (Sánchez-Goñi et al., 2023 and references therein), which offer long, continuous archives that enhance our understanding of floristic and climatic dynamics. Integrating these records has enabled us to situate Italian successions within a broader European framework, providing critical insights into vegetation shifts and climate oscillations at regional and global scales. Specifically, the Ohrid data document temperate and montane forest dynamics, as well as the persistence and subsequent retreat of subtropical taxa, which align with the patterns observed in the Italian sites (Fig. 7).

By harmonising terrestrial and marine records, we captured the intricate feedback between oceanic and continental systems. The three selected case studies from Semaforo, Vrica-Santa Lucia, and Montalbano Jonico illustrate how shifts in climate drivers influenced both vegetation and calcareous plankton. These findings emphasise the Mediterranean's dual role as both a recorder of global climate variability and a driver of regional ecosystem changes. This integrated approach has allowed us to refine chronologies, cross-validate climatic signals, and develop a more nuanced understanding of ecosystem responses to orbital- and sub-orbital-scale climate forcing. The marine record, including the deep-sea cores recovered by ODP expeditions (Figs 1 and 2), offers a parallel narrative, revealing changes in sea surface temperature, salinity, and ocean circulation patterns that correlate with changes in terrestrial environment. These marine sites underscore the interconnectedness of land-sea systems, allowing for a comprehensive understanding of palaeoenvironmental conditions. The synchronicity observed in marine proxies, such as planktonic foraminifera and calcareous nannofossils, reinforces the idea that climatic changes were the expression of complex atmospheric and oceanic dynamics.

Unravelling land-sea correlations during the Pliocene-Pleistocene in the Mediterranean, this contribution adopts a multidisciplinary approach that combines palynological data with marine microfossils, providing crucial insights into climate variability and ecosystem dynamics. These studies are also vital for tracing faunal histories, building on the pioneering work of Augusto Azzaroli, Danilo Torre, and Giovanni Ficcarelli, whose legacy continues to inspire interdisciplinary research. We are honoured to dedicate this work to their memory.

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