by Elena Turco[1], Frits Hilgen[2], Isabella Raffi[3], Agata Di Stefano[4], Luca Maria Foresi[5], Ann Holbourn[6], Silvia Maria Iaccarino[7], and Fabrizio Lirer[8]*

The Global Stratotype Section and Point (GSSP) of the Langhian Stage and of the Middle Miocene Subseries

[1] Dipartimento di Scienze Chimiche, della Vita e della Sostenibilità Ambientale, Università degli Studi di Parma, 43124 Parma, Italy; *Corresponding author, *E-mail: elena.turco@unipr.it*
[2] Department of Earth Sciences, University of Utrecht, 3508 TA Utrecht, The Netherlands
[3] International Research School of Planetary Sciences - IRSPS, Università degli Studi "G. d'Annunzio" di Chieti-Pescara, 66013 Chieti Scalo, Italy
[4] Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università degli Studi di Catania, 95129 Catania, Italy
[5] Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università degli Studi di Siena, 53100 Siena, Italy
[6] Institute of Geosciences, Christian-Albrechts Universität zu Kiel, D-24118 Kiel, Germany
[7] Full Professor in Paleontology (retired), Università degli Studi di Parma, 43124 Parma, Italy
[8] Dipartimento di Scienze della Terra, Sapienza Università di Roma, 00185 Roma, Italy

(Received: August 1, 2023; Revised accepted: October 3, 2023)

https://doi.org/10.18814/epiiugs/2023/023024

The Global Stratotype Section and Point (GSSP) of the base of Langhian Stage (base of the Middle Miocene Subseries) is defined at a level of 17.84 m in the "Lower La Vedova Beach" section in central Italy. This level marks the mid-point of the darker marly interval above "Megabed IV" which has been astronomically calibrated to the most prominent ~100-kyr eccentricity maximum, with an astronomical age of 15.981 Ma according to La2004 nominal solution, and of 15.978 Ma according to the La2011, in the 405-kyr maximum around 16.0 Ma. The GSSP level in the Lower La Vedova Beach section corresponds closely to the top of Chron C5Cn (at 15.795 m), which is considered the principal event for recognizing the boundary globally. This magnetic reversal with an astronomical age of 16.017 Ma (Turco et al., 2017) (15.97 Ma in Hilgen et al., 2012 ATNTS, 2012; 15.994 Ma in Raffi et al., 2020 in GTS2020) is preferred to the historical guiding criterion, the Praeorbulina *datum, which has been complicated by taxonomic confusion and revision (Turco et al., 2011a), and hence is considered less suitable for recognizing the boundary. The Lower La Vedova Beach section is preferred to the St. Peter's Pool section (in Malta) as it has an independent astronomical tuning and a better paleomagnetic signal. With the selected astrochronologic criterion close to an important magnetic reversal boundary we follow standard procedures developed by SNS to define Neogene GSSPs over the years. This procedure guarantees that the Langhian GSSP is directly incorporated in the integrated astronomically dated stratigraphic framework that nowadays underlies our standard GTS, while it is sufficiently close to the top of Chron C5Cn that the latter can be used for correlating the boundary time-stratigraphically on a global scale.*

In addition, a Standard Auxiliary Boundary Stratotype (SABS) is designated at Integrated Ocean Drilling Program (IODP) Site U1337, in the eastern equatorial Pacific, with the aim to directly link the open ocean benthic foraminiferal stable isotope record to the boundary definition. This level marks the mid-point of a darker interval that has been astronomically calibrated to the same prominent ~100-kyr eccentricity maximum. This level coincides with distinctive features in the stable isotope record, falls right in the middle of the Miocene Climatic Optimum (MCO) and is approximately one 405-kyr cycle older than the most dramatic oxygen isotope minimum dated astronomically at 15.6 Ma, marking the most extreme warming during the entire Miocene (Holbourn et al., 2013). It further corresponds closely to the top of Chron C5Cn, based on detailed cyclostratigraphic correlations to parallel Sites U1335 and U1336, which have an excellent magnetostratigraphy.

Biostratigraphically, the Langhian GSSP falls in the lower part of the Mediterranean planktonic foraminiferal Subzone MMi4a (Di Stefano et al., 2008; Iaccarino et al., 2011; Lirer et al., 2019), delimited by the First Occurrence (FO) of Globigerinoides sicanus *(3 apertures) at the base and the Beginning of the* Paragloborotalia siakensis *$Acme_a$ at the top, and calcareous nannofossil Subzone MNN4b (Di Stefano et al., 2008; 2023), defined by the Last Common Occurrence (LCO) of* Helicosphaera ampliaperta *and the Beginning of the* Sphenolithus heteromorphus *Paracme interval. With respect to (sub)tropical biozonations, the*

Langhian GSSP falls within the planktonic foraminiferal Zone M5 (Wade et al., 2011) and Zone N8 (Blow, 1969), defined by Base Praeorbulina sicana *(B) and Base* Orbulina suturalis*, and at the top of the calcareous nannofossil Zone CNM6 (Backman et al., 2012), defined by Base* S. heteromorphus *and Base* Discoaster signus (= D. petalosus)*, corresponding to the upper part of Zone NN4 (Martini, 1971).*

Introduction

The aim of this paper is to announce the formal ratification of the Global Stratotype Section and Point (GSSP) of the Langhian Stage and the Middle Miocene Subseries. The Langhian Stage, together with the succeeding Serravallian, constitutes the Middle Miocene Subseries in the International Chronostratigraphic Chart (Aubry et al., 2022).

During the last decades the progress made in establishing orbitally tuned stratigraphic frameworks, both in Mediterranean and in the open ocean, facilitated the standardization of most of the Neogene by the definition of GSSPs of all Pliocene Stages (Castradori et al., 1998; Van Couvering et al., 2000) and the Messinian, Tortonian and Serravallian stages of the Miocene (Hilgen et al., 2000, 2005, 2009). More recently, astronomically tuned stratigraphic frameworks were extended to the interval straddling the Burdigalian/Langhian boundary in the Mediterranean and open ocean. Following these studies, a proposal for the definition of the GSSP of the Langhian Stage in the La Vedova section (northern Italy) and a Standard Auxiliary Boundary Stratotype (SABS) at the Integrated Ocean Drilling Program (IODP) Site U1337 (in the eastern equatorial Pacific) (Turco et al., 2022) was submitted to the Subcommission on Neogene Stratigraphy (SNS) in 2022 for discussion and a formal vote. The revised proposal was unanimously approved by SNS voting members (quorum 100%, 19 votes positive) in March 2023 and, subsequently also by the International Commission on Stratigraphy (ICS) (18 delivered votes out of 20, 18 votes positive) in May 2023. Ratification by the Executive Committee of the International Union of Geological Sciences (IUGS) was obtained on 29 May 2023.

After a brief review of the historical Langhian, the guiding criteria and candidate sections we present a description of the selected stratotype sections and the definition of the GSSP level for the base of the Langhian Stage. This level in addition defines the base of the Middle Miocene Subseries.

Langhian Historical Stratotype

The Langhian Stage is the currently accepted global chronostratigraphic standard for the lower part of the Middle Miocene (Berggren et al., 1985, 1995; Harland et al., 1990; Lourens et al., 2004) and represents the lower stage of the recently formalized Middle Miocene Subseries (Aubry et al., 2022).

The Langhian Stage was introduced by Pareto in 1865 to indicate the sandy to marly successions of the middle part of Miocene, exposed in the Bormida valley in the Langhe region (Piedmont, northern Italy), above the now abandoned Stage "Bormidian" and below the Serravallian. The original concept of Pareto was modified by Mayer-Eymar (1868), who limited the term Langhian to the upper part of the succession, the so-called "Pteropod Marls", and by Vervloet (1966), who defined the type Langhian to correspond to the Cessole Formation or Cessole Marls (coinciding with Pteropod Marls) (Boni 1967; Gelati 1968), which thus became synonymous with the Langhian.

The stratotype section of the Langhian, located close to the Cessole Village (Piedmont, northern Italy), was designated by Cita and Premoli Silva (1960). The lower part of the stratotype, exposed in the Bricco del Moro section located on a hill south of the Bormida River, shows the gradual transition from the Cortemilia Formation to the Cessole Marls. The main part of the Langhian is exposed in the Bricco della Croce section, located on a slope north of the Bormida River, where the transition to the overlying Cassinasco Formation is abrupt. Cita and Premoli Silva (1960), in their study of planktonic foraminifera, recognized the various stages in the evolutionary *Globigerinoides-Orbulina* lineage following the taxonomy of Blow (1956) (*G. trilobus*, *G. bisphericus*, *Praeorbulina glomerosa curva*, *P. glomerosa glomerosa*, *P. glomerosa circularis*, *Orbulina suturalis* and *O. universa*). Specifically, the first evolutionary appearance of *Praeorbulina* (*Porticulasphera*) *glomerosa curva* was detected at the very base of the "Cessole Marls" (sample 5, op. cit.) (Fig. 1).

New data on planktonic foraminifera from the type Langhian were provided by Miculan (1994) and later by Fornaciari et al. (1997). These latter authors combined planktonic foraminifera and calcareous nannofossils in a revised composite section of the type-Langhian, which included three segments (A, B, and C) encompassing the uppermost part of the Cortemilia Formation, the Cessole Formation (Langhian stratotype of Vervloet, 1966) and the lowest part of the Cassinasco Formation (Fig. 2). Fornaciari et al. (1997) detected the *Praeorbulina* datum, i.e. First Occurrence (FO) of *P. sicana*, in the Cortemilia Formation at about 100 m below the base of the Cessole Formation (= base of the historical stratotype). These authors, in distinguishing the different stages of the *Globigerinoides-Praeorbulina* group, followed the concept of Jenkins et al. (1981), but adopted the criterion of Iaccarino and Salvatorini (1982), who regarded *P. glomerosa curva* as a junior synonym of *P. sicana* calling it *P. glomerosa sicana* (Fig. 2). However, according to Rio et al. (1997) this revised stratotype section did not represent the ideal section for defining a Global Stratotype Section and Point (GSSP), since it is badly exposed and shows sedimentary facies unsuitable for establishing a detailed chronology.

Later on, Di Stefano et al. (2008) highlighted discrepancies and uncertainties when they compared the biostratigraphic events recorded in several Mediterranean sections (Moria, Cretaccio and DSDP Site 372) with those recorded in the Langhian historical stratotype re-studied by Fornaciari et al. (1997), in particular concerning the evolutionary stages of the *Praeorbulina-Orbulina* lineage.

The most recent revision of the historical stratotype of Langhian was performed by Iaccarino et al. (2011) within a project dealing with high-resolution integrated stratigraphy of the Burdigalian/Langhian boundary interval in the Mediterranean. These authors re-examined the planktonic foraminifera of the Langhian type section focusing on a better definition of the position of the first stages in the *Globigerinoides–Praeorbulina* evolutionary lineage, following the review of Turco et al. (2011a). In this review, the *Praeorbulina* datum coincides

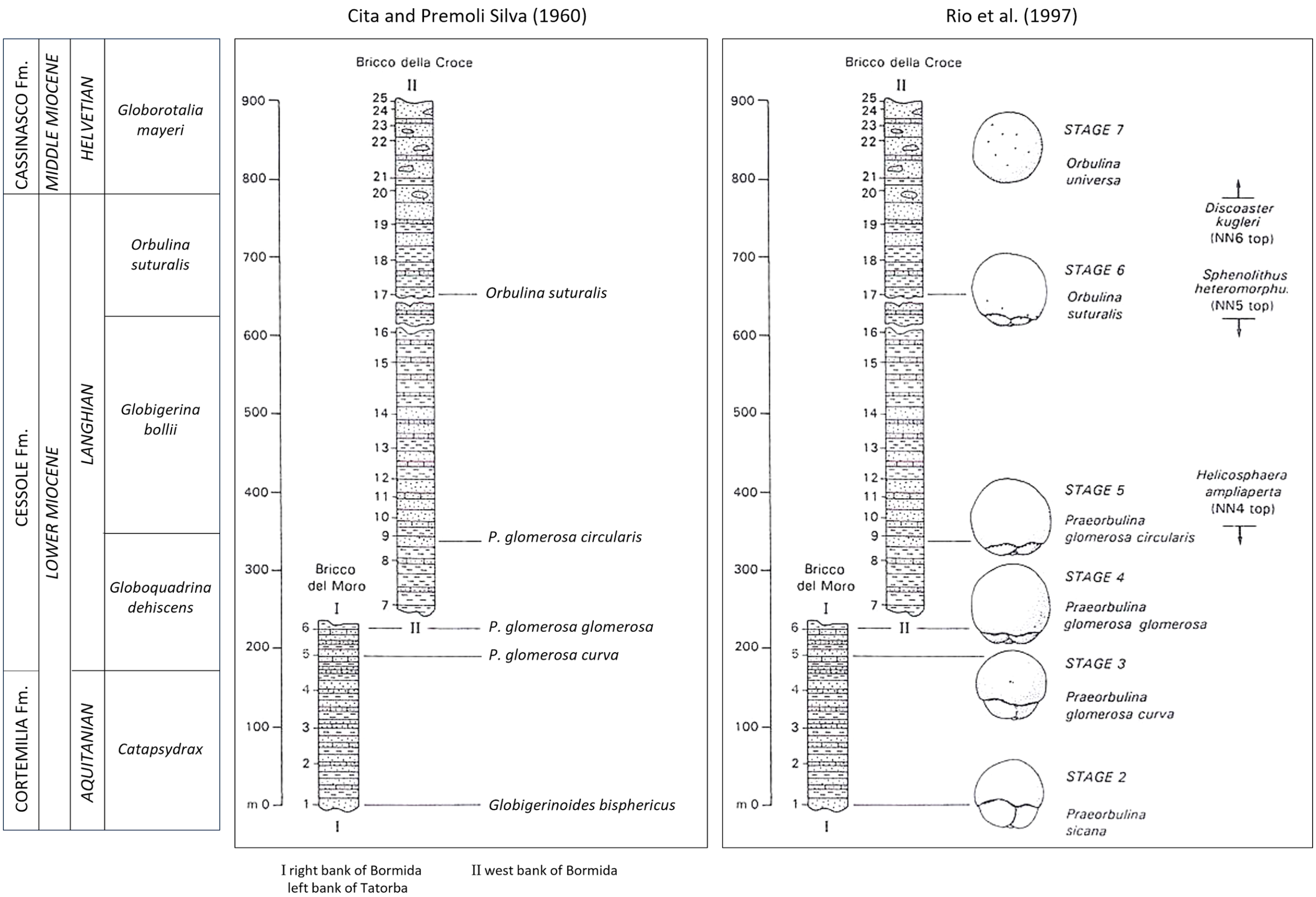

Figure 1. The original section of the type-Langhian showing the stratigraphic position of the various stages in the* Globigerinoides-Praeorbulina-Orbulina *lineage recognized by Cita and Premoli Silva (1960) following the taxonomy of Blow (1956). Note that later Blow (1969) considered* Globigerinoides bisphericus *as a younger synonym of* Globigerinoides sicanus. *Rio et al. (1997) reinterpreted these stages following the taxonomic concept of Jenkins et al. (1981) (Figure modified after Cita and Premoli Silva, 1960 and Rio et al., 1997).

with the First Occurrence (FO) of *P. glomerosa curva* instead of FO *P. sicana* which is included in the genus *Globigerinoides*. Moreover, Iaccarino et al. (2011) revised the composite section of Fornaciari et al. (1997) based on the original field descriptions, which included subsection A, corresponding to the Bricco del Moro section, and subsections B, C and D corresponding to the Bricco della Croce section (Fig. 3). Subsection D was sampled by Fornaciari et al. (1997) but was not included in their paper. The re-examination of the original samples carried out by Iaccarino et al. (2011) allowed the recognition of a gap within subsection B, which is partially covered by subsection D. *Globigerinoides sicanus* (with 3 apertures) (= *P. sicana* in Fornaciari et al., 1997) is present from the base of the section in the Cortemilia Formation upward and becomes more common in the Cessole Marls. *Praeorbulina glomerosa curva* is recorded in subsection D and is characterized by evolved specimens (with more than 4 apertures in the final whorl) suggesting that its FO should occur at a lower stratigraphic level. The randomly coiled *P. siakensis* Acme$_a$ End (A$_a$E), which usually occurs just below the *P. glomerosa curva* FO, is also not clearly recorded. Both biohorizons could be located in the underlying gap (Fig. 3). The results obtained by Iaccarino et al. (2011) further confirmed the conclusion of Rio et al. (1997) that the Langhian type composite section does not represent a suitable section to define the Langhian GSSP.

Guiding Criterion

Following the development of the first geomagnetic polarity time scales and initial biostratigraphic studies of the Langhian to Tortonian historical stratotypes, the coupled magneto-biochronology of the Middle Miocene was a controversial issue for more than a decade. This controversy mainly resulted from problems encountered in linking marine anomalies derived from seafloor anomaly profiles to polarity chrons deduced from magnetostratigraphic records of deep-sea cores and also of magnetic polarity studies combined with radio-isotopic dating; these problems were largely solved when more reliable records became available (see, Berggren et al., 1985).

Berggren et al. (1995) stated that:

"*The FAD of* Pr. sicana *is used to denote the base of the Langhian Stage and the lower/middle Miocene boundary (Cita and Blow, 1969), although precise correlation has not been demonstrated between the two. If the FAD of this taxon occurs somewhat lower (in the Cortemilia Formation) than the base of the stratotype Langhian Stage, the Burdigalian/Langhian (lower/middle Miocene) boundary may be more closely associated with the FAD of* Pr. glomerosa glomerosa *(Chron C5Cn.ln; 16.1 Ma).*"

Please note that Cita and Blow (1969) used the *Praeorbulina* datum

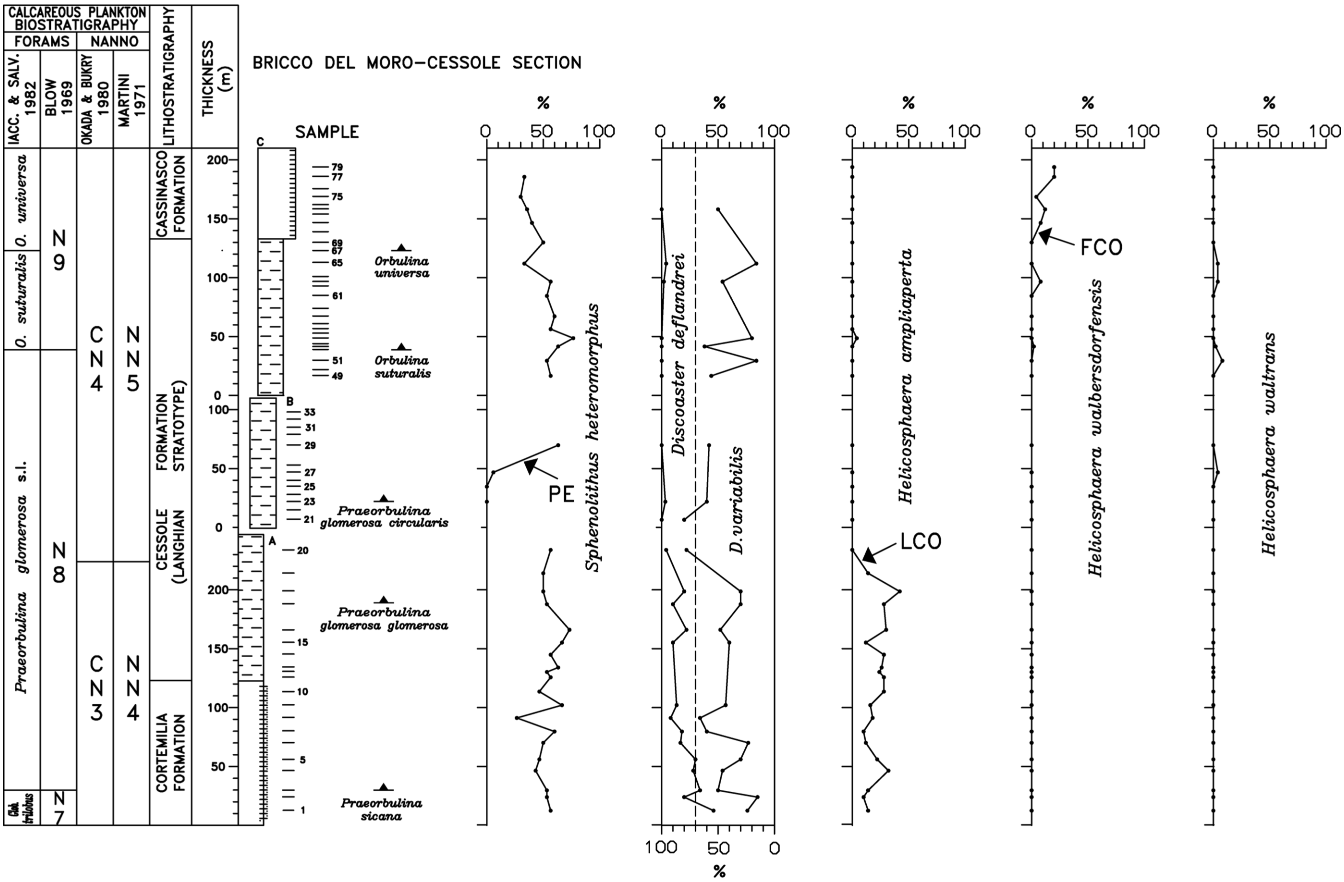

Figure 2. Planktonic foraminiferal and calcareous nannofossil events in the revised composite section of type Langhian of Fornaciari et al. (1997). Bioevent acronyms: PE (Paracme End); LCO (Last Common Occurrence); FCO (First Common Occurrence). The composite section consists of three subsections (A, B, C) which encompass the Cessole marls, the underlying turbidite Cortemilia Formation and the overlying Cassinasco Formation. According to Fornaciari et al. (1997) the* Praeorbulina *datum is represented by the First Occurrence (FO) of* P. sicana *and is recorded in the underlying turbidite Cortemilia Formation, more than 100 m below the base of the Cessole marls that represent the Langhian historical stratotype (from Fornaciari et al., 1997).

to denote the base of the Langhian but for them this evolutionary event is the appearance of *Praeorbulina glomerosa curva* not *P. sicana*.

Consequently, Fornaciari et al. (1997) suggested to define the Burdigalian/Langhian boundary at the *Praeorbulina* datum, which corresponds to the first occurrence of planktonic foraminifera belonging to the genus *Praeorbulina,* notwithstanding the fact that this event, evidenced by the FO of *P. sicana*, is found ~100 m below the Cessole marls in the Langhian type section. More recently, two criteria are mentioned in several papers that should preferably be used in tandem to define the base of the Langhian (Rio et al., 1997; Lourens et al., 2004). These criteria are the top of Chron C5Cn and the *Praeorbulina* datum.

However, recent studies show that in the Mediterranean these two events are separated by about 700 kyr, if the revised taxonomic concept of the *Praeobulina* genus is considered (Turco et al., 2011a, b; 2017). This revision implies that *P. sicana* is included in the genus *Globigerinoides* and that the *Praeorbulina* datum is defined by the FO of *P. glomerosa curva*. Accepting this taxonomic revision, the two criteria, top of Chron C5Cn and *Praeorbulina* datum, cannot be used in combination to define the base of the Langhian Stage. As a consequence, the choice of the guiding criterion will result in widely different durations for the Langhian stage. In case the *Praeorbulina* datum (i.e., FO of *P. glomerosa curva*) is chosen, then the Langhian Stage will have a duration of ~1.4 Myr. This short duration in combination with the potential diachroneity of the event between low-latitude open ocean and Mediterranean makes it unacceptable for defining the Langhian GSSP. According to the low-latitude biochronology (Wade et al., 2011 based on data of Berggren et al., 1995; ATNTS 2020 Raffi et al., 2020), the Base *P. curva* dated at 16.29 Ma and occurring very closely to Base *P. sicana* (at 16.39 Ma) is in fact strongly diachronous with respect to the Mediterranean where it is dated at 15.36 Ma (Turco et al., 2017). All this leaves us with the Chron C5Cn/C5Br reversal boundary as available criterion to define the boundary. Preference for this older criterion was also expressed during the meeting of the Working Group of the SNS (Subcommission for Neogene Stratigraphy) on the Langhian and Burdigalian GSSPs at the Strati 2015 congress held in Graz.

Mediterranean Candidate Sections

The historical Langhian stratotype is unsuitable for defining the GSSP if modern stratigraphic requirements, such as deep-sea settings and potential for developing an astrochronology, are considered (Iac-

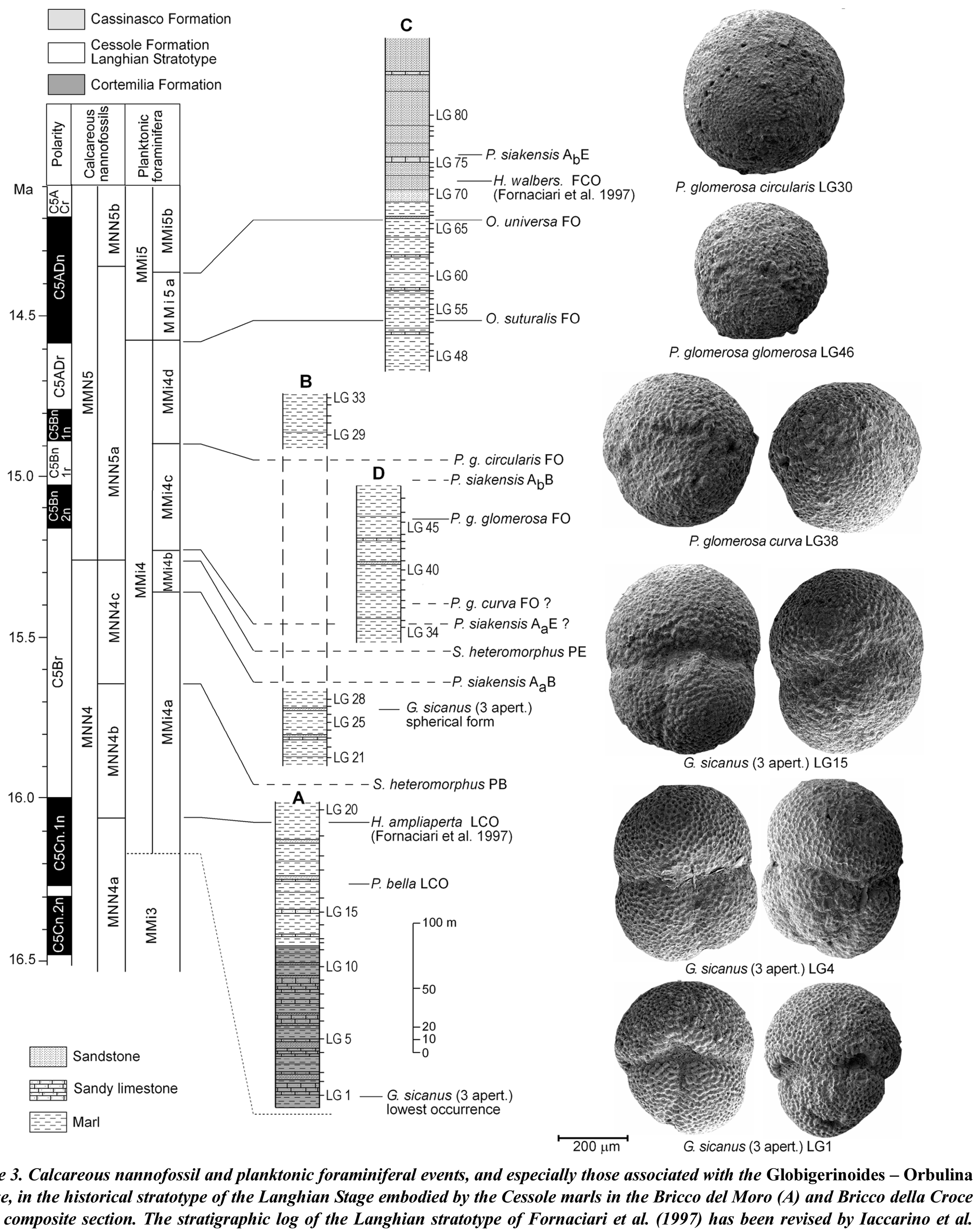

***Figure 3.** Calcareous nannofossil and planktonic foraminiferal events, and especially those associated with the* **Globigerinoides – Orbulina** *lineage, in the historical stratotype of the Langhian Stage embodied by the Cessole marls in the Bricco del Moro (A) and Bricco della Croce (B-D) composite section. The stratigraphic log of the Langhian stratotype of Fornaciari et al. (1997) has been revised by Iaccarino et al. (2011). Bioevent acronyms: A_aB (Acme$_a$ Beginning); A_aE (Acme$_a$ End); A_bB (Acme$_b$ Beginning); A_bE (Acme$_b$ End); FO (First Occurrence); FCO (First Common Occurrence); LCO (Last Common Occurrence); PB (Paracme Beginning); PE (Paracme End). Biozonal schemes: Fornaciari et al. (1996) emended by Di Stefano et al. (2008) for calcareous nannofossils and Iaccarino and Salvatorini (1982) emended by Di Stefano et al. (2008) and Iaccarino et al. (2011) for planktonic foraminifera. The lowest occurrence of* **G. sicanus** *(with 3 apertures) is found in the underlying turbidite Cortemilia Formation, more than 100 m below the base of the Cessole marls that represent the Langhian historical stratotype. The FO of* **Praeorbulina glomerosa** *curva (i.e., the* **Praeorbulina** *datum following Blow, 1969 and Turco et al., 2011a) falls in the Cessole marls although not clearly recorded (from Iaccarino et al., 2011).*

Table 1. Geographical coordinates of the Mediterranean sections, candidate for the definition of the Langhian GSSP

Section	Latitude	Longitude
Lower La Vedova Beach (base)	43°35′31.68″N	13°33′43.69″E
Moria	43°30.15′N	12°35.57′N
St. Peter's Pool (base)	35°49′58.60″N	14°33′43.88″E

carino et al., 2011). Thus, several land-based deep marine sections, namely the Lower La Vedova Beach section (Turco et al., 2011b; 2017) and Moria section in central Italy (Di Stefano et al., 2008; Di Stefano et al., 2015), and St. Peter's Pool section on Malta (Foresi et al., 2011) (Table 1), have been considered as alternative to the historical stratotype for defining the Langhian GSSP (Iaccarino et al., 2011).

The Moria section is clearly less suitable because it has a poor magnetostratigraphy and calcareous plankton (planktonic foraminifera and calcareous nannofossils) biostratigraphy, the latter as a consequence of the poor preservation (Iaccarino et al., 2011). The Lower La Vedova Beach section (LVB) has a magnetostratigrapic record which permits to pinpoint the top of Chron C5Cn. The preservation of planktonic foraminifera and calcareous nannofossils is generally moderate but permits to accurately pinpoint all the relevant bioevents (Turco et al., 2011b, 2017). So far, it is the only section for which an astronomically tuned age model has been established (Turco et al., 2017). The St. Peter's Pool section also straddles the interval containing the C5Cn/C5Br reversal boundary, although the section does not reach the interval across the FO of *P. glomerosa curva*, the younger - now obsolete - alternative guiding criteria for defining the boundary. Unfortunately, the C5Cn/C5Br reversal boundary cannot be identified in this section with certainty because its magnetostratigraphic record is rather poor (Iaccarino et al., 2011). However, and in contrast to the Lower LVB, the preservation of the calcareous nannofossils and planktonic foraminifera at St. Peter's Pool is good to very good, resulting in a reliable calcareous plankton biostratigraphy (Foresi et al., 2011) and a very good benthic foraminiferal stable isotope record (Russo et al., 2022).

Thus, the search for alternative sections to define the Langhian GSSP in the Mediterranean area resulted in two principal candidate sections, namely Lower La Vedova Beach situated in the coastal cliffs south of Ancona, Italy, and St. Peter's Pool on Malta Island (Foresi et al., 2011; Turco et al., 2011b, 2017). However, as the position of the top of Chron C5Cn is poorly defined and no independent tuning has thus far been established at St. Peter's Pool, the Lower La Vedova Beach section has been selected as prime candidate for defining the Langhian GSSP during the SNS Business Meeting held in Strati 2019 Congress and the succeeding discussions amongst the members of the Burdigalian and Langhian GSSPs Working Group directly involved in the proposal.

Lower La Vedova Beach Section

Stratigraphic Succession

The Lower La Vedova Beach section is one of a series of partial sections in which the long and cyclic deep marine succession exposed in the coastal cliffs south of Ancona (northern Italy) (Fig. 4a) can be logged and studied. This succession contains the entire Tortonian, Serravallian and Langhian stratigraphic intervals which are exposed (from young to old) in the Monte dei Corvi (MdC), La Vedova High Cliff (LVHC) and La Vedova Beach (LVB) sections (Fig. 4b). The succession can stratigraphically be further extended downwards in the direction of Ancona.

Importantly, the Tortonian GSSP has already been defined in this succession (at MdC) (Hilgen et al., 2003, 2005) and astronomically tuned ages for magnetochron boundaries from the sections have been incorporated in (the Neogene chapter of) GTS2012 (Hilgen et al., 2012). In addition, the time correlative levels exactly corresponding

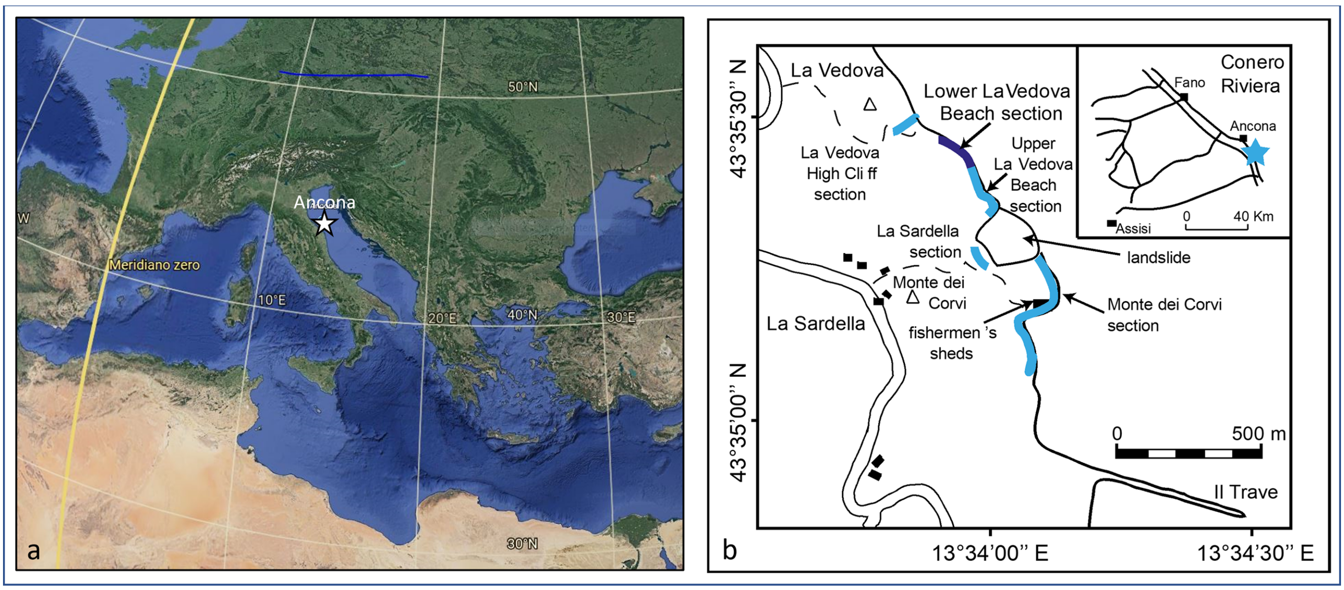

Figure 4. Location map of the partial sections of the Miocene succession exposed in the coastal cliff south of Ancona (northern Italy) (modified after Turco et al., 2017).

to the Serravallian and Messinian GSSPs defined respectively in and just outside the Mediterranean (Hilgen et al., 2000, 2009) can be easily identified with great precision.

The Langhian stratigraphic interval, exposed along the beach close to the locality of La Vedova, was previously studied by Montanari et al. (1997) and Mader et al. (2001, 2004 a, b). The La Vedova Beach section is the downward extension of the La Vedova High Cliff section (Mourik et al., 2010) that is exposed high in the cliffs and covers the stratigraphic interval straddling the Serravallian-Tortonian boundary between the MdC and LVB sections. Note that a short missing interval (covered by a landslide, Fig. 4b) has subsequently been logged and sampled at MdC following exposure after severe winter storms. The LVB section is divided in a Lower and an Upper section. The Upper LVB covers the interval between 14.17 and 15.1 Ma (Hüsing et al., 2010), while the Lower LVB section contains the extension back to 16.3 Ma (Turco et al., 2011b, 2017). It is the latter section that is of interest for defining the Langhian GSSP and that will be discussed in more detail below. The Lower LVB section, containing the thick megabeds (MBs) I to VII of Montanari et al. (1997), belongs to the upper part of the Massive Member of the Schlier Fm. The MBs are approximately 4 m thick and alternate with thinner marly intervals, both showing internal bedding on a smaller scale (Fig. 5). The upper half/part of the section shows a more marly development, with marly intervals regularly alternating with thinner calcareous marls and limestones on various scales. The regular alternating lithologies on the scale of the MBs could also be recognized in this part of the section and their numbering has been continued (MB *VIII-XIII*) (Fig. 5).

The lower part of the section encompassing MB II-VII is dissected by a fault, which initially caused problems in reconstructing the stratigraphy (Fig. 5). A single MB has been missed following the initial correlations across the fault, leading to misidentification of the MBs north of the fault (Turco et al., 2011b). This problem was solved through accurate correlations to the detailed pattern of MBs observed in the undeformed steep outcrops near Ancona and a new composite section at La Vedova was obtained (Fig. 6) (Turco et al., 2017).

Figure 7 focuses on the lower part of the succession which encompasses the Burdigalian-Langhian boundary interval.

Calcareous Plankton Biostratigraphy

Despite the moderate preservation, the calcareous plankton biostratigraphy resulted in a well-defined succession of events consistent with that found in other sections and cores in the Mediterranean and adjacent mid-latitude Atlantic (Figs. 8 and 9; see also Iaccarino et al., 2011; Di Stefano et al., 2011).

The most important planktonic foraminiferal events are connected with the *Globigerinoides-Praeorbulina-Orbulina* lineage. The first specimens of *G. sicanus* - with 3 apertures and elongate shape - are already present in the lowermost part of the section, but the actual FO of this taxon might be located lower in the succession. Sub-spherical specimens of *G. sicanus* again with 3 apertures, are first observed around 32 m, while the FOs of *P. glomerosa curva* and *P. glomerosa glomerosa* are recorded at 53.475 and 59.715 m, respectively (Turco et al., 2017). In addition, a distinct acme interval (Acme$_a$) of randomly coiled *Paragloborotalia siakensis* is recorded between 48.045

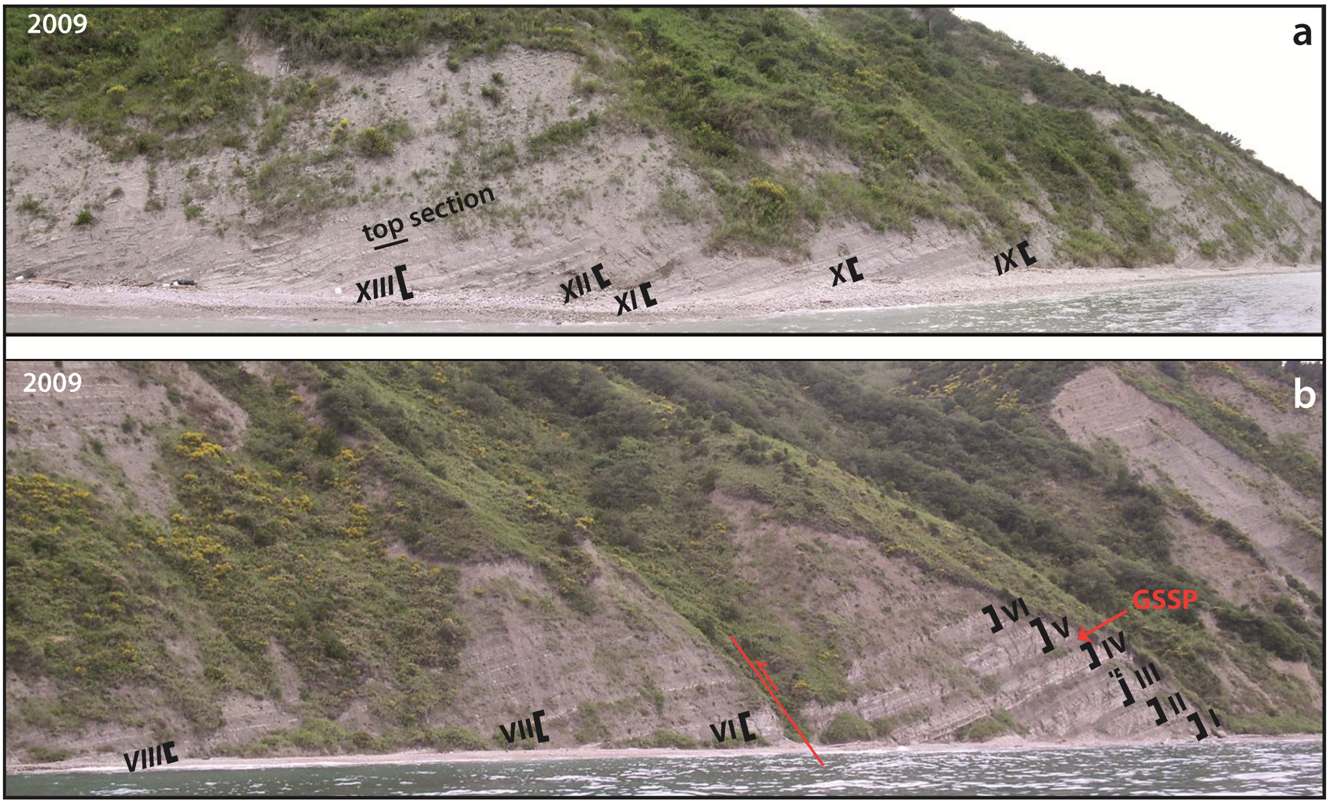

Figure 5. Megabeds I-XIII in the Lower Vedova Beach section. The base of the measured section coincides with the base of Megabeds II. The fault is indicated in the lower picture (b). The red arrow indicates the proposed GSSP level (modified after Turco et al., 2017).

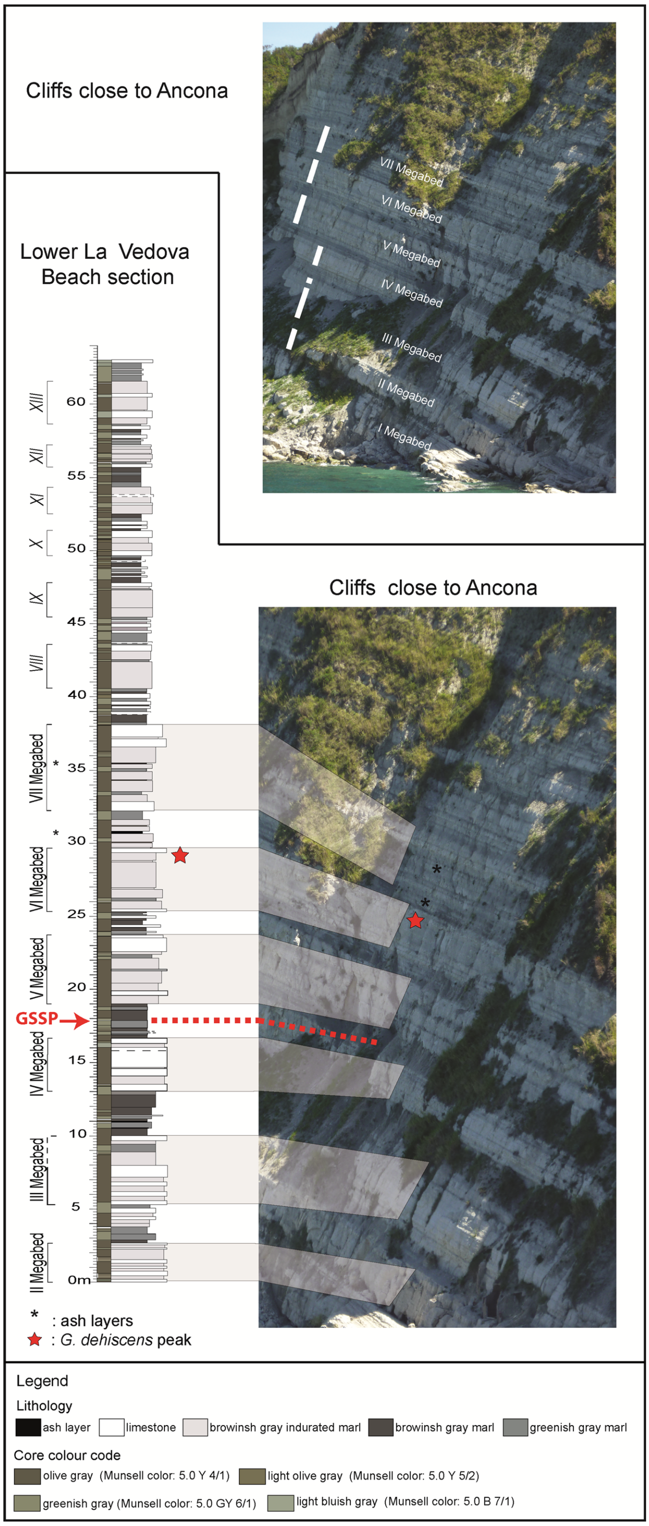

Figure 6. Megabeds I-VII in Ancona and comparison with the stratigraphic log of the Lower LVB section. The red arrow indicates the proposed GSSP level (modified after Turco et al., 2017).

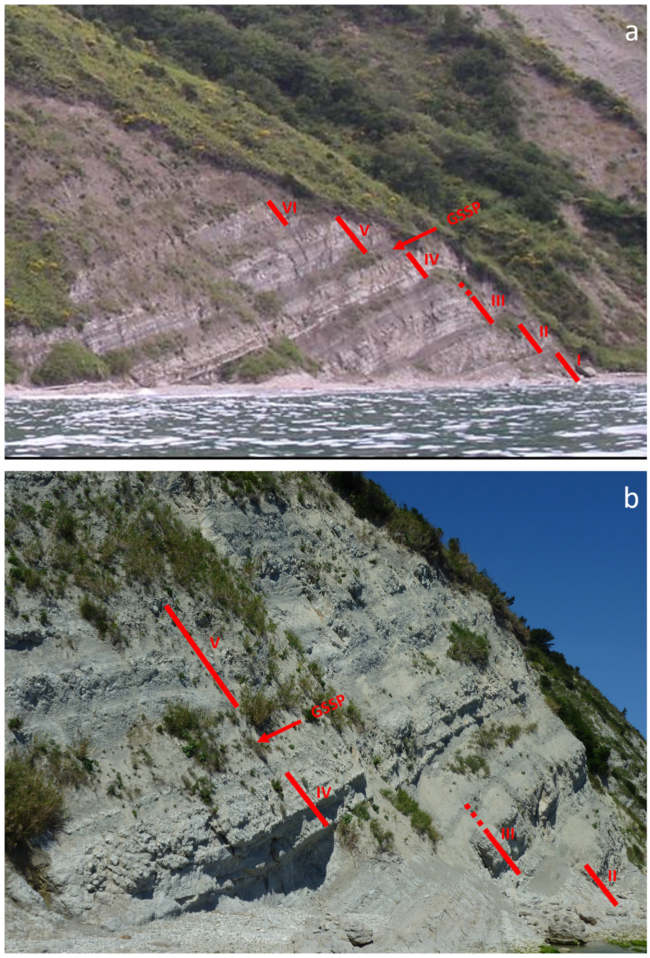

Figure 7. a) Enlargement of photograph b in Figure 5 showing the Megabeds I-VI interval of the Lower LVB section; b) Focus on the boundary interval showing the position of the proposed GSSP level (red arrow), i.e., the mid-point of the marly interval between Megabed IV and Megabed V (see text).

and 52.805 m. These biostratigraphic events indicate that the Lower LVB section encompasses the planktonic foraminiferal (sub)zones MMi3 (pars) to MMi4c.

The most prominent feature observed in the calcareous nannofossil biostratigraphy is the paracme interval of *Sphenolithus heteromorphus* (Di Stefano, 1995; Fornaciari et al., 1996) between 36.270 and 52.220 m, which delimits the MNN4c Subzone. In addition, the LCO of *Helicosphaera ampliaperta,* marking the MNN4a-b subzonal boundary, is recorded at 10.49 m, although two acme intervals with slightly lower abundances are found stratigraphically higher in the section. Finally, the FO and First Regular Occurrence (FRO) of *Helicosphaera waltrans* are recorded, with the latter pinpointed at 51.185 m (Turco et al., 2017).

Magnetostratigraphy

The characteristic remanent magnetization (ChRM) of the Upper La Vedova Beach section is carried by greigite and magnetite (Hüsing et al., 2010). Several lines of evidence indicate that the ChRM represents a primary magnetization. The opposite polarities occur in distinct stratigraphic intervals of the Lower La Vedova Beach section, and their directions are distributed in antipodal clusters, revealing a counterclockwise rotation that is consistent with other studies in this area of the central-northern Apennines. The two reversals are both situated in intervals with poor paleomagnetic data (Fig. 10).

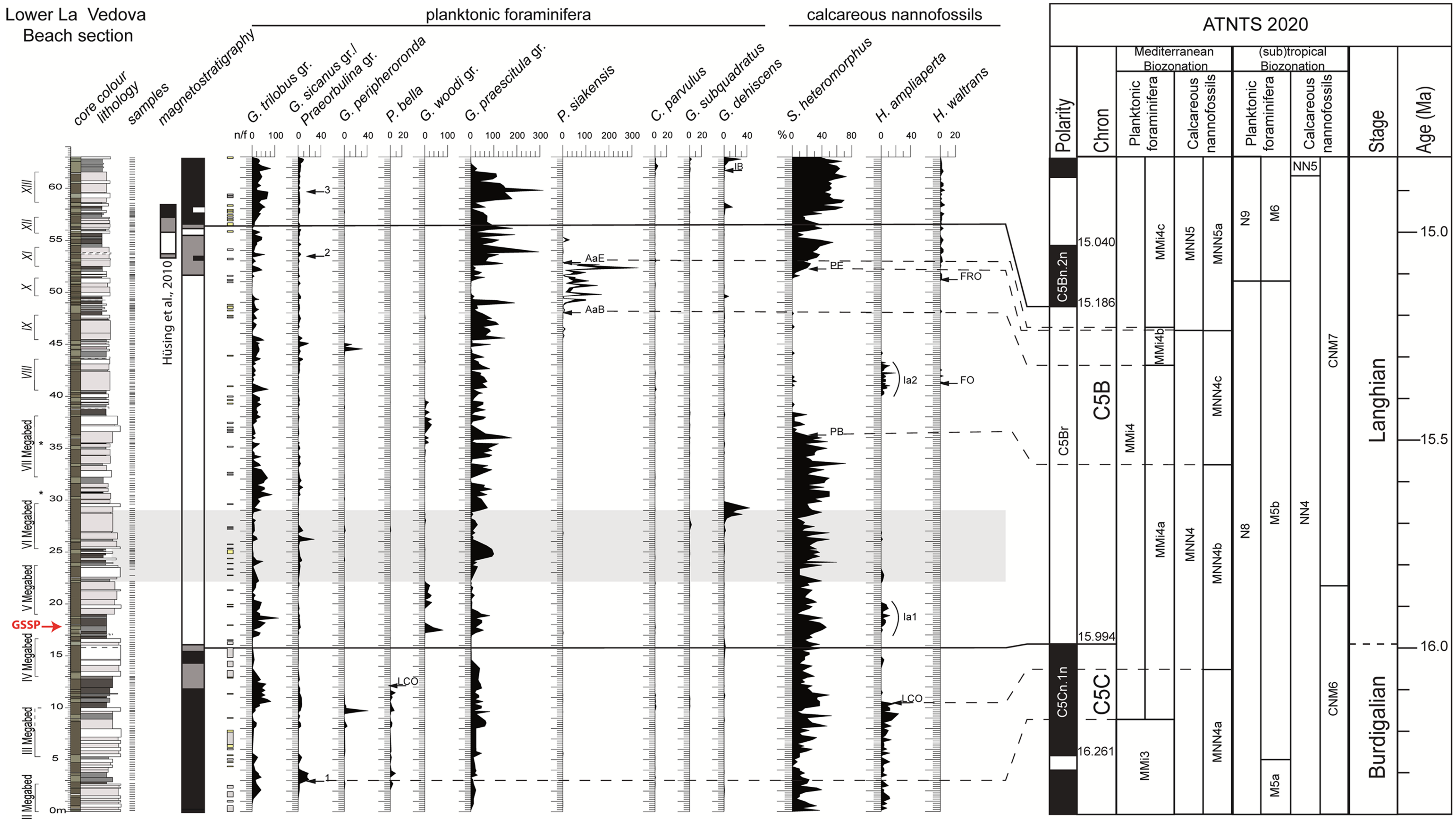

Figure 8. Lithology, cyclostratigraphy, magnetostratigraphy and calcareous plankton biostratigraphy of the Lower La Vedova Beach section. The gray band indicates the missing interval in the composite section of Turco et al. (2011b). The magnetostratigraphic record is correlated to ATNTS2020 (Raffi et al., 2020). The stratigraphic position of calcareous plankton events is shown beside the abundance patterns of marker species: numbers 1, 2 and 3 indicate the FOs of **G. sicanus** *(3 apertures),* **P. glomerosa curva** *and* **P. glomerosa glomerosa***, respectively; A_aB: Acme$_a$ Beginning; A_aE: Acme$_a$ End; FO: First Occurrence; FRO: First Regular Occurrence; Ia1, Ia2: abundance Influx; IB: Influx Beginning; LCO: Last Common Occurrence; PB: Paracme Beginning; PE: Paracme End. Mediterranean zonation of Lirer et al. (2019, and references therein) for planktonic foraminifera and of Fornaciari et al. (1996) emended in Di Stefano et al. (2008) and Di Stefano et al. (2023) for calcareous nannofossils are adopted. Mediterranean biozonation are compared with the low-latitude standard zonation of Blow (1969; N zones) and Wade et al. (2011, emended in Raffi et al., 2020; M zones) for planktonic foraminifera and those of Martini (1971; NN zones) and Backman et al. (2012, emended in Raffi et al., 2020; CNM zones) for calcareous nannofossils. Note, however, that (sub)tropical zonations cannot be applied to Mediterranean successions because: 1) the first occurrences of* **P. sicana, P. glomerosa glomerosa** *s.s. and* **O. suturalis***, which respectively identify the N7/N8 (and M4/M5a), M5a/M5b, and N8/N9 (and M5b/M6) (sub)zonal boundaries, are strongly diachronous between Mediterranean and low latitudes; 2) the first occurrence of the nannofossil* **D. signus***, which identifies CNM6/CNM7 zonal boundary, is not recorded in the studied Mediterranean successions. The red arrow indicates the proposed GSSP level. (modified after Turco et al., 2017).*

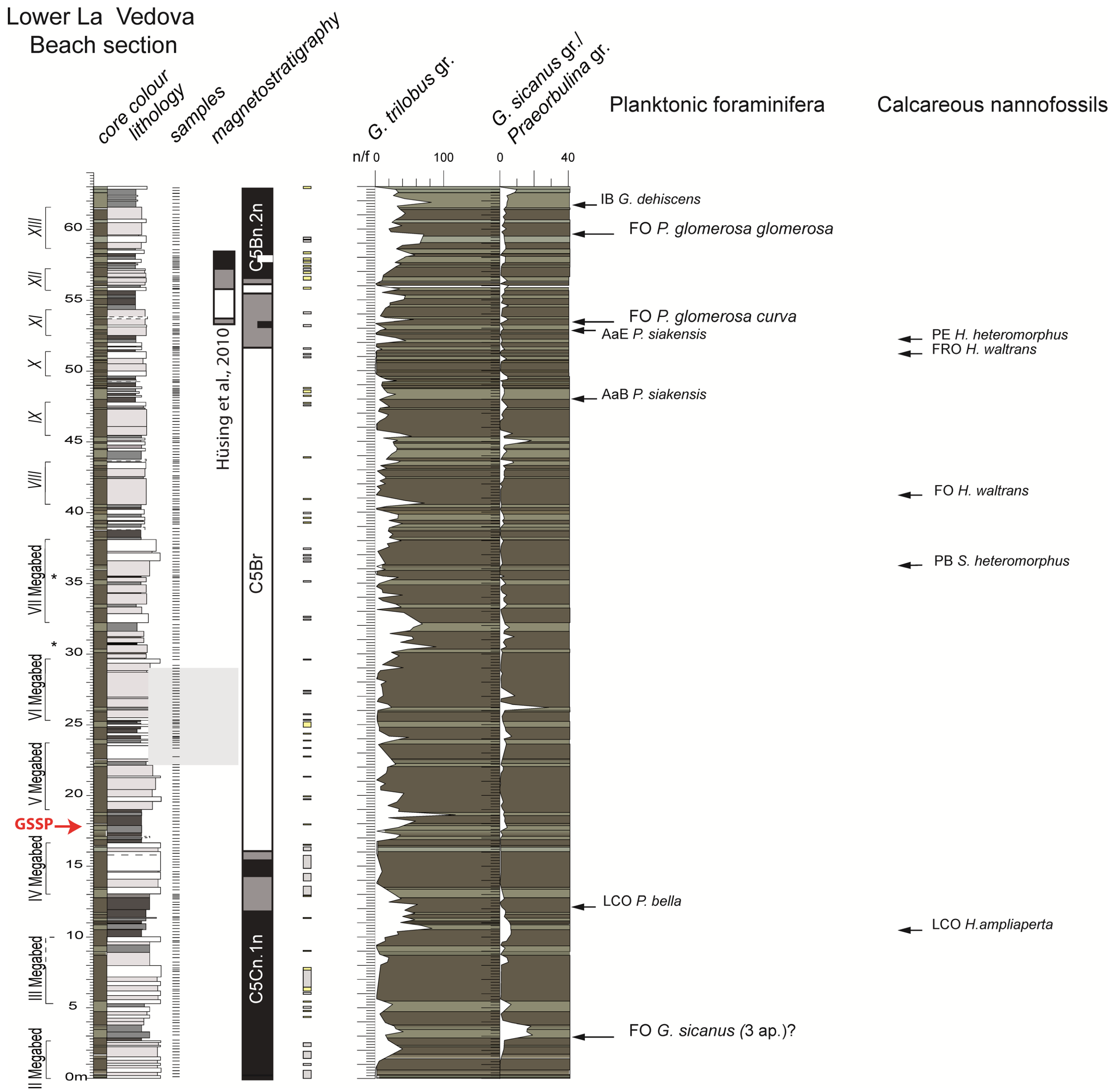

Figure 9. **Globigerinoides** ***trilobus gr. and*** **G. sicanus-Praeorbulina** ***gr., and the position of bioevents linked to the*** **G. sicanus-Praeorbulina** ***lineage in the Lower La Vedova Beach section. The gray band indicates the missing interval in the composite section of Turco et al. (2011b). Gray boxes close to abundance curves indicate scarcity or very poor preservation of planktonic foraminifera. Bioevents acronyms: A_aB (Acme$_a$ Beginning); A_aE (Acme$_a$ End); FO (First Occurrence); FRO (First Regular Occurrence); Ia1, Ia2 (abundance Influx); IB (Influx Beginning); LCO (Last Common Occurrence); PB (Paracme Beginning); PE (Paracme End). The pattern in*** **Globigerinoides trilobus** ***gr. follows the larger-scale cyclicity in the section and to lesser extent the smaller-scale cyclicity represented by the greenish marl layers. The red arrow indicates the proposed GSSP level (modified after Turco et al., 2017).***

Importantly for our proposal, the reversed tendencies between 12 and 14 m are explained by delayed acquisition of remanent magnetization caused by secondary (early/late diagenetic) growth of greigite (Turco et al., 2011b). The resultant magnetostratigraphy essentially contains two normal polarity intervals with a long reversed in between (Fig. 10).

The calcareous plankton biostratigraphy indicates that the magnetostratigraphic record extends from sub-chrons C5Cn.1n to C5Bn.2n (Fig. 10). The integrated magneto-biostratigraphic record of the Lower La Vedova Beach section provided new magnetostratigraphic age calibrations of calcareous plankton events, thus improving the existing Mediterranean biochronology for the late Burdigalian to early Langhian (Turco et al., 2011b, 2017).

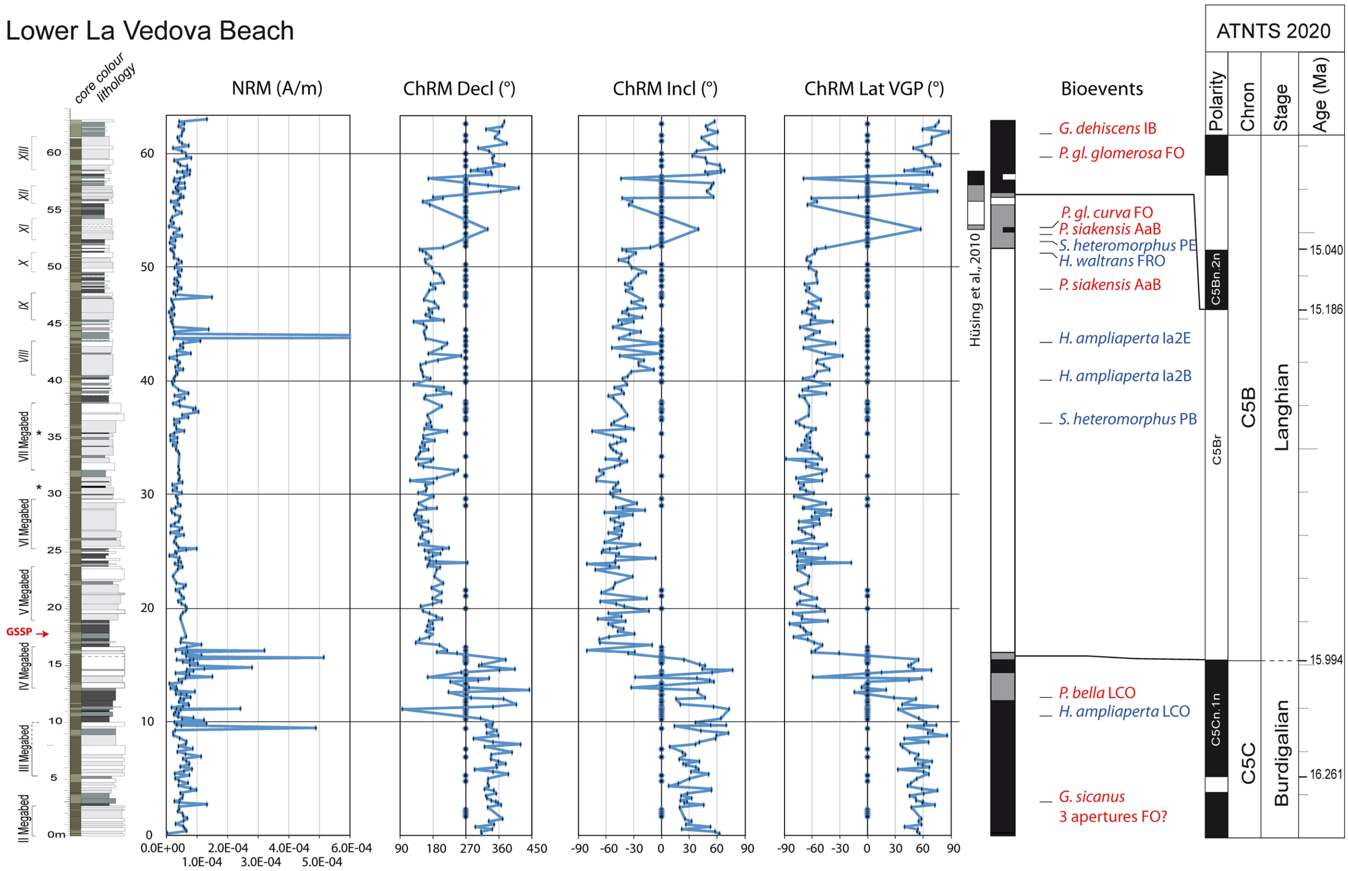

Figure 10. ChRM declination, inclination, VGP latitude, position of calcareous plankton events and correlations of the Lower La Vedova Beach section to the ATNTS2020 (Raffi et al. 2012). Bioevent acronyms: A_aB (Acme$_a$ Beginning); A_aE (Acme$_a$ End); FO (First Occurrence); FRO (First Regular Occurrence); Ia1, Ia2 (abundance Influx); IB (Influx Beginning); LCO (Last Common Occurrence); PB (Paracme Beginning); PE (Paracme End). Planktonic foraminiferal and calcareous nannofossil events are indicated in red and blue respectively. The red arrow indicates the proposed GSSP level (modified after Turco et al., 2011b, 2017).

Cyclostratigraphy and Tuning

The first order magnetobiostratigraphic age model implied that the regular MB scale alternations and their continuation higher in the marly part of the section are related to the ~100-kyr eccentricity cycle, while the smaller-scale alternations are dominantly precession controlled (Fig. 11). This interpretation was subsequently confirmed by the outcome of spectral analysis and band-pass filtering of the Magnetic Susceptibility (MS) and elemental records (in particular Rb/Sr ratio) (Fig. 12), starting from the magneto-biostratigraphic age model. The tuning of the MBs to ~100-kyr eccentricity was achieved by extending the existing tuning of the Upper LVB section downwards, and/while taking the expression of the 405-kyr eccentricity cycle in addition into account. The darker colored marly intervals of the cycles correspond to eccentricity maxima. This phase relation is based on the higher amplitude of the precession-related variations in these intervals. The more indurated carbonate-rich intervals marked by a reduction of the amplitude correspond to eccentricity minima. As a next step, the precession-scale variations in the records were tuned to precession and insolation (Turco et al., 2017).

However, in contrast to the eccentricity tuning, the tuning to precession is less certain. In the first place the expression of the precession-related variability is less clear than for instance in the younger MdC section. Secondly, the tuning to precession and obliquity is hampered due to uncertainties in the astronomical solution related to the uncertainties in the exact values of tidal dissipation and dynamical ellipticity (Td/dE), which both affect the precession and obliquity frequencies. And thirdly, there is the problem of the phase relation to precession and insolation, which is challenging as the relations between the various proxies do not remain constant in the entire La Vedova section. The darker marly intervals of the short eccentricity related cycles contain thin greenish-gray layers on the precession scale. For the tuning, we assumed that these layers and the associated maxima in *Globigerinoides* and terrestrial elemental indicators correspond to less oxygenated bottom water conditions and thus likely to precession minima and summer insolation maxima as is the case for all Mediterranean sapropels (Turco et al., 2017).

The eccentricity tuning of the succession provides astronomical ages for magnetic reversals and for calcareous plankton events, which are reported in Table 2.

Evaluation of Completeness of the Section

A critical issue for defining the Langhian GSSP at the Lower LVB is the inferred continuity of the section, especially in view of the fault and the observation of an extra *P. siakensis* acme interval (Acme$_0$) in

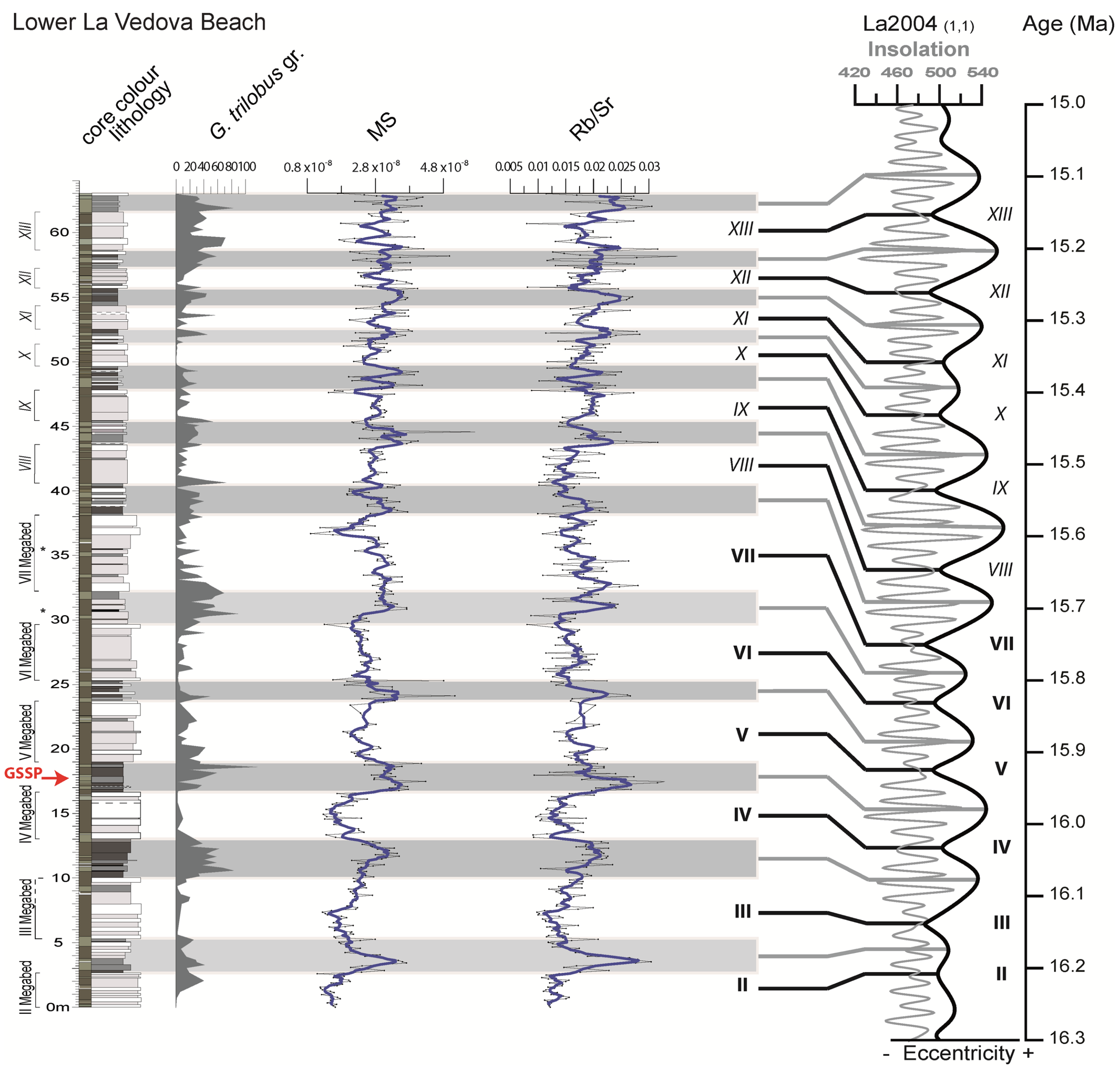

Figure 11. Astronomical tuning of the ~100-kyr eccentricity related cycles in MS and Rb/Sr to eccentricity of the La2004(1,1) solution (Laskar et al., 2004; from Turco et al., 2017). The 5 pma of MS and Rb/Sr records (thick lines) are plotted on top of the raw data (thin lines). In addition, the* Globigerinoides trilobus *gr. record is shown. The middle points of megabeds and the intervening marl intervals have been correlated to minima and maxima of 100 kyr eccentricity, respectively. The red arrow indicates the proposed GSSP level.

the St. Peter's Pool section on Malta (see, Foresi et al., 2011). The latter suggests the presence of a hiatus in the Lower LVB section in MB5. However, the characteristic bedding pattern of all the megabeds can be easily traced in the steep coastal cliffs over a distance of approximately 5 km in the direction of Ancona (particularly evident in the localities Spiaggia della Scalaccia and Monte Cardeto, Figs. 13 and 14), while no evidence has been found for an unconformity, suggesting that the succession is continuous. In addition, the succession has been extended downwards in the Cardeto - Spiaggia della Scalaccia composite section (Fig. 14), which provides a good magnetostratigraphic record from the top Chron C5Dn to bottom Chron C5Cn.1n (Fig. 15) (van Peer, 2013). Preliminary biostratigraphic data show an acme interval of *P. siakensis* associated with subchron C5Cn.2n (Fig. 15) (Turco et al., 2019). The relatively straightforward astronomical tuning of this composite is fully consistent with the Lower LVB tuning (Fig. 15). Moreover, the astronomical ages for the magnetic reversal boundaries of top Chron C5Dn to bottom Chron C5Cn.1n in this composite are in excellent agreement with the ages for the same chron boundaries of Kochhann et al. (2016), derived from the tuning of the $CaCO_3$ record of IODP Site U1336. This consistency provides another independent (compelling) argument for the continuity of the Lower LVB succession, the correctness of its tuning and, therefore, its suitability for defining the Langhian GSSP.

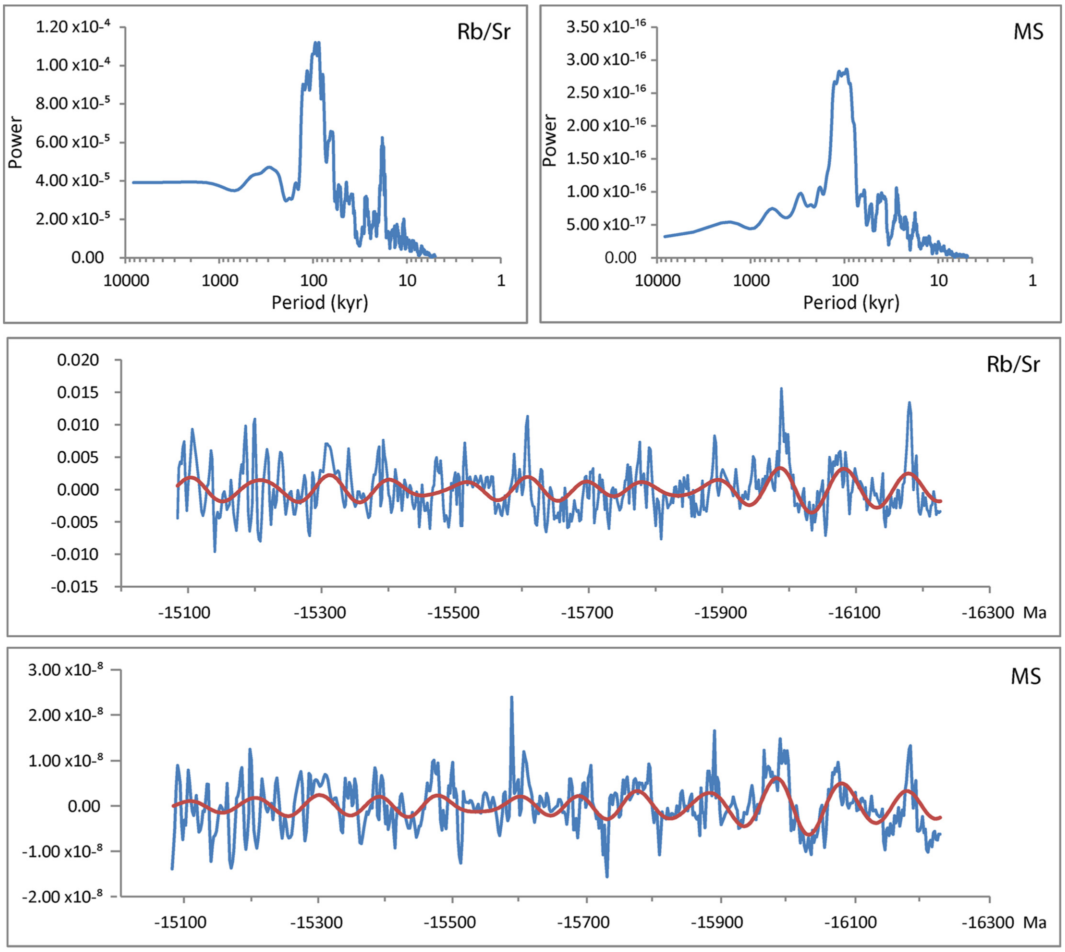

Figure 12. MTM spectra and results of bandpass filtering of the MS and Rb/Sr time series, based on the ~100-kyr eccentricity tuned age model shown in Figure 11, showing the dominance of the ~100-kyr cycle in the section (from Turco et al., 2017). The reader is referred to Turco et al. (2017) for similar spectra and results of filtering in the stratigraphic domain.

Table 2. Stratigraphic position and astronomical ages of magnetic reversals and calcareous plankton events based on the tuning to eccentricity (Turco et al., 2017) in stratigraphic order. Bioevent acronyms: A_aB (Acme$_a$ Beginning); A_aE (Acme$_a$ End); FO (First Occurrence); FRO (First Regular Occurrence); LCO (Last Common Occurrence); PB (Paracme Beginning); PE (Paracme End). Astronomical ages are calculated by means of linear interpolation between the two nearest calibration points assuming constant sedimentation rates. The stratigraphic position and the astronomical age of the proposed GSSP level (i.e., mid-point of the marly interval above Megabed IV which has been correlated to the most prominent ~100-kyr eccentricity maximum with an astronomical age of 15.981 Ma according to La2004 nominal solution) are indicated (see also text)

	Lower La Vedova Beach section	
Events	Stratigraphic position (m)	Astronomical age (Ma)
P. gl. glomerosa FO	59.715 ± 0.085	**15.163** ± 0.002
C5Bn.2n (o)	56.385 ± 0.305	**15.264** ± 0.009
P. glomerosa curva FO	53.475 ± 0.135	**15.356** ± 0.004
P. siakensis A_aE	52.805 ± 0.055	**15.374** ± 0.001
S. heteromorphus PE	52.220 ± 0.110	**15.389** ± 0.003
H. waltrans FRO	51.185 ± 0.115	**15.414** ± 0.003
P. siakensis A_aB	48.045 ± 0.095	**15.502** ± 0.002
S. heteromorphus PB	36.270 ± 0.100	**15.736** ± 0.001
GSSP level	**17.840**	**15.981**
C5Cn.1n (y)	15.795 ± 0.305	**16.017** ± 0.005
P. bella LCO	12.205 ± 0.095	**16.067** ± 0.001
H. ampliaperta LCO	10.490 ± 0.110	**16.093** ± 0.002
G. sicanus (3ap.) FO?	2.895 ± 0.185	**16.189** ± 0.002

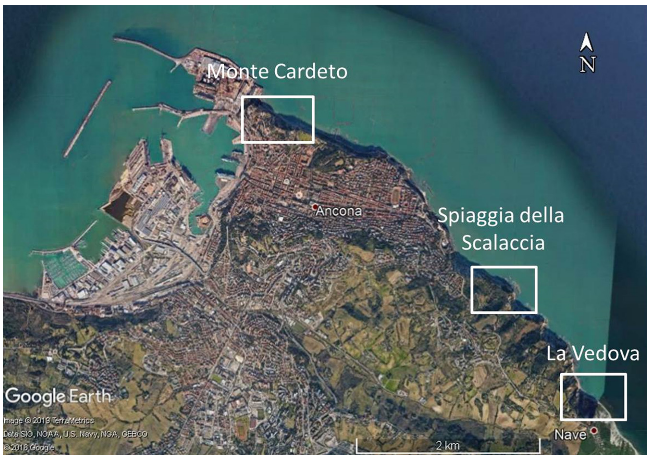

Figure 13. Location map of Monte Cardeto, Spiaggia della Scalaccia and La Vedova.

Figure 14. Photograph of Monte Cardeto section. In the top part of the outcrop the seven megabeds are present.

Accessibility

The Lower La Vedova Beach section is exposed along the beach below the locality La Vedova (Ancona). Although an Ordinance of the Mayor of Ancona forbids to reach and to stand on this tract of the coast, we obtained an amendment to this Ordinance in order to allow scientists to visit the section for research purposes. It is possible for geologists to ask the municipality of Ancona for permission to visit the section only for research purposes declaring to take on the responsibility of any risk and in the possession of an insurance.

The section can be reached by path number 312 of the Parco del Conero (Ancona) (https://www.google.com/maps/d/viewer?mid=1pjcF6079P4vnp36LLfbhyPNw1MipiLF7&ll=43.58511956799091%2C13.555942920623773&z=13), although it is temporarily forbidden, or more easily by boat from either Ancona or Portonovo.

GSSP Definition

Adopted strategy for defining the GSSP level

Now that the Lower LVB section meets the strict criteria for defining a GSSP, we can proceed with defining the Langhian GSSP or Langhian/Burdigalian boundary in this section. Hereby we follow the same line of reasoning used to define most Neogene and Quaternary GSSPs before, namely by starting from a characteristic cyclostratigraphic pattern that is sufficiently close to a major magnetic reversal boundary and/or important bioevents to enhance global correlatability.

In our opinion, and that of SNS before, the characterization of sedimentary cycles linked to astronomical pacing provides a strong means of correlation with a near-time significance, also leading to direct correlations of Mediterranean land-based deep marine sections to (well) tuned deep marine records, using a high-resolution integrated stratigraphic approach with astronomical tuning at its center. For instance, published astrochronologic frameworks formed the basis for estimating diachrony of calcareous nannofossil events between the Atlantic, Pacific and Indian Oceans (Raffi et al., 2006). Importantly, such frameworks directly provide a very accurate and precise means to numerically date stratigraphic horizons, and in particular, also chronostratigraphic boundaries. Nowadays, such an astronomically dated framework already underlies the standard GTS for the entire Cenozoic to which most if not all Neogene GSSPs are directly tied through astronomical calibration. The Neogene GSSP proposals based on an astrochronologic criterion have all been accepted by SNS and ICS and ratified by IUGS (see https://stratigraphy.org/gssps/ for relevant details). Moreover, as far as we know, all these boundaries have been in use without any serious problem for 15 to 25 years, which is also reason not to depart from this common SNS procedure.

One of the main reasons to define the Langhian GSSP following the astrochronologic approach is that the magnetostratigraphic signal in the Lower LVB section (see, Turco et al., 2011, 2017) leaves some uncertainty in accurately and precisely pinpointing the exact position of the reversal boundary, so that a date for it would always be with potential error. This uncertainty is considered less favorable for allocating a chronostratigraphic horizon that has to be tied to the standard Neogene time scale, which is based on astronomical dating, on the basis of the magnetostratigraphy at La Vedova. Comparable problems were also encountered when defining other GSSPs in the Mediterranean, such as the Piacenzian GSSP and the Gelasian GSSP and present-day Neogene/Quaternary boundary (Castradori et al., 1998; Rio et al., 1998). The Zanclean GSSP or Miocene/Pliocene boundary can be considered a special but also very illustrative case, as it is defined at the base of the Trubi at Eraclea Minoa, 5 precession related cycles below the oldest magnetic reversal boundary, the Lower Thvera, of the Pliocene, and reflecting the Pliocene reflooding following the Messinian Salinity Crisis (Van Couvering et al., 2000). Yet, this GSSP, correlating to insolation cycle 510, as counted from the present with an astronomical age of 5.33 Ma according to the La93 solution, functions perfectly well. Integrating cyclicity and astronomical solution in similar fashion as for the Zanclean, all current Neogene GSSPs have been simultaneously defined and dated. In this way, the stratigraphic record is directly projected onto the standard geological time scale, which is based on astronomical dating as well. As such it seems safe to state that astronomical cycles offer maximum potential in chronostratigraphy and chronology, surpassing that of magnetic signals. Yet, close proximity to an important magnetic reversal/chron boundary strongly enhances the global correlatability potential of all these GSSPs.

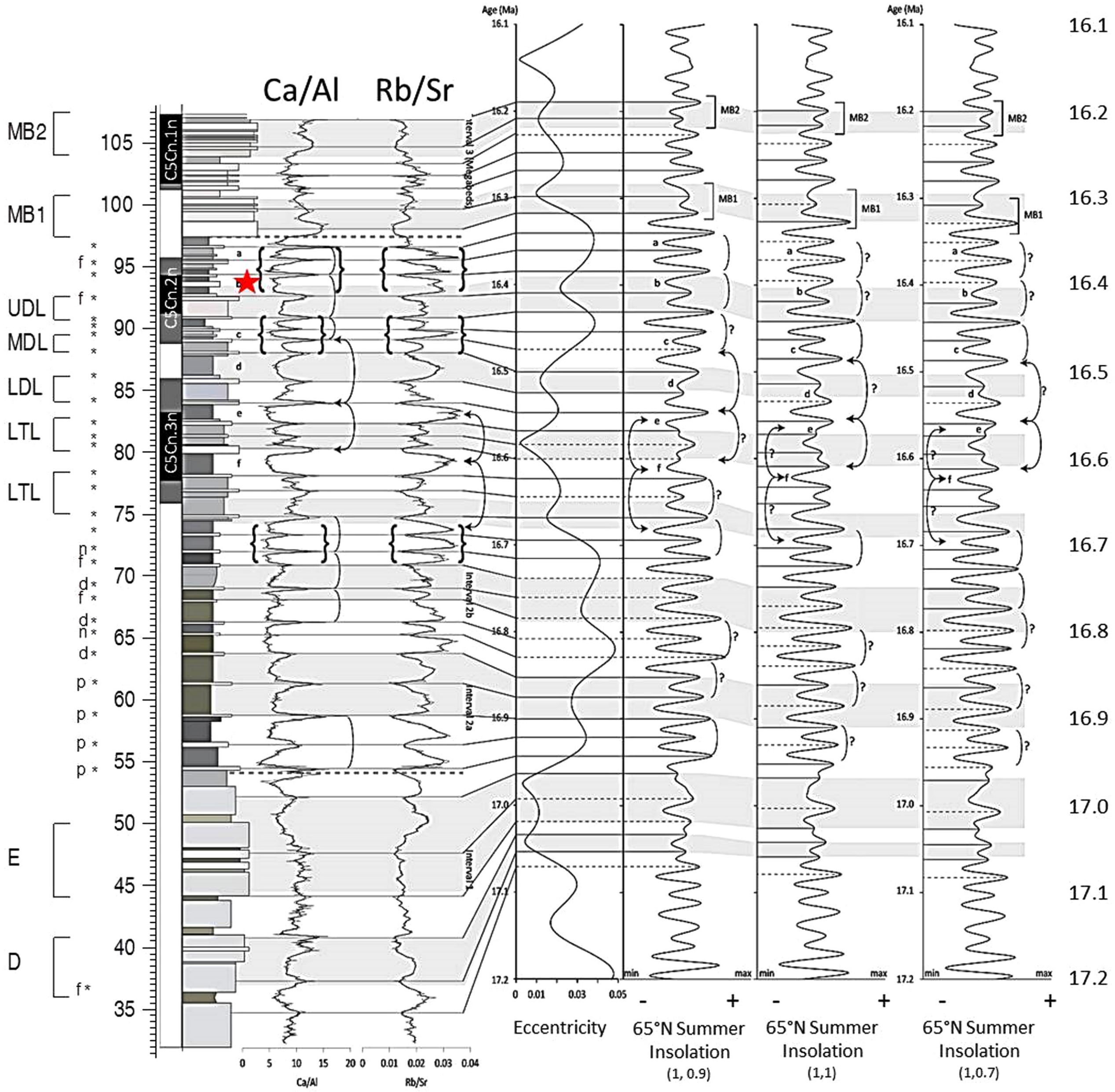

Figure 15. Magnetostratigraphy and astronomical tuning of the Monte Cardeto section. Ca/Al and Rb/Sr records have been tuned to the eccentricity and 65°N summer insolation curves. Red star marks the P. siakensis acme associated with subchron C5Cn.2n (van Peer, 2013; Turco et al., 2019).

Selected astrochronologic criterion

We therefore prefer to define the Langhian GSSP starting from an astrochronologic criterion. For this purpose, we selected the exact level of 17.84 m, marking the mid-point of the dark marly interval above "Megabed IV" that has been astronomically tuned to the most prominent ~100-kyr eccentricity maximum in the 405-kyr long eccentricity maximum around 16.0 Ma with an astronomical age of 15.981 Ma according to La2004 nominal solution and of 15.978 according to La2011a. The level at 17.84 m is located sufficiently close to the top of C5Cn (at 15.795 m, with an astronomical age of 16.017 Ma), which not only remains the main event for identifying the boundary on a global scale in sections that lack astrochronology, but - in common practice - can be thought as being practically time equivalent to the boundary with an age difference of 36 kyr. Importantly, such a prominent short 100-kyr eccentricity maximum results in a marked climate response, as observed in our sedimentary paleoclimate archives (see, Turco et al., 2017).

An alternative option would be to select the mid-point of the whitish interval (~13-16.6 m, i.e., Megabed IV) below, at 14.85 m, as this level corresponds to the older short 100-kyr eccentricity minimum and is located somewhat closer to the reversal boundary. However, the climate response to such eccentricity minima is less distinctive than the response to short eccentricity maxima also because the maxima are clearly modulated by the long 405-kyr eccentricity cycle, as can be seen in stable isotope records from the open ocean. In fact, the most extreme climate response is recorded at 15.6 Ma, one long 405-kyr eccentricity maximum post-dating the selected criterion for the GSSP. The isotope signals associated with the short eccentricity minima do not show this strong modulation effect of long eccentricity and often reach more or less similar baseline values.

A further alternative option to define the GSSP, and in fact closest to the magnetic reversal boundary, would be the base of the dark marl bed or better the boundary between the dark marl and whitish limestone bed/interval (at 16.6 m). However, in this case the phase relation with eccentricity becomes less certain as it is not clear whether this level corresponds to the inflection point halfway between the eccentricity minimum and maximum, because it is in addition controlled by the smaller-scale precession related variability. This argumentation about the best tuning strategy elaborates on, for example, Martinson et al. (1987), who discuss different tuning strategies for marine (oxygen) isotope stages.

Yet, there is one important difference with all younger Neogene GSSPs definitions and that is that precession and obliquity are no longer reliable in the astronomical solution around 16 Ma for tuning, due to the problem of the tidal dissipation and dynamical ellipticity. Both these parameters affect precession and obliquity (their values back to 16 Ma are not yet exactly known), but not eccentricity which only depends on the planetary part of the solution. Thus, using the tuning of a marked climate cycle/event to eccentricity (and thus not to precession and/or obliquity) for defining the Langhian GSSP also makes sense. And, as mentioned before, our approach follows the long-standing tradition by SNS in defining GSSPs (see ICS website: https://stratigraphy.org/gssps/).

Open-Ocean Standard Auxiliary Boundary Stratotype (SABS)

In view of the importance of benthic foraminiferal isotope records in establishing a global integrated stratigraphy and astrochronology for the Miocene, it was considered appropriate to select a Standard Auxiliary Boundary Stratotype (SABS) (Head et al., 2022a, b) based on one of the deep-sea successions drilled in the open ocean as an alternative to St. Peter's Pool. This has the additional advantage that the low latitude calcareous plankton biostratigraphy can be incorporated as well. IODP Site U1337, drilled in the eastern equatorial Pacific (Fig. 16) during Leg 320/321 (Pälike et al., 2010), was selected as SABS, as it contains a continuous succession across the Burdigalian/Langhian boundary with a good-quality benthic isotope record that has been astronomically tuned (Holbourn et al., 2015, 2022).

In addition, tuned age models have been developed for parallel Sites U1335-U1336, following a stepwise procedure by first correlating their isotope records to the astronomically tuned (isotope) records of Sites U1337 and U1338, followed by the fine tuning of minima in the higher-resolution XRF-scanner derived $CaCO_3$ records to ~100-kyr eccentricity maxima (Kochhann et al., 2016). Unfortunately, a magnetostratigraphy is lacking for Site U1337, but this can be overcome through detailed cyclostratigraphic correlations (stable isotopes, $CaCO_3$) to Sites U1335 and U1336 that have a reliable magnetostratigraphy across the boundary interval.

Comparison of the initial astronomical ages for the younger end of

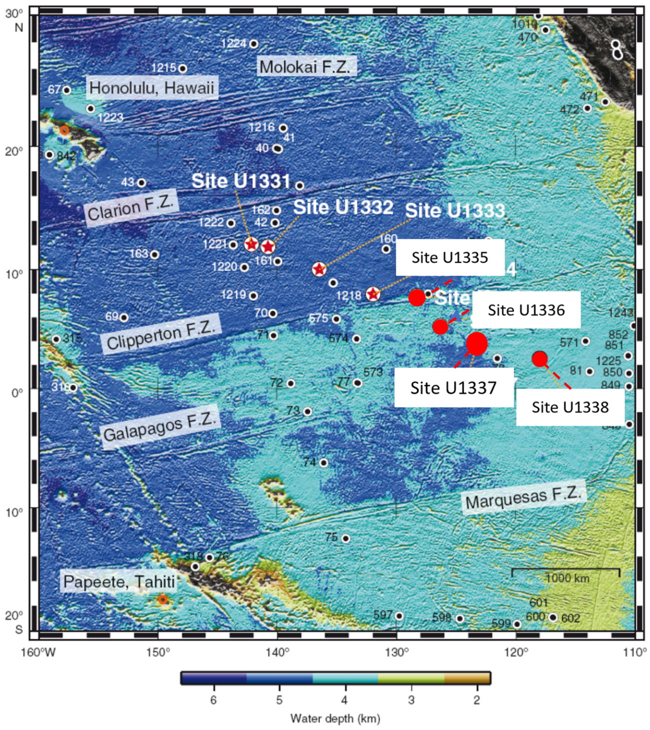

Figure 16. Location map of sites drilled during Expedition 320/321. Red stars: sites drilled during Expedition 320; red circles: sites drilled during Expedition 321; black circles: previous DSDP and ODP sites. F.Z.: fracture zone (modified after Pälike et al., 2010).

Chron C5Cn, the main event for identifying the boundary on a global scale, revealed a significant discrepancy with the reversal being approximately ~100-kyr younger at Sites U1335 and U1337 than at Site U1336 and the Lower LVB (Holbourn et al., 2015; Kochhann et al., 2016; Turco et al., 2017). This issue has been resolved, as initial misfits in the Site U1337 shipboard splice (a missing and a duplicated ~100-kyr eccentricity related cycle, see e.g., Wilkens et al., 2013 and Holbourn et al., 2022) have been corrected. In addition, the intercalation of two distinct turbidites perturbs the cycle pattern in the $CaCO_3$ record of Site U1335, complicating its tuning. Removing these turbidites results in a very similar pattern and tuning of the $CaCO_3$ cycles, eliminating the ~100-kyr younger C5Cn reversal age at this site compared to Site U1336 and the Lower LVB.

Following these splice revisions, the U1337 astronomical ages based on the tuning of the $\delta^{18}O$ record down to 18 Ma have been revised by Holbourn et al. (2022). The Site U1337 tuned chronology is based on correlation of $\delta^{18}O$ minima to maxima in a composite eccentricity-tilt-precession target curve, derived from La2004 with equal weight of eccentricity and obliquity and 0.3 weight of precession (ET+0.3P). Here we include this open ocean record for the interval between 14.9 and 17.0 Ma, as its tuning is largely consistent with that of the carbonate cycles in Sites U1335 and U1336 (see Kochhann et al., 2016) (Fig. 17).

In the open ocean Site U1337, here proposed as SABS, the GSSP level can be identified with the mid-point of a darker interval that has been astronomically calibrated to the same prominent ~100-kyr eccentricity maximum as the mid-point of the marly interval above Megabed IV at the Lower LVB. At Site U1337, this level coincides

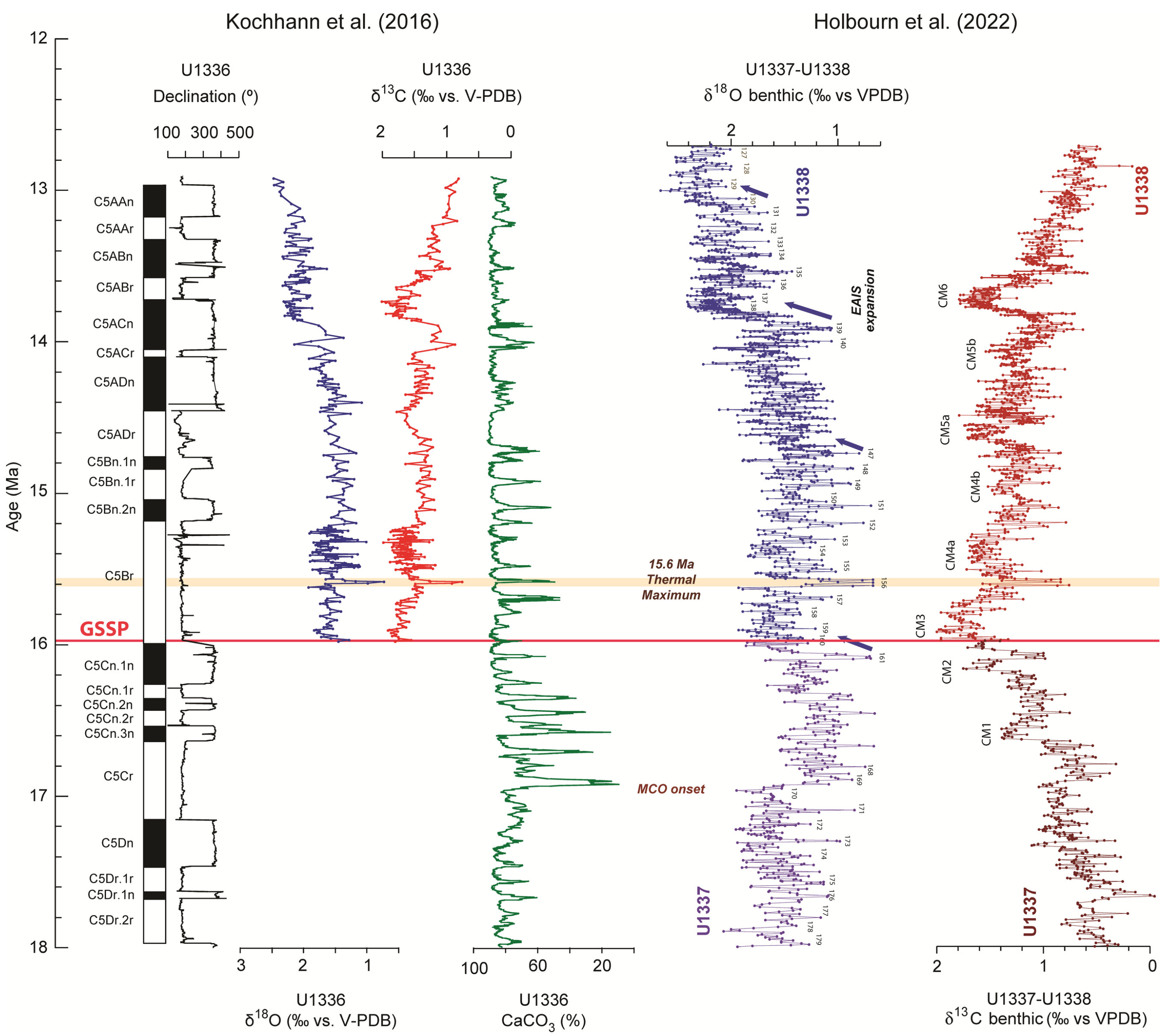

Figure 17. Astronomically tuned stable isotope and $CaCO_3$ (%) records of Site U1336 (from Kochhann et al., 2016) and Sites U1337-U1338 (from Holbourn et al., 2022). Stable isotope data of Site U1336 are from Voigt et al. (2016) and XRF-scanner derived $CaCO_3$ (%) from Shackford et al. (2014) and Wilson (2014). The red line indicates the position of the proposed GSSP level which closely approximates the top of Chron C5Cn at Site U1336. CM1-CM6: Carbon isotope maxima; EAIS: East Antarctic Ice Sheet; MCO: Miocene Climatic Optimum; (Figure modified after Kochhann et al., 2016 and Holbourn et al., 2022).

with a minimum in the oxygen isotope record (cycle 160 in Holbourn et al., 2022) and an increase in the carbon isotope record (CM3 event) around 16 Ma (Fig. 17). At Site U1336, this level coincides with a $CaCO_3$ minimum which is very close to the top of Chron C5Cn (Fig. 17). This level is approximately one 405-kyr eccentricity cycle older than the most dramatic isotope minima in $\delta^{18}O$ and $\delta^{13}C$ dated astronomically at 15.6 Ma, marking the most extreme warming during the entire Miocene (Holbourn et al., 2014, 2022; Kochhann et al., 2016), both at Sites U1337 and U1336 (Fig. 16).

In terms of biostratigraphy the GSSP level falls within the planktonic foraminiferal Zone M5 (Wade et al., 2011) and Zone N8 (Blow, 1969), defined by Base of *Praeorbulina sicana* and Base of *Orbulina suturalis*, and in the uppermost part of the calcareous nannofossil Zone CNM6 (Backman et al., 2012) (corresponding to the upper part of Zone NN4 of Martini 1971). Flaws of this definition, however, are (i) the age calibration of Base of *Praeorbulina* species, that at low latitudes is markedly older than in the Mediterranean; (ii) as with the considered reference sites, the definition of the biostratigraphic signal is not detailed, based on relatively low sample resolution determined by the standard shipboard procedures. For these reasons, the stratigraphic position of calcareous plankton biohorizons straddling the interval across the Burdigalian/Langhian boundary (Base of *G. sicanus*, *P. curva*, *P. glomerosa*, R/S *P. siakensis* as for planktonic foraminifera, Base *Discoaster signus* and Top common *Discoaster deflandrei* as for calcareous nannofossils) are not placed precisely and coherently at Sites U1335, U1336, U1337 and U1338, which results in uncertainties concerning their relative position with respect to the boundary level. Nevertheless, the observed biohorizons closer to the boundary level are Base *D. signus* and Top common *D. deflandrei* that occur ca. 6 m (about 3-4 ~100-kyr eccentricity cycles) above the boundary at Site U1337 and in equivalent stratigraphic position at Site 1338 (I. Raffi, unpublished). The biohorizon Top common *D. deflandrei* should correspond to the *D. deflandrei* Acme End as defined in Mediterranean at DSDP Site 372 (Di Stefano et al., 2008, with an inferred age of 15.67 Ma according to the revised age-model of Baldassini et al., 2021). The R/S coiling direction change of *P. siakensis* is detected at Site U1337 above Base *P. glomerosa* (shipboard data, Pälike et al., 2010). According to a recent study by King et al. (2023), based on quantitative analysis, the R/S coiling direction change of *P. siakensis* at Site 1337 is dated at 15.368 Ma following the age model of Kochhann et al. (2016).

Langhian GSSP and Standard Microfossil Zonations

Planktonic Foraminifera

The GSSP falls within Zone M5 (Wade et al., 2011) and Zone N8 (Blow, 1969). The lower boundary of zones M5 and N8 is defined by Base *Praeorbulina sicana*, dated at 16.39 Ma (ATNTS 2020 Raffi et al., 2020). However, according to the taxonomic revision presented in Turco et al. (2011a), this zonal species should be incorporated in the genus *Globigerinoides* following Blow (1969). According to ATNTS2020 (Raffi et al., 2020) the planktonic foraminiferal bioevent that better approximates the boundary level is Base *Praeorbulina glomerosa* s.s., which defines the lower boundary of Subzone M5b (Wade et al., 2011). However, at Site U1337 the stratigraphic position of this event with respect to the GSSP level is poorly defined. Note that the age calibration of Base *Praeorbulina glomerosa* s.s., dated at 16.27 Ma (ATNTS2020, Raffi et al., 2020) results markedly diachronous with respect to the Mediterranean (*P. glomerosa glomerosa* FO dated at 15.16 Ma, Turco et al., 2017).

Calcareous Nannofossils

The GSSP falls within standard zones NN4 (Martini, 1971), CN3 (Okada and Bukry, 1980) and close to the top of Zone CNM6 (Backman et al., 2012) (ATNTS 2020 Raffi et al., 2020). The top of Zone CNM6 is defined by Base *Discoaster signus* (= *D. petalosus*) (dated at 15.85 Ma) which is slightly older than Top common *Discoaster deflandrei* (dated at 15.80 Ma) (ATNTS 2020 Raffi et al., 2020). These two biohorizons closely approximate the GSSP.

Larger Foraminifera

The GSSP is slightly younger than the shallow benthic foraminiferal SBZ 25-26 zonal boundary. The base of Zone SB 26 is defined by the FO of *Borelis* gr. *melo* (in the Mediterranean domain only) and the disappearance of *Miogypsina* (see Hilgen et al., 2012). Bassi et al. (2021), however, reported the presence of *B. melo* in the Mediterranean in the Aquitanian.

Dinoflagellates

The GSSP falls within Subzone DM3b in the northwestern Europe zonation (King, 2016). The top of this subzone is defined by the Base of *Labyrinthodinium truncatum*, tentatively dated at about 15.2 Ma (ATNTS 2020 Raffi et al., 2020).

Radiolarians

The GSSP falls within radiolarian zone RN4 close to Base *Corcanopsis cristata* dated at 15.797 Ma (ATNTS 2020 Raffi et al., 2020).

Diatoms

The GSSP approximates Base Subzone *Cestodiscus peplum* a (Barron, 1985), defined by the Base of the nominal taxon dated at 16.15 Ma (ATNTS 2020 Raffi et al., 2020).

Regional Stages

The GSSP corresponds to Altonian/Clifdenian regional stage boundary in New Zealand and the Karpatian/Badenian and Kotsakhurian/Badenian boundaries in the Central and Eastern Paratethys, respectively (see, Hilgen et al., 2012; Raffi et al., 2020). Note that the FO of *Praeorbulina curva* is the defining event in the case of the regional stage boundary in New Zealand, but that this event is much younger in the Mediterranean with a tuned age of 15.356 Ma (Turco et al., 2017).

Continental Records

The Langhian GSSP at La Vedova coincides approximately with the Hemingfordian/Barstovian boundary in terms of the North American Land Mammal ages (see, Hilgen et al., 2012). However, it makes a difference whether that boundary is defined on the basis of multivariate faunal analysis (16.3 Ma) or immigrant taxa (FA *Plithocyon* and *Zygolophodon*; 16.0 Ma). In Europe, the GSSP is preceded by the MN4-5 boundary at 16.4 Ma, which in addition corresponds to the lower-middle Aragonian boundary.

The GSSP coincides with the final stages of the main phase of the Columbia River flood basalts lasting from 16.7 to 15.9 Ma (Kasbohm and Schoene, 2018).

Climate, Isotope, Sequence Stratigraphy and Sea-Level

The GSSP falls in the Miocene Climatic Optimum (MCO), the interval between 17 and 14.7 Ma characterized by the lightest deep marine $\delta^{18}O$ values (minimum ice) and the heaviest $\delta^{13}C$ values, corresponding to the Monterey $\delta^{13}C$ isotope excursion paced by long 405-kyr eccentricity cycles (astrochronozones nos. 35 to 41/42, Raffi et al., 2020). Specifically, the boundary postdates the beginning of the MCO and the Monterey excursion by approximately one million years and predates, by 405 kyr or one long eccentricity cycle, the $\delta^{18}O$ spike at 15.6 Ma, with the lightest values linked to hyperthermal-like conditions, CO_2 release and a maximum in the 2.4 Myr eccentricity cycle (Holbourn et al., 2014, 2022). Based on boron isotope data, atmospheric pCO_2 was slightly higher during the MCO than the remainder of the Miocene, but still at a level similar to or slightly higher (400-600 ppmv) than today (Steinthorsdottir et al., 2021); however, we should not forget that typical peak interglacial CO_2 concentrations almost never exceeded 300 ppm and normally reached values of 280 only (Petit et al., 1999) and that the present-day climate system is not in equilibrium. Global (eustatic) sea-level was supposedly somewhat higher during the MCO compared to the early and late Miocene, and some 100 m above present-day sea-level (Haq et al., 1987; Miller et al., 2020). The Langhian GSSP also approximates a sustained $\delta^{18}O$ increase that punctuated the MCO and suggests a transient glacial expansion and CO_2 decrease (Mi2 Event of Miller et al., 1991). This short-term climate change is contemporaneous with a marked $\delta^{13}C$ increase corresponding to the onset of CM3, one of the most prominent $\delta^{13}C$ maxima of the Monterey Excursion (Holbourn et al., 2022). The GSSP further coincides with the end of the main eruption of the Columbia River flood basalts, which lasted from 16.7 to 15.9 Ma, when more than 95% of the CR basalts were formed and which may have significantly contributed to the Miocene Climatic Optimum (Kasbohm and Schoene, 2018).

Summary

The Langhian GSSP should preferably be defined at or close to the selected primary boundary criterion, the younger end of C5Cn, in the Lower La Vedova Beach section. This criterion with an astronomical age very close to 16 Ma is preferred to the classical *Praeorbulina* datum, which has been complicated by taxonomic confusion and revision, and hence is considered less suitable for defining the boundary. However, instead of the magnetic reversal boundary, we define the boundary at 17.84 m in the middle of the dark colored marls above Megabed IV. This level, which corresponds closely to the top of C5Cn, is astronomically calibrated to the most prominent ~100-kyr eccentricity maximum in the 405-kyr maximum centered around 16 Ma. The ~100-kyr maximum has an age of 15.981 Ma according to La2004 nominal solution, and of 15.978 Ma according to the La2011 (Fig. 18).

In addition, the IODP Site U1337, a deep-sea site from the eastern equatorial Pacific, is designated as SABS with the aim to directly link the open ocean benthic isotope record to the boundary definition. This

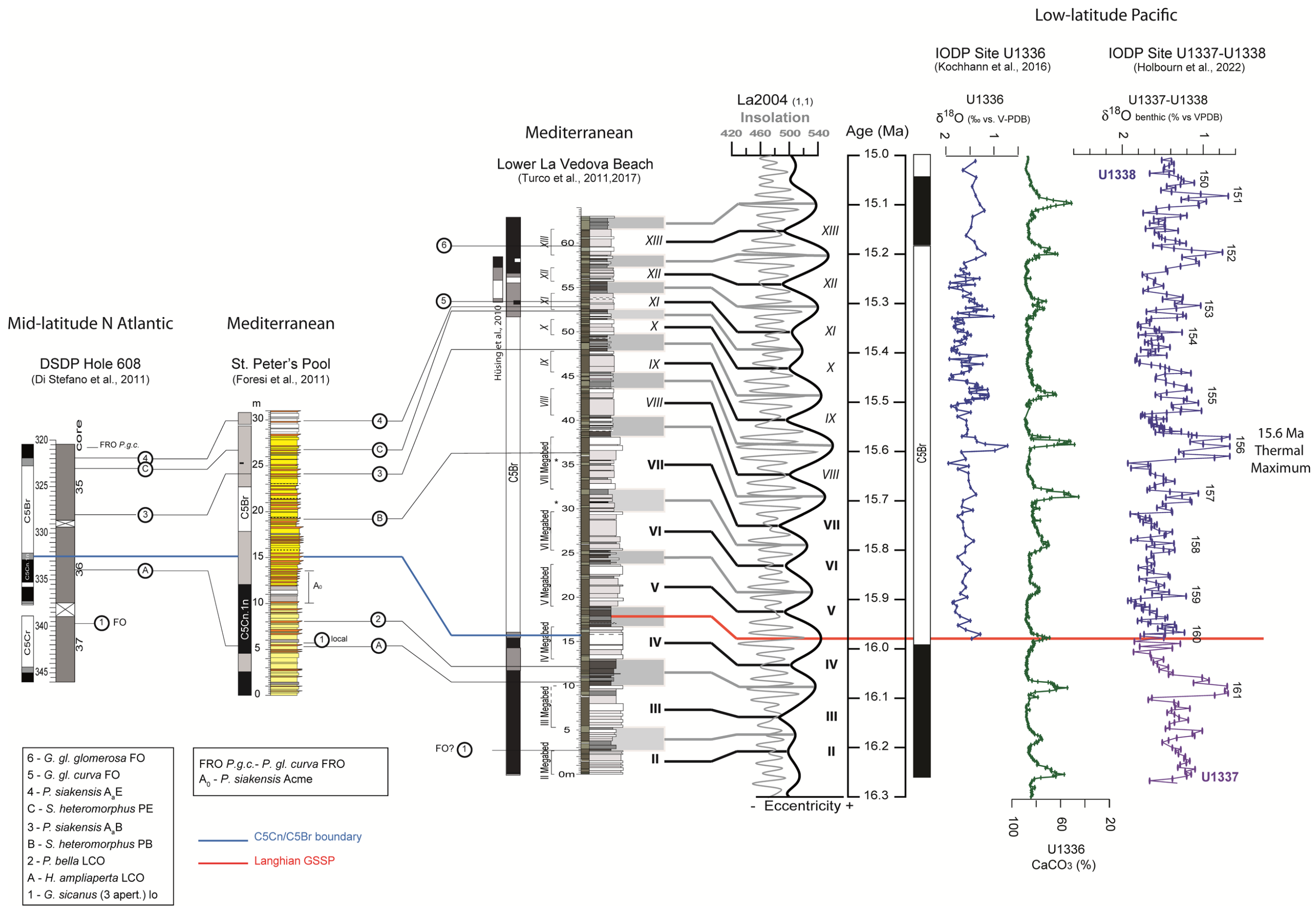

Figure 18. Correlation of mid-latitude North Atlantic, Mediterranean and equatorial Pacific successions across the boundary interval and the position of Langhian GSSP level in the Lower La Vedova Beach section and Sites U1336 and U1337-U1338. This level closely approximates the top of Chron C5Cn, the principal event for correlating the base of the Langhian Stage globally. Stable isotope data of Site U1336 are from Voigt et al. (2016) and XRF-scanner derived $CaCO_3$ (%) from Shackford et al. (2014) and Wilson (2014).

level marks the mid-point of a darker interval that has been astronomically calibrated to the same distinct ~100-kyr eccentricity maximum and coincides with distinctive features in the stable isotope records. Also, this level corresponds closely to the top of C5Cn, based on detailed cyclostratigraphic correlations to parallel Sites U1335 and U1336 having an excellent magnetostratigraphy (Fig. 18).

The addition of the SABS in the open ocean further shows that the boundary is ~400-kyr older than the most prominent peak in the stable isotopes dated astronomically at 15.6 Ma. This peak has been identified as an eccentricity-paced hyperthermal event within the Miocene Climatic Optimum (MCO) by Holbourn et al. (2013, 2022). The boundary corresponds to the previous 405-kyr long eccentricity cycle (maximum) and falls right in the middle of the MCO.

Acknowledgements

We are grateful to the members of the Subcommission on Neogene Stratigraphy and the International Commission on Stratigraphy for the fruitful discussion and comments which contributed to improve the final version of the proposal. We are also grateful to the municipality of Ancona for the kind support. We thank an anonymous reviewer and the Editor-in-Chief of Episodes for their suggestions.

References

Aubry, M.P., Miller, K.G., Turco, E., Flores, J.A., Gladenkov, A., Grunert, P., Hilgen, F., Nishi, H., Holbourn, A., Krijgsman, W., Lirer, F., Piller, W.E., Quillévéré, F., Raffi, I., Robinson, M., Rook, L., Tian, J., Triantaphyllou, M., and Vallejo, F., 2022, Ratification of Neogene subseries as formal units in international chronostratigraphy. Episodes, v. 45, pp. 445–453, doi:10.18814/epiiugs/2022/022008

Backman, J., Raffi, I., Rio, D., Fornaciari, E., and Palike, H., 2012, Biozonation and biochronology of Miocene through Pleistocene calcareous nannofossils from low and middle latitudes. Newsletters Stratigraphy, v. 45, pp. 221–244, doi:10.1127/0078-0421/2012/0022

Baldassini, N., Foresi, L.M., Lirer, F., Sprovieri, M., Turco, E., Pelosi, N., and Di Stefano, A, 2021, Middle Miocene stepwise climate evolution in the Mediterranean region through high-resolution stable isotopes and calcareous plankton records. Marine Micropaleontology, v. 167, 102030; doi:10.1016/j.marmicro.2021.102030

Barron, J.A., 1985, Late Eocene to Holocene diatom biostratigraphy of the equatorial Pacific Ocean, Deep Sea Drilling Project Leg 85. In: Mayer, L., Theyer, F., et al. (Eds.), Initial Reports of the Deep Sea Drilling Project, 85, Washington (U.S. Govt. Printing Office), pp. 413–456, doi:10.2973/dsdp.proc.85.108.1985

Bassi, D., Braga, J.C, Di Domenico, G., Pignatti, J., Abramovich, S., Hallock, P., Könen, J., Kovacs, Z., Langer, M.R., Pavia, G., and Iryu, Y., 2021, Palaeobiogeography and evolutionary patterns of the larger foraminifer *Borelis* De Montfort (Borelidae). Papers in Palaeontology, v. 7, Part 1, pp. 377–403.

Berggren, W.A., Kent, D. V., and Van Couvering, J. A., 1985, The Neogene, Part 2. Neogene geochronology and chronostratigraphy. In: Snelling, N. J. (Ed.), The chronology of the geological record. Geological Society of London, Memoir, 10, pp. 211–259.

Berggren, W.A., Kent, D.V., Swisher III, C.C., and Aubry, M.-P., 1995, A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J. (Eds.), Geochronology, Time Scales and Global Stratigraphic Correlation: A Unified Temporal Framework for an Historical Geology. SEPM Special Publication, v. 54, pp. 129–212.

Blow, W.H., 1956, Origin and evolution of the foraminiferal genus *Orbulina* d'Orbigny. Micropaleontology, v. 2, pp. 57–70.

Blow, W.H., 1969, Late middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: Bronniman, P., and Renz, H.H. (Eds.), Proceedings of the First International Conference on Planktonic Microfossils, Geneva, 1967, 1, pp. 199–422.

Boni, A., 1967, Notizie sul Serravalliano tipo. In: Selli, R. (Ed.), Guida alle escursioni del IV Congresso RCMNS, 47–63. Bologna, University of Bologna.

Castradori, D., Rio, D., Hilgen, F.J., and Lourens, L.J., 1998, The Global Standard Stratotype-section and Point (GSSP) of the Piacenzian Stage (Middle Pliocene). Episodes, v. 21, pp. 88–93.

Cita, M. B., and Blow, W. H., 1969, The biostratigraphy of the Langhian, Serravallian and Tortonian stages in the type sections in Italy. Rivista Italiana di Paleontologia e Stratigrafia, v. 75, pp. 549–603.

Cita, M. B., and Premoli Silva, I., 1960, Pelagic foraminifera from the type Langhian. Proceedings International Paleontological Union, v. 22, pp. 39–50.

Di Stefano, A., 1995, Biostratigrafia a nannofossili calcarei dei sedimenti medio-supramiocenici del settore occidentale del Plateau Ibleo (Sicilia sud-orientale). Bollettino Società Geologica Italiana, v. 34, pp.147–162.

Di Stefano, A., Baldassini, N., Maniscalco, R., Speranza, F., Maffione, M., Cascella, A., and Foresi, L.M., 2015, New bio-magnetostratigraphic data on the Miocene Moria section (Northern Apennines, Italy): connections between the Mediterranean and the Atlantic Ocean. Newsletter on Stratigraphy, v. 48, pp. 135–152, doi: 10.1127/nos/2015/0057

Di Stefano, A., Baldassini, N., Raffi, I., Fornaciari, E., Incarbona, A., Negri, A., Bonomo, A., Villa, G., Di Stefano, E., and Rio, D., 2023, Neogene-Quaternary Mediterranean calcareous nannofossils Biozonation and Biochronology: a review. Stratigraphy in press.

Di Stefano, A., Foresi, L. M., Lirer, F., Iaccarino, S.M., Turco, E., Amore, F.O., Mazzei, R., Morabito, S., Salvatorini, G., and Abdul Aziz, H.A., 2008, Calcareous plankton high-resolution biomagnetostratigraphy for the Langhian of the Mediterranean area. Rivista Italiana di Paleontologia e Stratigrafia, v. 11, pp. 51–76.

Di Stefano, A., Verducci, M., Cascella, A., and Iaccarino, S.M., 2011, Calcareous plankton events at the Early/Middle Miocene transition of DSDP Hole 608: comparison with Mediterranean successions for the definition of the Langhian GSSP. Stratigraphy, v. 8, pp. 145–161.

Foresi, L. M., Verducci, M., Baldassini, N., Lirer, F., Mazzei, R., Salvatorini, G., Ferraro, L., and Da Prato, S., 2011, Integrated stratigraphy of St. Peter's Pool section (Malta): new age for the Upper Globigerina Limestone Member and progress towards the Langhian GSSP. Stratigraphy, v. 8, pp. 125–143.

Fornaciari, E., Di Stefano, A., Rio, D., and Negri, A., 1996, Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. Micropaleontology, v. 42, pp. 37–63.

Fornaciari, E., Iaccarino, S., Mazzei, R., Rio, D., Salvatorini, G., Bossio, A., and Monteforti B., 1997, Calcareous plankton biostratigraphy of the Langhian historical stratotype. In: Montanari, A., Odin, G.S., Coccioni, R. (Eds.), Miocene Stratigraphy: An Integrated Approach. Developments in Palaeontology and Stratigraphy, 15, Elsevier, Amsterdam, pp. 89–96.

Gelati, R., 1968, Stratigrafia dell'Oligo–Miocene delle Langhe tra le valli dei fiumi Tanaro e Bormida di Spigno. Rivista Italiana di Paleontologia e Stratigrafia, v. 74, pp. 875–964.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic. Science, v. 235, pp. 1156–1167.

Harland, W. B., Cox, A. V., Craig, L., Smith, A., and Smith, D., 1990, A Geological Time Scale 1989. Cambridge University Press, Cambridge, 131 p.

Head, M.J., Aubry, M.-P., Piller, W.E., and Walker, M., 2022a, The Standard Auxiliary Boundary Stratotype: a replacement for the Auxiliary Stratotype Point in supporting a Global boundary Stratotype Section and Point (GSSP). Episodes, doi:10.18814/epiiugs/2022/022012

Head, M.J, Aubry, M.-P., Piller, W.E., and Walker, M., 2022b, Standard Auxiliary Boundary Stratotype (SABS) approved to support the Global boundary Stratotype Section and Point (GSSP). Episodes, doi:10.18814/epiiugs/2022/022008

Hilgen, F.J, Abdul Aziz, H., Bice, D., Iaccarino, S., Krijgsman, W., Kuiper, K., Montanari, A., Raffi, I., Turco, E., and Zachariasse, W.-J., 2005, The global boundary stratotype section and point (GSSP) of the Tortonian stage (upper Miocene) at Monte dei Corvi. Episodes, v. 28, pp. 6–17.

Hilgen, F.J., Abdul Aziz, H.A., Krijgsman, W., Raffi, I., and Turco, E., 2003, Integrated stratigraphy and astronomical tuning of the Serravallian and lower Tortonian at Monte dei Corvi (Middle–Upper Miocene, northern Italy). Palaeogeography Palaeoclimatology Palaeoecology, v. 199, pp. 229–264.

Hilgen, F.J, Abels, H.A., Iaccarino, S., Krijgsman, W., Raffi, I., Sprovieri, R., Turco, E., and Zachariasse, W.J., 2009, The Global Stratotype Section and Point (GSSP) of the Serravallian Stage (Middle Miocene). Episodes, v. 32, pp. 152–166.

Hilgen, F.J., Iaccarino, S., Krijgsman, W., Villa, G., Langereis, C.G., and Zachariasse, W. J., 2000. The Global Boundary Stratotype Section and Point (GSSP) of the Messinian Stage (Uppermost Miocene). Episodes, v. 23, pp. 172–178.

Hilgen, F.J., Lourens, L.J., and van Dam, J.A., 2012, The Neogene Period. In: Gradstein, F., Ogg, J., Schmitz, M., and Ogg, G. (Eds.), The Geological Time Scale 2012. Elsevier, Amsterdam, pp. 923–978.

Holbourn, A., Kuhnt, W., Clemens, S., Prell, W., and Andersen, N., 2013, Middle to late Miocene stepwise climate cooling: Evidence from a high-resolution deep water isotope curve spanning 8 million years. Paleoceanography, v. 28, pp. 688–699.

Holbourn, A., Kuhnt, W., Kochhann, K.G.D., Andersen, N., and Sebastian Meier, K.J., 2015. Global perturbation of the carbon cycle at the onset of the Miocene climatic optimum. Geology, v. 43, pp. 123–126. doi:10.1130/G36317.1

Holbourn, A., Kuhnt, W., Kochhann, K.G.D., Matsuzaki, K.M., and Andersen, N., 2022, Middle Miocene Climate-Carbon Cycle Dynamics: Keys for Understanding Future Trends on a Warmer Earth? In: Aiello, I., Barron, J., and Ravelo, C. (Eds.), Understanding the Monterey Formation and Similar Biosiliceous Units across Space and Time. Geological Society of America, Special Paper, 556, doi:10.1130/2022.2556(05)

Holbourn, A., Kuhnt, W., Lyle, M., Schneider, L., Romero, O., and Andersen, N., 2014, Middle Miocene climate cooling linked to intensification of eastern equatorial Pacific upwelling. Geology, v. 42, pp. 19–22, doi:10.1130/G34890.1

Hüsing, S.K., Cascella, A., Hilgen, F.J., Krijgsman, W., Kuiper, K.F., Turco, E., and Wilson, D., 2010, Astrochronology of the Mediterranean Langhian between 15.29 and 14.17 Ma. Earth and Planetary Science Letters, v. 290(3-4), pp. 254–269, doi:10.1016/j.epsl.2009.12.002

Iaccarino, S., and Salvatorini, G., 1982, A framework of planktonic foraminifera biostratigraphy for Early Miocene to Late Pliocene Mediterranean area. Paleontologia Stratigrafica ed Evoluzione, v. 2, pp. 115–125.

Iaccarino, S., Di Stefano, A., Foresi, L.M., Turco, E., Baldassini, N., Cascella, A., Da Prato S., Ferraro, L., Gennari, R., Hilgen, F.J., Lirer, F., Maniscalco, R., Mazzei, R., Riforgiato, F., Russo, B., Sagnotti, L., Salvatorini, G., Speranza, F., and Verducci, M., 2011, High-resolution integrated stratigraphy of the upper Burdigalian–lower Langhian in the Mediterranean: the Langhian historical stratotype and new candidate sections for defining its GSSP. Stratigraphy, v. 8, pp. 199–215.

Jenkins, D. G., Saunders, J. B., and Cifelli, R., 1981, The relationship of *Globigerinoides bisphericus* TODD 1954 to *Praeorbulina sicana* (De Stefani) 1952. Journal of Foraminiferal Research, v. 11, pp. 262–267.

Kasbohm, J., and Schoene, B., 2018, Rapid eruption of the Columbia River flood basalt and correlation with the mid-Miocene climate optimum. Science Advances, v. 4, doi:10.1126/sciadv.aat8223.

King, C., 2016, Biostratigraphy. In: King, C., Gale, A.S., and Barry, T.L. (Eds.), A revised correlation of Tertiary rocks in the British Isles and adjacent areas of NW Europe. Geological Society of London, Special Reports, 27, 1957, doi:10.1144/SR27.3.

King, D.J., Wade, B.S., and Miller, G.C, 2023, Biostratigraphic utility of coiling direction in Miocene planktonic foraminiferal genus *Paragloborotalia*. Newsletters on Stratigraphy, v. 56, pp. 331–355, doi:10.1127/nos/2023/0681

Kochhann, K.G.D., Holbourn, A., Kuhnt, W., Channell, J.E.T., Lyle, M., Shackford, J.K., Wilkens, R.H., and Andersen, N., 2016, Eccentricity pacing of eastern equatorial Pacific carbonate dissolution cycles during the Miocene Climatic Optimum. Paleoceanography, v. 31, pp. 1176–1192, doi:10.1002/2016PA002988

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., and Levrard, B., 2004, A long term numerical solution for the insolation quantities of the Earth. Astronomy and Astrophysics, v. 428, pp. 261–285.

Lirer, F., Foresi, L.M., Iaccarino, S.M., Salvatorini, G., Turco, E., Cosentino, C., Sierro, F.J., and Caruso, A., 2019, Mediterranean Neogene planktonic foraminifer biozonation and biochronology. Earth-Science Reviews, v. 196, 102869, doi: 10.1016/j.earscirev.2019.05.013

Lourens, L.J, Hilgen, F.J., Shackleton, N.J., Laskar, J., and Wilson, D., 2004, The Neogene Period. In: Gradstein, F.M., Ogg, J.G., and Smith, A.G. (Eds.), A Geological Time Scale 2004, Cambridge University Press, Cambridge, pp. 409–440.

Mader, D, Cleaveland, L., Koeberl, C., Bice, D., and Montanari, A., 2004a, High-resolution geochemical proxies of a short Langhian pelagic sequence at the Cònero Riviera, Ancona (Italy): some palaeoenvironmental and cyclostratigraphic considerations. Palaeogeography, Palaeoclimatology Palaeoecology, v. 211, pp. 325–344.

Mader, D., Koeberl, C., and Montanari, A., 2004b, Geochemistry of a Langhian pelagic marly limestone sequence of the Cònero Riviera, Ancona (Italy) and the search for the Ries impact signature: A progress report. In; Dypvik, H., Clays, P., and Burchell, M. (Eds.), Cratering in marine Environments and on Ice Impact Studies, Springer Verlag, v. 5, pp. 149–184.

Mader, D., Montanari, A., Gattacceca, J., Koeberl, Ch., Handler, R., and Coccioni, R., 2001, $^{40}Ar/^{39}Ar$ dating of a Langhian biotite-rich clay layer in the pelagic sequence of the Cònero Riviera, Ancona, Italy. Earth and Planetary Science Letters, v. 194, pp. 111–126.

Martini, E., 1971, Standard Tertiary and Quaternary Calcareous Nannoplankton Zonation. Proceedings of the II Planktonic Conference, Roma, 1970. Edizioni Tecnoscienza, v. 2, pp. 739–785.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C.Jr., and Shackleton, N.J, 1987, Age Dating and the Orbital Theory of the Ice Ages: Development of a High-Resolution 0 to 300,000-Year Chronostratigraphy. Quaternary Research, v. 27, pp. 1–29.

Mayer–Eymar, Ch., 1868, Tableau synchronistique des terrains tertiaires supérieurs. Zurich: ETH Library.

Miculan, P., 1994, Planktonic foraminiferal biostratigraphy of the middle Miocene in Italy. Bollettino Società Paleontologica Italiana, v. 33, pp. 299–339.

Miller, K.G., Browning, J.V., John Schmelz, W., Kopp, R.E., Mountain, G.S., and Wright, J.D., 2020, Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. Science Advances, 6(20), doi:10.1126/sciadv.aaz1346.

Miller, K.G., Wright, J.D., Fairbanks, R.G., 1991, Unlocking the ice house: Oligocene–Miocene oxygen isotopes, eustasy and margin erosion. Journal of Geophysical Research, v. 96, pp. 6829–6848, doi: 10.1029/90JB02015

Montanari, A., Beaudoin, B., Chan, L.S., Coccioni, R., Deino, A., De Paolo, D.J., Emmanuel, L., Fornaciari, E., Kruge, M., Lundblad, S., Mozzato, C., Portier, E., Renard, M., Rio, D., Sandroni, P., and Stankiewicz, A., 1997, Integrated stratigraphy of the Middle and Upper Miocene pelagic sequence of the Conero Riviera (Marche region, Italy). In: Montanari, A., Odin, G.S. and Coccioni, R. (Eds.), Miocene Stratigraphy: An Integrated Approach. Developments in Palaeontology and Stratigraphy, 15, Elsevier, Amsterdam, pp. 409–450.

Mourik, A.A., Bijkerk, J.F., Cascella, A., Huesing, S.K., Hilgen, F.J., Lourens, L.J., and Turco, E., 2010, Astronomical tuning of the La Vedova High Cliff Section (Ancona, Italy) – Implications of the Middle Miocene climate transition for Mediterranean sapropel formation. Earth and Planetary Science Letters, v. 297, pp. 249–261.

Okada, H., and Bukry, D., 1980, Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975). Marine Micropaleontology, v. 5, pp. 321–325.

Pälike, H., Lyle, M., Nishi, H., Raffi, I., Gamage, K., Klaus, A., and the Expedition 320/321 Scientists, 2010, Proc. IODP, 320/321: Tokyo (Integrated Ocean Drilling Program Management International, Inc.).

Pareto, L., 1865. Note sur les subdivisions que l'on pourrait établir dans les terrains tertiaires de l'Apennin septentrional. Societé Géologique de France, Bulletin, v. 22, pp. 210-217.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davisk, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzmank, E., and Stievenard, M., 1999, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature, v. 399, pp. 429–436, doi:10.1038/20859

Raffi, I., Backman, J., Fornaciari, E., Pälike, H., Rio, D., Lourens, L., and Hilgen, F., 2006, A review of calcareous nannofossil astrobiochronology encompassing the past 25 million years. Quaternary Science Reviews, v. 25, pp. 3113–3137.

Raffi, I., Wade, B., and Palike, H., 2020. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M. (Eds), Geologic Time Scale 2020, v. 2, pp. 1141–1215, doi:10.1016/B978-0-12-824360-2.00029-2

Rio, D., Cita, M.B., Iaccarino, S., Gelati, R., and Gnaccolini, M., 1997, Langhian, Serravallian and Tortonian historical stratotypes. In: Montanari, A., Odin, G. S. and Coccioni, R. (Eds.), Miocene stratigraphy: An integrated approach. Developments in Palaeontology and Stratigraphy, 15, Elsevier, Amsterdam, pp. 57–87.

Rio, D., Sprovieri, R., Castradori, D., and Di Stefano, E., 1998, The Gelasian Stage (Upper Pliocene): a new unit of the Global Standard Chronostratigraphic Scale. Episodes, v. 21, pp. 82–87.

Russo, B., Ferraro, L., Correggia, C., Alberico, I., Foresi, L.M., Vallefuoco, M., and Lirer F., 2022, Deep-water paleoenvironmental changes based on early-middle Miocene benthic foraminifera from Malta Island (central Mediterranean). Palaeogeography, Palaeoclimatology, Palaeoecology, v. 586, 110722, doi:10.1016/j.palaeo.2021.110722

Shackford, J. K., Lyle, M., Wilkens, R.H., and Tian, J., 2014, Data report: Raw and normalized elemental data along the Site U1335, U1336, and U1337 splices from X-ray fluorescence scanning. In: Pälike, H., et al. (Eds.), Proceedings of the IODP, vol. 320/321, Integrated Ocean Drill. Program Manage. Int., Inc., Tokyo, pp. 1–17, doi:10.2204/iodp.proc.320321.216.2014

Steinthorsdottir, M., Coxall, H.K., de Boer, A.M., Huber, M., Barbolini, N., Bradshaw, C.D., Burls, N.J., Feakins, S.J., Gasson, E., Henderiks, J., Holbourn, A.E., Kiel, S., Kohn, M.J., Knorr, G., Kürschner, W.M., Lear, C.H., Liebrand, D., Lunt, D. J., Mörs, T., Pearson, P. N., Pound, M.J., Stoll, H., and Strömberg, C.A.E., , 2020, The Miocene: the Future of the Past. Paleoceanography and Paleoclimatology, e2020PA004037, doi:10.1029/2020PA004037

Turco, E., Cascella, A., Gennari, R., Hilgen, F.J., Iaccarino, S.M., and Sagnotti, L., 2011b, Integrated stratigraphy of the La Vedova section (Conero Riviera, Italy) and implications for the Burdigalian/Langhian boundary. Stratigraphy, v. 8, pp. 89–110.

Turco, E., Cascella, A., Hilgen, F.J., Hüsing, S.K., Krijgsman, W., and Van Peer, T.E., 2019, High-resolution integrated stratigraphy and astronomical tuning of the Monte Cardeto - Spiaggia della Scalaccia composite section (Ancona, Italy) between 17.3 and 16.2 Ma. The onset of the Miocene Climatic Optimum in the Mediterranean. 3rd International Congress on Stratigraphy STRATI 2019, Milano (Italia), 2-5 July 2019.

Turco, E., Hüsing, S., Hilgen, F.J., Cascella, A., Gennari, R., Iaccarino, S.M., and Sagnotti, L., 2017, Astronomical tuning of the La Vedova section between 16.3 and 15.0 Ma. Implications for the origin of megabeds and the Langhian GSSP. Newsletters on Stratigraphy, 50(1), pp. 1–29, doi:10.1127/nos/2016/0302

Turco, E., Iaccarino, S.M., Foresi, L., Salvatorini, G., Riforgiato, F., and Verducci, M., 2011a, Revisiting the taxonomy of the intermediate stages in the *Globigerinoides – Praeorbulina* lineage. Stratigraphy, v. 8, pp. 163–187.

Van Couvering, J.A., Castradori, D., Cita, M.B., Hilgen, F.J., and Rio, D., 2000, The base of the Zanclean Stage and of the Pliocene Series. Episodes, v. 23, pp. 179–187.

Van Peer, T., 2013, Astronomically tuned magnetocyclostratigraphy of late Burdigalian marine sediments at Monte Cardeto, Ancona, Italy. Unpublished MSc-thesis at http://dspace.library.uu.nl/handle/1874/279858

Vervloet, C.C., 1966, Stratigraphical and micropaleontological data on the Tertiary of Southern Piedmont (Northern Italy). Utrecht: Schotanus, 88 p.

Voigt, J., Hathorne, E.C., Frank, M., and Holbourn, A., 2016, Minimal influence of recrystallization on middle Miocene benthic foraminiferal stable isotope stratigraphy in the eastern equatorial Pacific. Paleoceanography, v. 31, pp. 98–114, doi:10.1002/2015PA002822

Wade, B.S., Pearson, P.N., Berggren, W.A., and Pälike, H., 2011, Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. Earth-Science Reviews, v. 104, pp. 111–142.

Wilkens, R.H., Dickens, G.R., Tian, J., Backman, J., and the Expedition 320/321 Scientists, 2013, Data report: revised composite depth scales for Sites U1336, U1337, and U1338. In: Pälike, H., Lyle, M., Nishi, H., Raffi, I., Gamage, K., Klaus, A., and the Expedition 320/321 Scientists, Proc. IODP, 320/ 321: Tokyo (Integrated Ocean Drilling Program Management International, Inc.).

Wilson, J. K., 2014, Early Miocene carbonate dissolution in the eastern equatorial Pacific. PhD thesis, 87 pp., Tex. A&M Univ.

Elena Turco is Associate Professor of Micropaleontology and Paleoecology at the University of Parma (Italy). She is Vice-Chair of the Subcommission on Neogene Stratigraphy (SNS) and member of the SNS Working Groups for the definitions of the Global Stratotype Sections and Points (GSSPs) of the Langhian and Burdigalian stages. She formerly was SNS Secretary and a member of the SNS Working Groups for the definition of the GSSPs of the Tortonian and Serravallian Stages. Her main research interests focus on high resolution planktonic foraminiferal biostratigraphy and biochronology, integrated stratigraphy, and paleoecology and paleoclimatology of Neogene successions from the Mediterranean and open-ocean areas.

Frits Hilgen is past chair of the Subcommission on Neogene Stratigraphy and current SNS-ISSC member. He is chair of the working group to define the remaining Langhian (which is now defined) and Burdigalian GSSPs of the Neogene. His main research interests lie in astronomical climate forcing, cyclostratigraphy and high-resolution integrated stratigraphy and time scales. He contributed in a significant way to the development of the astronomical time scale for the Cenozoic, to define many GSSPs in the Neogene within astronomically calibrated integrated stratigraphic frameworks and to intercalibrate astronomical and radioisotopic dating techniques.

Isabella Raffi was a Full Professor in Paleontology-Paleoecology at the University of Chieti-Pescara (Italy) until 2022. As calcareous nannofossil paleontologist works on Cenozoic Biostratigraphy, Biochronology and the use of nannofossils for paleoclimate reconstructions. She has a long-term experience of scientific ocean drilling, participated to six ODP and IODP expeditions as paleontologist and to IODP Exp. 320-321 as Co-Chief Scientist. She was Chair of SNS of the ICS (2012 to 2020). She received the Honorary Doctorate in Natural Sciences from Stockholm University (2012), the International Prize "Prof. Luigi Tartufari" of Accademia dei Lincei for Geoscience (2020) and the ICS award "Digby Mc Laren medal" (2023).