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

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ABSTRACT: Results of high-resolution integrated stratigraphic studies (calcareous plankton and magnetostratigraphy) of three Mediterranean sections (La Vedova in Central Italy, Contrada Pesciarello in Sicily and St. Peter's Pool in Malta) and one deep-sea core from the mid-latitude North Atlantic (DSDP Hole 608) are here synthesized. They are compared with those of previously studied deep marine sections in the Mediterranean including the historical stratotype, with the aim to select the most suitable section and criterion to define the Langhian GSSP (Global Stratotype Section and Point). This study significantly improves the existing magnetobiostratigraphic framework for the upper Burdigalian-lower Langhian and opens new perspectives for defining the Langhian GSSP.

An extensive review of the first stages of the *Globigerinoides-Praeorbulina* evolutionary lineage pointed out that the *Praeorbulina* datum, historically used (and/or suggested) to approximate the base of the Langhian, coincides with the First Occurrence (FO) of *P. glomerosa curva* instead of *P. sicana* which is here included in the genus *Globigerinoides.* The FO of *P. glomerosa curva* occurs close to the C5Br/C5Bn.2n reversal boundary. As a consequence, the two recommended guiding criteria to recognize the base of the Langhian, i.e. the *Praeorbulina* datum and the top of Chron C5Cn.1n, can not be applied together, as these two events differ in age by ~740 kyr. The selection of either of these two criteria will imply a different duration for the Langhian: relatively short, in case the FO of *P. glomerosa curva* is selected, or longer and probably more acceptable, in case the top of Chron C5Cn.1n is selected.

The primary calcareous plankton biohorizons which, according to our data, appoximate the top of Chron C5Cn.1n, are the Last Common Occurrence (LCO) of the calcareous nannofossil *Helicosphaera ampliaperta* and the LCO of the planktonic foraminifer *Paragloborotalia bella.* Other calcareous plankton events have been recorded close to the same magnetic reversal, such as a short influx of *H. ampliaperta* (Ia_1) and the *Paragloborotalia siakensis* $Acme_0$. The *P. siakensis* $Acme_a$ End (A_aE) and the *Sphenolithus heteromorphus* Paracme End (PE) represent the primary plankton biohorizons associated with the *P. glomerosa curva* FO.

Two of the three studied Mediterranean sections (La Vedova and St. Peter's Pool), each from different point of view, are potentially suitable to be proposed as candidates for the definition of the Langhian GSSP. Yet, further studies on stable isotope stratigraphy and cyclostratigraphy, including astronomical tuning are necessary before the most suitable section and guiding criterion can be selected.

Key words: calcareus plankton stratigraphy, magnetostratigraphy, Langhian GSSP, Mediterranean, mid-latitude North Atlantic Ocean.

INTRODUCTION

The Langhian Stage, introduced by Pareto in 1865, 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). The original concept was modified by Mayer-Eymar in 1868, who limited the term to the upper part of the succession, the so-called "Pteropod Marls". Vervloet (1966) defined the type Langhian to correspond to the Cessole Formation or Cessole Marls (Boni 1967; Gelati 1968), which thus became synonymous with the Langhian. The stratotype section of the Langhian, located in the Langhe region (Piedmont, northern Italy) close to the Cessole Village, was designated by Cita and Premoli Silva (1960). The lower part of the stratotype is exposed in the Bricco del Moro section located on a hill south of the Bormida River and 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, which is 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 original study, recognized the various stages in the evolutionary *Globigerinoides-Orbulina* lineage (*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.).

New data on planktonic foraminifera from the type Langhian were provided by Miculan (1994) and, more recently, by Fornaciari et al. (1997), who combined planktonic foraminifera and calcareous nannofossils and detected the *Praeorbulina* datum, i.e. First Occurrence (FO) of *P. sicana*, about 100m in the Cortemilia Formation 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* (see Turco, Iaccarino et al. 2011). However, the entire section is badly exposed and shows sedimentary facies unsuitable for establishing a detailed chronology. Hence, it does not represent the ideal section and succession for defining a Global Stratotype Section and Point (GSSP), which must guarantee the recognition of chronostratigraphic boundaries and, hence, units on a global scale (Rio et al. 1997).

Within the Subcommission on Neogene Stratigraphy (SNS), a working group has been designated with the aim to identify suitable sections both in Mediterranean and in extra-Mediterranean regions for defining the GSSP of the Langhian stage, and pointing out the best guiding criteria for recognizing its base. According to Rio et al. (1997) and Lourens et al. (2004), the Burdigalian/Langhian boundary should be located in a lithological position close to Chron C5Cn and the *Praeorbulina* datum. Moreover, Lourens et al. (2004), in the absence of a formally defined GSSP, provisionally placed the base of the Langhian at the top of Chron C5Cn.1n, astronomically dated at 15.974 Ma, in the Astronomically Tuned Neogene Time Scale (ATNTS2004).

In a previous study of the Mediterranean area, several sections considered potentially suitable for defining the Langhian GSSP were investigated (Di Stefano et al. 2008). The Moria section (central Italy), which encompasses the Burdigalian/Langhian boundary, proved to be unsuitable for high-resolution biostratigraphy, due to poor preservation of the calcareous plankton, while the Cretaccio section (Tremiti Islands, southern Italy) contains *P. glomerosa sicana* at its very base and has no magnetostratigraphy. The Miocene succession in the Balearic Basin (DSDP Leg 42 Site 372) provides a reliable magnetostratigraphy which does not reach the C5Br/C5Cn boundary and yields *P. glomerosa sicana* from its base upwards (Abdul Aziz et al. 2008). Moreover, comparing the biostratigraphic revision of the Langhian stratotype by Fornaciari et al. (1997) with the results of Di Stefano et al. (2008), some discrepancies and uncertainties as to the correlation and stratigraphic position of bioevents were noticed, in particular concerning the evolutionary stages in the *Praeorbulina-Orbulina* lineage.

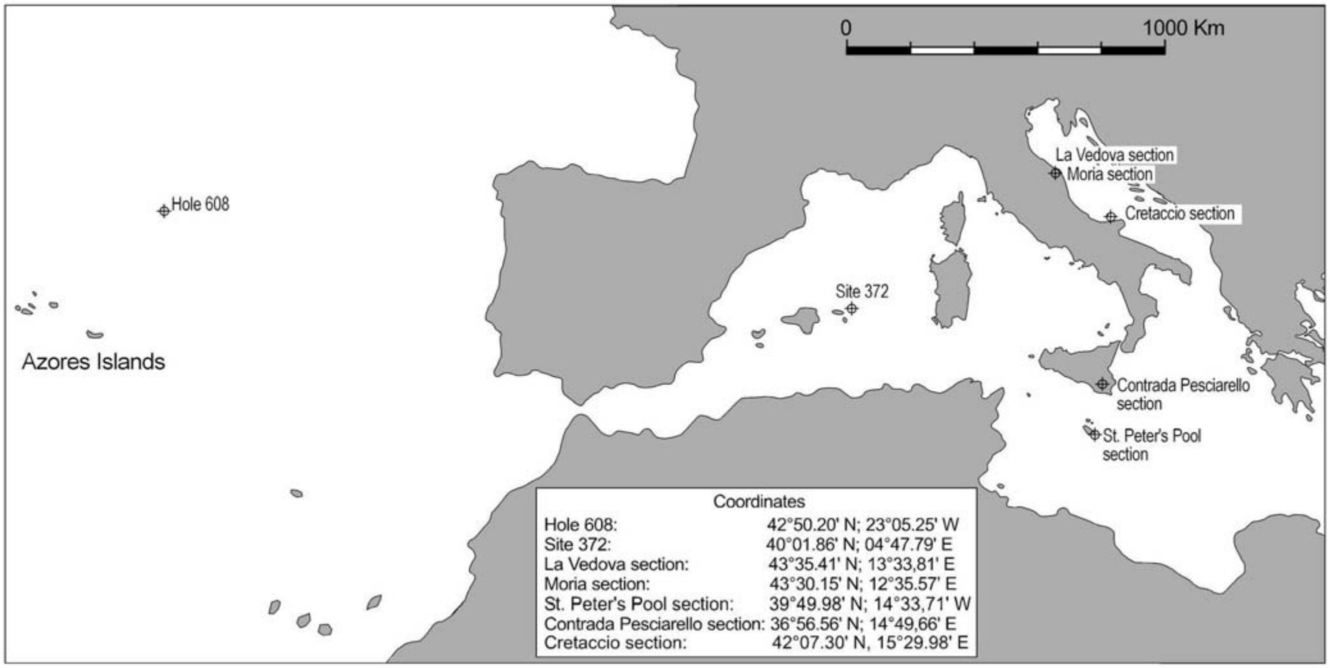
Meanwhile, the standard geological time scale for the Neogene has remarkably improved in accuracy, precision and resolution over the last decades. This is mainly due to an integrated (cyclostratigraphy, magnetostratigraphy, calcareous plankton biostratigraphy, stable isotope stratigraphy and radiometric dating) high-resolution stratigraphic approach combined with astronomical tuning. The tuning of Mediterranean marine sections, which results, among others, in astronomical ages for chron boundaries, has now been extended back to 15.26 Ma (Mourik et al. 2010; Hüsing et al. 2010).

As a part of an Italian research project with the aim to identify other deep marine successions suitable for defining the Langhian GSSP, three Mediterranean sections, namely La Vedova in Central Italy, Contrada Pesciarello in Sicily and St. Peter's Pool in Malta (text-fig. 1), were studied with a high resolution integrated stratigraphic approach (Turco, Cascella et al. 2011; Di Stefano, Verducci et al. 2011; Foresi et al. 2011). In this paper we present a synthesis of these detailed magnetobiostratigraphic studies and provide an updated framework for the upper Burdigalian-lower Langhian interval in the Mediterranean. This framework is compared with the magnetobiostratigraphic record of the DSDP Leg 94 Hole 608 (North Atlantic Ocean, text-fig. 1) reinvestigated by Di Stefano, Verducci, Cascella and Iaccarino (2011). In addition, we present a new revision of the Langhian historical stratotype, based on up-to-date biostratigraphic results, which revealed sampling gaps and errors in the construction of the composite stratigraphic log by Fornaciari et al. (1997).

STUDIED SECTIONS AND TAXONOMIC CONCEPT

The magnetostratigraphic records and the quantitative distribution patterns of the most significant planktonic foraminifer and calcareous nannofossil taxa of the investigated deep-marine successions (La Vedova, Contrada Pesciarello, St Peter's Pool, and Hole 608) are presented in text-figure 2. The calcareous plankton assemblages were studied applying quantitative analysis except for the planktonic foraminifera of the La Vedova section, which were analysed with a semiquantitive approach not only because of the moderate preservation but also to obtain a distribution pattern of very rare taxa.

One of the main goals of this multidisciplinary study was the re-examination of the first stages of the evolution of the *Globigerinoides-Praeorbulina* lineage, with a special attention to the *Praeorbulina* datum, i.e. the biohorizon historically used (and/or suggested) to approximate the base of the Langhian (Cita and Premoli Silva 1960; 1968; Cita and Blow 1969; Rio et al. 1997; Lourens et al. 2004). Based on the re-examination of the lineage, Turco, Iaccarino et al. (2011) evaluated the different taxonomic concepts of *Auctorum* (mainly Blow 1956; 1969; Jenkins et al. 1981) and concluded that the taxonomy of Jenkins et al. (1981) who considered *bisphericus* and *sicanus* two distinct species belonging to *Globigerinoides* and *Praeorbulina* genera, respectively, cannot be applied to the studied assemblages. In fact, the most representative individuals intergrading from *G. trilobus* to *Praeorbulina* are mainly characterized by three apertures at the base of the last chamber which are not referable either to *G. bisphericus* or to *P. sicana* sensu Jenkins et al. (1981) having two and four apertures respectively. On the contrary, they fall within the variability of *G. sicanus* sensu Blow (1969) and Kennett and Srinivasan (1983). Moreover, Turco, Iaccarino et al. (2011) proposed that only specimens with a spherical shape and at least 4 apertures in the final whorl



TEXT-FIGURE 1
Location map of the La Vedova, C.da Pesciarello and St. Peter's Pool sections and DSDP Leg 94 Hole 608.

belong to the genus *Praeorbulina*, i.e. in agreement with the concept adopted by Blow (1969). Consequently, the *Praeorbulina* datum coincides with the FO of *Praeorbulina glomerosa curva*.

MAGNETOBIOSTRATIGRAPHY OF THE STUDIED SECTIONS

La Vedova

The La Vedova section outcropping along the Conero Riviera, near Ancona in central Italy, is one of the most complete and continuous sections that covers the interval encompassing the Burdigalian/Langhian boundary (Turco, Cascella et al. 2011). The main calcareous plankton biohorizons recorded in the La Vedova section (text-fig. 2, Tab. 1) are from bottom to top: the occurrence of *G. sicanus* (3 apertures) at about 3m, the LCO (Last Common Occurrence) of *Helicosphaera ampliaperta*, the LCO of *Paragloborotalia bella,* the Paracme Beginning (PB) of *Sphenolithus heteromorphus*, the Acme$_a$ Beginning (A$_a$B) of *Paragloborotalia siakensis*, the Paracme End (PE) of *S. heteromorphus*, the Acme$_a$ End (A$_a$E) of *P. siakensis*, the FO of *P. glomerosa curva*, and the FO of *P. glomerosa glomerosa*. Additional events are two influxes of *H. ampliaperta* above its LCO (Ia$_1$ and Ia$_2$) and the Influx Beginning (IB) of *Globoquadrina dehiscens* of Hüsing et al. (2010). Paleomagnetic measurements revealed two reversals (text-fig. 2) that, compared with previous magnetobiostratigraphic studies of younger sediments in the La Vedova section (Hüsing et al. 2010) and Site 372 (Abdul Aziz et al. 2008), are correlated to the C5Cn.1n/C5Br and the C5Br/C5Bn.2n chron boundaries (Turco, Cascella et al. 2011). The correlation of these two reversals to the ATNTS2004 of Lourens et al. (2004) was used to calculate ages for the calcareous plankton biohorizons through linear interpolation of the sedimentation rate (tab. 2).

The first finding of *G. sicanus* (3 apertures) is recorded within C5Cn.1n, below the LCO of *H. ampliaperta*; the *P. glomerosa curva* FO, dated at 15.23 Ma, postdates the *P. siakensis* A$_a$E and *S. heteromorphus* PE and falls within Chron C5Br close to the Chron C5Br/C5Bn.2n boundary. The LCOs of *H. ampliaperta* and *P. bella* approximate the C5Cn.1n/C5Br boundary dated at 15.974 Ma (Lourens et al. 2004).

Contrada Pesciarello

The Contrada Pesciarello bore hole located in Sicily (Hyblean Plateau) spans an interval, the base of which is younger than the LCO of *H. ampliaperta* and the top older than the *P. siakensis* A$_a$E (Di Stefano, Verducci et al. 2011). The section ranges from 15.163 to 15.968 Ma according to the proposed cyclostratigraphic interpretation of the $CaCO_3$ record, thus remaining within the C5Br reversed interval (text-fig. 2, tab. 2). The biostratigraphic record is of a good quality and the following biohorizons are recorded: the *S. heteromorphus* PB, the *P. siakensis* A$_a$B, the *S. heteromorphus* PE, two influxes of *H. ampliaperta*, (Ia$_1$ and Ia$_2$) and the FO of *Helicosphaera waltrans* (tab. 1). The *P. siakensis* Acme$_0$ End is dubiously reported from the base of the section. The inferred ages for the recorded biohorizons are reported in Table 2 and are based on the integration of the available magnetostratigraphy and the proposed cyclostatigraphic interpretation.

St. Peter's Pool

The St. Peter's Pool section is located on Malta Island and is representative of the Upper Globigerina Limestone member (Foresi et al. 2011). The high resolution integrated stratigraphic

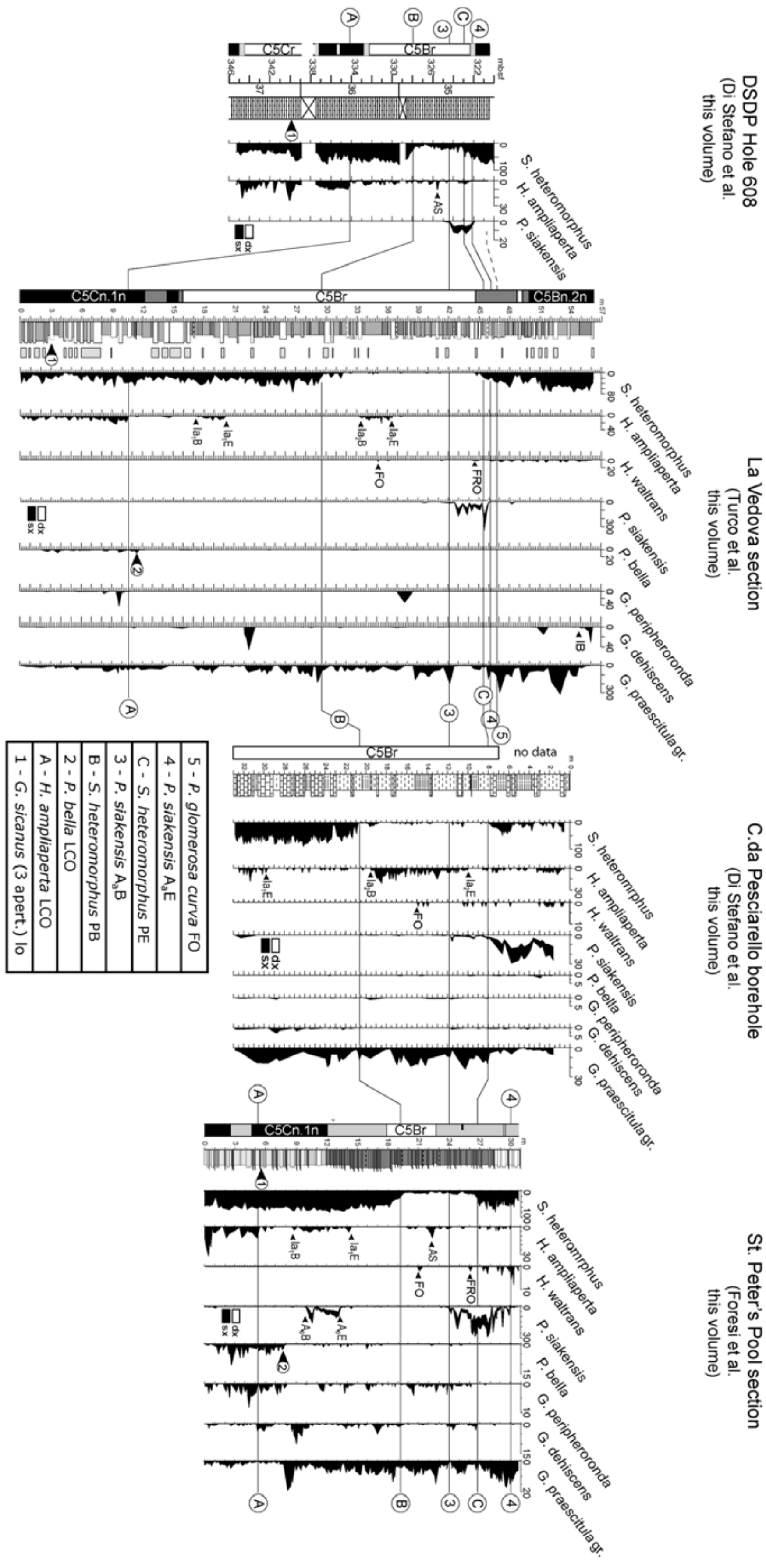

DSDP Hole 608
(Di Stefano et al.
this volume)
La Vedova section
(Turco et al.
this volume)
C.da Pesciarello borehole
(Di Stefano et al.
this volume)
St. Peter's Pool section
(Foresi et al.
this volume)
S. heteromorphus
H. ampliaperta
H. waltrans
P. siakensis
P. bella
G. peripheroronda
G. dehiscens
G. praescitula gr.
C5Cr
C5Br
C5Cn.1n
C5Bn.2n
no data
5 - P. glomerosa curva FO
4 - P. siakensis A$_a$E
C - S. heteromorphus PE
3 - P. siakensis A$_a$B
B - S. heteromorphus PB
2 - P. bella LCO
A - H. ampliaperta LCO
1 - G. sicanus (3 apert.) lo

TABLE 1
Stratigraphic depth and samples of the main calcareous plankton biohorizons recorded in the investigated sections.

Section	DSDP Hole 608			La Vedova			St. Peter's Pool			C.da Pesciarello		
Biohorizon	sample	depth mbsf	mean depth mbsf	samp.	depth m	mean depth m	samp.	depth m	mean depth m	samp.	depth m	mean depth m
6 - *P. glomerosa glomerosa* FO				16 15	52.84 53.01	52.925						
5 - *P. glomerosa curva* FO				44 43	46.55 46.82	46.685						
4 - *P. siakensis* AaE	35/2/95-97 35/2/75-77	322.15 321.05	322.50	46 45	45.96 46.17	46.065	256 257	29.88 29.95	29.91			
D - *S. heteromorphus* PE	35/3/35-37 35/3/25-27	323.50 322.95	323.00	49 48	45.32 45.54	45.430	225 226	26.72 26.83	26.77	59 90	7.88 7.93	7.90
C - *H. waltrans* FO/FRO				55 54	44.28 44.51	44.395	172 174	20.89 21.11	21.00	114 115	14.89 14.89	14.94
3 - *P. siakensis* AaB	35/3/145-147 35/3/125-127	324.15 323.95	324.05	71 70	41.16 41,35	41.255	199 201	23.89 24.19	24.04	93 95	11.56 11.75	11.66
B - *S. heteromorphus* PB	35/6/85-87 35/6/75-77	328.05 327.95	328.00	128 127	29.38 29.58	29.480	153 155	19.08 19.37	19.22	165 166	20.74 20.83	20.78
2 - *P. bella* LCO				224 223	12.11 12.30	12.205	59 61	7.82 8.17	7.99			
A - *H. ampliaperta* LCO	36/4/3-37 36/4/15-17	334.15 333.95	334.05	232 231	10.38 10.60	10.490	35 38	5,12 5.42	5.27			
1 - *G. sicanus* (3 apertures) lo	37/1/105-107 37/1/55-57	339.95 339.45	339.70	271 268	2.71 3.08	2.895	39 40	5.57 5.68	5.62			

study reveals the great potential of this section for establishing a detailed biostratigraphy of the upper Burdigalian - lower Langhian. The accurate biostratigraphic framework is linked to the magnetostratigraphic record which allows the recognition of the C5Cn/C5Br boundary, although with a large uncertainty interval (text-fig. 2). The bioevents characteristic of this stratigraphic interval are from bottom to top: the LCO of *H. ampliaperta*, the occurrence of *G. sicanus* (3 apertures) at 5.6 m, the LCO of *P. bella*, the Ia$_1$ influx of *H. ampliaperta*, the Acme$_0$ interval of *P. siakensis*, the Paracme interval of *S. heteromorphus*, the FO of *H. waltrans*, the Abundance Spike (AS) of *H. ampliaperta*, and the Acme$_a$ interval of *P. siakensis* (text-fig. 2, Tab. 1). Other biohorizons recorded only in this section are described by Foresi et al. (2011). Unfortunately, this section does not reach the *Praeorbulina* datum.

DSDP Leg 94 Hole 608

DSDP Hole 608, well known in the literature for its excellent magnetostratigraphic record, has been re-examined in detail to check the calcareous plankton distribution (Di Stefano, Verducci, Cascella and Iaccarino 2011) in the interval between 320 (Core 35) and 346 mbsf (Core 37). The magnetostratigraphic record (Miller et al. 1991; Krijgsman and Kent 2004) allowed the correlation of the Miocene magnetostratigraphy to the Geomagnetic Polarity Time Scale (GPTS). According to the available data two main reversal boundaries fall within this interval, namely the C5B/C5C boundary at an average depth of 323.23 mbsf and C5C/C5D at an average depth of 344.69 mbsf (text-fig. 2). The biostratigraphic record of the re-investigated interval includes, beside the LO (Last Occurrence) of *Catapsydrax dissimilis* (at 341.75 mbsf), the occurrence of *G. sicanus* (3 apertures) within Chron C5Cr, the LCO and AS of *H. ampliaperta*, the PB and PE of *S. heteromorphus* and the A$_a$B and A$_a$E of *P. siakensis* (text-fig. 2, Tab. 1), which up to now were thought to represent events restricted to the Mediterranean area. The presence of such biohorizons at Hole 608 in the mid-latitude North Atlantic Ocean is of great importance, as it provides the possibility to biostratigraphically correlate the Mediterranean and Atlantic Ocean with a higher resolution and apply the Mediterranean zonation (as emended by Di Stefano et al. 2008) to the mid-latitude Atlantic Ocean.

←TEXT-FIGURE 2
Magnetobiostratigraphic correlations between the investigated sections based on the distribution of selected taxa. Abundance pattern of the taxa is expressed in percentages except for the planktonic foraminifera of the La Vedova section expressed as number of specimens per field. Acronyms for the biohorizons: lo: lowest occurrence; FO: First Occurrence; FRO: First Regular Occurrence; LCO: Last Common Occurrence; A$_a$B: Acme$_a$ Beginning; A$_a$E: Acme$_a$ End; PB: Paracme Beginning; PE: Paracme End; IB and IE: Influx Beginning and Influx End; AS: Abundance Spike.

TABLE 2
Calibration of the main biohorizons recorded in the investigated sections.

Section	DSDP Hole 608		La Vedova		St.Peter's Pool	C.da Pesciarello		DSDP Site 372	
Biohorizon	(sub)chron	Age (Ma)	(sub)chron	Age (Ma)	(sub)chron	chron	Age (Ma)	chron	Age (Ma)
6 - *P. glomerosa glomerosa* FO			C5Bn.2n	15,106±0,001				C5Bn.2n	15,102
5 - *P. glomerosa curva* FO			C5Br	15,231±0,003				C5Br	
4 - *P. siakensis* A_aE	C5Bn.2n	15,138±11ky	C5Br	15,246±0,003	C5Br			C5Br	15,435
D - *S. heteromorphus* PE	C5Br	15,254±6ky	C5Br	15,261±0,003		C5Br	15,270±2ky	C5Br	15,527
C - *H. waltrans* FO/FRO			C5Br	15,286±0,003	C5Br	C5Br	15,471±2ky	C5Br	
3 - *P. siakensis* A_aB	C5Br	15,322±6ky	C5Br	15,361±0,002		C5Br	15,381±3ky	C5Br	
B - *S. heteromorphus* PB	C5Br	15,656±2,5ky	C5Br	15,644±0,002	C5Br	C5Br	15,657	C5Br	15,949
2 - *P. bella* LCO			C5Cn.1n	16,030±0,001	C5Cn.1n				
A - *H. ampliaperta* LCO	C5Cn1n	16,160±11ky	C5Cn.1n	16,057±0,002	C5Cn.1n				
1 - *G. sicanus* (3 apertures) lo	C5Cr	16,844±26ky	C5Cn.1n	16,177±0,003	C5Cn.1n				

REVISION OF THE LANGHIAN HISTORICAL STRATOTYPE

The location of the Bricco del Moro and Bricco della Croce sections, which together comprise the historical stratotype of the Langhian, is indicated on the geological map of the Langhian type area in text-figure 3. Di Stefano et al. (2008) highlighted discrepancies and uncertainties when they compared the biostratigraphic events recorded in the investigated sections (Moria, Cretaccio and DSDP Site 372) with those recorded in the Langhian historical stratotype re-studied by Fornaciari et al. (1997). Therefore, we checked again the planktonic foraminifera of the type section focussing our attention on a better definition of the position of the stages in the *Globigerinoides–Praeorbulina* evolutionary lineage, in particular the range of *G. sicanus* and the FO of *P. glomerosa curva*, as adopted in this study.

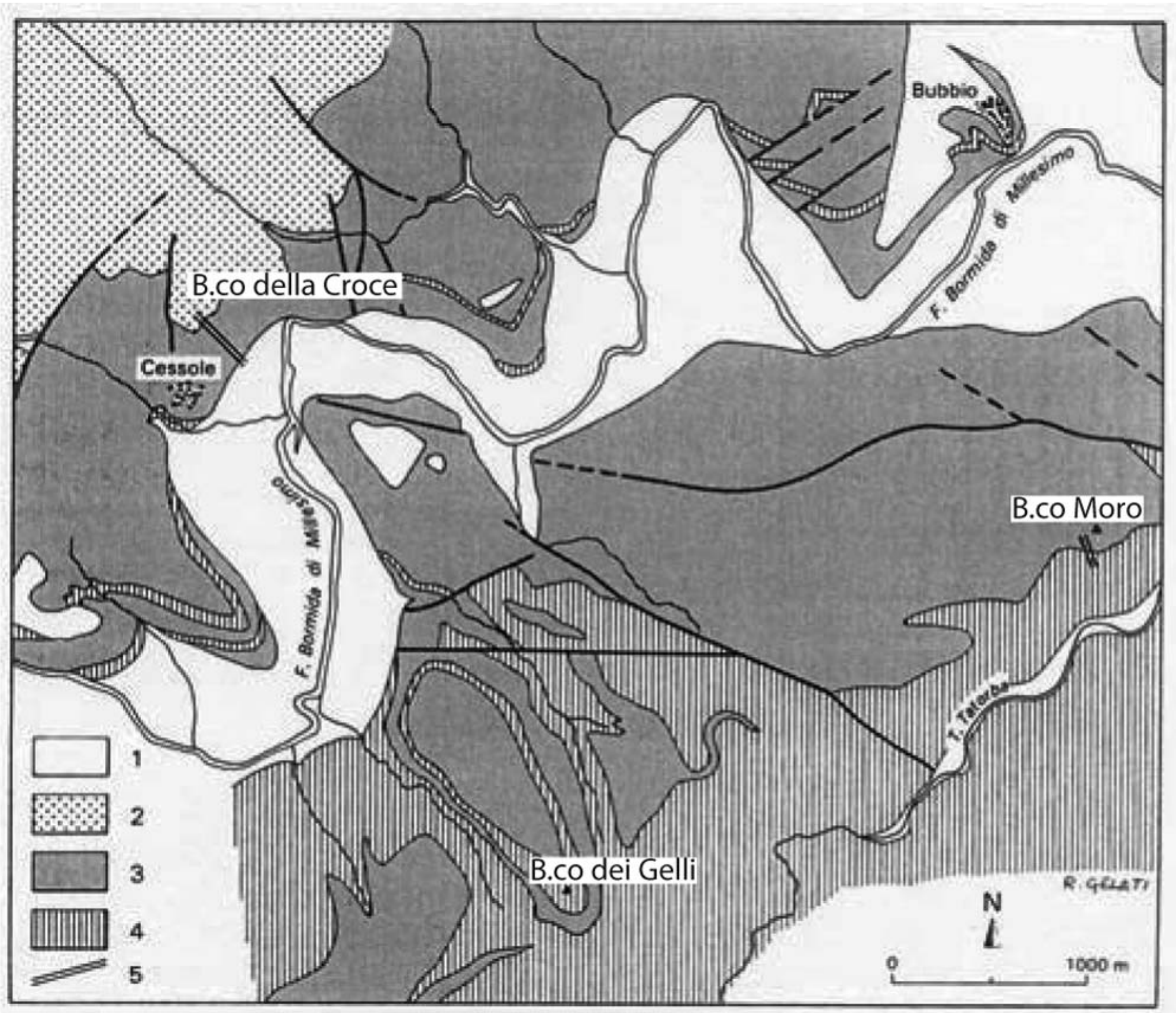
The composite section of Fornaciari et al. (1997) included three segments (A, B, C) which encompassed the uppermost part of the Cortemilia Formation, the Cessole Formation (Langhian stratotype of Vervloet, 1966) and the lowest part of the Cassinasco Formation. The new composite section is based on the original field descriptions of Fornaciari et al. (1997), which included subsection A (text-fig. 4), corresponding to the Bricco del Moro section, and subsections B, C and D corresponding to the Bricco della Croce section. Subsection D was sampled by the Authors, but was not included in their paper. The re-examination of the original samples allowed us to recognize a gap within subsection B, which is partially covered by subsection D.

G. sicanus (3 apertures), i.e. *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. *P. glomerosa curva* is recorded in subsection D and is characterized by evolved specimens (more than 4 apertures in the final whorl) suggesting that its FO should occur at a lower stratigraphic level. Also the *P. siakensis* A_aE, which usually occurs just below the *P. glomerosa curva* FO, is not clearly recorded. Both biohorizons could be located in the underlying gap (text-fig. 4).

The stratigraphic position of the biohorizons based on the present revision fits quite well with the results obtained from the high-resolution calcareous plankton biostratigraphic studies of Di Stefano et al. (2008), and those reported by Di Stefano, Verducci et al. (2011), Di Stefano, Verducci, Cascella and Iaccarino (2011), Foresi et al. (2011) and Turco, Cascella et al. (2011). Unfortunately, the relatively low resolution, the presence of gaps and the moderate preservation of the calcareous plankton prevented us from detecting some biohorizons that are useful for Mediterranean correlations. In particular, the *P. bella* LCO seems to occur below the LCO of *H. ampliaperta,* while the *S. heteromorphus* PB, *P. siakensis* A_aB, *S. heteromorphus* PE, *P. siakensis* A_bB and *P. glomerosa circularis* FO all fall within gaps between subsections (text-fig. 4).

AN INTEGRATED MAGNETOBIOSTRATIGRAPHIC FRAMEWORK FOR THE MEDITERRANEAN UPPER BURDIGALIAN-LOWER LANGHIAN

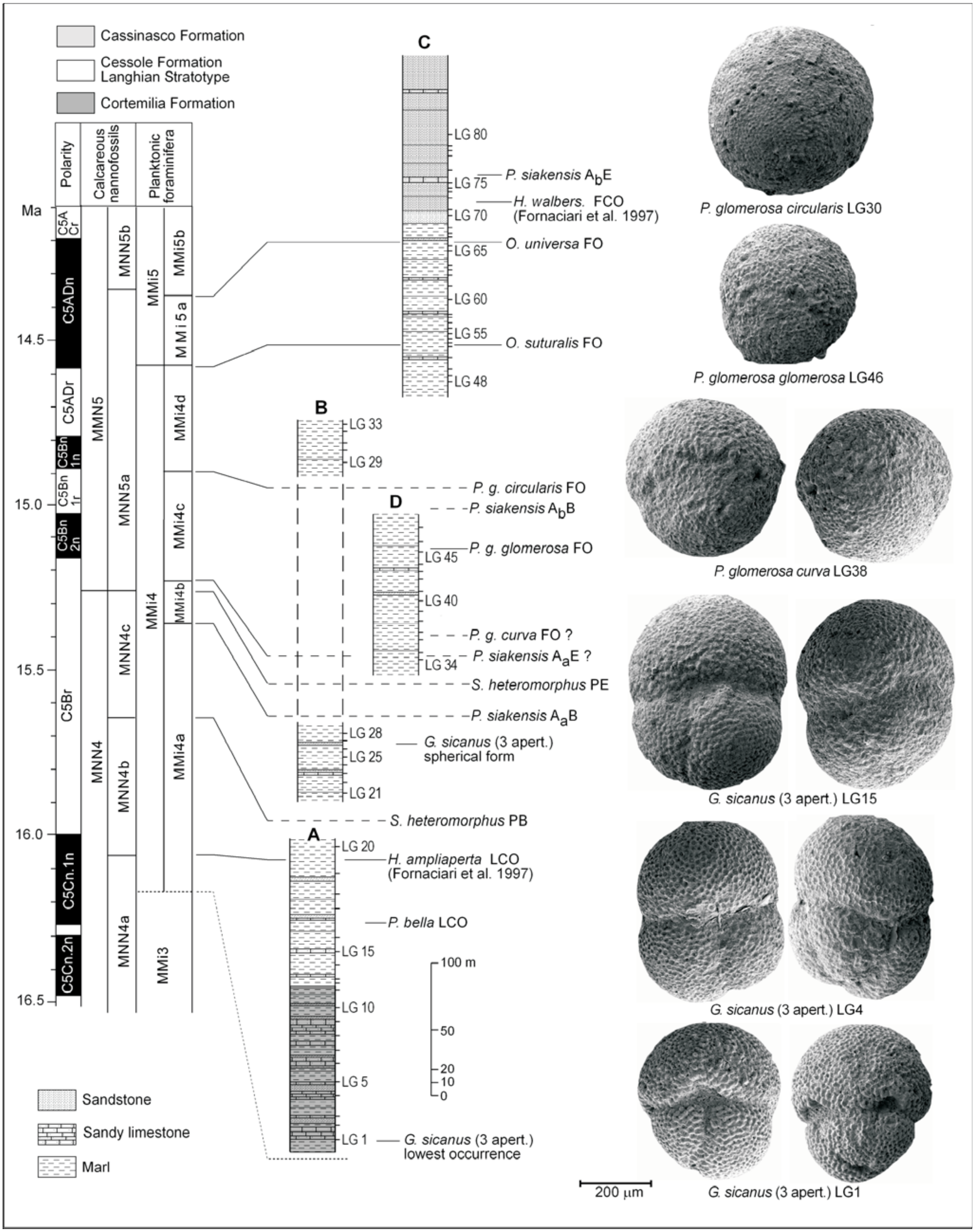
High-resolution magnetobiostratigraphic studies carried out on the Mediterranean sections of Moria and Cretaccio and DSDP Site 372 (Di Stefano et al. 2008), St. Peter's Pool (Foresi et al. 2011), Contrada Pesciarello bore hole (Di Stefano, Verducci, et al. 2011) and La Vedova (Turco, Cascella et al. 2011) allowed us to identify a succession of primary and auxiliary calcareous plankton biohorizons (text-fig. 5). Some of these events, were also recognized at DSDP Hole 608 (Di Stefano, Verducci, Cascella and Iaccarino 2011) allowing the correlation with the extra-Mediterranean area; moreover, the available magnetostratigraphic record, provide an up-to-date magnetobiochronologic framework for the Mediterranean upper Burdigalian-lower Langhian (text-fig. 6). The primary calcareous plankton events recorded in most of the sections and of greater stratigraphic value are from bottom to top (text-fig. 5, Tabs. 1, 2, 3):



TEXT-FIGURE 3
Geological map of the type area of the Langhian Stage. 1: alluvial deposits; 2: Cassinasco Formation; 3: Cessole Formation; 4: Cortemilia Formation; 5: location of the composite stratotype section of Bricco del Moro and Bricco della Croce (after Rio et al. 1997).

***Globigerinoides sicanus* (3 apertures) FO**. According to the revision of Turco, Iaccarino et al. (2011), *G. sicanus* can have 2 to 3 apertures in the final whorl following the concept of Blow (1956, 1969) and Kennett and Srinivasan (1983). The occurrence of specimens with 3 apertures is recorded in all the sections and represents the oldest biohorizon in the La Vedova section and at Hole 608 (mid-latitude Atlantic Ocean) (text-fig. 5). In the Mediterranean, the lowest occurrence is recorded in Subchron C5Cn.1n but at different stratigraphic levels with respect to the LCO of *H. ampliaperta*: it occurs below this biohorizon at La Vedova (FO ?), while it is found slightly above it at the St. Peter's Pool and Moria sections (text-fig. 5). This discrepancy can be explained by the rarity and scattered distribution of *G. sicanus* (3 apertures) within the planktonic foraminiferal assemblages.

At Hole 608, the lowest occurrence of *G. sicanus* (3 apertures) is recorded in the middle part of Chron C5Cr probably representing its FO in open ocean (text-fig. 5). Therefore, this biohorizon seems to be diachronous with respect to the Mediterranean area, but it can not be excluded that this taxon is also present in older sediments in the Mediterranean. To unravel whether this event is diachronous or not, it is necessary to extend high resolution biostratigraphic studies to older levels. Following the taxonomic revision of the first stages of the *Globigerinoides-Praeorbulina* lineage (Turco, Iaccarino et al. 2011), the Mediterranean FO (?) of *G. sicanus* (3 apertures) corresponds to the FO of *P. glomerosa sicana* (base of Zone MMi4) documented by Di Stefano et al. (2008) in the Moria section and by Fornaciari et al. (1997) in the historical stratotype.



TEXT-FIGURE 4

Revised stratigraphic log of the Langhian stratotype with the main calcareous plankton biohorizons correlated to the ATNTS2004 (Lourens et al. 2004) and the zonal schemes of Fornaciari et al. 1996 emended by Di Stefano et al. (2008) for calcareous nannofossils and Iaccarino and Salvatorini (1982) emended (Di Stefano et al. 2008; this paper) for planktonic foraminifera. A: Bricco del Moro section; B, C, D: Bricco della Croce section.

TABLE 3
Stratigraphic depth and samples of *G. sicanus* (3 apertures) lowest occurrence, *P. glomerosa curva* FO, *P. glomerosa glomerosa* FO in the previously investigated Cretaccio and Moria sections and DSDP Site 372 (Di Stefano et al. 2008).

Section	Cretaccio			Moria			DSDP Site 372		
Biohorizon	samp.	depth m	mean depth m	samp.	depth m	mean depth m	sample	depth mbsf	mean depth mbsf
6 - *P. glomerosa glomerosa* FO	212 210	19.40 19.15	19.28	266 260	43.49 42.51	43.00	29/1/130-132 28/6/148-150	388.80 386.98	387.89
5 - *P. glomerosa curva* FO	134 131	13.74 13.59	13.66	233 234	39.09 39.20	39.14	30/2/0-2 30/2/35-37	398.50 398.85	398.67
1 - *G. sicanus* (3 apertures) lo	104 101	10.52 10.24	10.38	120 114	19.26 19.12	18.69	31/6/108-110 31/6/145-147	424.58 424.15	424.36

The adopted taxonomic concept implies a nomenclatural emendation of the definition of the lower MMi4 boundary of Iaccarino and Salvatorini (1982) emended by Di Stefano et al. (2008) (see Appendix).

***Helicosphaera ampliaperta* LCO**. This well known Mediterranean biohorizon, which defines the base of Zone MNN4b, as emended by Di Stefano et al. (2008), is recorded in most of the sections. It occurs within Subchron C5Cn.1n, both at La Vedova with an age of 16.06 Ma and at Hole 608 with an age of 16.16 Ma (Tab. 2). The difference in age suggests a slight diachroneity between the Mediterranean and Atlantic Ocean, but can also be explained by the uncertainty in placing the C5Cn.1n/CBr reversal boundary in the La Vedova section and/or by a difference in the resolution of the two magnetostratigraphic records of these successions.

***Sphenolithus heteromorphus* Paracme Interval**. The interval of virtual absence or strongly reduced abundance of this taxon is an event well documented in Langhian successions of the Mediterranean (Di Stefano 1995; Fornaciari et al. 1996; Maiorano 1998, Di Stefano et al. 2008) and represents a very useful correlation tool defining the Subzone MNN4c. It has also been easily recognized in the studied sections. It occurs entirely within Chron C5Br and lasts about 400 kyr in all the sections (Tab. 2). The age of the base and top of the paracme is comparable between La Vedova, C.da Pesciarello and Hole 608 (Tab. 2), but is younger than the age estimated for Site 372 (at 15.94 and 15.52 Ma, respectively) (Tab. 2), thus indicating that the inferred age of the two events in the lowermost part of Site 372 (Abdul Aziz et al. 2008; Di Stefano et al. 2008) is affected by mistakes possibly due to the no-recovery interval. The paracme interval is not recorded in tropical areas (i.e., Site 925, Backman and Raffi, 1997), suggesting a paleoceanographic control.

***Paragloborotalia siakensis* Acme$_a$ Interval.** This acme interval, highlighted by Di Stefano et al. (2008) in the lower part of the Langhian, is characterized by the random occurrence of sinistral and dextral coiled specimens of *P. siakensis.* This interval, which defines the Subzone MMi4b (Di Stefano et al. 2008), is recorded in all the Mediterranean sections and also at Hole 608. Its base falls within Chron C5Br with ages of 15.32 Ma at Hole 608, 15.36 Ma at La Vedova and 15.38 Ma at C.da Pesciarello (Tab. 2). At La Vedova and C.da Pesciarello the beginning of the acme is placed where the species starts to be continuously present (Turco, Cascella et al. 2011; Di Stefano, Verducci et al. 2011). If we consider the abundance increase of the taxon at 42.79m at La Vedova and at 8.55m at C.da Pesciarello as the beginning of the Acme, the age of this event is more similar (15.325 Ma and 15.290 Ma respectively) to that of Hole 608 (Tab. 2). At Site 372, the base probably falls within the uncored interval between 415 and 405 mbsf (Di Stefano et al. 2008). The top of the acme, has an age varying between 15.138 Ma at Hole 608, 15.246 Ma at La Vedova and 15.435 Ma at Site 372 (Tab. 2), being diachronous between the different areas. At C.da Pesciarello the expression of the acme is more extended as compared to the other sections and its top is not reached. Compared with the magnetostratigraphy, the A$_a$E falls within the reversed interval of Chron C5Br at Site 372 and La Vedova, and at the transition of Subchron C5Br/C5Bn2n at Hole 608 (Tab. 2).

***Helicosphaera waltrans* FO, FRO and FCO**. These events were widely discussed by Fornaciari et al. (1996), who pointed out that the FCO of the species appeared as a more useful biohorizon than the FO. However, the percentage of this taxon rarely exceeds 10%. The FCO is recognizable in the three sections studied by Di Stefano et al. (2008), whereas in the present study the same biohorizon is not evident. On the contrary we recognized the FO of the species within the lower part of the *S. heteromorphus* Paracme interval in all the sections studied with the exception of Hole 608 where *H. waltrans* is absent. It must be added that typical specimens are very rare in the initial distribution range, whereas forms transitional to *Helicosphaera mediterranea* are more frequent. At La Vedova and St. Peter's Pool, a more continuous distribution with low percentages (First Regular Occurrence = FRO) of *H. waltrans* is recorded close to the *S. heteromorphus* PE (text-fig. 2) upwards. Both events (FO and FRO) fall within C5Br (Tab. 2).

***Praeorbulina glomerosa curva* FO.** The FO of *P. glomerosa curva* occurring within the basal part of Zone MMi4c (text-fig. 6) postdates the *S. heteromorphus* PE and the *P. siakensis* A$_a$E in the La Vedova, Moria and Cretaccio sections and at Site 372 (Tabs. 1 and 3). This event is not reached at C.da Pesciarello and St. Peter's Pool (text-figs. 2 and 5, Tab.1). It falls in the upper part of C5Br at La Vedova with an estimated age of 15.23 Ma as at Site 372 (Tab. 2). The lowest occurrence of *P. glomerosa curva* at Hole 608, recorded in Subchron C5Bn.2n with an age of 15.033 Ma, does not represent its FO because the specimens are characterized by evoluted forms (more than 4-5 apertures in the final whorl) (Di Stefano, Verducci, Cascella and Iaccarino 2011).

***Praeorbulina glomerosa glomerosa* FO**. This bioevent occurs within Zone MMi4c (text-fig. 6) and has been recorded in the La Vedova, Cretaccio and Moria sections and at Site 372 (Di Stefano et al. 2008) (Tabs. 1 and 3). The numerous apertures in the last whorl allow an easy recognition of this taxon. According to Turco, Cascella et al. (2011), the biohorizon falls within C5Bn.2n with an age of 15.106 Ma in the La Vedova section. A similar age has been estimated at Site 372 (15.102 Ma, Abdul Aziz et al. 2008) (Tab. 2).

Additional events not yet sufficiently documented in the literature of the Mediterranean Middle Miocene, potentially useful to increase biostratigraphic resolution, are:

***Paragloborotalia bella* LCO.** This biohorizon, which has only been recorded in the La Vedova and St. Peter's Pool sections occurs within Zone MMi4b (text-fig. 6), postdates the LCO of *H. ampliaperta* and falls within Chron C5Cn.1n, close to the C5Cn/C5Br boundary. At C.da Pesciarello, the rare and sporadic occurrence of this taxon testifies that its LCO falls below the base of the bore hole in agreement with the magnetostratigraphic record. More documentation is needed to fully evaluate its potential and reliability as a marker event for the Mediterranean biozonation of the Langhian.

***Helicosphaera ampliaperta* Influxes/AS.** Some influxes of this taxon are recorded above its LCO: a lower influx (Ia_1), which is found above the *P. bella* LCO in the La Vedova and St. Peter's Pool sections, could be partly time equivalent to the lower influx recorded at C.da Pesciarello, and may correspond to a similar interval documented in the Moria section in the same stratigraphic position (Di Stefano et al. 2008); a higher influx (Ia_2), found within the *S. heteromorphus* Paracme Interval in the La Vedova and C.da Pesciarello sections, should include the Abundance Spike (AS) highlighted by Fornaciari et al. (1996) and Di Stefano et al. (2008) and recorded at St Peter's Pool and Hole 608. Both influxes fall within Chron C5Br (text-fig. 2).

***Paragloborotalia siakensis* Acme$_0$ Interval.** This acme has only been recorded in the St. Peter's Pool section where it ranges from 10.11 to 13.55m. At C.da Pesciarello the top of this acme seems to be present (text-fig. 2). This interval which falls within Zone MMi4a, could be of great importance because it encompasses the C5Cn.1n/C5Br reversal boundary. Unfortunately, the Acme$_0$ has not been observed in the other sections, suggesting an environmental control on its areal distribution supported by the fact that Malta and Sicily, where the event has been recognized, both belong to the same paleoceanographic realm.

***Globoquadrina dehiscens* Influx**. This influx which postdates the FO of *P. glomerosa glomerosa* has been recorded by Di Stefano et al. (2008) and Hüsing et al. (2010) within Zone MMi4c (text-figs. 2 and 6). It can be considered as an additional event in the biostratigraphic record of the Langhian when associated with an abrupt decrease of *Globorotalia praescitula* gr. and with the occurrence of *Globigerinoides subquadratus* and *Catapsydrax parvulus*.

TOWARDS THE DEFINITION OF THE LANGHIAN GSSP

Introduction

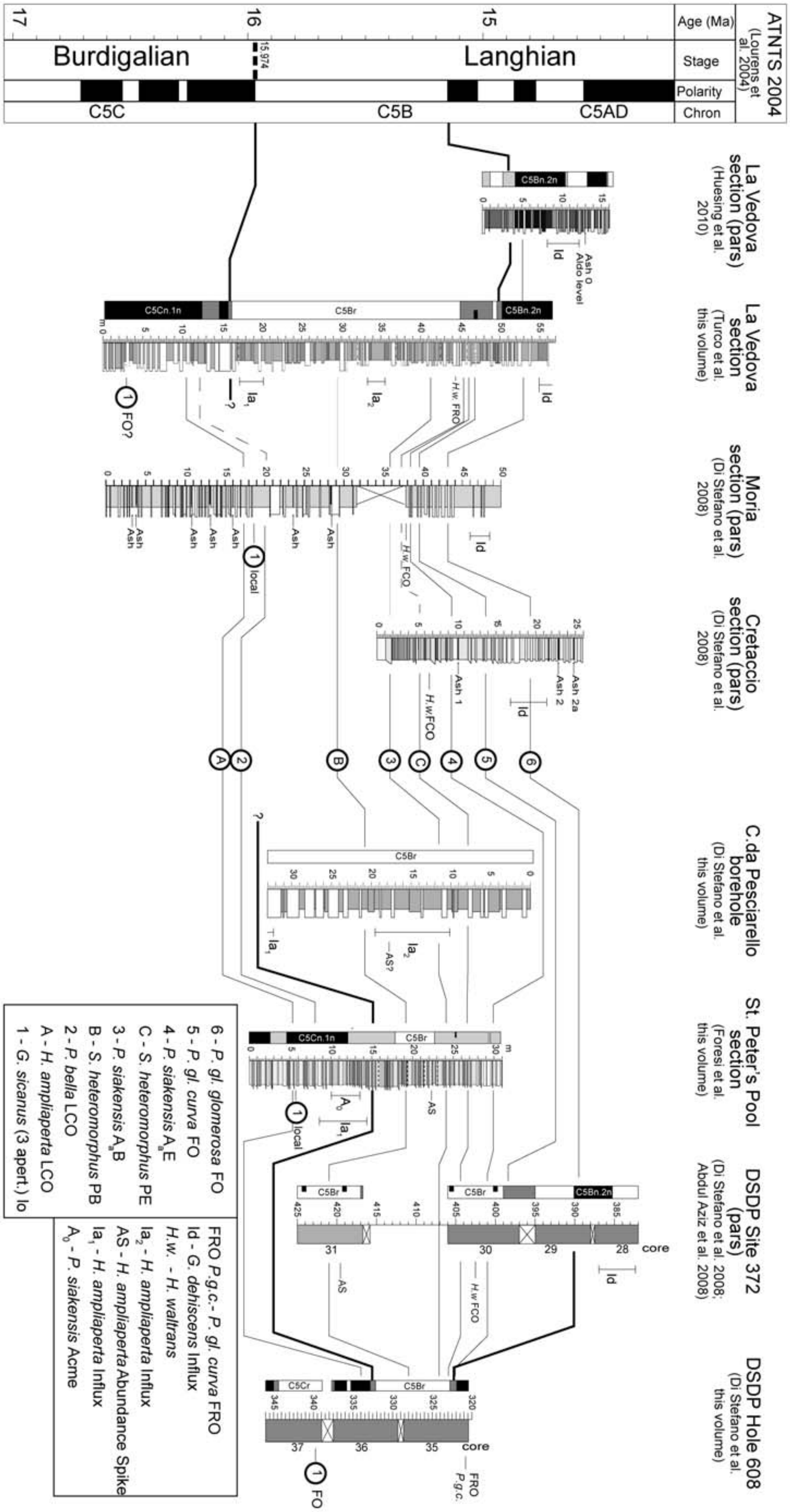
The combination of stratigraphic guidelines (Hedberg 1976; Salvador 1994) and new stratigraphic methodologies (magnetostratigraphy, high resolution integrated calcareous plankton biostratigraphy, astro-cyclostratigraphy, Ar/Ar dating) led to a new approach in global chronostratigraphy and resulted in the introduction of the GSSP concept for stage boundaries (Cowie 1986; Remane et al. 1996) for overcoming the problems associated with the definition of Chronostratigraphic Units in a single stratotype section.

These new stratigraphic methodologies and their application in constructing integrated stratigraphic frameworks also had consequences for the selection of guiding criteria to define the base of a stage. The GSSP concept has been formally expressed in the International Stratigraphic Guide of Salvador (1994). In particular, the definition of a stage is restricted to its lower boundary that is globally recognizable and defined in a deep marine section.

The basic requirements for the definition of a GSSP are a deep marine succession that is continuous across the boundary interval and suitable for integrated stratigraphic studies. Moreover, the guiding criteria for the definition of the boundary must guarantee the recognition of the boundary on a global scale. The formal definition of the base of a stage at a well recognizable/defined point facilitates communication among Earth Scientists as it permits to export the boundary as a timeline away from the GSSP, using multiple stratigraphic tools (biostratigraphy, magnetostratigraphy, stable isotope stratigraphy and cyclostratigraphy). In the Neogene, the GSSPs of the Zanclean (Van Couvering et al. 2000), Piacenzian (Castradori et al. 1998) and Gelasian (Rio et al. 1998) Stages of the Pliocene, and the Messinian and Tortonian Stages of the Upper Miocene (Hilgen et al. 2000; Hilgen et al. 2005) and the Serravallian Stage of the Middle Miocene (Hilgen et al. 2009) have been ratified and are without exception defined in astronomically tuned sections thereby facilitating incorporation in the standard GTS. The only stages in the Neogene which currently lack a formal definition via GSSPs are the Langhian and Burdigalian.

The recommended guiding criteria for defining the boundary: *Praeorbulina* datum and Chron C5Cn.1n

TEXT-FIGURE 5 →
Correlation panel between all the investigated sections encompassing the Burdigalian/Langhian (B/L) boundary.


ATNTS 2004
(Lourens et al. 2004)
Age (Ma)
Stage
Polarity
Chron
Burdigalian
Langhian
15.974
C5C
C5B
C5AD
La Vedova section (pars)
(Huesing et al. 2010)
La Vedova section
(Turco et al. this volume)
Moria section (pars)
(Di Stefano et al. 2008)
Cretaccio section (pars)
(Di Stefano et al. 2008)
C.da Pesciarello borehole
(Di Stefano et al. this volume)
St. Peter's Pool section
(Foresi et al. this volume)
DSDP Site 372 (pars)
(Di Stefano et al. 2008; Abdul Aziz et al. 2008)
DSDP Hole 608
(Di Stefano et al. this volume)
C5Bn.2n
C5Cn.1n
C5Br
C5Cr
Ash 0
Aldo level
Ash 1
Ash 2
Ash 2a
Ash
H.w. FRO
H.w. FCO
FO?
local
FO
FRO P.g.c.
core
6 - P. gl. glomerosa FO
5 - P. gl. curva FO
4 - P. siakensis AaE
C - S. heteromorphus PE
3 - P. siakensis AaB
B - S. heteromorphus PB
2 - P. bella LCO
A - H. ampliaperta LCO
1 - G. sicanus (3 apert.) lo
FRO P.g.c.- P. gl. curva FRO
Id - G. dehiscens Influx
H.w. - H. waltrans
Ia2 - H. ampliaperta Influx
AS - H. ampliaperta Abundance Spike
Ia1 - H. ampliaperta Influx
A0 - P. siakensis Acme

The *Praeorbulina* datum and the top of Chron C5Cn are the two events that, according to Rio et al. (1997) and Lourens et al. (2004), should preferably be selected for defining the base of the Langhian with respect to its historical definition. However, these two events are clearly located far apart in the investigated sections, if we start from the revised taxonomic concept for the evolutionary *Globigerinoides-Praeorbulina* lineage. In that case, the *Praeorbulina* datum which is defined by the FO of *P. glomerosa curva* (Turco, Iaccarino et al. 2011) approximates the base of Chron C5Bn.2n (La Vedova, DSDP Site 372 and DSDP Hole 608) and is ~740 kyr younger than the top of Chron C5Cn, dated at 15.974 Ma. Therefore, both events can not be used as guiding criterion to recognize the Burdigalian/ Langhian boundary at the same time.

The selection of either of these two events will imply a different duration for the Langhian, which is either very short (1.41 myr), in case the *Praeorbulina* datum is adopted, or much longer (2.154 myr), in case the top of C5Cn is adopted. For the "short" option of the Langhian, the *P. siakensis* Acme$_a$E and the *S. heteromorphus* PE represent the primary calcareous plankton events associated with the FO of *P. glomerosa curva*. For the "longer" option, the primary calcareous plankton biohorizons, which approximate the top of C5Cn, are the LCO of the nannofossil *H. ampliaperta* and the LCO of the planktonic foraminifer *P. bella*; secondary events include the *H. ampliaperta* Influx 1 (Ia$_1$) and the *P. siakensis* Acme$_0$E.

Globigerinoides sicanus (3 apertures), which corresponds to *P. sicana*/*P. glomerosa sicana* (*Auctorum*), shows a random and irregular distribution limiting its biostratigraphic value. Its lowest occurrence is recorded within C5Cn.1n in the Mediterranean (FO?) (Foresi et al. 2011; Turco, Cascella et al. 2011) and in the middle part of Chron C5Cr in the mid-latitude Atlantic Ocean (Di Stefano, Verducci, Cascella and Iaccarino 2011), where it likely represents its FO (text-fig. 5). It is therefore, either diachronous between the mid-latitude Atlantic and the Mediterranean or represents an older event (unfortunately, we have at present no reliable data from older sections in the Mediterranean). As a consequence, this event is not useful to approximate the base of the Langhian.

Other criteria for defining the boundary

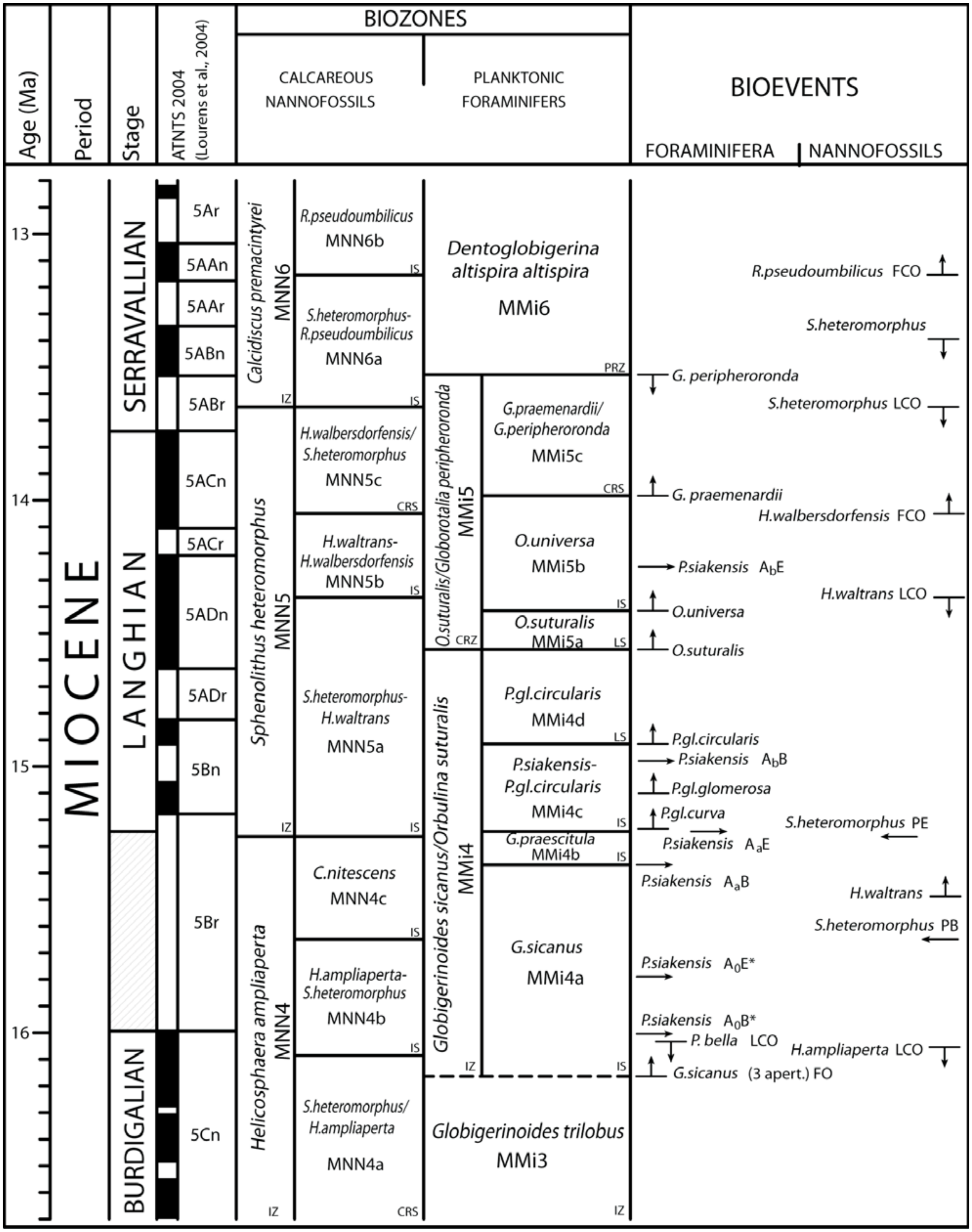
Other criteria, such as geochemical proxies and astronomical tuning, will also play an important role in selecting the most suitable section and guiding criterion to formally define the Burdigalian/Langhian boundary. Although not considered as (primary) criterion by Remane et al. (1996; added to the list of criteria in Gradstein et al. 2004), the section should preferably be suitable for astronomical tuning to provide optimal age constraints. In fact, orbitally tuned cyclostratigraphies played a decisive role in selecting the most suitable section and level for defining Neogene GSSPs, with the exception of the Paleogene/Neogene boundary and, hence, the Aquitanian GSSP (Steininger et al. 1997). Also the unit-stratotype concept of Hilgen et al. (2006) should be taken into account when the suitability of the La Vedova and St. Peter's Pool sections for defining the Langhian GSSP is discussed. This concept holds that GSSP sections may serve as unit stratotypes at the same time, covering the interval from the base of a stage up to the level that - time-stratigraphically - correlates with the base of the next younger stage in a continuous and well-tuned deep marine succession having an integrated stratigraphic framework. In this way, a stage is also defined by its content and not only by its boundaries. GSSP sections that can also serve as unit-stratotype for global stages form already the backbone of the new integrated late Neogene time scale and, as such, provide the basis for reconstructing Earth's history (Hilgen et al. 2006).

Other potential guiding criteria can be found hidden in geochemical proxy records, especially benthic stable isotope records. For the Langhian GSSP, especially the major global event in the oxygen isotopes (Mi2 event), associated with Langhian global cooling and preceding the onset of the Middle Miocene Climatic Optimum (MMCO event), is relevant. Data from open ocean marine records (i.e., Wright and Miller 1992) reveal that the Mi2 event falls close to the C5Cn/C5Br boundary, although its recognition in high-resolution isotope records is ambiguous (Holbourn et al. 2005; 2007). Note that a similar criterion, the Mi3b shift in the oxygen isotopes associated with the end of the Middle Miocene climate transition towards the present-day Icehouse World, was recently adopted for defining the Serravallian GSSP (Hilgen et al. 2009), as the preferred bio-event, the LO of *S. heteromorphus*, proved to be diachronous between the Mediterranean and low-latitude Atlantic. Finally, the base of the Langhian might correspond to the well-known Langhian transgression, associated with the glacio-eustatic sea-level change corresponding to sequence boundary Lan1 of Hardenbol et al. (1998) and supposedly to sequence boundary TB2.3 of Haq et al. (1987).

Comparing the candidate sections for defining the Langhian GSSP

Moria, La Vedova and St. Peter's Pool are continuous deep marine sections encompassing the Burdigalian/Langhian boundary in the Mediterranean. In the Moria section, the preservation of the calcareous plankton is poor and, hence, the succession of biostratigraphic events can not easily be recognized. *G. sicanus* (3 apertures) is present from 18.69m upwards, while the FO of *P. glomerosa curva* occurs at 39.2m. In addition, the magnetostratigraphy is of a poor quality (Deino et al. 1997). In the La Vedova section, the succession of calcareous plankton events can be easily recognized, despite the fact that the preservation is generally moderate. *G. sicanus* (3 apertures) is first observed at 2.89m, while the *Praeorbulina* datum (FO of *P. glomerosa curva*) is recorded at 46.68m. The magnetostratigraphic data are of an acceptable quality and allow the identification of the C5Cn/CBr reversal boundary. At St. Peter's Pool, the calcareous plankton is well preserved and allows the straightforward recognition of all primary biohorizons and associated secondary events, such as the *Paragloborotalia acrostoma* LO at 0.22m, the LCO of *Globigerinoides diminutus* at 7.78m, the Acme$_0$ of *P. siakensis* and the FCO of *Globorotalia praescitula*. The paleomagnetic signal is rather poor, but the C5Cn/C5Br boundary can be recognized, albeit with a large uncertainty. The *G. sicanus* (3 apertures) lowest occurrence is recorded at 5.62m in the basal part of the section, while the FO of *P. glomerosa curva* is not reached in the top part of the section.

As to astronomical tuning, Moria, La Vedova and St. Peter's Pool sections are cyclic and have a high potential for establishing a reliable astronomical tuning, which is the subject of ongoing studies. The La Vedova section reveals megabeds at its base and a distinct clustering of basic cycles, which, in view of the magnetobiostratigraphic age constraints presented in Turco, Cascella et al. (2011), should reflect the dominant expression of



TEXT-FIGURE 6
Up-to-date magnetostratigraphy and calcareous plankton biostratigraphy for the Langhian. Biozonations are from Fornaciari et al. 1996 emended by Di Stefano et al. (2008) for calcareous nannofossils and Iaccarino and Salvatorini (1982) emended (Di Stefano et al. 2008; this paper) for planktonic foraminifera. The lower boundary of MMi4a is indicated with a dashed line because it is based on the FO of *G. sicanus* (3 apertures) in the Mediterranean (see remarks the Appendix). The barred zone represents the stratigraphic range of the B/L boundary according to the two existing guiding criteria (top of C5Cn and FO of *P. glomerosa curva*). The asterisk in *P. siakensis* Acme$_0$ Beginning and End indicates the absence of a numerical age.

climatic precession (basic cycles) and the ~100-kyr eccentricity cycle (clusters). Also Moria is distinctly cyclic and reveals basic cycles in the interval corresponding to the megabeds at La Vedova. At St. Peter's Pool section, basic small-scale cycles characterized by a cyclic alternation of calcareous marl, marly limestone and jutting bioturbated hardened limestone can be distinguished and are organized in larger-scale cycle clusters. These clusters are separated by intervals characterized by homogeneous marly layers. We speculate that they are associated with short (100-kyr) eccentricity.

Regarding the unit-stratotype approach, the Moria section covers only part of the Langhian and, in addition, contains an unexposed interval in the middle upper part. The La Vedova section has the advantage that it covers the entire Langhian when it is combined with the La Vedova Beach section of Hüsing et al. (2010) and the La Vedova High Cliff (LVHC) section of Mourik et al. (2010). The integrated stratigraphy of these sections covering the younger part of the Langhian has already been published and both these sections have been reliably tuned (Hüsing et al. 2010; Mourik et al. 2010). A disadvantage is that the La Vedova High Cliff section, being located high in the cliffs, is very difficult to reach. This interval was not exposed along the beach as it was covered by a landslide. However, winterstorms have removed part of the landslide and the upper part of the LVHC section is now also exposed along the beach, including the connection to the Monte dei Corvi beach section. The unit-stratotype concept (Hilgen et al. 2006) may also be a valid criterion for St. Peter's Pool as it can be correlated to the Ras il Pellegrin section located on the opposite side of Malta where the GSSP of the Serravallian is defined (Abels et al. 2005; Hilgen et al. 2009; Mourik et al. 2011). In addition the section is very easy to reach and can be extended below its present base for another 100m of deep-marine sediments (actually subject of current high resolution stratigraphic study).

Climate proxy records, such as stable isotopes and geochemical elements, have yet not been established, but are the subject of ongoing studies directed at the two main candidate sections, La Vedova and St. Peter's Pool, to define the Langhian GSSP. The moderate to sometime poor preservation of the foraminiferal carbonate hampers the construction of a reliable high-resolution isotope record for La Vedova, while such a record can be expected for St. Peter's Pool in view of the good foraminiferal preservation. However, despite the moderate preservation, the bulk carbonate isotope record of the La Vedova High Cliff section did reveal the Mi3b and CM6 isotope events (Mourik et al. 2010).

Clearly the most suitable section and criterion/criteria can only be selected after the completion of ongoing studies directed at the astronomical tuning of the sections and at establishing high-resolution climate proxy records.

CONCLUSIONS

The high-resolution calcareous plankton biostratigraphy and magnetostratigraphy of four deep marine sections, three of them located in the Mediterranean area (La Vedova in central Italy, C.da Pesciarello on Sicily, and St Peter's Pool on Malta) and one at mid-latitudes in the North Atlantic (DSDP Hole 608 of Leg 94) led to a considerable improvement of the integrated stratigraphic framework for the upper Burdigalian - lower Langhian interval.

Most of the biohorizons occur in the same order both in the Mediterranean sections and at Hole 608 and are magnetostratigraphically well constrained. In the Mediterranean, the main calcareous plankton biohorizons and their magnetostratigraphic position are the FO (?) of *G. sicanus* (3 apertures) (C5Cn.1n), the LCO of *H. ampliaperta* (C5Cn.1n), the PB of *S. heteromorphus* (C5Br), the A_aB of *P. siakensis* (C5Br), the PE of *S. heteromorphus* (C5Br), the A_aE of *P. siakensis* (C5Br and C5Br/C5Bn.2n transition), and the FO of *P. glomerosa curva* (top most part of C5Br). Additional biohorizons such as the LCO of *P. bella* (C5Br), the two influxes of *H. ampliaperta*, the $Acme_0$ of *P. siakensis* and the influx of *G. dehiscens* are restricted to a limited number of sections, but could potentially improve the resolution of the biostratigraphy of the Langhian.

The resulting magnetobiostratigraphic data suggest that a continuous succession is present in all sections (text-fig. 5), which together encompass the interval between the upper part of the Subzone MNN4a and the lower part of Subzone MNN5a, in terms of the calcareous nannofossil biozonation, and between the upper part of the Zone MMi3 to the lower part of Subzone MMi4c of the planktonic foraminifer biozonation. Furthermore, magnetobiostratigraphic correlations between all the Middle Miocene sections in the Mediterranean (Di Stefano et al. 2008; Di Stefano, Verducci et al. 2011; Di Stefano, Verducci, Cascella and Iaccarino 2011; Foresi et al. 2011; Turco, Cascella et al. 2011) in combination with the revision of the historical stratotype, allowed us to improve the integrated stratigraphic framework for the Langhian. This step is considered crucial for defining the Langhian GSSP.

The *Praeorbulina* datum (*P. glomerosa curva* FO in the present acceptation) and the C5Cn/C5Br reversal boundary, the two conventional criteria for the recognition of the Langhian base suggested by Rio et al. (1997) and Lourens et al. (2004), differ in age by ~740 kyr. This implies that they can not be used to define the boundary at the same time. The Langhian Stage would become rather short (1.41 myr ranging from 15.23 Ma to 13.82 Ma base of the Serravallian) if the *Praeorbulina* datum is selected as boundary criterion, while its duration becomes longer (2.15 myr, ranging from 15.974 Ma to 13.82 Ma) and probably more acceptable if the C5Cn/C5Br reversal is used. However, the age of the base of the Langhian will depend on the astronomical tuning of the chosen GSSP.

La Vedova and St. Peter's Pool are the two sections most suitable for defining the Langhian but they differ in quality for different criteria. The preservation of the calcareous plankton is better at St. Peter's Pool; this resulted in a higher quality and more detailed biostratigraphy, and will facilitate the construction of a reliable stable isotope record. On the other hand, the magnetostratigraphy of the La Vedova section is of a higher quality, which allows to (more) precisely pinpoint the C5Cn/C5Br reversal boundary, one of the two conventional criteria for recognizing the Burdigalian-Langhian boundary. The most suitable section and criterion can only be selected after ongoing studies directed at establishing an astronomical tuning and geochemical proxy records are completed. Nevertheless, we feel that both La Vedova and St. Peter's Pool are suitable sections for defining the Langhian GSSP. The fact that they are complementary to one another in many aspects opens the option of defining both a GSSP and auxiliary boundary section.

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APPENDIX

Emendation of the Mediterranan planktonic foraminifer zonal scheme reported in Di Stefano et al. (2008)

The re-examination of the *Globigerinoides–Praeorbulina* lineage by Turco, Iaccarino et al. (2011) led to the distinction of *G. sicanus* and *P. glomerosa curva.* Therefore, Zone MMi4 (*Praeorbulina glomerosa* s. l. Zone) of Di Stefano et al. (2008) is here emended in its nomenclatural and lower boundary definition.

***Globigerinoides sicanus/Orbulina suturalis* Zone (MMi4)**

(Interval Zone)

Authors: Iaccarino and Salvatorini (1982) emended (Di Stefano et al. 2008; this paper)

Definition: interval between the FO of *G. sicanus* (3 apertures) and the FAD of *Orbulina suturalis*

Magnetostratigraphy: from Subchron C5Cn.1n (?) to Chron C5CADn

***Globigerinoides sicanus* Subzone (MMi4a)**

(Interval zone)

Authors: Iaccarino and Salvatorini (1982) emended (Di Stefano et al. 2008; this paper)

Definition: interval between the FO of *G. sicanus* (3 apertures) and the *P. siakensis* Acme$_a$ Beginning.

Magnetostratigraphy: from Subchron C5Cn.1n (?) to Chron C5Br.

Remarks: In the present study we are unable to state whether the lowest occurrence of *G. sicanus* (3 apertures), detected in the Mediterranean area, represents its FO. In fact, the lowest occurrence of the taxon has been recorded at La Vedova within Chron C5Cn.1n at 16.17 Ma, while at the mid-latitude Atlantic Hole 608 the biohorizon is remarkably older falling within Chron C5Cr at 16.84 Ma and should represent its FO in the open ocean. Further studies are needed to unravel whether *G. sicanus* (3 apertures) is present in sediments older than C5Cn.1n also in the Mediterranean area. At present, the stratigraphic meaning of the zone remains unchanged with respect to the Di Stefano et al. (2008) zonation, because the lowest occurrence of *G. sicanus* (3 apertures) is considered as time equivalent to the FO of *P. glomerosa sicana* of Di Stefano et al. (2008). Within this interval the LCOs of *P. bella* and *H. ampliaperta* are recognizable.

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