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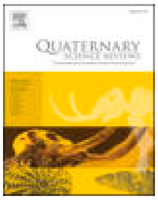

Monte San Nicola (Sicily): Gelasian GSSP and base Quaternary/Pleistocene

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ABSTRACT

The Gelasian Stage, established in 1998 at Monte San Nicola (Southern Sicily) as the third Stage for the Pliocene Series above the Zanclean and the Piacenzian, was overlooked for years but regained global recognition in 2009, when the base of both the Pleistocene Series and the Quaternary System was lowered to match the Piacenzian/Gelasian boundary. In recent years, independent research groups have been collecting scientific data at Monte San Nicola from two sections, namely the "historical" GSSP profile and the nearby Mandorlo section. Evidence collected in the "historical" section prove that the current GSSP definition does no longer meet the standards for a modern formal chronostratigraphic boundary, and the relevant host section is affected by tectonic reductions that prevent achieving a continuous and reliable chronostratigraphic record. On the contrary, the Mandorlo section offers a pristine depiction of the geological and biotic events that are expected to occur from the Piacenzian/Gelasian boundary up to the base Calabrian, which possibly make it the best reference profile globally for investigating the Neogene – Quaternary transition. We provide a commented review of the current state of the scientific knowledge on the Monte San Nicola stratigraphy in the view of possible actions to be taken soon, such as the definition of the Astronomical Unit Stratotype and Astrochronozones for the Gelasian Stage.

1. Introduction

Establishing formal chronostratigraphic standards, global in scope and use, is one of the main tasks to be accomplished by the Earth scientist's community (e.g., Hedberg, 1976; Salvador, 1994). Since Hedberg (1976), this issue was addressed via the definition of Global Stratotype Sections and Points (GSSPs) that have been implemented so far for a large part of the Geologic Time Scale (GTS; Gradstein et al., 2020). Improvements in data acquisition and interpretation and the ever-growing need for higher resolutions for probing into the geologic past accelerated the obsolescence of proxies and definition criteria for many GSSPs, even those only recently approved. Among them is the

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GSSP for the Gelasian Stage, defined by Rio et al. (1998) in the badlands of Monte San Nicola (MSN; southern Sicily). This GSSP remained long overlooked and only regained scientific relevance in 2009, when the base of the Pleistocene Series was lowered to match the Piacenzian/Gelasian boundary (Gibbard and Head, 2010). It was immediately clear that the chronostratigraphic foundations on which the Gelasian GSSP was established no longer meet the requirements for a "modern" Stage boundary. Aware of this urgency, the original Gelasian GSSP proponents founded in 2010 the SAGE (SAve the GElasian) research team – which includes the senior Authors of this paper and specialists from different Italian and international institutions – aimed at collecting novel, high-resolution scientific data from several profiles across the MSN badlands. Scientific results achieved so far concur that still today the MSN stratigraphic record represents the best reference area globally for the upper Piacenzian to lower Calabrian interval. However, we collected evidence that the eastern sectors of MSN – where the Gelasian GSSP is located – are affected by tectonic deformation that cause a significant reduction of the local stratigraphic record. The best alternative in this regard is represented by the Mandorlo section (Capraro et al., 2022), located in the central-western part of MSN, which offers a relatively undisturbed succession spanning the entire Gelasian Stage in a continuous way. The demonstrable continuity, as also evidenced by further field observations, make the Mandorlo section the best available candidate for defining a Gelasian Astro-Unit-Stratotype (AUS) and its constituent Astrochronozones (Hilgen et al., 2026). The Mandorlo section also provides a viable option for relocating the Gelasian GSSP without compromising the stability of the GTS, should the scientific community feel the need for a less problematic placement of the Piacenzian-Gelasian boundary and base Quaternary. In fact, all the criteria and markers employed by Rio et al. (1998) for the definition and recognition of the boundary would be maintained, and significantly improved.

2. Monte San Nicola and the Gelasian Stage

2.1. Historical remarks

The Gelasian Stage (Rio et al., 1998) is a relatively new

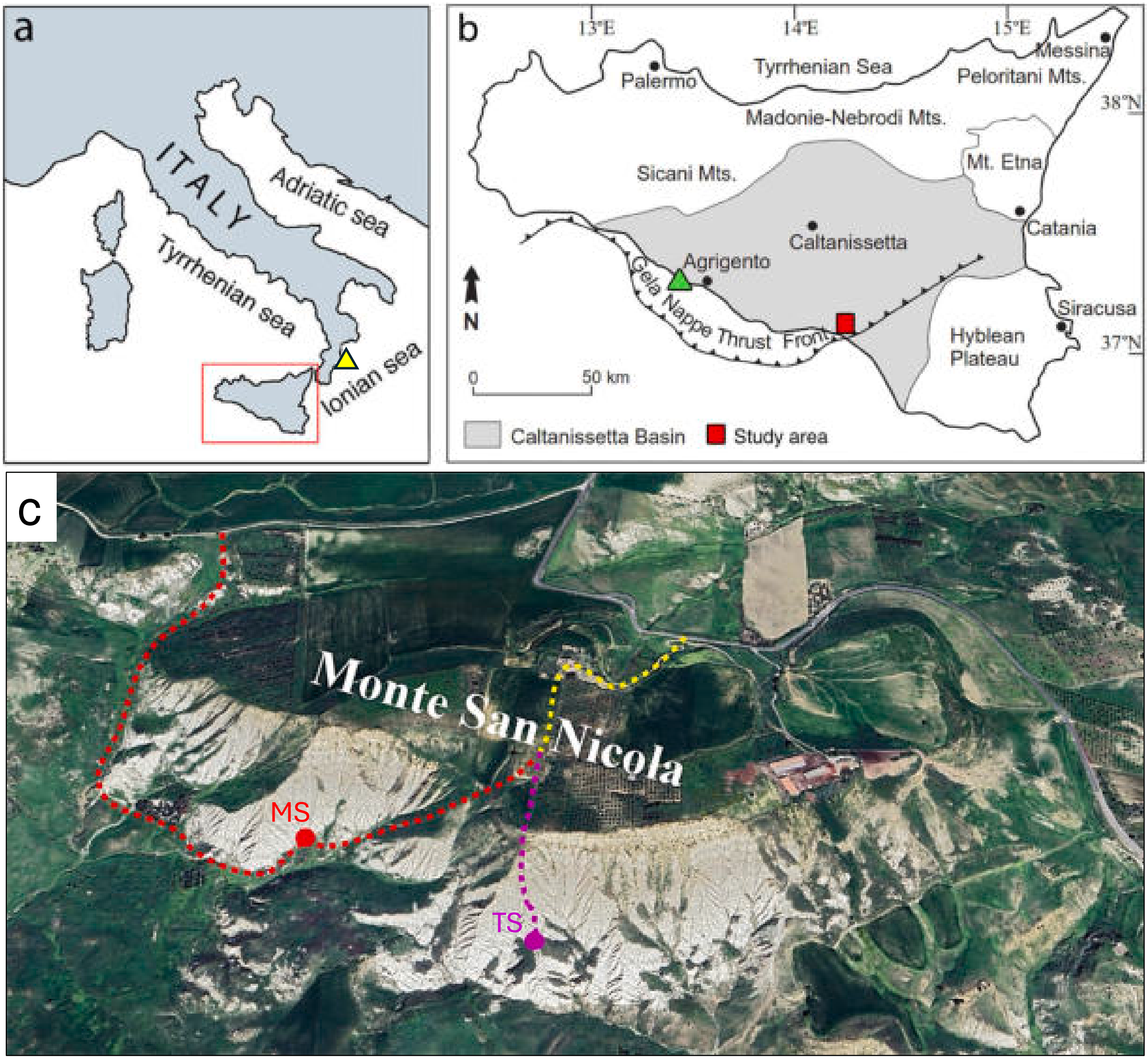


Fig. 1. Location of the study area and sections cited in the text. A: The red square indicates Sicily; the yellow triangle identifies the location of the Singa section, in southeastern Calabria. B: Location of the Punta Piccola section (green triangle) and position of the study area (red box), both located at the southern margin of the Caltanissetta sedimentary basin. C: Map of MSN and location of the sections mentioned in the text. Yellow dashed line: the traditional access pathway to the summit of Monte San Nicola. MS: base of the Mandorlo section (red dot), which can be reached either from the top of MSN or from the "Statale 9" road (red dashed lines). TS: base of the "historical" MSN section, Gelasian GSSP site (purple dot), with indication of the descent from the top pf MSN (purple dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Chronostratigraphic Unit both in terms of name, position, and rank within the Global Chronostratigraphic Scale. For decades, the Pliocene Series (after Lyell, 1833) was subdivided into two Stages, the Zanclean (Lower Pliocene; Seguenza, 1868) and the Piacenzian (Upper Pliocene; Mayer-Eymar, 1858; Pareto, 1865). The "traditional" Piacenzian stage-stratotype, as defined by Barbieri (1967) in the Arda valley (Northern Italy), was believed to extend continuously up to the base of the Pleistocene, as formerly defined at Vrica (c. 1.8 Ma; Aguirre and Pasini, 1985). Rio et al. (1988) and Raffi et al. (1989) demonstrated that the upper part of the "historical" Piacenzian unit-stratotype harbours major stratigraphic hiatuses, and the lithological transition from open-marine muds to regressive yellow sands in the Arda valley (the "Astian" Auct.), at about 2.6 Ma, is close in age to the global cooling usually referred to as "the beginning of the ice ages" (e.g., Shackleton et al., 1984). To both emphasize within the GTS the global relevance of the climatic and biotic events at c. 2.6 Ma and close the gap atop of the "historical" Piacenzian stratotype, Rio et al. (1988, 1991, 1994) proposed establishing a new Upper Pliocene Stage, the Gelasian (Rio et al., 1994), equivalent in time and scope to the traditional "Astian" unit Auct. This scenario was consistent with the historical tripartite division of the Pliocene Series (Seguenza, 1868), widely accepted among Italian stratigraphers and petroleum geologists (Vai, 1996). Accordingly (Rio et al., 1998), the Gelasian Stage covers the interval between the top of the Piacenzian (Castradori et al., 1998) and the base of the Calabrian (Cita et al., 2006, 2008, 2012). The relevant GSSP was formally ratified in the open-marine MSN succession, not far from where the Zanclean and Piacenzian GSSPs have also been defined (Van Couvering et al., 2000; Castradori et al., 1998). The "Gelasian" (Rio et al., 1994) is named after the nearby historical city of Gela. In 2009, the highly debated resolution to lower the Pliocene/Pleistocene (Neogene/Quaternary) boundary to the base of the Gelasian (Gibbard and Head, 2009; Gibbard et al., 2010) decapitated the Pliocene Series at c. 2.6 Ma, thus reinstating the Piacenzian as the Upper Pliocene Stage and redefining the Gelasian as Lower Pleistocene.

2.2. Geologic setting

The MSN stratigraphy is exposed along the southern flank of the homonymous hill, in the municipality of Butera, less than 10 km inland from the coastal city of Gela (southeastern Sicily; Fig. 1). The local succession was deposited at the southeastern margin of the Neogene Caltanissetta sedimentary basin (Fig. 1), where small piggyback basins accommodated an expanded upper Neogene and Quaternary stratigraphy (e.g., Ogniben, 1969; Lickorish et al., 1999; Ghisetti et al., 2009; Lentini and Carbone, 2014; Catalano et al., 2013; Gasparo Morticelli et al., 2015). The basal part of the Pliocene-Pleistocene MSN succession belongs to the "Trubi" Fm. (Zanclean-Piacenzian p.p.; Cita and Gartner, 1973; Castradori et al., 1998), consisting of whitish marly limestones and grey/beige marls, void of macrofossils, deposited at an estimated depth of ca. 1000 m (Castradori et al., 1998; Caruso et al., 2011) after the Messinian salinity crisis (De Visser et al., 1989). At MSN, the Trubi Fm. is truncated and only represented by its upper part (ca. 40 m) resting directly on top of the Numidian Flysch (Rio et al., 1994, and references within). The rapid but gradual transition to the overlying c. 125 m thick Monte Narbone Fm (Piacenzian p.p.-Calabrian p.p.; Rio et al., 1984; Di Stefano et al., 1993). is marked by a sudden increase in regional terrigenous input and the beginning of a shallowing-upward trend (Bonaduce and Sprovieri, 1984), evidenced by the change in sediment colour to grey/blue, decreasing rock competence, occurrence of sparse displaced macrofossils, and increasing sediment accumulation rates (Capraro et al., 2022). The general increase in organic carbon burial at ca. 3.2 Ma (Grant et al., 2022) is marked in the central Mediterranean by the first appearance of Mediterranean Precession-Related Sapropel layers (MPRSs; e.g., Hilgen, 1991b; Cramp and O'Sullivan, 1999; Rohling et al., 2015). Specifically, the Monte Narbone Fm. contains four MPRS clusters (from the bottom upwards: O, A, B and C; Verhallen, 1987) that provide long-distance correlation throughout the central-eastern Mediterranean. The local succession is overlain by a package of yellow fossiliferous shallow-water sandstones, Calabrian in age, pointing to the definitive uplift of the area.

2.3. Scientific background (pre-2020)

The first known study of the MSN stratigraphy was that of Spaak (1983), who analysed the local planktic foraminifer assemblages as part of a long Mediterranean record that also include sections in Calabria, Sicily, and Crete. This pioneering work contributed to improving the biostratigraphic zonation for the entire Pliocene (in its pre-2009 definition) and set the foundations for the following investigations in the MSN area, which were essentially carried out on his "historical" stratigraphic profile (Fig. 1). Bonaduce and Sprovieri (1984) accomplished a biostratigraphic and paleoenvironmental study of the "historical" MSN section of Spaak (1983) by integrating planktic foraminifera and ostracods. Their results demonstrate that the base common of *Cytheropteron testudo* – a "northern guest" ostracod species employed as marker of the base Quaternary, as originally defined in the Vrica section (MPl6 Zone, c. 1.8 Ma; Colalongo et al., 1980) – is significantly older at MSN (upper MPl5 Zone; c. 2.35 Ma according to Bonaduce and Sprovieri, 1984). Sprovieri et al. (1986) and Howell et al. (1988) performed the first high-resolution geochemical studies on three laminated layers belonging to clusters B and C at MSN with the aim of reconstructing the surface and bottom water conditions during sapropel deposition in the Upper Pliocene to Lower Pleistocene interval (in its pre-2009 definition). They developed a basin stratification model by integrating micropaleontological and geochemical analyses, such as total organic carbon, carbonate contents, and $\delta^{18}O$ and $\delta^{13}C$ data for the planktic foraminifer *Globigerinoides ruber*. Howell et al. (1988) also compared the MSN laminites studied by Sprovieri et al. (1986) with analogues from the Vrica and Capo Bianco sections. Driever (1988) accomplished quantitative studies on the calcareous nannofossil assemblages in the "historical" section at MSN, with the goal of improving the available biostratigraphic framework for the Mediterranean Pliocene. In his accurate description of the local stratigraphy, he stressed that the occurrence of several normal faults provides obvious hiatuses in the lower part of the Monte Narbone Fm. Bertoldi et al., 1989 employed segments of the MSN succession in the attempt to reconstruct the long-term evolution of vegetation and climate across the Pliocene-Pleistocene interval. As later confirmed by Rio et al. (1996) for the coeval Marecchia Valley record (Northern Italy), Bertoldi et al. (1989) concluded that the onset of the NHG (i.e., MIS 100-MIS 96 glacial triplet) provided a deep but overall transient perturbation in the regional climatic setup of the central Mediterranean. Specifically, the sparse and poorly preserved pollen content of the "historical" MSN section revealed that early Gelasian cold spells (arguably, the MIS 100 – MIS 96 glacial triplet) accelerated the disappearance of struggling "Tertiary" tropical and subtropical taxa (e.g., Symplocaceae, Cyrillaceae, Sapotaceae; Bertoldi, 1985), but they did not cause major permanent changes in the flora and vegetation of southern Italy, which promptly recovered afterwards. Hilgen (1991b) considered the cyclically organized MSN section as one of the segments to be used for constructing the first astronomically calibrated time scale (ATS) for the Pliocene and Pleistocene. However, he eventually employed the Singa section (Ionian Calabria) as the physical reference for the Gelasian interval of the ATS, because of its paleomagnetic record (Zijderveld et al., 1991) and stratigraphic completeness. Channell et al. (1992) published the first integrated bio- and magnetostratigraphic study of the MSN succession (Fig. 2), thus providing the main scientific foundation to the GSSP proposal of Rio et al. (1994). They sampled a 161 m-thick section along the "historical" MSN profile, including the basal "Trubi" interval. Notably, the Authors report on the presence of several E-W trending normal faults consistent with those previously identified by Driever (1988). Sampling resolution for magnetostratigraphic analyses was 1 m from the base section up to a *"reddish*

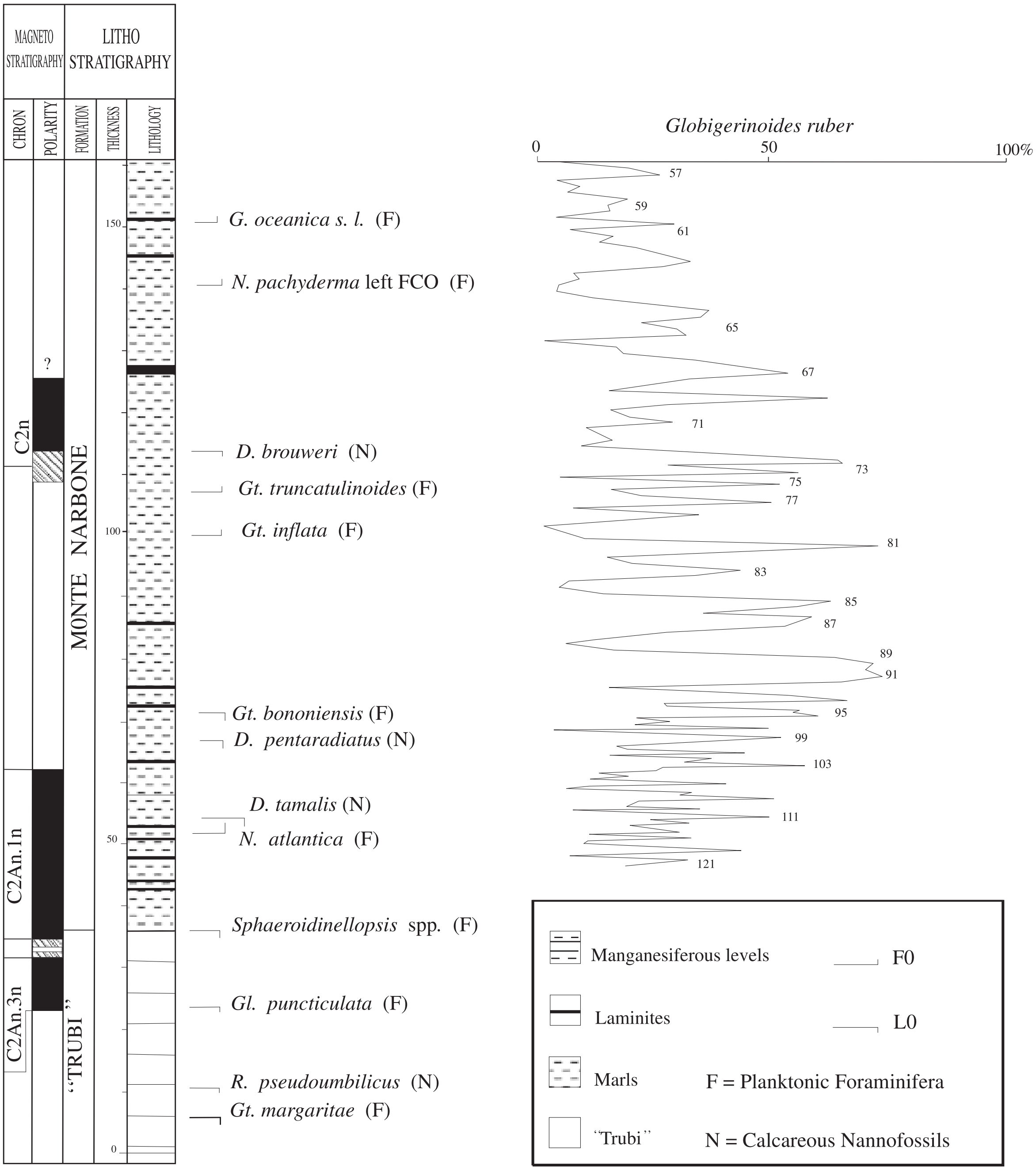


Fig. 2. Chronostratigraphic framework for the MSN section at the time the Gelasian GSSP was defined. Left: magnetobiostratigraphy and lithological log, after Channell et al. (1992). Right: abundance fluctuations of *Globigerinoides ruber*, interpreted as a surrogate for recognizing oxygen isotope stages (Rio et al., 1994). Position of the Nicola bed (Piacenzian/Gelasian boundary) is marked as A5 (in red). Modified from Rio et al. (1998).

laminated layer" (i.e., sapropel A5, at the top of cluster A), and increased to 4 m from that point on; sampling resolution for biostratigraphic analyses was 0.5 m. Nannofossil biostratigraphy demonstrated that the MSN section spans from Zone MNN14/15 to Zone MNN19b (Rio et al., 1990), NN15 to NN19 (Martini, 1971), CN11b to CN13a (Okada and Bukry, 1980), MNN14 to MNQ19a (Di Stefano et al., 2023). Planktic foraminifer biostratigraphy ranges from Zone MPl3 to the *Globigerina cariacoensis* Zone (Cita, 1973, 1975, emended by Sprovieri, 1992) and from Zone N19 to N21 (Blow, 1969). Overall, the section encompasses from the middle – late Zanclean (>4 Ma) to the early Calabrian (~1.6 Ma). Most of the samples analysed for paleomagnetic investigation did not yield a stable magnetization component and had to be discarded, pointing to a poor preservation of the original paleomagnetic signal throughout the section. The sparse paleomagnetic data allowed positioning the midpoint of the Gauss/Matuyama (C2An/C2r) geomagnetic reversal 1 m below the "Nicola bed", although with a very large uncertainty (± 2m). In their Gelasian GSSP proposal, Rio et al. (1994) for the first time introduced the name "Nicola bed" (after Monte San Nicola) for indicating the distinctive sapropel A5 (top of sapropel cluster A), which was recommended as a practical physical marker of the Piacenzian/Gelasian boundary. After the Gelasian GSSP was ratified (Rio et al., 1998), scientific interest towards the "historical" MSN section waned rapidly. Aiello et al. (2000) and Bonaduce et al. (2000) reinvestigated the very samples set of Bonaduce and Sprovieri (1984) for taxonomic and stratigraphic/paleoenvironmental purposes, respectively. Both studies emphasized that a major turnover occurred in ostracod assemblages in the middle part of the MPl5 Zone, pointing to a major change in regional paleoclimatic and paleoenvironmental conditions. Unfortunately, we could not pinpoint the relevant stratigraphic interval within the MSN succession, due to the lack of physical stratigraphic constraints in the original lithological log of Bonaduce and Sprovieri (1984). The first study of a stratigraphic section other than the traditional GSSP profile was that of Becker et al. (2005), who accomplished a high-resolution investigation along a section located c. 500 m west of the "historical" GSSP site. They demonstrated that the MIS 100 glaciation harbours a high-frequency climatic variability in the sub-milankovitch domain (6-8 kyr), evocative of the Heinrich and Dansgaard-Oeschger events of the late Pleistocene (Bond et al., 1992; Dansgaard et al., 1993; Heinrich, 1988; Mayewski et al., 1997). For the first time, they proved that a strong suborbital climatic variability existed well before the last glacial period, as later confirmed by several investigations (e.g., Martrat et al., 2007; Hodell et al., 2015; Capraro et al., 2023; Hodell et al., 2023). This suborbital paleoclimatic signal is hardly detectable in ocean and open-Mediterranean sedimentary cores, which further emphasizes the relevance of MSN for high-resolution paleoenvironmental and palaeoceanographic reconstructions (Becker et al., 2005; Bolton et al., 2010; Hayashi et al., 2020). Herbert et al. (2015) reconstructed a composite upper Neogene and Quaternary alkenone-derived record of past sea-surface temperatures (SSTs) for the central Mediterranean by splicing together data from Punta Piccola, the "historical" MSN profile, Vrica, and the deep-sea ODP Sites 964 and 967. Notably, samples from MSN yielded anomalous SST results, allegedly due to bad alkenone preservation, and had to be corrected by −0.8 °C to fit those obtained at Punta Piccola. Indeed, research data for this article (McClymont et al., 2020) reveal that, in constructing their composite SST record, Herbert et al. (2015) only included sparse MSN data points for the interval below the "Nicola bed". Results show that the MIS 100-MIS 96 glacial triplet at ca. 2.6 Ma, correlative to the definitive onset of the NHG, represented a strong but transient cooling event, thus corroborating the conclusions of Bertoldi et al. (1989). After a severe cold episode taking place in MIS 78 (ca. 2.09 Ma), correlative to the "first deep glaciation" of Rohling et al. (2014), a systemic decrease in SSTs started at ca. 1.84 Ma, very close to the former Pliocene/Pleistocene (i.e., Neogene/Quaternary) boundary (Selli et al., 1977; Aguirre and Pasini, 1985).

3. The current Gelasian GSSP: state of the art

3.1. Definition

The GSSP for the Gelasian Stage was formally ratified in the "historical" MSN section of Spaak (1983) at "*the base of the marly layer overlying sapropel MPRS 250, located at 62 m in the Monte San Nicola section The astrochronological age of sapropel MPRS 250 (mid-point), corresponding to precessional cycle 250 from the present, is 2.588 Ma* (Lourens et al., 1996)*, which can be assumed as the age of the boundary.*" (Rio et al., 1998). Accordingly (Fig. 2), the practical physical marker of the Piacenzian/Gelasian boundary in its type-area is the distinctive "Nicola bed" of Rio et al. (1994) (i-cycle 250, in MIS 103: Hilgen, 1991b; Lourens et al., 1996), formally referred to as sapropel A5 (after Verhallen, 1987). The base Gelasian predates by c. 60 kyr the prominent MIS 100 – MIS 96 glacial triplet (Lisiecki and Raymo, 2005). The main proxy for global correlation of the Gelasian GSSP is the Gauss/Matuyama (C2r/C2An) geomagnetic reversal, which Channell et al. (1992) coarsely pinpointed 1 m below the "Nicola bed" in the "historical" MSN section. The boundary (Fig. 2) is also approximated by the Top of nannofossil species *Discoaster pentaradiatus* and *D. surculus* that, in the Mediterranean (Sprovieri et al., 1998), occurred at c. 2.51 Ma (MIS 99) and c. 2.55 Ma (MIS 100), respectively (Di Stefano et al., 2023), by the Top of planktic foraminifer *Globorotalia bononiensis* in MIS 96, and by short-lived influxes of *Neogloboquadrina atlantica* during the MIS 100, MIS 98 and MIS 96 glaciations (Lourens et al., 1992; Becker et al., 2005). The Top of the radiolarian species *Stichocorys peregrina* (Sanfilippo et al., 1985), the Base of the diatom *Nitzschiajoussaea* in low-latitude regions, and the Top of *Denticulopsis kamtschatica* in the North Pacific (Barron, 1985) also approximate the Gauss/Matuyama reversal and hence the Gelasian base.

3.2. Pros and cons for the current Gelasian GSSP

The competent scientific bodies approved the GSSP proposal of Rio et al. (1994) as fully compliant to the applicable guidelines and consistent with the investigation standards of that era (Rio et al., 1998). The boundary still stands today (Gradstein et al., 2020), but retrospectively, the Gelasian GSSP characterisation is outdated and lacks many of the stratigraphic, paleoclimatic and paleoenvironmental proxies that are nowadays routine in the study of marine Neogene and Quaternary sediments. Below is a checklist of the basic GSSP requisites according to Remane et al. (1996) with reference to the current Piacenzian/Gelasian boundary as defined by Rio et al. (1998) in the "historical" MSN section.

1) Exposure over an adequate thickness of sediment: YES. The Gelasian "historical" section is widely and continuously exposed over >90 m of open-marine sediments encompassing the entire Gelasian Stage (Rio et al., 1998) and extending downward well into the underlying Trubi Fm. (Piacenzian; Channell et al., 1992).
2) Continuous sedimentation: YES. No evidence exists of erosional surfaces or sedimentary hiatuses across the boundary.
3) High sedimentation rates: YES. The mean sedimentation rate across the Piacenzian/Gelasian boundary is perfectly amenable to investigations in the orbital time domain (Hilgen, 1991b).
4) Absence of synsedimentary and tectonic disturbances: NO. Driever (1988) and Channell et al. (1992) stressed that the "historical" MSN section and the surroundings areas are affected by a network of faults and joints, which result in significant stratigraphic displacements with possible doublings and gaps. Rio et al. (1998) eluded the problem by limiting the scope of their GSSP proposal to a short and undisturbed stratigraphic interval straddling the "Nicola bed".
5) Absence of metamorphism and strong diagenetic alteration: YES. Apart from modern surface weathering, no diagenetic cementation, metamorphism and/or strong alteration occur.
6) Abundance and diversity of well–preserved fossils: YES. The MSN section is very rich in very well preserved marine micro- and meiofossils, such as calcareous nannoplankton, foraminifera, and ostracods (see above). Terrestrial pollen grains are unfortunately scarce, and generally poorly preserved (Bertoldi et al., 1989; Bertoldi, pers. comm.).
7) Absence of vertical facies changes at or near the boundary: YES, apart from the Nicola bed itself. The boundary is located at the very base of the marly clays conformably overlying the top of the "Nicola bed", which points to the base of a long stratigraphic interval of consistent depositional setting and style, persistently dominated by mud settling, after the deposition of sapropel A5. The next major lithologic change occurs c. 17 m above the boundary, at the base of sapropel B1.
8) Favourable facies for long–range biostratigraphic correlations: YES. The MSN section is made of marine, richly fossiliferous open-marine sediments that contain several microfossil species with high biostratigraphic and paleoenvironmental significance and long-distance correlation potential.
9) Amenability to radiometric dating: NO. The MSN sedimentary succession is reported to be void of distinct volcaniclastic layers.
10) Magnetostratigraphy: YES/NO. Channell et al. (1992) published a record of the Gauss/Matuyama (C2An/C2r) geomagnetic reversal, which was pinpointed 1 m below the Nicola bed. However, the position of the paleomagnetic boundary was rather arbitrarily defined within a long interval of uncertain

paleomagnetic directions and most of the analysed samples did not yield a stable magnetization component, suggesting that the paleomagnetic signal is poorly preserved throughout the section.

11) Chemostratigraphy: NO. No detailed δ^{18}O, δ^{13}C or alkenone-based SST record had been reconstructed for the “historical” MSN section at the time the Gelasian GSSP was established.
12) Amenability to cyclostratigraphy and astronomical tuning: YES/NO. Although the sapropel layers of clusters O, A, B and C and the pervasive sedimentary cyclicity in the intervening stratigraphy provide tight age constraints by means of correlation to the summer insolation curves (Hilgen, 1991b), the presence of fault-related stratigraphic gaps prevented attaining an astronomical tuning of the boundary interval in the “historical” MSN section.
13) Accessibility: YES/NO. The section can be reached by means of a long, and physically demanding hike through rough terrain, or by descending a very steep ridge from the summit of Monte San Nicola. The GSSP cannot be seen from above: pinpointing the “golden spike” position is only possible once the exact spot has been reached. Also, sampling is only possible along a steep slope following a composite trajectory.
14) Free access: YES. Although located within private property, the GSSP site can be accessed freely.
15) Permanent protection of the site: NO. The section is self-protected, being located within the bare badlands of Monte San Nicola. The outcrops are steep and remote, unsuitable for cultivation and not of interest for land development. Still, further protection policies may be enforced by the local government, if required.
16) Possibility to fix a permanent marker: YES. So far, the “golden spike” has not been fixed due to the lack of interest by both the local government and the competent scientific bodies. However, nothing stands in the way of a future change of plans.

4. Recent advances (post-2020)

In the last few years, the MSN area has been independently investigated by two research groups. The SAGE team started working at MSN in 2010, albeit publication of the data and results collected so far was accelerated by the announcement that a GELSTRAT group, an international project launched in 2021 under the patronage of SACCOM-INQUA, was starting a high-resolution investigation across the Gelasian GSSP in its type-section. So far, both groups have published critical and complementary contributions that improved the available knowledge on the stratigraphy and the events that occurred across the Piacenzian-Gelasian transition in two key sections, as summarized below.

4.1. The Mandorlo section

The “Mandorlo” section (Fig. 3), exposed immediately east of the section studied by Becker et al. (2005), has been the focus of the SAGE group research at MSN. Capraro et al. (2022) reconstructed an integrated record of physical stratigraphy, magnetostratigraphy, and calcareous plankton biostratigraphy at Mandorlo, showing that the section encompasses the entire Gelasian Stage (Fig. 4) and correlates very well with the coeval central Mediterranean reference sections (Fig. 5). Specifically, it was possible to constrain the position of the Gauss/Matuyama (C2An/C2r) geomagnetic reversal at 0.3 ± 0.4 m above the “Nicola bed” (Fig. 4), a substantial improvement with respect to the previous low-resolution record of Channell et al. (1992). Zanola et al. (2024a) presented a high-resolution study (sampling interval of 5 cm) for a 10 m long stratigraphic interval straddling the “Nicola bed” at Mandorlo, from sapropel A4 up to the glacial termination of MIS 100 (200 total samples). This study, which provided the very first (and only, as of today) high-resolution benthic δ^{18}O and paleomagnetic records across the Piacenzian/Gelasian boundary at MSN, complemented the high-resolution benthic δ^{18}O study accomplished by Becker et al. (2005) on a shorter interval from the top of the Nicola bed to above MIS100. Based on the excellent match between the LR04 benthic stack of Lisiecki

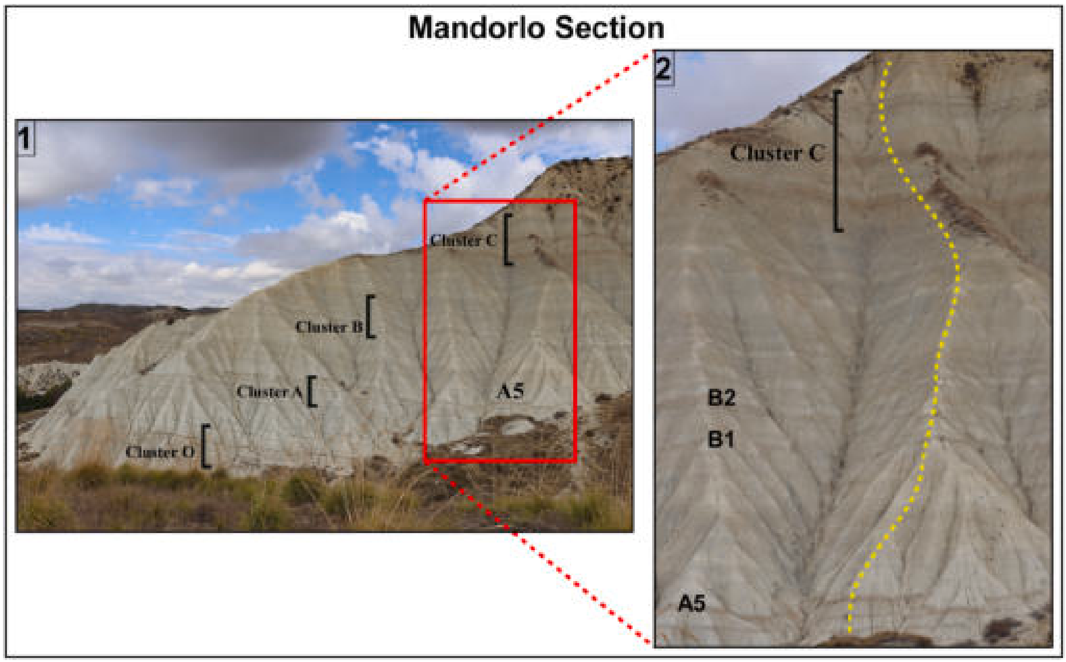


Fig. 3. A: Overview on the Mandorlo area (NW sector of MSN) with indication of the position of sapropel clusters O to C. A5: the Nicola bed, marking the Piacenzian/Gelasian boundary. B: detail on the Mandorlo section, with indication of the prominent sapropel layers A5, B1 and B2. The yellow stippled line marks the trajectory followed by Capraro et al. (2022) for sampling the Mandorlo profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

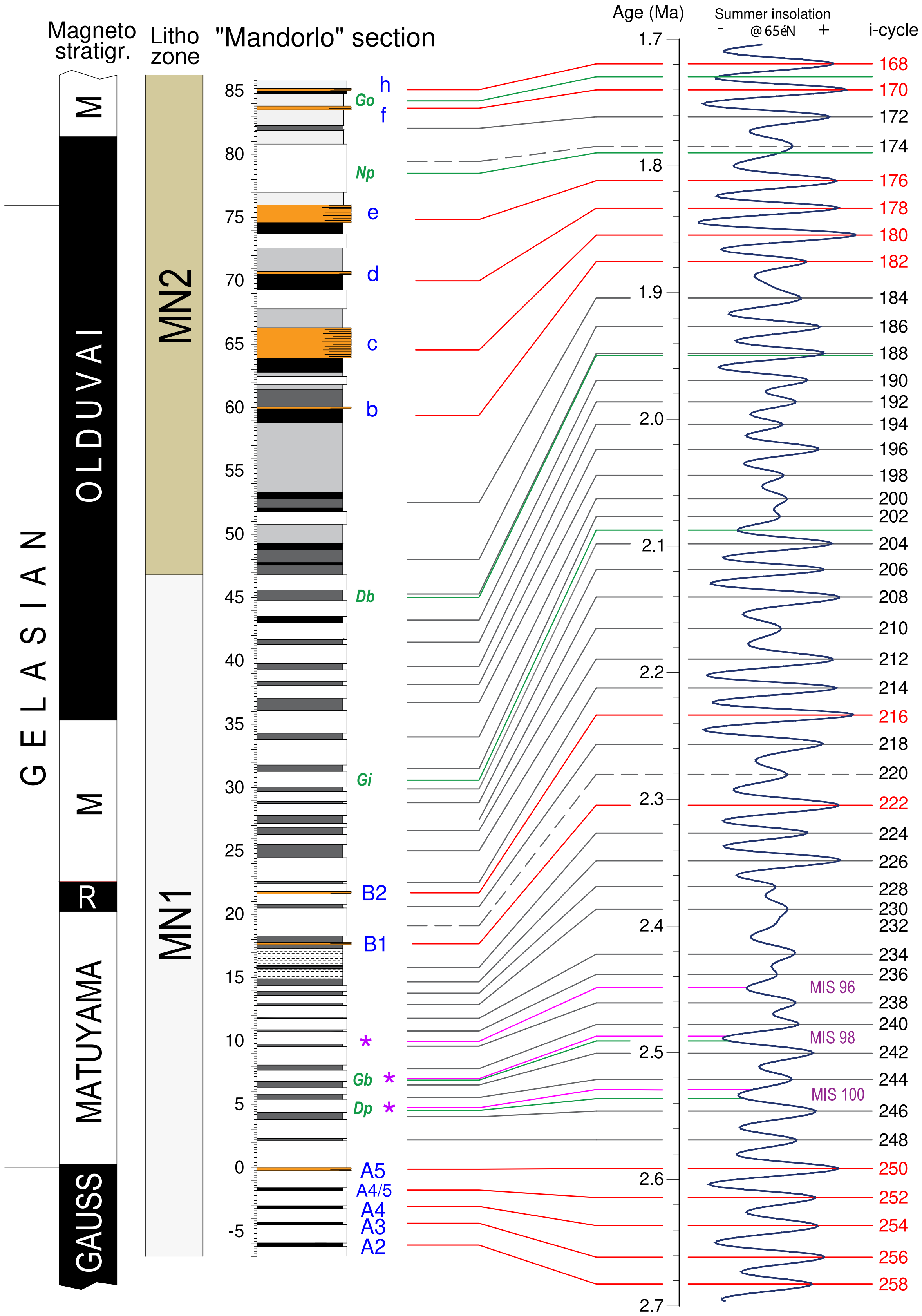


Fig. 4. Magnetobiostratigraphic framework and astronomical tuning for the Mandorlo section as proposed by Capraro et al. (2022), to which we refer for details. Blue labels indicate sapropel layers. Green labels indicate relevant bihorizons: Dp = Top *Discoaster pentaradiatus*. Gb = Top *Globorotalia bononiensis*. Gi = Base *Globorotalia inflata*. Db = Top *Discoaster brouweri*. Np = Base common *Neogloboquadrina pachyderma*. Go = Base *Gephyrocapsa oceanica*. Purple asterisks indicate influxes of *Neogloboquadrina atlantica*, correlative to MIS 100, 98 and 96 glacial stages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

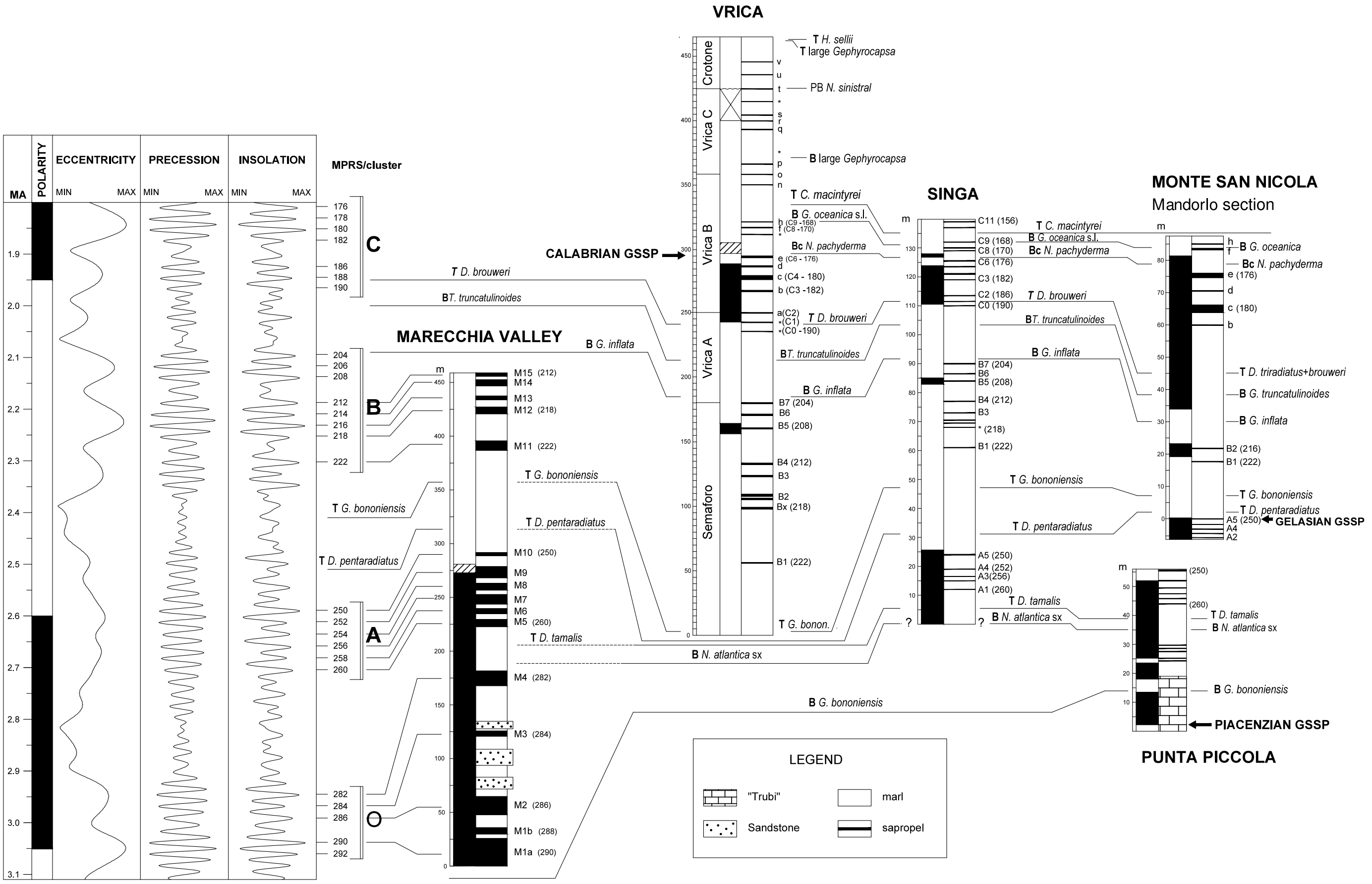


Fig. 5. Correlation of the Mandorlo section (also indicated here as "Monte San Nicola") with other coeval reference sections in northern Italy (Marecchia Valley), southern Italy (Singa, Vrica) and Sicily (Punta Piccola). Tie points are provided by calcareous plankton biostratigraphy and the MPRSs of clusters O (M), A, B, C. Precession cycles (i-cycles) are indicated in brackets. Modified from Capraro et al. (2022), to which we refer for details.

and Raymo (2005) and the $\delta^{18}O$ record reconstructed at Mandorlo for the benthic foraminifer *Uvigerina* spp., Zanola et al. (2024a) proved that both the "Nicola bed" and the Gauss/Matuyama geomagnetic reversal occurred in MIS 103 (Fig. 6). Beyond the predictable obliquity-driven glacial-interglacial cyclicity, the signal analysis performed by Zanola et al. (2024a) exposed a strong climate variability at the suborbital time scale in their benthic $\delta^{18}O$ record. Oscillations in the c. 5 kyr time domain, consistent with the 4-8 kyr cycles found by Becker et al. (2005) within MIS 100, are present throughout, though especially prominent during cold intervals (Fig. 7). Bonomo et al. (2024) published a paleoenvironmental reconstruction for the Mandorlo section based on the study of calcareous nannoplankton assemblages, further supported by robust statistical and signal analyses. They recognized and discussed major shifts in the nutricline depth that occurred with a precessional frequency, thus following summer insolation and, possibly, North African monsoon activity. Signal analyses revealed a periodicity of c. 5-8 kyr in the relative abundance of ecologically significant nannoplankton taxa, reminiscent of the late Quaternary Heinrich events, which confirms the existence of a strong suborbital climatic variability in the central Mediterranean at the Pliocene-Pleistocene transition (Fig. 7). Bonomo et al. (2024) used a modern (albeit challenging and time-consuming) approach in estimating the intensity of nannofossil reworking by including both archaic (pre-Gelasian) and mechanically damaged specimens. The relevant curve (Fig. 6) shows a very close correlation to the sea-level oscillations of Jakob et al., 2020 demonstrating that the deep marine environment at MSN at that time was susceptible to eustatically driven changes in sediment supply from the basin margin. Zanola et al. (2024b) presented new surface-water proxy data from the Mandorlo section, such as the planktic $\delta^{18}O$ record for *Globigerinoides ruber* and a high-resolution alkenone-derived SST record. Once again, signal analyses disclosed the occurrence of millennial-scale climatic variabilities in the 5-8 kyr time domain (Fig. 7), which Zanola et al. (2024b) interpreted either as variability in the Atlantic Meridional Overturning Circulation strength, or as the resonance (harmonics) of precession-driven low-latitude processes. Data interpretation and conclusions of Zanola et al. (2024b) were questioned by Addante et al. (2025b), which urged the SAGE team to publish a reply (Zanola et al., 2025) (see below). Radmacher et al. (2025) performed a micro-X-ray CT study on the "Nicola bed" by investigating sapropel A5 in a site adjacent to the Mandorlo section, which was also combined with sedimentological and micropaleontological observations. Their study shows that the abundances of planktic foraminifera tests oscillate considerably across the "Nicola bed", most likely in response to high-frequency changes in regional climate conditions. They conclude that the fine sedimentary structures (laminae) of the "Nicola bed" are perfectly preserved at Mandorlo, suggesting that the local sedimentary record is continuous across the Piacenzian/Gelasian boundary and allowing to a very precise positioning of the base Gelasian in this section.

4.2. *The "historical" Gelasian GSSP section*

The SAGE group (Capraro et al., 2022) attempted the first "modern" integrated study in the "historical" GSSP section, which was entirely sampled and described in its physical stratigraphic traits starting exactly from the Gelasian GSSP location (red circle in Fig. 8). The stratigraphic interval below the "Nicola bed" was not considered for this study, due to the evidence of tectonic deformation within sapropel cluster A (Fig. 8). Field data, corroborated by biostratigraphic analyses, confirmed the

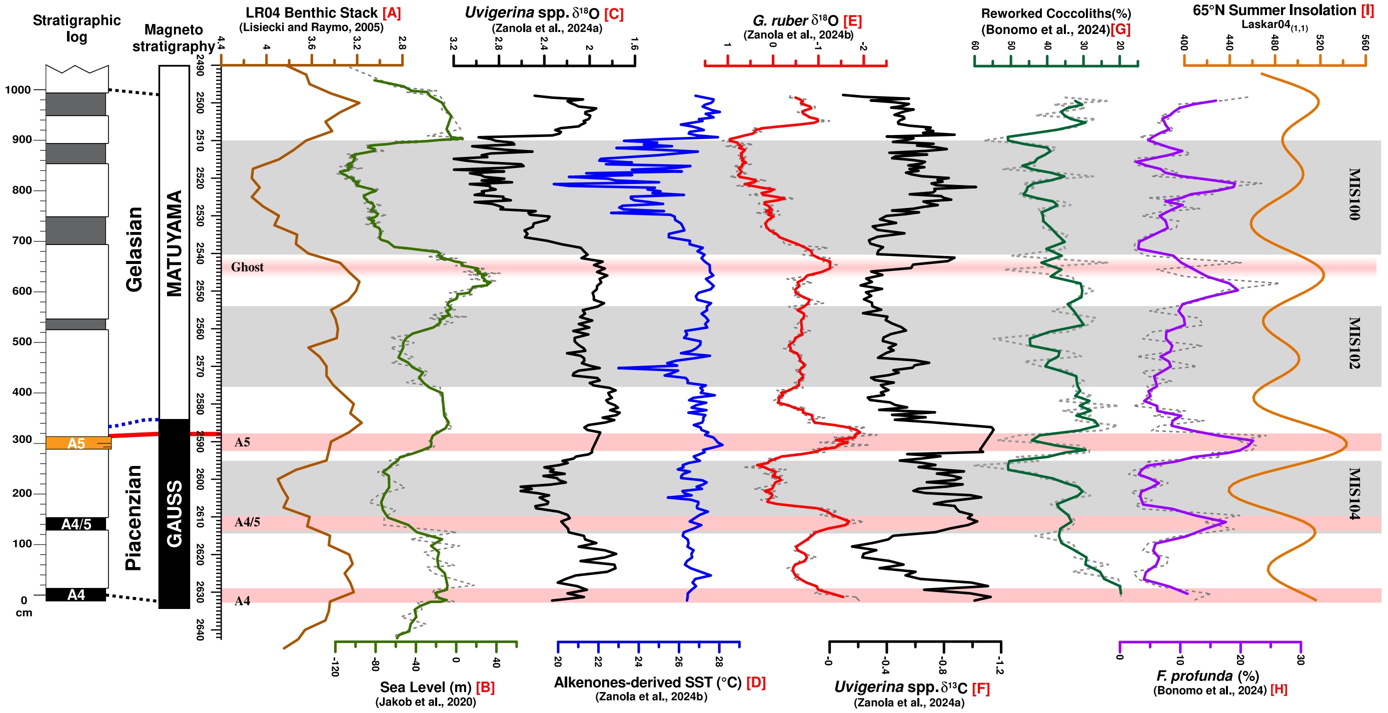


Fig. 6. Compilation of the main high-resolution instrumental data achieved at Mandorlo across the Piacenzian/Gelasian boundary, compared to the LR04 benthic stack of Lisiecki and Raymo (2005) and the sea-level reconstruction of Jacob et al. (2020) (far left) and the isolation curve at 65 °N (Laskar et al., 2004) (far right). Data are after Zanola et al. (2024a, b) and Bonomo et al. (2024). Pink horizontal bands mark the stratigraphic position of sapropel layers; grey bands indicate glacial stages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

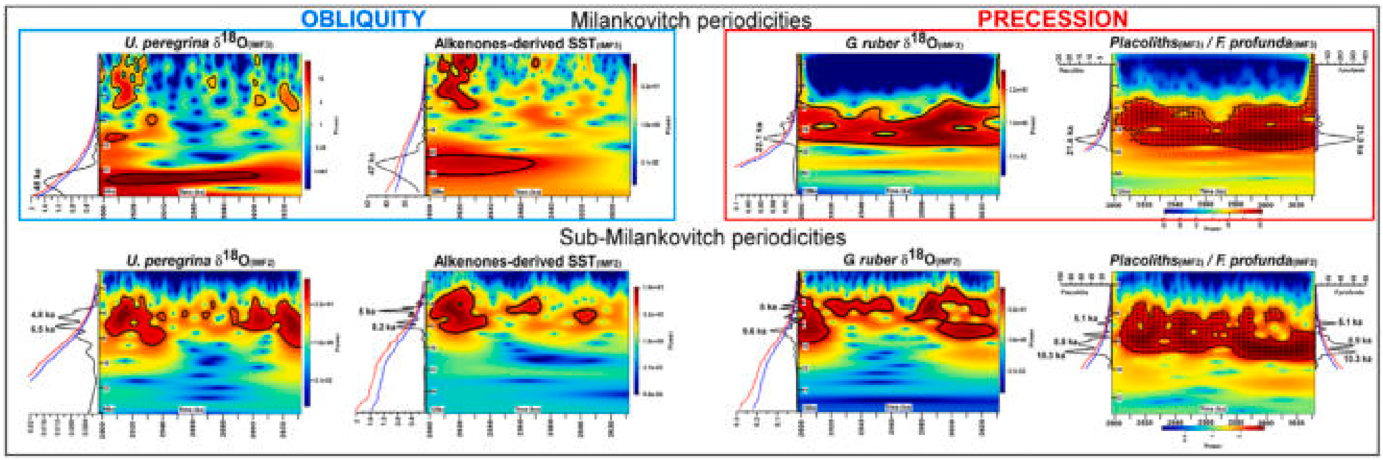


Fig. 7. Signal analysis (wavelets) of the high-resolution δ^{18}O and alkenone-derived SST records at Mandorlo, showing the presence of both orbital (precession and obliquity) and sub-orbital periodicities (after Zanola et al. (2024a, b) and Bonomo et al. (2024)).

observations of Driever (1988) and Channell et al. (1992) that the GSSP profile is crosscut by numerous faults and joints which make it impossible to obtain a continuous, record across and especially above the Piacenzian/Gelasian boundary. By comparison with the relatively undisturbed Mandorlo profile (Fig. 9), Capraro et al. (2022) concluded that 5 m or more of the original lower Gelasian stratigraphy have been tectonically reduced in the "historical" GSSP section. Furthermore, paleomagnetic properties proved to be very poor and, despite the detailed investigation, it was not possible to reconstruct a reliable paleomagnetic record throughout the section (Capraro et al., 2022). For these reasons, the SAGE team decided to discard the "historical" section for further studies. Head and Caruso (2022) introduced GELSTRAT, a scientific program sponsored by SACCOM- INQUA aimed at achieving an integrated high-resolution stratigraphic and paleoclimatic record across the Neogene/Quaternary transition in its type locality. For this purpose, they selected the "historical" GSSP section as the main study target. Radmacher et al. (2023) investigated the microlaminated "Nicola bed" in the "historical" MSN section by means of non-destructive micro-X-ray CT imaging. Microscale analyses suggest that "*… the top of the Nicola bed is bioturbated over an interval of several centimeters, which obscures precise recognition of the GSSP horizon*" (Radmacher et al., 2023; Addante et al., 2024 presented a high-resolution δ^{18}O record for the planktic species *Globigerina bulloides* and the quantitative study of calcareous nannofossil and planktic foraminifer assemblages between sapropels A2 and A5 (the "Nicola bed") in the "historical" MSN section. Considering the sampling pace of 5 cm, the average temporal resolution of this study was ~0.8 kyr. Regrettably, the use of *G. bulloides* for constructing the δ^{18}O record and the lack of a benthic δ^{18}O curve prevent a

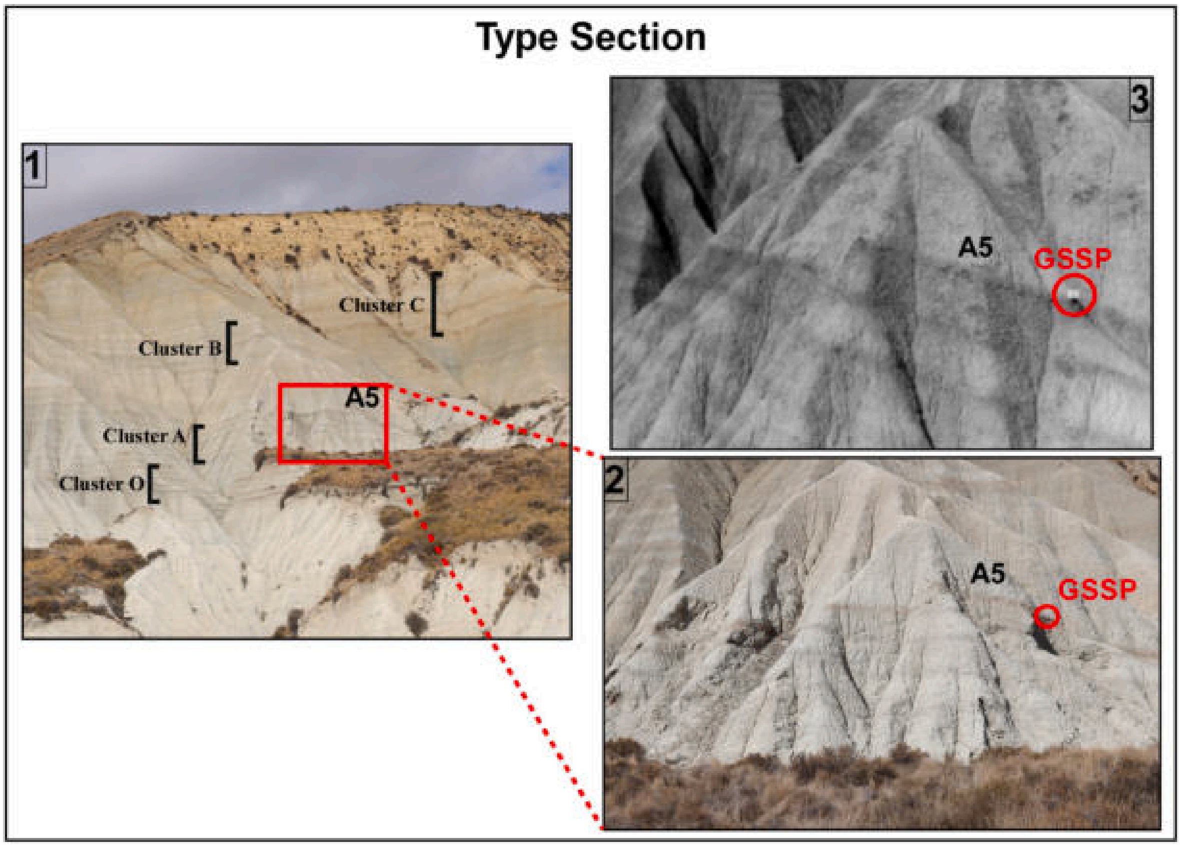


Fig. 8. 1: Overview on the “historical” GSSP area (SE sector of MSN) with indication of the position of sapropel clusters O to C. A5: the Nicola bed, marking the Piacenzian/Gelasian boundary. 2: detail on the “type” MSN section, with indication of Nicola bed (A5) and the exact Gelasian GSSP location (red circle). The yellow arrow indicates the gully investigated by the GELSTRAT team. 3: location of the Gelasian GSSP (red circle) as reported by Rio et al. (1998). Tectonic deformation below the Nicola bed (A5) is evident in both panels 2 and 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

direct comparison between the GELSTRAT and Mandorlo sections. The age model of Addante et al. (2024) was reconstructed by tuning each sapropel (including the “ghost” sapropel of Becker et al., 2005) to precession minima/insolation maxima. The Authors report on a pronounced $\delta^{18}O$ maximum at 2.606 Ma (MIS 104) coincident with a spike (>12%) of the subpolar planktic foraminifer *Neogloboquadrina atlantica*, which they interpreted as the earliest Mediterranean evidence for the southward migration of the Subarctic Front. Addante et al. (2024) speculated that the variability observed in calcareous nannofossil assemblages was forced by both obliquity and precession, although this assumption was not corroborated by signal analysis. In fact, the wavelet and power-spectrum analyses later performed by Bonomo et al. (2024) at Mandorlo on selected nannofossil taxa demonstrate that the orbital-scale oscillations identified within the nannofossils assemblage were solely driven by the precession-modulated insolation variability (21-kyr cycles) in the Northern Hemisphere. Fasone et al. (2024) characterized the chemical and mineralogical composition of sediments across sapropel cluster A, where individual sapropel layers cannot be unambiguously recognized and positioned in the field by means of traditional physical stratigraphic investigations (Addante et al., 2024) because *“… visual observation alone is insufficient for defining the precise thickness of sapropelic layers”* (Addante et al., 2025b). By combining sediment colorimetry and geochemical analyses, Fasone et al. (2024) revised the stratigraphic position and thicknesses of sapropel layers specified by Addante et al. (2024), including the “Nicola bed”, and concluded that the marl/sapropel alternation followed precession-related changes in freshwater runoff and stratification of the water column, while obliquity paced carbonate productivity in response to changes in the intensity of deep-water circulation and upwelling. However, the Authors failed to characterize individual sapropel layers by means of spikes in the Ba/Al ratio, as routinely done in eastern Mediterranean sedimentary records (e.g., Calvert, 1983; Wehausen and Brumsack, 1998; Gallego-Torres et al., 2010). More specifically, Fasone et al. (2024) interpreted the episodic decoupling between sapropelic intervals and Ba/Al peaks as the result of a random remobilization of the relevant geochemical markers, thus hindering the original purpose of replacing field observations with allegedly more precise geochemical analyses. Addante et al. (2025a) and Girone et al. (2026) expanded their previous study by constructing a new multi-proxy record extending from sapropel A2 to MIS 99, which combines planktic $\delta^{18}O$, alkenone-derived SSTs, and the quantitative study of calcareous nannofossils and planktic foraminifer assemblages. Again, thicknesses and relative positions of individual sapropel layers in their stratigraphic log, including the “Nicola bed”, differ substantially from those published previously by Addante et al. (2024) and Fasone et al. (2024), confirming that the stratigraphic record in the “historical” MSN section is ambiguous. The SST record of Addante et al. (2025a) points to a major SST drop immediately below the “Nicola bed” (MIS 104) concomitant with the massive influx of *N. atlantica* previously reported by Addante et al. (2024). Surprisingly, all the coeval high-resolution Mediterranean foraminifer records available to date, such as Punta Piccola (southwestern Sicily; Sprovieri et al., 2006), the nearby Mandorlo section, Singa (Ionian Calabria; Lourens et al., 1992), and open-sea sediment cores as well (e.g., Sprovieri et al., 1998; Serrano, 2020), point to insignificant abundances of *N. atlantica* in MIS 104, at odds with the GELSTRAT record (Fig. 10). In the attempt to account for these unique findings, Addante et al. (2025b) suggested that the age model of Zanola et al., 2024a is incorrect, supposedly due to a wrong interpretation of the

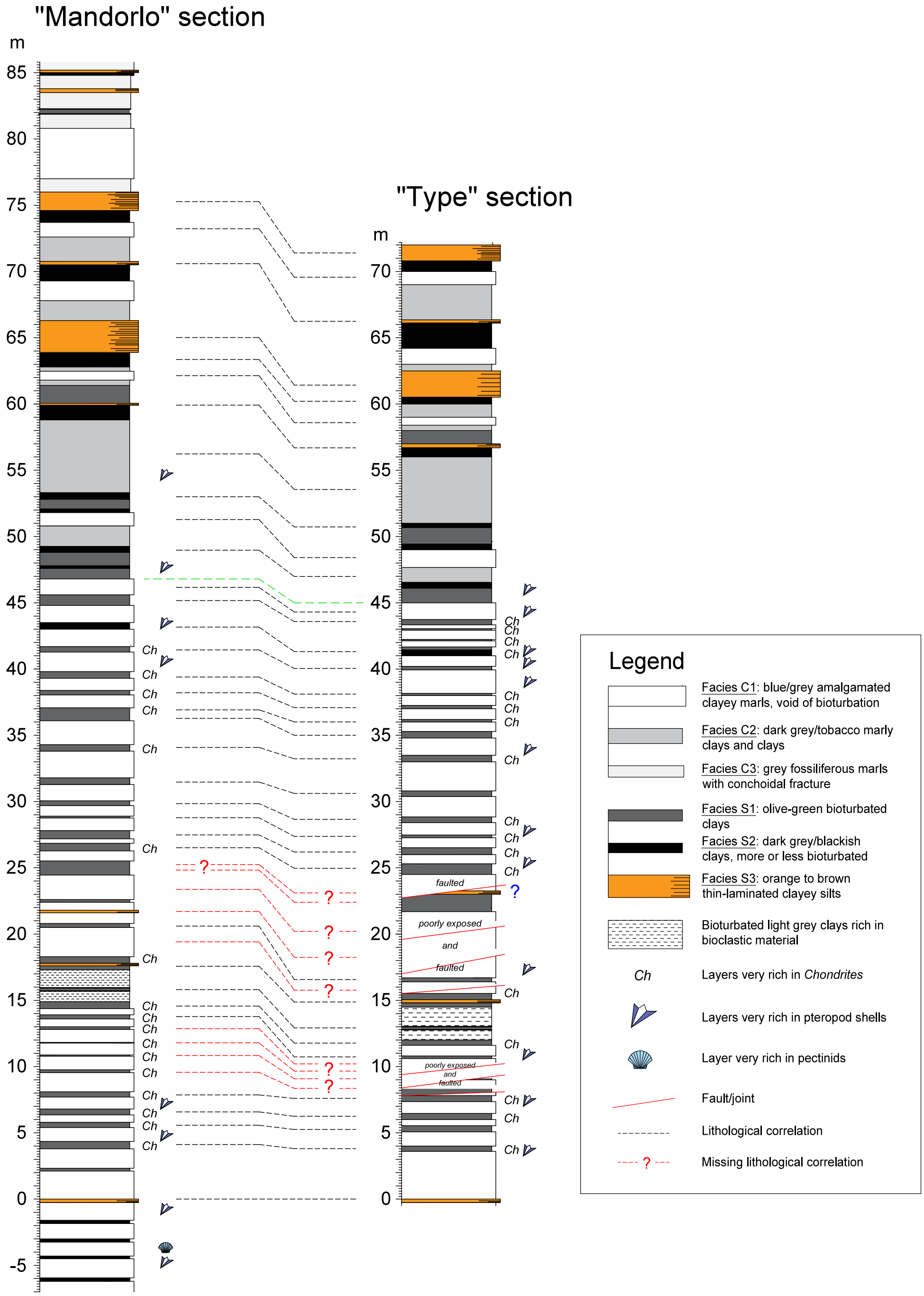
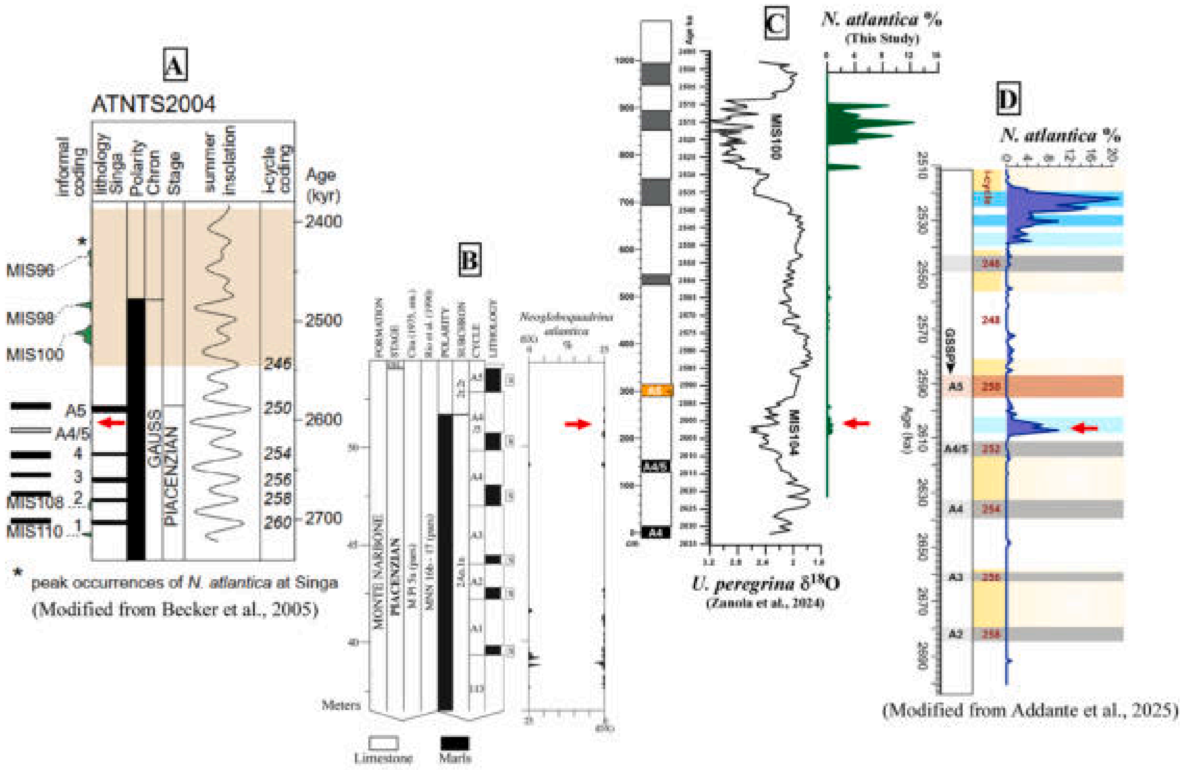


Fig. 9. Comparison between the stratigraphic logs reconstructed by Capraro et al. (2022) for the Mandorlo and the "type" GSSP section, showing that the latter suffers from tectonic reduction in the stratigraphy above the Nicola bed (base Gelasian). Note that the "type" section was only sampled from sapropel A5 upwards, due to the tectonic deformation visible across cluster A (see Fig. 8).

Mandorlo physical stratigraphic and sapropel records. This allegation compelled the SAGE group to publish a comment (Zanola et al., 2025) indicating that the agreement between the benthic δ18O record reconstructed for the Mandorlo section, the LR04 benthic δ18O stack of Lisiecki and Raymo (2005), and the record of global sea-level changes of Jacob et al. (2020) unambiguously links the glacial stages above and below the Nicola bed to MIS 102 and MIS 104, respectively. Moreover, the well-defined record of the Gauss/Matuyama geomagnetic reversal at Mandorlo leaves no room for error or alternative interpretations (Channell et al., 2020) in confirming that the cold event in the SST record of Zanola et al. (2024b) above the Nicola bed corresponds to MIS 102 and not MIS 104, as suggested by Addante et al. (2025a).

5. The Piacenzian/Gelasian boundary at Mandorlo

The continuously exposed Mandorlo section (Capraro et al., 2022) is devoid of major tectonic disturbances and deformations (Fig. 2), though small vertical displacements can be observed all around (Radmacher et al., 2025; Addante et al., 2025b). Capraro et al. (2022) investigated the Mandorlo section following a virtually undisturbed profile (Fig. 3) and produced a detailed physical stratigraphic log showing that individual MPRSs and less prominent lithological changes can be unambiguously recognized, measured, and described (Fig. 4). They attempted the first astronomical tuning for the Mandorlo, showing that the entire Gelasian interval can be calibrated to the insolation record and that the



(Modified from Becker et al., 2005)

(Modified from Sprovieri et al., 2006)

(Modified from Addante et al., 2025)

Fig. 10. Relative abundances of the subpolar planktic foraminifer *Neogloboquadrina atlantica* in central Mediterranean high-resolution records across the Piacenzian/Gelasian boundary. Lefto to right: Singa section (Calabria, Southern Italy; data from Lourens et al., 1992); Punta Piccola (Sprovieri et al., 2006); Mandorlo section (unpublished SAGE data); MSN "type" section (GELSTRAT; Addante et al., 2025a). *N. atlantica* is virtually absent (less than 1% of the total assemblage) in all record across MIS 104 (i.e., between sapropel A4/5 and A5) except for the GELSTRAT record, where it is reported to attain abundances of ca. 12% of the total assemblage.

duration of possible stratigraphic gaps in the studied profile, if any, is less than half a precession cycle (Fig. 4). On the contrary, field observations alone are insufficient to define the position and thickness of sapropel layers (the prominent Nicola bed included) in the "historical" MSN section, and geochemical analyses could not help constructing a definite stratigraphic log (Addante et al., 2024, 2025a, 2025b; Fasone et al., 2024). The Mandorlo section preserves an excellent record of the magnetobiostratigraphic events that are expected to occur across the Piacenzian – Gelasian transition (Capraro et al., 2022; Zanola et al., 2024a, 2024b) and extends continuously from the upper Piacenzian to the lower Calabrian (Fig. 4; see details in Capraro et al., 2022). The stratigraphic record can be extended downwards by tracing the prominent sapropel layers of cluster A westward, where the underlying stratigraphy – including sapropel cluster O and the well-bedded Trubi Fm. – are well-exposed (Fig. 3). The physical marker for the Gelasian GSSP is the "Nicola bed", the uppermost member of sapropel cluster A. It can be easily recognized for being distinctively orange in colour and thinly laminated, while the underlying sapropels are grey/brown, massive, and thoroughly bioturbated (Capraro et al., 2022). At Mandorlo, laminations at the top of the "Nicola bed" are well preserved even at the microscopic scale (Radmacher et al., 2025), which allows for a precise positioning of the Piacenzian/Gelasian boundary. Astronomically calibrated age for the midpoint of the "Nicola bed" is 2.588 ± 0.006 Ma (Lourens et al., 1996) that, corrected by the average sediment accumulation rates across the Piacenzian/Gelasian boundary (c. 8 cm/kyr; Zanola et al., 2024a), provides an estimated age for the base Gelasian (top of sapropel A5) of 2.587 ± 0.006 Ma. The section yielded a clear-cut and well-defined position of the Gauss/Matuyama (C2An/C2r) geomagnetic reversal, which serves as the main criterion for the definition and recognition of the Piacenzian/Gelasian boundary. At Mandorlo, the event was pinpointed 30 cm above the top of the "Nicola bed" (Capraro et al., 2022), in agreement with the coarse positioning proposed by Channell et al. (1992) in the "historical" section (−1 ±2 m). Zanola et al. (2024a) calculated an age of 2.585 ± 0.006 Ma for the Gauss/Matuyama (C2An/C2r) geomagnetic reversal at Mandorlo, in excellent agreement with most records globally (e.g., Cande and Kent, 1995; Lourens et al., 1996; Ohno et al., 2012; Channell et al., 2020).

The benthic $\delta^{18}O$ record reconstructed by Zanola et al. (2024a, b) closely mirrors the LR04 benthic stack of Lisiecki and Raymo (2005), thus proving that the Mandorlo section preserves a complete and direct response to the glacial/interglacial (obliquity-driven) climate variability (Fig. 6). Furthermore, the close match between the planktic $\delta^{18}O$ and $\delta^{13}C$ curves, the physical stratigraphic record, and oscillations in ecologically sensitive calcareous plankton species point to a complete record of regional (i.e., precession-driven) climatic and environmental changes in the Mandorlo section (Fig. 6). The section also proved to preserve an unrivalled record of paleoclimatic and paleoenvironmental events in the suborbital time domain, a feature that can be hardly observed elsewhere even in more recent open-Mediterranean and ODP sediment cores (e.g., Hodell et al., 2023; Mayewski et al., 1997; Harada et al., 2006; Cacho et al., 2000; Moreno et al., 2005; Sánchez Goñi et al., 2002; Head, 2019).

The following bioevents approximate the Piacenzian/Gelasian boundary: the Highest Occurrence (HO) of calcareous nannofossil *D. pentaradiatus*, pinpointed at c. 4.8 m above the top of the "Nicola bed", with a calculated age of 2.512 ± 0.006 Ma (full MIS 100; Zanola et al., 2024a); the HO of calcareous nannofossil *D. surculus*, at 2.8 m, with an age of 2.546 ± 0.006 Ma (MIS 101; Zanola et al., 2024a); the Top common of planktic foraminifer *Globorotalia bononiensis*, at c. 7 m, with an age of 2.498 ± 0.006 Ma (MIS 99; Zanola et al., 2024a).

Chronostratigraphic positions and calculated ages of the events above are consistent with those obtained for the central and eastern Mediterranean (Hilgen, 1991b; Lourens et al., 1996; Sprovieri et al., 1998; Raffi et al., 2006; Di Stefano et al., 2023; Lirer et al., 2019).

Finally, access to the Mandorlo section is quick, safe, and easy. In this regard, it is worth mentioning that members of the INQUA Executive Committee attending the Meeting "The Plio-Pleistocene successions from Southern Sicily and the Gelasian GSSP" in March 2010 had the chance to inspect the "Nicola bed" at Mandorlo, away from the more daring and remote GSSP site. Likewise, participants to the SQS-INQUA GELSTRAT Symposium in September 2021 reached the summit of MSN to observe the Mandorlo section from above, which they later reached for a close examination of the Piacenzian/Gelasian boundary instead of visiting the "historical" profile. Considering these critical points, we recommend the Mandorlo section as the best available profile for investigating the Piacenzian/Gelasian boundary and the Gelasian stratigraphy as well.

6. Conclusions

The MSN succession has the potential to provide the most comprehensive and detailed chronostratigraphic record available across the Piacenzian/Gelasian boundary. Data reviewed and presented in this paper confirm its critical role in characterizing the biotic, climatic, and geologic events that occurred across the boundary in the central Mediterranean area, and globally. Ongoing investigations in the MSN area confirm the reliability and practicality of the markers employed by Rio et al. (1998) to approximate the Gelasian GSSP, and further improved their chronological resolution and correlatability at the global scale. This goal was achieved by the implementation of new proxies, such as the high-resolution δ^{18}O and δ^{13}C records for both planktic and benthic foraminiferal species.

Coeval on-land exposures of open-marine sediments exist in southern Calabria (e.g., the Singa section; Zijderveld et al., 1991) and within the Crotone basin (Ionian Calabria), where less remarkable alternatives are widespread (Capraro et al., 2006, 2011; Massari et al., 2010). However, these sections have not proven so far to offer a record of both Milankovitch and sub-Milankovitch climate variability and the relevant small-scale sedimentary response as manifold and comprehensive as those preserved at Mandorlo (Becker et al., 2005; Bonomo et al., 2024; Zanola et al., 2024a, 2024b). Extra-Mediterranean counterparts, such as the Miyazaki section in southwestern Japan (Oda et al., 2011), are nowhere near of offering a stratigraphic record of comparable detail and completeness. However, advances made by the SAGE and GELSTRAT projects in recent years proved that the MSN area housing the Gelasian GSSP of Rio et al. (1998) is affected by severe tectonic deformation and associated stratigraphic reduction in the interval straddling the Piacenzian/Gelasian boundary. This limitation also precludes the chance of selecting the "historical" GSSP section at MSN to define the AUS for the Gelasian Stage in a formal way (Hilgen et al., 2026). The nearby Mandorlo section is easier to reach, better exposed, and less tectonically disturbed than the "historical" MSN section. Furthermore, it provided a superior paleomagnetic record, and the high-resolution stable isotope record confirms that the Mandorlo stratigraphy is continuous and undisturbed at least up to the bottom of sapropel B1 (early MIS 89). For these reasons, should the scientific community feel the need to enhance the accuracy and reliability of the stratigraphic record across the Piacenzian/Gelasian boundary and its global correlatability, relocating the Gelasian GSSP to the base of the Mandorlo section would be the most logical alternative. This option would allow enforcing the same criteria and markers employed by Rio et al. (1998) in their original definition. Specifically, the GSSP for the Gelasian Stage (also marking the Piacenzian/Gelasian, Pliocene/Pleistocene and Neogene/Quaternary boundaries) would be pinpointed at the base of the marly clays conformably overlying the top of the "Nicola bed" (MPRS A5, i-cycle 250, in MIS 103; Zanola et al., 2024a) in the Mandorlo section of Capraro et al. (2022). The boundary would be approximated by the Gauss/Matuyama (C2An/C2r) geomagnetic reversal, which was identified c. 30 cm above the top of the "Nicola bed", and by the Top of *D. surculus* and *D. pentaradiatus*, which were detected at c. 2.8 m and 4.8 m, respectively. The revised age of the boundary would be 2.587 ± 0.006 Ma, calculated by implying an astronomically derived age of 2.588 ka for the midpoint of the "Nicola bed" (Lourens et al., 1996) and an average sediment accumulation rate of 8 cm/kyr across the "Nicola bed" (Zanola et al., 2024a). Accordingly, relocating the Gelasian GSSP to the Mandorlo section would require no or only very minor changes to its definition and/or amendments to the GTS. The Mandorlo section is also amenable to host the AUS for the Gelasian Stage (Hilgen et al., 2026). Once accepted and formally defined, the Gelasian AUS would provide a strong and compelling extra case for relocating the Gelasian GSSP at Mandorlo.

Author contributions

Capraro, L.: Conceptualization, Funding acquisition, Writing – original draft.

Bonomo, S.: Conceptualization, Visualization, Writing – review and editing.

Incarbona, A.: Conceptualization, Visualization, Writing – review and editing.

Hilgen, F.J.: Supervision, Validation, Writing – review and editing.

Zanola, E.: Supervision, Validation, Writing – review and editing.

Di Stefano, A.: Funding acquisition, Supervision, Validation.

Dela Pierre, F.: Supervision, Validation.

Ferraro, S.: Investigation, Supervision, Validation.

Ferretti, P.: Supervision, Validation.

Fornaciari, E.: Supervision, Validation.

Galeotti, S.: Supervision, Validation.

Macrì, P.: Supervision, Validation.

Negri, A.: Supervision, Validation.

Raffi, I.: Supervision, Validation.

Rodrigues, T.: Supervision, Validation.

Speranza, F.: Supervision, Validation.

Spiering, B.R.: Supervision, Validation.

Tesei, T.: Investigation, Supervision, Validation.

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Declaration of competing interest

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

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Data availability

No new data are presented in this MS

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