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Short Communication

Monsoon variability and high latitude climate signals in the Central Mediterranean at the Pliocene- Pleistocene transition: The Gelasian stratotype section (Monte San Nicola, Sicily) [Global and Planetary Change, volume 249, 104788]: Comment

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ABSTRACT

The stratigraphic record of Monte San Nicola (southern Sicily, Italy), where the Global Boundary Stratotype Section and Point (GSSP) for the Gelasian Stage (Lower Pleistocene) has been defined, has been studied by our research group for fifteen years. In 2021, another working group (GELSTRAT) started investigating the Monte San Nicola stratigraphy in a location close to the GSSP section, with results that differ significantly from those published by our team. In particular, major discrepancies in the alkenone-derived paleotemperature reconstructions led the GELSTRAT team to suggest that our age model is invalid, and they inferred that we had made a wrong interpretation of the physical stratigraphic record. In this comment, we demonstrate that our chronological model is correct, while the stratigraphic profile studied by the GELSTRAT team should be approached with care, due to the presence of tectonic displacements, truncations, and uncertain lithological evidence for critical marker beds, such as the sapropel layers below the Nicola bed.

1. Introduction

In the context of the GELSTRAT project, aimed at detailing the Pliocene-Pleistocene boundary in its type area (Head and Caruso, 2022), Addante et al. (2025) presented an alkenone-based paleotemperature reconstruction along a sedimentary profile (hereafter GS section) located c. 20 m west of the original Gelasian "type" GSSP section (Fig. 1) in Monte San Nicola (hereafter MSN section), Sicily, Italy (Rio et al., 1998). Their results differ substantially from the alkenone-derived paleotemperature record obtained by Zanola et al. (2024b) for another coeval profile in the MSN area, namely the Mandorlo section of Capraro et al. (2022). In commenting the discrepancy between the records, Addante et al. (2025) conclude: "*We do not have a definitive explanation for this discrepancy, although we point out that further anomalies can be noted in the alkenone record obtained in the Mandorlo section and specifically in the C_{37}pattern (Supplementary), suggesting that the chronology and/or sapropel location of the Mandorlo section require to be revised, with the possibility the large cooling placed at ~ 2570 ka by*Zanola et al. (2024a)*be*

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more appropriately correlated to MIS 104". Based on the alkenone record, Addante et al. (2025) conjecture that the age model for the Mandorlo section reconstructed by Zanola et al. (2024a, 2024b) is incorrect due to our misinterpretation of the local stratigraphic record. In our knowledge, however, paleotemperature records have never been employed as surrogates – let alone superior substitutes – of globally validated chronostratigraphic proxies such as the benthic $\delta^{18}O$ and palaeopolarity records, nor they should be, given their strictly regional scope. In this comment, we demonstrate that our chronological framework established for the Mandorlo section is accurate, as it was developed based on a set of sound stratigraphic constraints that, on the other hand, have not been presented so far for the GS section.

2. Reply

2.1. The Mandorlo section

Capraro et al. (2022) published the first results of a multidisciplinary study on the Mandorlo section, a new profile exposed in the western sectors of the MSN area that was demonstrated to provide a complete and continuous stratigraphic record throughout the Gelasian Stage. The section yielded a wide array of crucial products, ranging from the identification of major expected bio- and magnetostratigraphic features to the recognition of individual precession-related sedimentary couplets, which allowed for the first astronomical tuning of the whole Gelasian stratigraphy in its reference area. Accordingly, it was demonstrated that the duration of possible sedimentary hiatuses in the Mandorlo section, if any, is less than half a precession cycle. Capraro et al. (2022) also investigated the "type" Gelasian GSSP section of Rio et al. (1998) to prove that the local succession contains major gaps, as 5 m at least of the lower Gelasian stratigraphy have been obliterated by faulting. For these reasons, the "type" section was discarded for future high-resolution studies.

2.2. The Nicola bed and its identification in the field

The Nicola bed is a prominent Mediterranean Precession-Related Sapropel (MPRS) that was proposed by Rio et al. (1994) as the marker bed for the GSSP of the Gelasian Stage (Rio et al., 1998). It represents the top member of sapropel cluster A (A5, according to the labeling of Zijderveld et al., 1991), and it stands out from all the sapropels below (the massive, dark brown to grey MPRSs A1 to A4/5) for being uniquely orange and thin laminated (Capraro et al., 2022). Moreover, the Nicola bed is overlain by a very distinctive stratigraphy, and the following sapropel (i.e., MPRS B1) is located c. 17 m above it (Capraro et al., 2022). For these reasons, identification of the Nicola bed cannot be missed in areas that are well exposed and void of major tectonic disturbances, such as the Mandorlo section. Not by chance, Radmacher et al. (2025) acknowledged that the Nicola bed is extremely well preserved at Mandorlo, in contrast with the poor conditions found in the GS section (Radmacher et al., 2023). Altogether, we are positive that the Nicola bed and the adjacent marker beds (i.e., the sapropel layers of cluster A and B) have been singled out properly during our extensive and accurate survey in the MSN area.

2.3. Age model

The high-resolution $\delta^{18}O$ record reconstructed at Mandorlo by Zanola et al. (2024a, 2024b) for the benthic species *Uvigerina peregrina*, possibly the closest available proxy of glacioeustasy for the Mediterranean (see discussion in Capraro et al., 2017), is the chronostratigraphic pillar on which our age model was built (Fig. 2). Our benthic $\delta^{18}O$ record (not yet available for the GS section) was calibrated using the benthic $\delta^{18}O$ stack of Lisiecki and Raymo (2005), arguably the most accurate depiction of the global glacial/interglacial climate variability over the last 5 Myr, as the target curve. Recognition of the Gauss/Matuyama boundary c. 30 cm above the Nicola bed (Zanola et al., 2024a) confirms that the geomagnetic reversal occurred in MIS 103, in agreement with what is observed in most paleomagnetic records worldwide (e.g., Laj and Channell, 2007, 2015; Ohno et al., 2012; Cande and Kent, 1995; Lourens et al., 1996). This critical evidence could not be achieved in the "type" section, where rock magnetic properties are very poor (Capraro et al., 2022), nor it has been published so far for the GS section.

The astronomically derived ages for midpoints of glacial-interglacial transitions and sapropel layers A2 to A5 were used as chronological ties (see details in Zanola et al., 2024a). As expected, all the lithological intervals identified as sapropels correspond to "light" peaks in the $\delta^{18}O$ record for the surface-dweller *Globigerinoides ruber* (Fig. 2; Zanola et al., 2024b). Notably, the age obtained for the "ghost" sapropel interval at c. 2544 ka – which has no lithological expression at MSN and is only approximated by a negative peak in our planktic $\delta^{18}O$ curve (Fig. 2) – matches the age first obtained by Becker et al. (2005) for a profile adjacent to the Mandorlo section. Our $\delta^{18}O$ record for *U. peregrina* shows striking similarities not only with the benthic $\delta^{18}O$ stack of Lisiecki and Raymo (2005) but also with the reconstruction of global sea level changes of Jakob et al. (2020) and the fluctuations in reworked coccoliths abundances at Mandorlo (Bonomo et al., 2024), which can be considered as a proxy for oscillations in the base level of erosion (i.e., increasing/decreasing terrigenous input).

Further validation to our large-scale chronological interpretation of the Mandorlo record is provided by the calcareous plankton biostratigraphy (Capraro et al., 2022) and the quantitative study of nannofossils

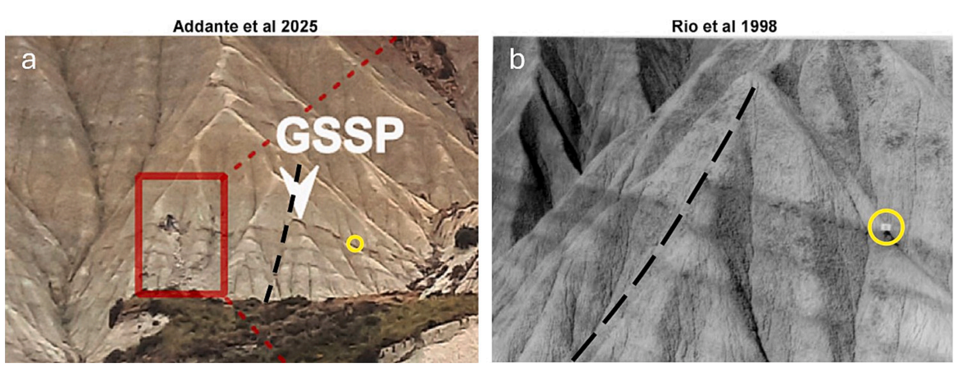

Fig. 1. a) location of the GS sampling profile (red box) and alleged position of the Gelasian GSSP (white arrowhead) according to Addante et al. (2025). The yellow ring indicates the true position of the Gelasian GSSP as indicated by Rio et al. (1998) (b, right panel), proving that the section sampled by the GELSTRAT working group is not that hosting the Piacenzian/Gelasian boundary. Instead, the GS section develops west of a major fault (black dashed lines) dislocating the whole sapropel cluster A, with noticeable effects on the local stratigraphic record (see the uneven distribution of sapropel layers within cluster A and the poor preservation of the Nicola bed (A5) left of the fault in Fig. 1b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

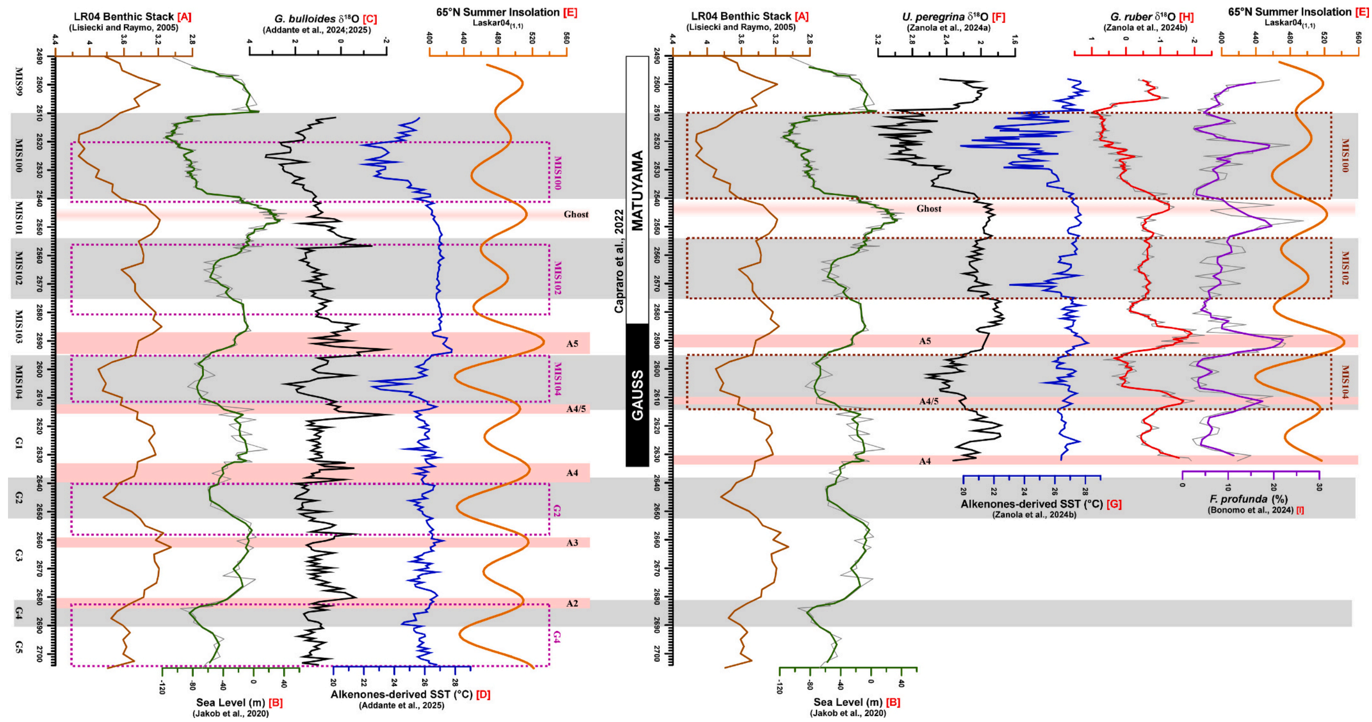

Fig. 2. Comparison between the available datasets for the GS (left panel) and Mandorlo sections (right panel) in the interval straddling the Nicola bed. The vertical scale (ka) is the same for both records. The LR04 $\delta^{18}O$ benthic stack of Lisiecki and Raymo (2005) (**A**) and the sea level reconstruction of Jakob et al. (2020) (**B**) are reported for reference in both panels. The horizontal grey bands mark the duration of glacial stages G4 to MIS 100, as indicated in Lisiecki and Raymo (2005). Dotted boxes designate the chronostratigraphic position of glacial intervals within each section according to their individual age models, showing that the duration of glacial intervals at Mandorlo fits that of Lisiecki and Raymo (2005) while a significant mismatch exists throughout the GS section. Black lines (**C** and **F**) indicate the $\delta^{18}O$ records used in reconstructing the age models for each section, these being the shallow-infaunal benthic *U. peregrina* at Mandorlo and the planktic *G. bulloides* for the GS section. The similarity between our $\delta^{18}O$ record of *U. peregrina* and the benthic stack of Lisiecki and Raymo (2005) proves that the Mandorlo record mimics the amplitude and timing of global glacial/interglacial cycles. Position of the Gauss/Matuyama geomagnetic reversal at Mandorlo (center) confirms that the Nicola bed falls within MIS 103. Blue lines (**D** and **G**) indicate the alkenone-based paleotemperature reconstruction for both sections. The MIS 100 glaciation, represented poorly in the GS section, yielded a detailed record of suborbital cyclicities at Mandorlo (see Zanola et al., 2024a, 2024b for details). The $\delta^{18}O$ record for the surface-dweller planktonic foraminifer *G. ruber* (**H**) and the relative abundance of the deep-dweller *F. profunda* (**I**) are indicative of warm, well-stratified surface waters and/or surface freshwater lenses (e.g. Rohling et al., 2004, Beaufort et al., 1997; Incarbona et al., 2022). As expected for an open-marine Mediterranean record, "light" peaks in the $\delta^{18}O$ record of *G. ruber* and abundance intervals of *F. profunda* are in phase with the deposition of sapropel layers (pink horizontal bands). Correlation between individual sapropel layers and the $\delta^{18}O$ record of *G. bulloides* in the GS section (left panel) is much less sharp and consistent. A special feature is the "ghost" sapropel of Becker et al. (2005) at 2544 ka that, although void of any lithological expression in both sections, is clearly marked at Mandorlo by a "light" peak in the $\delta^{18}O$ record of *G. ruber* and high abundances of *F. profunda*. Evidence of the event in the GS record is flimsy, however the same "ghost" sapropel has been exploited as a key chronological tie point for deriving the age model of Addante et al. (2024, 2025). Finally, the insolation curve (**E**) emphasizes that the duration of glacial MIS 100 in the GS record (one insolation cycle) is largely underestimated, as the event is known to have spanned almost two insolation cycles (Becker et al., 2005), which further questions the chronological framework proposed by Addante et al. (2024, 2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assemblages of Bonomo et al. (2024), showing long- and short-term changes that are closely in agreement with the events and oscillations recognized in the physical stratigraphic and $\delta^{18}O$ records. Periods of increased stratification of the water column, marked either by the deposition of sapropel-related layers or simply by major oscillations in our planktic $\delta^{18}O$ record, correspond to prominent peaks in the relative abundance of *Florisphaera profunda* (Fig. 2). This signal is much weaker in the GS record (not shown here), where peaks of *F. profunda* comparable to those found at Mandorlo only occur at the Nicola bed and, to a lesser extent, in correspondence with the alleged sapropel A3 of Addante et al. (2025, Supplementary data).

In conclusion, the available evidence concurs that the chronological interpretation of the Mandorlo section proposed by Zanola et al. (2024b) is correct. The excellent agreement between our benthic $\delta^{18}O$ curve, the LR04 benthic $\delta^{18}O$ stack and the record of global sea-level changes offers a much more dependable chronological lead than any alkenone-derived SST record, eventually binding the glacial stages above and below the Nicola bed to MIS 102 and MIS 104, respectively. The sharp record of the Gauss/Matuyama geomagnetic reversal achieved at Mandorlo further validates our age model, leaving no room for error or alternative interpretations in confirming that the cold event in the SST record of Zanola et al. (2024b) above the Nicola bed corresponds to MIS 102, not MIS 104 as suggested by Addante et al. (2025).

2.4. Reliability of the GS record

We have no conclusive explanation for the discrepancies that exist between the records published by Zanola et al. (2024a, 2024b) and those presented by Addante et al. (2024, 2025), and even between the latter (Table 1; Fig. 3). We insist that the GS profile is not the same as the "true" Gelasian GSSP section, because it is located c. 20 m west of the spot where Rio et al. (1998) placed the golden spike (Fig. 1). Although more accessible than the "type" section and deceptively amenable to high-resolution investigations, the GS profile has been for a long time discarded as a potential study section due to the presence of severe tectonic disturbances in the very gully sampled by the GELSTRAT group (Rio and Di Stefano, pers. comm.; our unpublished field data).

Recently (May and June 2025), we visited the type Gelasian GSSP area to reexamine the local stratigraphic succession. The GS sampling profile can be identified unambiguously, being marked by a series of

Table 1
Stratigraphic boundaries and relative thicknesses of individual sapropels layers of cluster A for the GS and Mandorlo sections. Reference stratigraphic zero was the top of sapropel A1 for the GS section and the top of the Nicola bed (sapropel A5) for the Mandorlo. Surprisingly, the thicknesses and positions provided by Addante et al. (2024) and Addante et al. (2025) differ considerably, although the studied sample set is reportedly the same.

	GS section		MSN section	
Sapropels	Addante et al., 2024	Addante et al., 2025	Capraro et al., 2022	Zanola et al., 2024a, 2024b
A5	760 to 795 cm = 35 cm	730 to 770 cm = 40 cm	−35 to 0 cm = 35 cm	−35 to 0 cm = 35 cm
A4/5	650 to 672 cm = 22 cm	615 to 650 cm = 35 cm	−185 to −160 cm = 25 cm	185 to −160 cm = 25 cm
A4	465 to 515 cm = 50 cm	440 to 490 cm = 50 cm	−330 to −300 cm = 30 cm	−330 to −300 cm = 30 cm
A3	315 to 335 cm = 20 cm	290 to 310 cm = 20 cm	−460 to −430 cm = 30 cm	
A2	165 to 200 cm = 35 cm	140 to 175 cm = 35 cm	−620 to −595 cm = 25 cm	
Top A1	0 cm	0 cm		

long steel nails hammered into the bedrock by GELSTRAT operators (Fig. 4) as further confirmed by a local news video report (https://www.rainews.it/tgr/sicilia/video/2021/09/sic-geologi-ricerca-butera-gela-clima-2c0784dc-c5ca-48f7-ba87-61b2286357a0.html). After the removal of a thick regolith layer along the GS gully, it was revealed that the Nicola bed and the surrounding stratigraphy are disrupted by a dense network of joints and small faults (Fig. 4). At least two main faults displace the Nicola bed (Fig. 4a-c): 1) a N-dipping fault, visible across multiple culminations in the eastern MSN badlands, which we interpret as a normal fault based on the obvious vertical displacement of sapropel layers of cluster O immediately west of the GS area; 2) a striated, N-S trending sub-vertical strike-slip fault running along the GS section. Their cross-cutting relations are unclear, but the faults of relevance are potentially synchronous. Other minor faults, some of which striated, and joints occur in a variety of orientations that are generally consistent with coexisting normal and strike slip fault regimes. Most minor faults and joints are highlighted by veins of recrystallized gypsum and by oxides patinas that occasionally display strike-slip and transtensive oblique striations (Fig. 4d, f).

3. Conclusions

Results of our survey demonstrate that the Mandorlo section provides a pristine stratigraphic record in the interval straddling the Nicola bed, i.e., the base of the Gelasian Stage, and allows for a detailed and comprehensive depiction of the events occurring across the Pliocene–-Pleistocene transition. By contrast, the chronological constraints

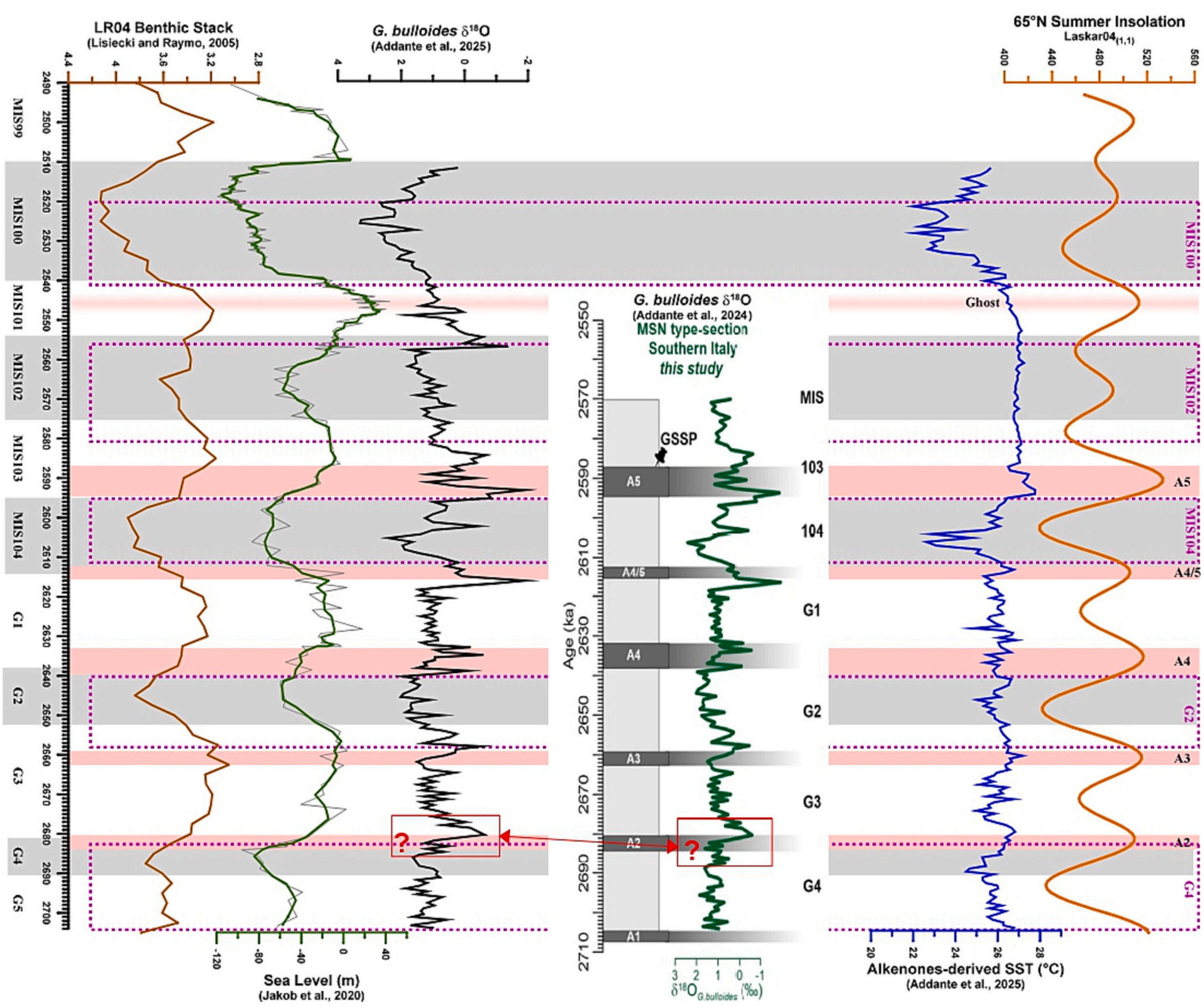

Fig. 3. The δ[18]O record of *G. bulloides* for the GS section as published by Addante et al. (2024) and Addante et al. (2025), showing that 5 to 6 samples beneath sapropel A2 (i.e., 25 to 30 cm) have been removed in the 2025 version (red boxes). This discrepancy was not addressed in Addante et al. (2025) and remains unexplained. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

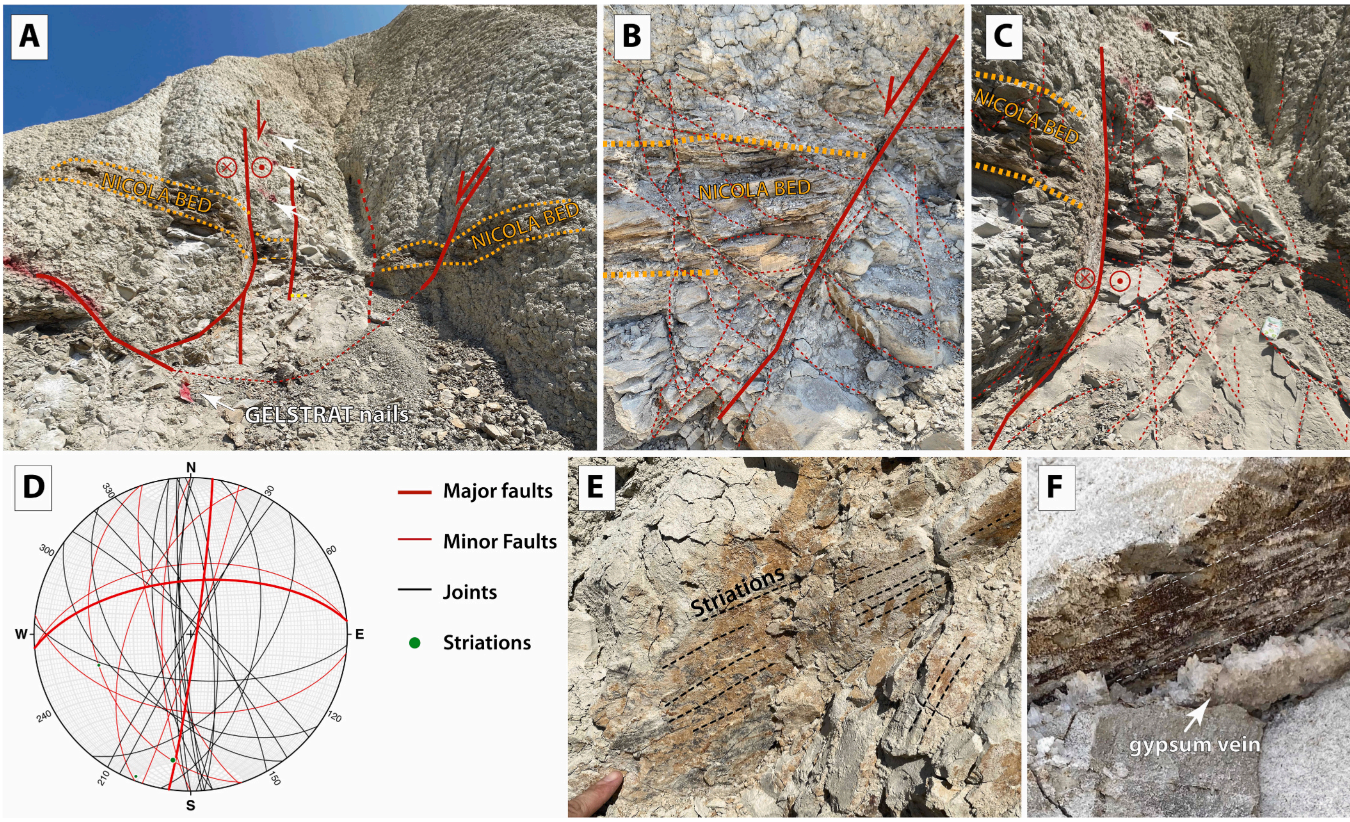

Fig. 4. Tectonic disturbances affecting the GS section. Solid lines indicate major faults that mark clear lithological contrasts. Dashed lines indicate minor faults and fractures (red) or striations (black and white). **A**) Overview of the GS gully. The Nicola bed is highly discontinuous and truncated by fault surfaces. White arrows indicate the nails left by GELSTRAT operators. **B**) Detail of the Nicola Bed truncated by the main normal fault (see text). Minor conjugate faults and fracture systems, often filled by gypsum veins and/or marked by oxides, are also visible. **C**) The Nicola bed truncated by the N-S trending strike-slip fault close to the nails left by GELSTRAT operators (white arrows). **D**) Lower hemisphere (Schmidtt net) projection of structures measured in the GS gully. **E**) Detail of the oxide-stained striated fault plane from panel **C**. **F**) Detail of a striated minor fault immediately below the Nicola bed, with oxide patinas covered by a recrystallized gypsum vein. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

available for the GELSTRAT record are not equally strong, and the presence of a thick network of faults and joints cutting through the GS section suggests that the profile investigated by Addante et al. (2024, 2025) is unsuitable for high-resolution studies. Tectonic displacements, truncations, and the flimsy lithological evidence for critical marker beds, such as the sapropel layers below the Nicola bed, implies that the results obtained for the GS section should be considered with caution. Altogether, data acquired from the GS record do not pose a challenge to those obtained so far for the Mandorlo section that, as of today, offers the most complete, detailed and reliable record available across the Piacenzian/Gelasian boundary in its type-area, and beyond.

CRediT authorship contribution statement

Elena Zanola: Writing – review & editing, Validation, Investigation, Conceptualization. **Sergio Bonomo:** Writing – review & editing, Validation, Supervision, Investigation, Data curation, Conceptualization. **Alessandro Incarbona:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Telemaco Tesei:** Writing – review & editing, Validation, Supervision, Methodology, Investigation. **Agata Di Stefano:** Project administration, Supervision. **Patrizia Ferretti:** Supervision. **Eliana Fornaciari:** Validation, Supervision. **Simone Galeotti:** Supervision. **Patrizia Macrì:** Validation, Supervision. **Isabella Raffi:** Validation, Supervision. **Teresa Rodrigues:** Supervision. **Fabio Speranza:** Supervision. **Enrico Di Stefano:** Validation, Supervision. **Rodolfo Sprovieri:** Supervision. **Domenico Rio:** Validation, Supervision. **Luca Capraro:** Writing – original draft, Writing – review & editing, Validation, Supervision, Methodology, Project administration, Investigation, Data curation, Conceptualization.

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. This work was funded by the Italian Ministry of University and Research (PRIN 20227ZCCFX to LC and ADS).

Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

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