by Claudia Agnini[1], Jan Backman[2], Flavia Boscolo-Galazzo[3], Daniel J. Condon[4], Eliana Fornaciari[1], Simone Galeotti[5,16], Luca Giusberti[1], Paolo Grandesso[1], Luca Lanci[5,16], Valeria Luciani[6], Simonetta Monechi[7], Giovanni Muttoni[8], Heiko Pälike[9], Maria Letizia Pampaloni[10], Cesare A. Papazzoni[11], Paul N. Pearson[3], Johannes Pignatti[12], Isabella Premoli Silva[8], Isabella Raffi[13], Domenico Rio[1], Lorenzo Rook[7], Diana Sahy[4], David J.A. Spofforth[14], Cristina Stefani[1], and Bridget S. Wade[15]

Proposal for the Global Boundary Stratotype Section and Point (GSSP) for the Priabonian Stage (Eocene) at the Alano section (Italy)

[1] Dipartimento di Geoscienze, Università di Padova, Padova, Italy; *Corresponding author, *E-mail: claudia.agnini@unipd.it*
[2] Department of Geological Sciences, Stockholm University, Stockholm, Sweden
[3] School of Earth and Ocean Sciences, Cardiff University, Cardiff, United Kingdom
[4] British Geological Survey, Keyworth, Nottingham, United Kingdom
[5] Dipartimento di Scienze Pure e Applicate, Università di Urbino Carlo Bo, Urbino, Italy
[6] Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, Italy
[7] Dipartimento di Scienze della Terra, Università di Firenze, Firenze, Italy
[8] Dipartimento di Scienze della Terra "Ardito Desio", Università di Milano, Milano, Italy
[9] Marum, University of Bremen, Bremen, Germany
[10] Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Roma, Italy
[11] Dipartimento di Scienze Chimiche e Geologiche, Università di Modena e Reggio Emilia, Modena, Italy
[12] Dipartimento di Scienze della Terra, Università La Sapienza, Roma, Italy
[13] Dipartimento di Ingegneria e Geologia, Università "G. d'Annunzio", Chieti-Pescara, Italy
[14] CGG MCNV (GeoSpec), Llandudno, United Kingdom
[15] Department of Earth Sciences, University College of London, London, United Kingdom
[16] Institute for Climate Change Solutions, Pesaro e Urbino, Italy

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The base of the Priabonian Stage is one of two stage boundaries in the Paleogene that remains to be formalized. The Alano section (NE Italy) was elected by consensus as a suitable candidate for the base of the Priabonian during the Priabonian Working Group meeting held in Alano di Piave in June 2012. Further detailed research on the section is now followed by a formal proposal, which identifies the base of a prominent crystal tuff layer, the Tiziano bed, at meter 63.57 of the Alano section, as a suitable candidate for the Priabonian Stage. The choice of the Tiziano bed is appropriate from the historical point of view and several bio-magnetostratigraphic events are available to approximate this chronostratigraphic boundary and guarantee a high degree of correlatability over wide geographic areas. Events which approximate the base of the Priabonian Stage in the Alano section are the successive extinction of large acarininids and Morozovelloides (planktonic foraminifera), the Base of common and continuous Cribrocentrum erbae and the Top of Chiasmolithus grandis (nannofossils), as well as the Base of Subchron C17n.2n and the Base of Chron C17n (magnetostratigraphy). Cyclostratigraphic analysis of the Bartonian-Priabonian transition of the Alano section as well as radioisotopic data of the Tiziano tuff layer provide an absolute age (37.710 – 37.762 Ma, respectively) of this bed and, consequently, of the base of the Priabonian Stage.

Introduction

According to the guidelines of the International Commission on Stratigraphy (ICS), stages should be defined by their lower boundary, which is identified in a specific stratigraphic layer in a reference section, the Global Stratotype Section and Point (GSSP). This implies that a GSSP has to be defined in a sedimentary succession where sedimentation is continuous and expanded across the boundary interval (Remane et al., 1996; Remane, 2003). The ICS revised guidelines (Remane et al., 1996) also recommend that a section proposed as a candidate for a GSSP has to comply with a series of requirements in order to be suitable to give the best documentation of marker events occurring across the boundary transition. The perfect section should thus meet a set of requirements regarding general geology (good exposure over an adequate thickness, continuous sedimentation, adequate sedimentation rate, absence of synsedimentary and tectonic disturbances, absence of metamorphism and strong diagenetic alteration), biostratigraphy (abundance and diversity of well-preserved fossils, absence of vertical facies changes, favorable facies for long-range biostratigraphic correlation) and other non-biostratigraphic characteristics (radioisotopic data, magnetostratigraphy, chemostratigraphy). A new GSSP should be identified, permanently, within the section (i.e., the golden spike) which should be freely accessible with long-lasting protection of the site.

Once a candidate section for a GSSP has been recognized, as is the case of the Priabonian, what still remains to be done is to define the GSSP level. The ICS guidelines recommend that "*The boundary definition will normally start from the identification of a level which can be characterised by a marker event of optimal correlation potential. This marker event may be a magnetic reversal, some kind of geochemical or isotopic signal, or the first appearance or last occurrence of a fossil species. However, only the boundary point in the section, the GSSP (Cowie et al., 1986) formally defines the boundary. This means that an occurrence of the primary marker does not automatically determine the boundary. Other markers should therefore be available near the critical level, in order to support chronostratigraphic correlation in sections other than the GSSP*" (p. 79 in Remane et al., 1996).

This clarifies that the boundary level and the primary stratigraphic marker are different concepts; once a boundary level in the stratotype has been formally defined and ratified it is generally identified by a physical marker ('golden spike') to which all other stratigraphic sections should be correlated with whatever means are available. Golden spikes are special locations in the global rock succession that define the base of chronostratigraphic units (within the rock sequence) for alignment with geochronologic units (time). Stratigraphers are mindful of the fact that even the best stratigraphic marker is neither omnipresent nor perfectly synchronous so the primary marker becomes just one of various tools that may support accurate correlation from the GSSP to any other section of interest. The recommendation that a GSSP should contain multiple events close to the boundary level has been a guiding principle in our search for the best boundary level along with other desirable characteristics, such as that the chosen level should try to respect historical usage as far as possible and the desirability of geological materials that can be directly dated (Remane et al., 1996).

The Priabonian Stage: historical background

The Priabonian Stage is named after the village of Priabona, which is located in the eastern Lessini Mountains of northeastern Italy. The stage was proposed by Munier-Chalmas and de Lapparent in deLapparent (1893, p. 1219) and later reiterated by Munier-Chalmasand de Lapparent (1894, p. 479), on the basis of documentation available from a number of sedimentary successions of the Lessini Shelf area. Subsequently, much effort has been made to overcome serious problems encountered in correlating middle-upper Eocene marine stratigraphic records across Europe and the Mediterranean. Among the different sections indicated by Munier-Chalmas and de Lapparent (1894), the Priabona section was formally proposed by Hardenbol (1968) as the stratotype section of the Priabonian. This proposal was accepted at the Eocene Colloquium held in Paris in 1968, at which time a suite of five parastratotype (= auxiliary stratotype; Cowie et al., 1986) sections was also proposed (Cita, 1969), namely the Granella and Ghenderle (or Val Bressana) sections in the Lessini Mountains, the Brendola and Mossano sections in the Berici Hills, and the Possagno section in the Venetian Prealps. The sections in the Lessini Mountains (Priabona, Granella and Ghenderle) are located close to the margin of a carbonate platform (the Lessini Shelf; Bosellini, 1989) connected to the north with emergent land. Their content in calcareous plankton is poor, which makes precise correlation difficult to establish (Verhallen and Romein, 1983). The sections in the Berici Hills (Brendola and Mossano sections) were deposited on the Lessini Shelf although in a more distal position compared to the Lessini Mountains sections. Despite that, calcareous plankton are also scarce in the section (Luciani et al., 2002). The last and most promising auxiliary stratotype section is at Possagno; this succession was deposited on the gentle ramp between the Lessini Shelf and the Belluno Trough. Because of its deeper depositional setting it is characterized by abundant calcareous plankton which has allowed the construction of a consistent biochronostratigraphic framework (Bolli, 1975; Agnini et al., 2006).

Traditional Paleontological Criteria for Recognizing the Base of the Priabonian Stage

In shallow-water sections, the Base (B) of *Nummulites fabianii,* which defines the Base of Shallow Benthic foraminiferal Zone SB19 (Serra-Kiel et al., 1998) has been the master paleontological criterion for recognizing the Priabonian Stage. The Base of *N. fabianii* has been recognized in the Priabona and Mossano sections (Hottinger, 1977; Parisi et al., 1988; Bassi and Loriga Broglio, 1999; Bassi et al., 2000) as well as in several other Tethyan shallow-water successions (e.g., Strougo, 1992; Serra-Kiel et al., 1998).

In deep-water sections, where calcareous plankton fauna and flora are usually more abundant, the base of the Priabonian Stage has been traditionally recognized either by the extinction of the muricate planktonic foraminifera *Morozovelloides* and large acarininids, which coincide with the Base of Zone E14 (Berggren and Pearson, 2005; Wade et al., 2011), or with the Base of the nannofossil *Chiasmolithus oamaruensis*, which defines the Base of Zone NP18 (Martini, 1971). A virtual correspondence between the Base of *N. fabianii* (Base of Zone SB 19) and the Base of *C. oamaruensis* (Base of Zone NP18) was for a long time generally accepted (Serra-Kiel et al., 1998). However, data from the northern Mediterranean area indicate that the Base of *N. fabianii* there lies at a higher correlative level, namely in the upper part of Zone NP18 or middle part of Zone E14 (Papazzoni and Sirotti, 1995). More recently, a number of new records have confirmed that the Base of Zone SB19 is much higher than the calcareous plankton biohorizons that have been used to approximate the base of the Priabonian (i.e., the Top of large acarininids and *Morozovelloides*, the Base of *C. oamaruensis*, the Bc (Base of continuous and common) of *C. erbae* and the Top of *C. grandis*; Papazzoni et al., 2014; Cotton et al., 2017; Rodelli et al., 2018; Luciani et al., 2020). Specifically, the Base of Zone SB19 is now thought to be close to the CNE18-19 zonal boundary and lies in the lowermost part of Zone E15 (Cotton et al., 2017). The corresponding difference in time between potential Priabonian marker horizons is significant, potentially over two million years.

Position of the Priabonian Stage in the Eocene Series

In their overview of the Paleogene System/Period Luterbacher et al. (2004) still used the lower/early, middle and upper/late subdivision for the Eocene Series/Epoch, but the most recent version of the Geological Time Scale (Vandenberghe et al., 2012) as well as the official International Chronostratigraphic Chart edited by ICS (http://www.stratigraphy.org/index.php/ics-chart-timescale) does not use sub-series/sub epoch (lower/early, middle and upper/late) as formal subdivisions for the Eocene (see Pearson et al., 2017 for a review). We thus refrain from using these terms in a formal sense. The history of the chronostratigraphic subdivision of the Eocene is complicated (e.g., Berggren et al., 1985, 1995; Luterbacher et al., 2004; Vandenberghe et al., 2012). As argued by Berggren et al. (1995), the problem with the placement of the base of the Priabonian has been intimately linked with the difficulties in correlating the classical NW Europe sections, located in the Paris and London basins, with those cropping out in the Veneto region of the Mediterranean area (Munier-Chalmas and de Lapparent, 1894).

Current Practice in Recognizing the base of the Priabonian

Over the past three decades, the compilations published by Berggren and co-workers (1985, 1995) have represented a fundamental reference for the entire community of marine and continental stratigraphers. Berggren et al. (1985) carefully reviewed the status of the Bartonian/Priabonian boundary, which they placed at the Base of *C. oamaruensis* (calcareous nannofossil Zone NP18) founded on the best correlation tools available at that time. According to this concept, the base of the Priabonian correlates with the younger part of Chron C17n (Fig. 4 in Berggren et al., 1985). Berggren et al. (1995) indicated that the Bartonian/Priabonian boundary is correlative with the Base of *C. oamaruensis*, that is the Base of Zone NP18, for which they provided a revised estimated age of 37.0 Ma (Fig. 2 in Berggren et al., 1995). Since 1995 a considerable amount of new research has been conducted on the calcareous plankton biostratigraphy and biochronology of the interval (Wade, 2004; Fornaciari et al., 2010; Wade et al., 2011; 2012; Agnini et al., 2011; 2014). Agnini et al. (2011) demonstrated that the Base of *C. oamaruensis* (Base of Zone NP18), although poorly reproducible (Fornaciari et al., 2010), is much closer to the successive extinctions of large muricate planktonic foraminifera than previously thought. Most importantly, the Top of large acarininids and *Morozovelloides* are consistently found to occur closely spaced (+ 85 kyr and 2 kyr, respectively) relative to the Top of *C. grandis* (Base of Subzone CP15a of Okada and Bukry, 1980) and the Base of common and continuous *C. erbae* (Base of Zone CNE17 of Agnini et al., 2014). All these new data are of considerable importance to constrain the critical interval in which the Priabonian GSSP should be defined.

Possible Markers for Identifying the Priabonian GSSP

According to the historical overview briefly discussed above, the base of the Priabonian in marine stratigraphic records has been identified using the following events:

1) the Base of *Nummulites fabianii*, by definition the Base of Zone SB19, applied in shallow water facies (e.g., Serra-Kiel, 1998);

2) the Top of large muricate planktonic foraminifera (large acarininids and *Morozovelloides*), coinciding with the Base of Zone E14 (Wade et al., 2011) which is defined by the Top of *Morozovelloides crassatus.*

3) the Base of *Chiasmolithus oamaruensis,* Base of Zone NP18, (e.g., Berggren et al., 1985, 1995), which is consistently found close to the Top of *C. grandis* and the Base of common and continuous *C. erbae.*

4) The Base of Subchron C17n.1n, as proposed by Berggren et al. (1985, 1995) and provisionally suggested for practical reasons by Vandenberghe et al. (2012; GTS2012).

All the aforementioned events, with the exception of the Base of *N. fabianii* which is now demonstrated to lie well above the current use of Priabonian, fall relatively close one to each other. It was thus concluded that the Priabonian GSSP should be defined across an interval in which these events occur, which extends from the Base of Subchron C17n.3n to the Base of Subchron C17n.1n.

Selecting the area of the Priabonian GSSP: the Alano section

The time frame of the Priabona section regarded as "stratotypic" by Hardenbol (1968) is controversial because of the shallow-water transgressive nature of the basal portion of the succession (Setiawan, 1983). The base of the section appears to be younger than the base of the Priabonian stage according to current practices of recognition (e.g., Setiawan, 1983; Brinkhuis, 1994). Specifically, the common and continuous occurrence of *Isthmolithus recurvus* is widely used as an intra-Priabonian biohorizon defining the Base of Zone NP19 and Subzone CP15b (Fornaciari et al., 2010; Agnini et al., 2011). This biohorizon is documented from the base of the Priabona section suggesting that, at least the lower part of the 'Priabonian', as currently understood (see discussion above), is missing in the Priabona section (Verhallen and Romein, 1983). Among the five parastratotypes proposed by Cita (1969) for the Priabonian, the Granella, Ghenderle, Brendola and Mossano sections are unsuitable for defining a chronostratigraphic unit because of the scarcity of calcareous plankton and/or major facies changes (e.g., Luciani et al., 2002). The deep-water Possagno section was potentially more suitable. Previous studies performed in the 1970s have provided a solid framework based on calcareous plankton biostratigraphy (Bolli, 1975) but unfortunately the critical transition from the Bartonian to the Priabonian is poorly exposed, and no compelling candidacy of the Priabonian GSSP could be thus advanced for this section (Agnini et al., 2011). More suitable to define the base of the Priabonian would be a section that is stratigraphically more continuous and well exposed with marker events that are well constrained in time and suitable for global correlation. The Alano section, located ~ 50 km to the NE of the historical Priabona section, meets all the requirements for serving as suitable Priabonian GSSP (Figs. 1-2).

This sedimentary succession, consisting of ~ 120 m of hemipelagic marls, is easy to access, crops out continuously, is unaffected by any invasive structural deformation, is rich in calcareous plankton, is provided with magnetic minerals that carry a primary magnetostratigraphic signal, and in general contains an expanded and complete record of the critical interval for defining the GSSP of the Priabonian (Agnini et al., 2011; Fig. 3). The integrated, highly-resolved bio-magnetostratigraphic framework provided for the Alano section (Agnini et al., 2011)

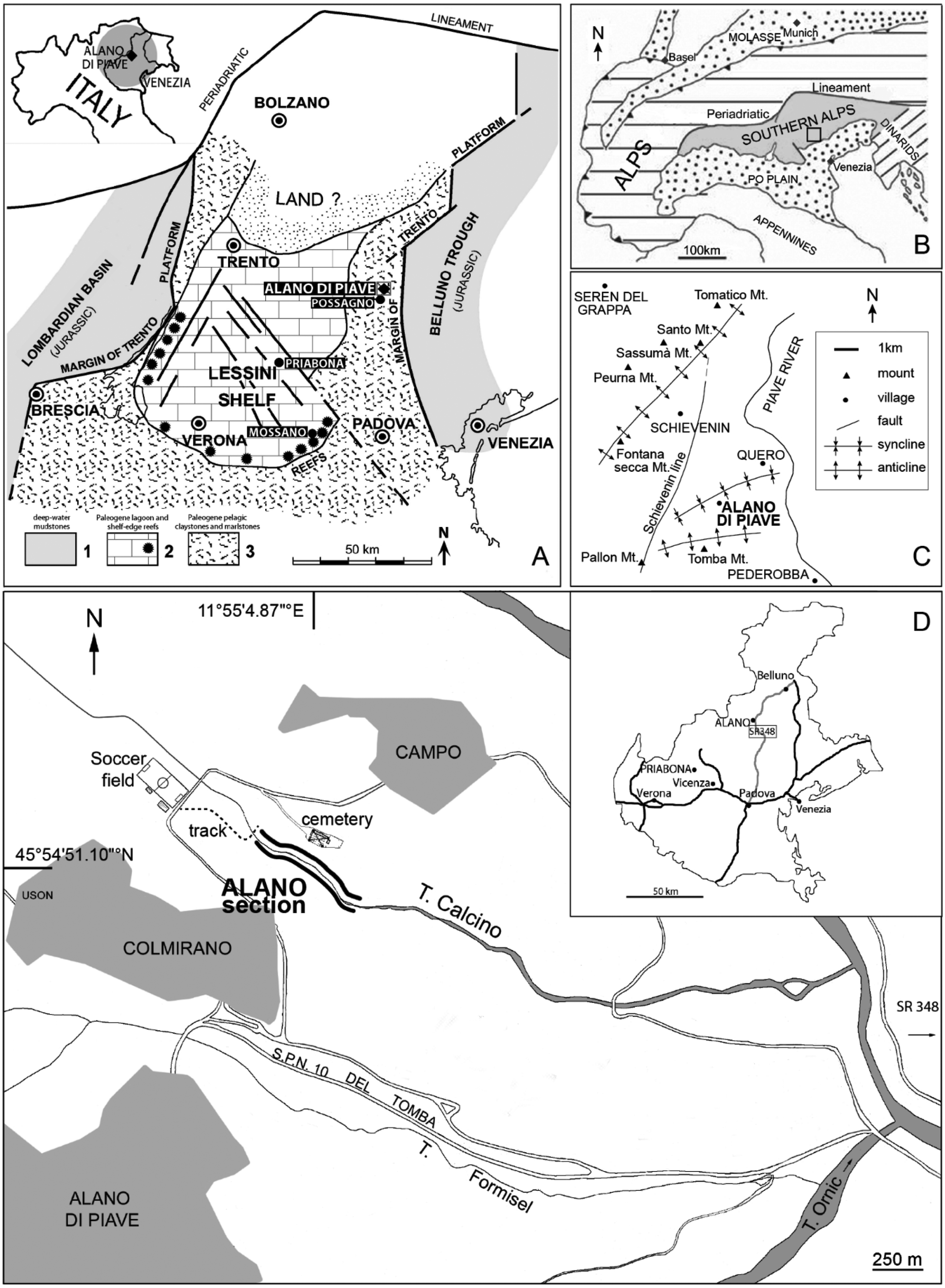

Figure 1. (modified after Agnini et al., 2011). Geographic and geological context of the Alano section. (A) Paleogeographic reconstruction of the main paleogeographic elements of the southern Alps during the Paleogene (adapted from Bosellini and Papazzoni, 2003). (B) the Southern Alps, a major structural subdivision of the Alpine chain, located to the south of the Periadriatic lineament; □ = Studied areas (adapted from Doglioni and Bosellini, 1987). (C) Simplified structural sketch of the study area; □ Grey square in (A) includes the structural map provided. (D) Location map of the study area with indication of the Alano section. The easiest access to the section (dashed line) is shown.

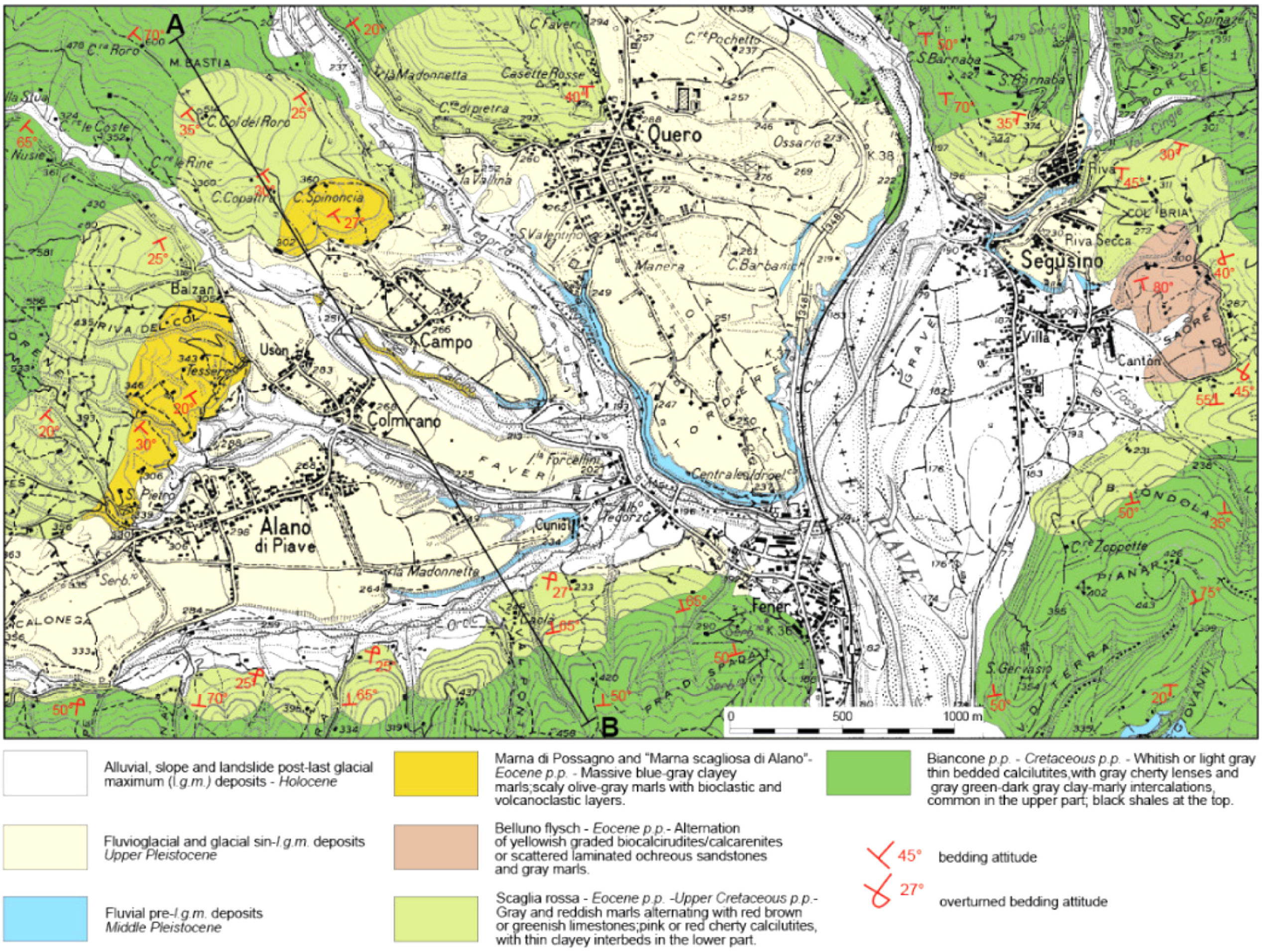

Figure 2. (modified after Agnini et al., 2011). Geological map of the study area. A legend with a detailed description of lithostratigraphic units is also reported in the lower part of the figure.

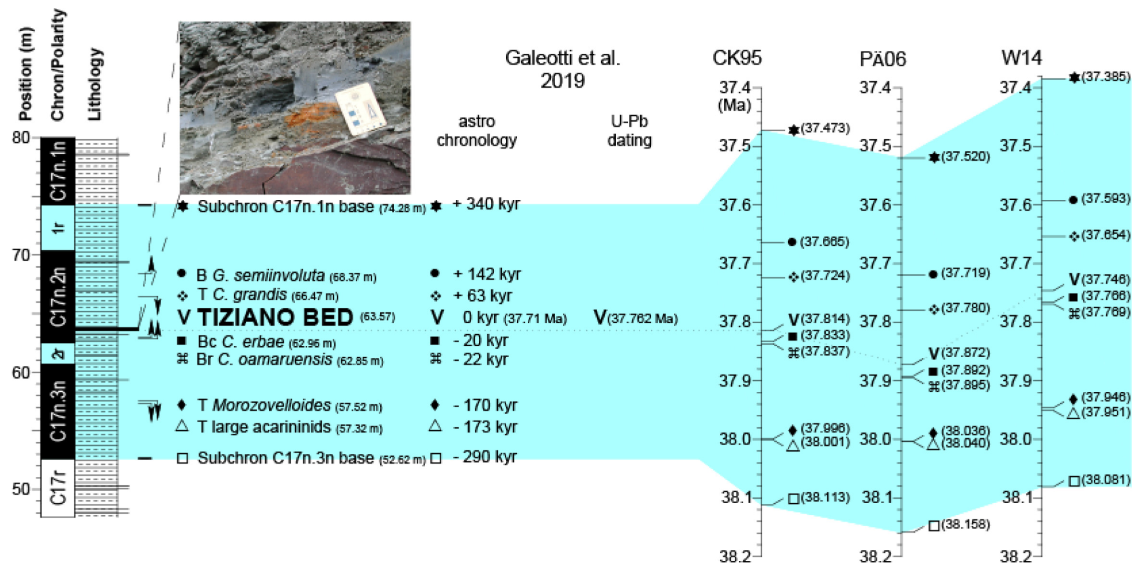

Figure 3. (modified after Agnini et al., 2011). Close-up of the critical interval for defining the base of the Priabonian. Bio-magnetostratigraphic events considered as useful for approximating the Bartonian/Priabonian boundary, that is the base of the Tiziano bed (picture up left in the figure), are plotted against magnetostratigraphy and lithology. Age estimations for the Tiziano bed as well as for biomagnetostratigraphic events are calculated using different time scales (CK95, Cande and Kent 1995; PÄ06, Pälike et al., 2006; W14, Westerhold et al., 2014) and are reported on the right side. Br-Base rare; Bc-Base common and continuous; T-Top. The light blue shaded band identifies the Bartonian-Priabonian transition, the critical interval where the Priabonian GSSP should be defined. ★ = Subchron C17n.1n base; ● = Base Globigerinatheka semiinvoluta; ❖ = Top Chiasmolithus grandis; V = Tiziano bed; □ = Base common and continous Cribrocentrum erbae; ⌘ = Base rare (Br) Chiasmolithus oamaruensis; ♦ = Top Morozovelloides; △ = Top large acarininids; □ = Subchron C17n.3n base.

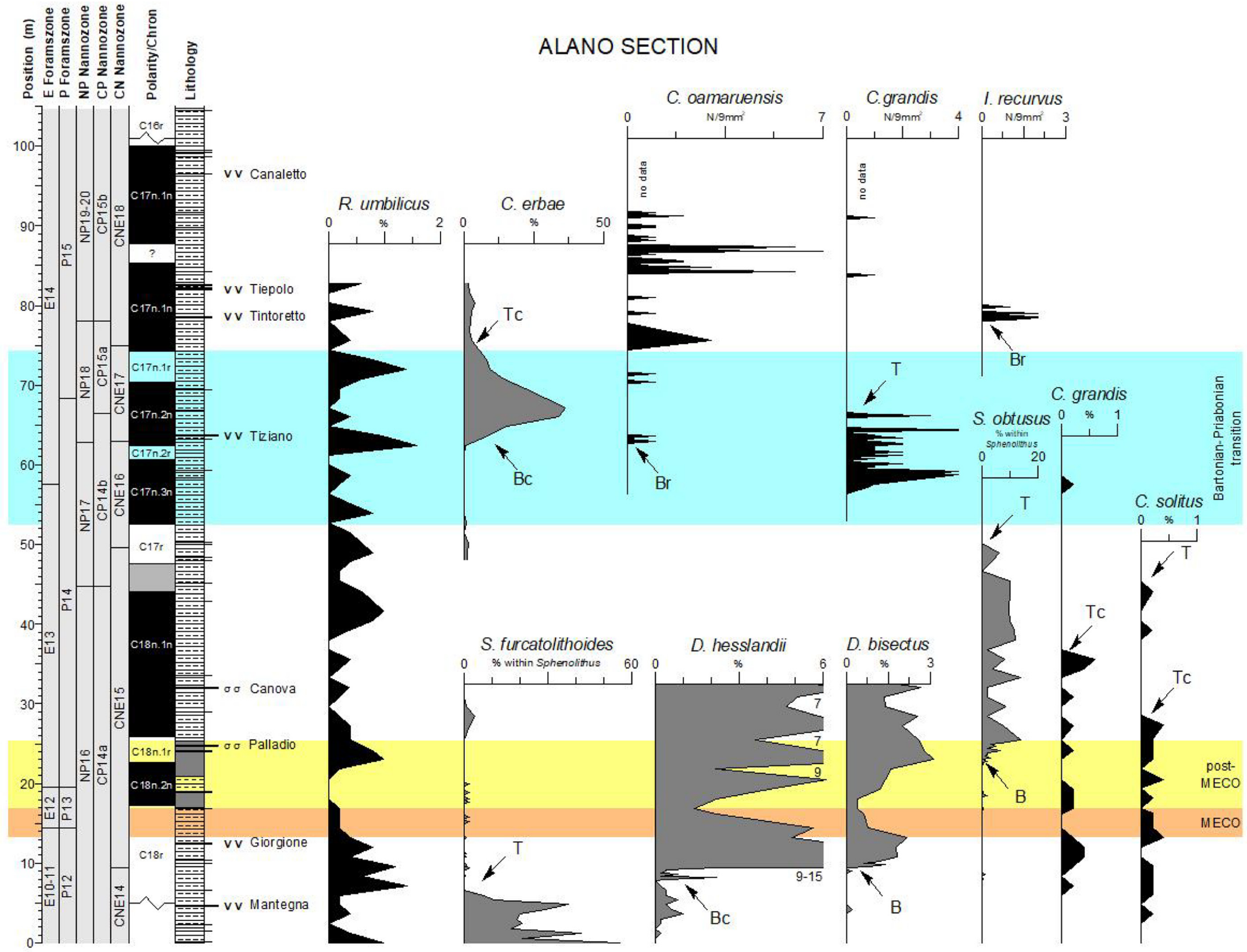

Figure 4. (modified after Agnini et al. 2011). Quantitative distribution patterns of selected calcareous nannofossils and resulting biostratigraphic classification of the Alano section according to the zonal schemes of Martini (NP; 1971), Okada and Bukry (CP; 1980) and Agnini et al., (CN; 2014). Planktonic foraminiferal biozonations are after Berggren et al. (P zones; 1995) and Berggren and Pearson (2005) or Wade et al., 2011 (E zones). The positions of the crucial biohorizons in the Bartonian-Priabonian transition is reported in Table 1. Br-Base rare; B-Base; Bc-Base common and continuous; Tc-Top common; T-Top. The shaded orange band indicates the MECO, the shaded yellow band marks the post-MECO interval and the light blue shaded band identifies the Bartonian-Priabonian transition, the critical interval where the Priabonian GSSP should be defined.

can be used as a starting reference record to strengthen the traceability potential of some of the marker events outside the local depositional basin.

To investigate the wider correlation potential, calcareous plankton data available for the Alano section (Figs. 4-5) were compared with data acquired at ODP Site 1052 (western North Atlantic; Fig. 6). This exercise showed that the successive extinction of large acarininids and *Morozovelloides* occurred consistently in the middle part of Chron C17n.3n (Wade, 2004; Agnini et al., 2011). Wade et al. (2012) emphasized the desirable features of these closely spaced and easily recognized extinction events for global correlation in low and mid latitudes, providing corroborating evidence for their robustness and synchrony across the Atlantic Ocean.

The same approach was performed for calcareous nannoplankton and permits constraint of the relative timing among some calcareous nannofossil biohorizons and their relationship with planktonic foraminiferal bioevents (Fig. 3). The Base of *C. oamaruensis*, one of the traditional events used to approximate the base of the Priabonian, occurs at the Base of Subchron C17n.2n, but its reproducibility is generally considered very poor (Fornaciari et al., 2010; Agnini et al., 2011). Nevertheless, the highly resolved biostratigraphic dataset available for the studied section pointed out two further biohorizons: the Base of common and continuous *C. erbae*, marking the Base of Zone CNE17 (Fig. 4; Agnini et al., 2014) and the Top of *C. grandis*, defining the Base of Subzone CP15b (Okada and Bukry, 1980). These two closely spaced biohorizons are consistently found within Subchron C17n.2n in the proximity to the Base of *C. oamaruensis* (Fornaciari et al., 2010; Agnini et al., 2011, 2014).

In summary, calcareous plankton (i.e., planktonic foraminifera and calcareous nannofossils) provide an excellent series of biohorizons

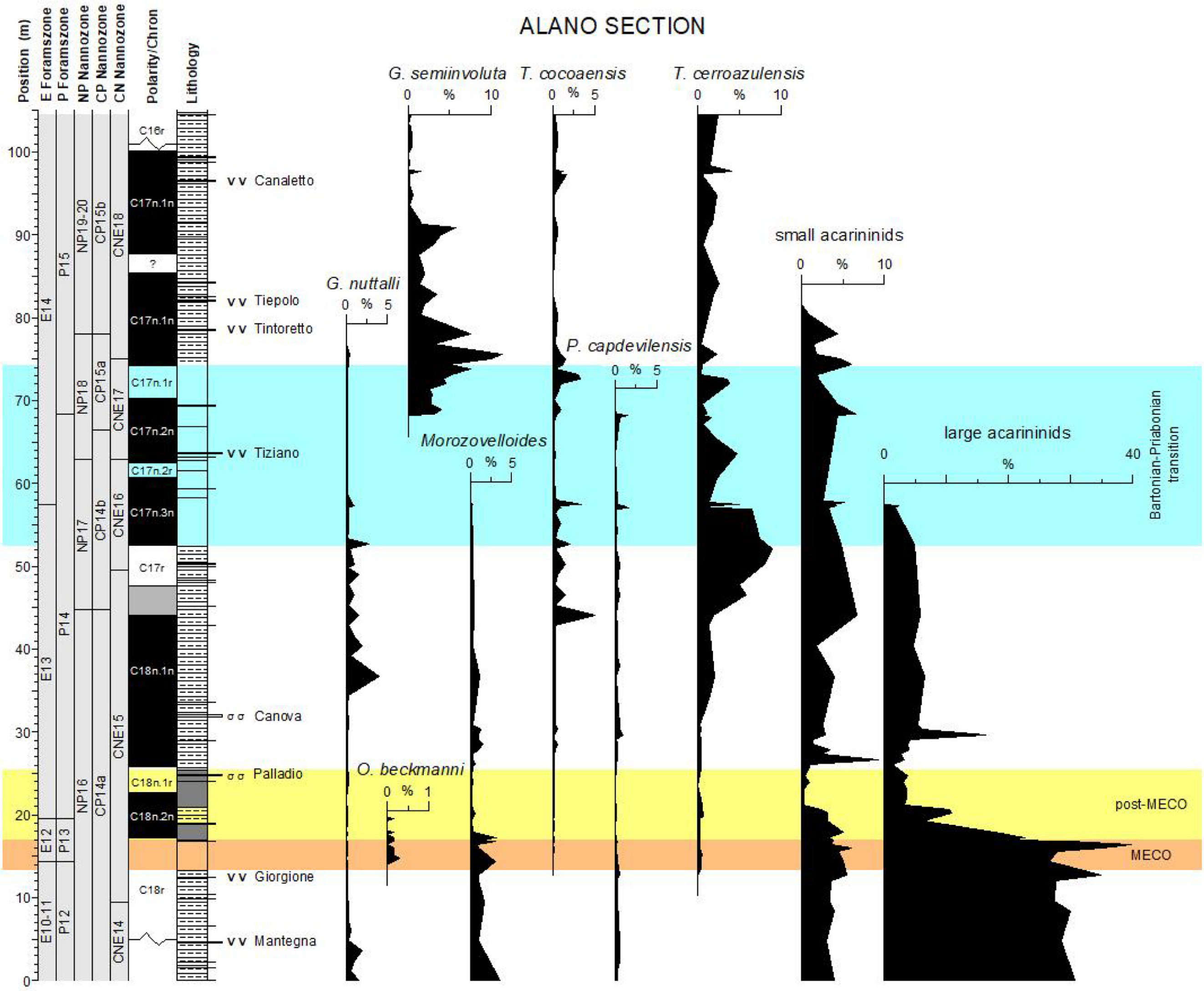

Figure 5. (modified after Agnini et al. 2011). Planktonic foraminiferal data and resulting biostratigraphic classification of the Alano section according to the zonal schemes of Berggren et al. (1995), Berggren and Pearson (2005) or Wade et al., (2011). Calcareous nannofossil biozonations are after Martini (NP; 1971), Okada and Bukry (CP; 1980) and Agnini et al., (CN; 2014). The relative abundance of each taxon is reported in terms of percentage with respect to the entire assemblage. The shaded orange band indicates the MECO, the shaded yellow band marks the post-MECO interval and the light blue shaded band identifies the Bartonian-Priabonian transition, the critical interval where the Priabonian GSSP should be defined.

with a high reproducibility and good correlation potentials through the candidate interval for the GSSP. They are closely spaced, with the Top of large acarininids and *Morozovelloides* preceding the Base of common and continuous *C. erbae* and the Top of *C. grandis* by ~ 230 kyr, if a floating chronology based on cycle counting is adopted (Fig. 3; Galeotti et al., 2019).

The good magnetostratigraphy available at Alano (Agnini et al., 2011) as well as the astrochronology based on cycle counting of $\delta^{13}C$ and wt.% $CaCO_3$ records and U-Pb radio-isotopic dating (Galeotti et al., 2019), represent important additional datasets that improve the correlation potential of the Priabonian GSSP. In conclusion, recent research has confirmed that the Alano section is an appropriate section for defining the Priabonian GSSP, i.e., for the Bartonian/Priabonian boundary.

Summary on Background Studies on the Alano Section

The entire Alano section has been described and studied in detail by Agnini et al. (2011) and Fornaciari et al. (2010). Cyclostratigraphic study and radioisotopic analyses have recently been performed in the Alano section (Galeotti et al., 2019), and a correlation between the bathyal Alano and Varignano sections (Belluno and Lombardian basins, respectively) has been attempted (Luciani et al., 2020). In addition, the basal portion of this sedimentary sequence has been the object of recent studies (Spofforth et al., 2010; Luciani et al., 2010; Toffanin et al., 2011; Boscolo-Galazzo et al., 2013, 2016) revealing the occurrence of a detailed record of the Middle Eocene Climatic Optimum (MECO; Bohaty and Zachos, 2003; Bohaty et al., 2009).

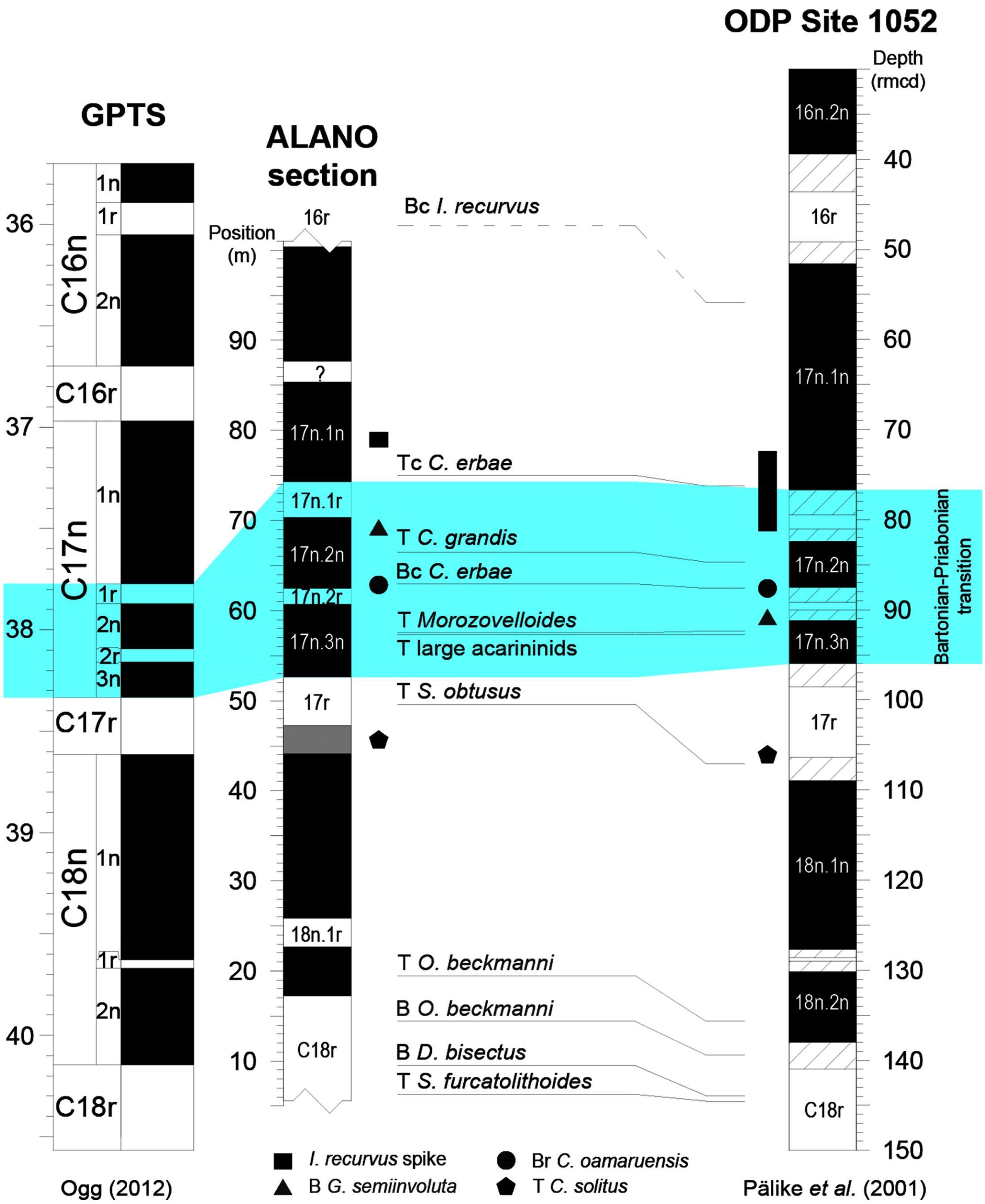

Figure 6. (modified after Agnini et al. 2011). Calcareous plankton correlation between the Alano section and ODP Site 1052 (western North Atlantic; Pälike et al., 2001) and resulting interpretation of the magnetostratigraphy of the Alano section. The geomagnetic polarity time scale of Ogg (2012; GTS12) is plotted on the left side. The light blue shaded band identifies the Bartonian-Priabonian transition, the critical interval where the Priabonian GSSP should be defined.

Geological Setting

The Alano section at Alano di Piave is located in the Italian Southern Alps (NE Italy; Fig. 1), a major structural element of the Alpine chain, interpreted as a south verging fold-and-thrust belt (Doglioni and Bosellini, 1987) resulting from the polyphase deformation of the southern margin of the Mesozoic Tethyan ocean (Bernoulli, 1972). In particular, the Alano section crops out in the Venetian Southern Alps (Fig. 1), and its constituent sediments deposited in the Belluno Basin, a paleogeographic domain resulting from the drowning of Triassic-Lower Jurassic shallow-water carbonate platforms (Winterer and Bosellini, 1981). Deep-water facies persisted in the south-western sector of the Belluno Basin, surrounded by shallower areas to the west (the Lessini Shelf; Bosellini, 1989) and east (the Friuli Platform; Fig. 1), until the late Eocene (Cita, 1975; Trevisani, 1997). The Alano section is located ~ 8 km NNE from the well-known Priabonian beds of the Possagno section (Bolli, 1975). More details on the geological context and evolution of the study area are given in Agnini et al. (2011).

The Stratigraphic Succession

The Alano section mainly consists of greyish hemipelagic marls intercalated with a number of millimeter to centimeter thick sandy-silty layers, which are particularly useful as marker beds along the section (Figs. 7, 8). The general bedding strike is 130-140°N and the dip is ~20–25° S. Apart from being tilted, the section is unaffected by significant structural deformation. The sandy layers can be easily traced

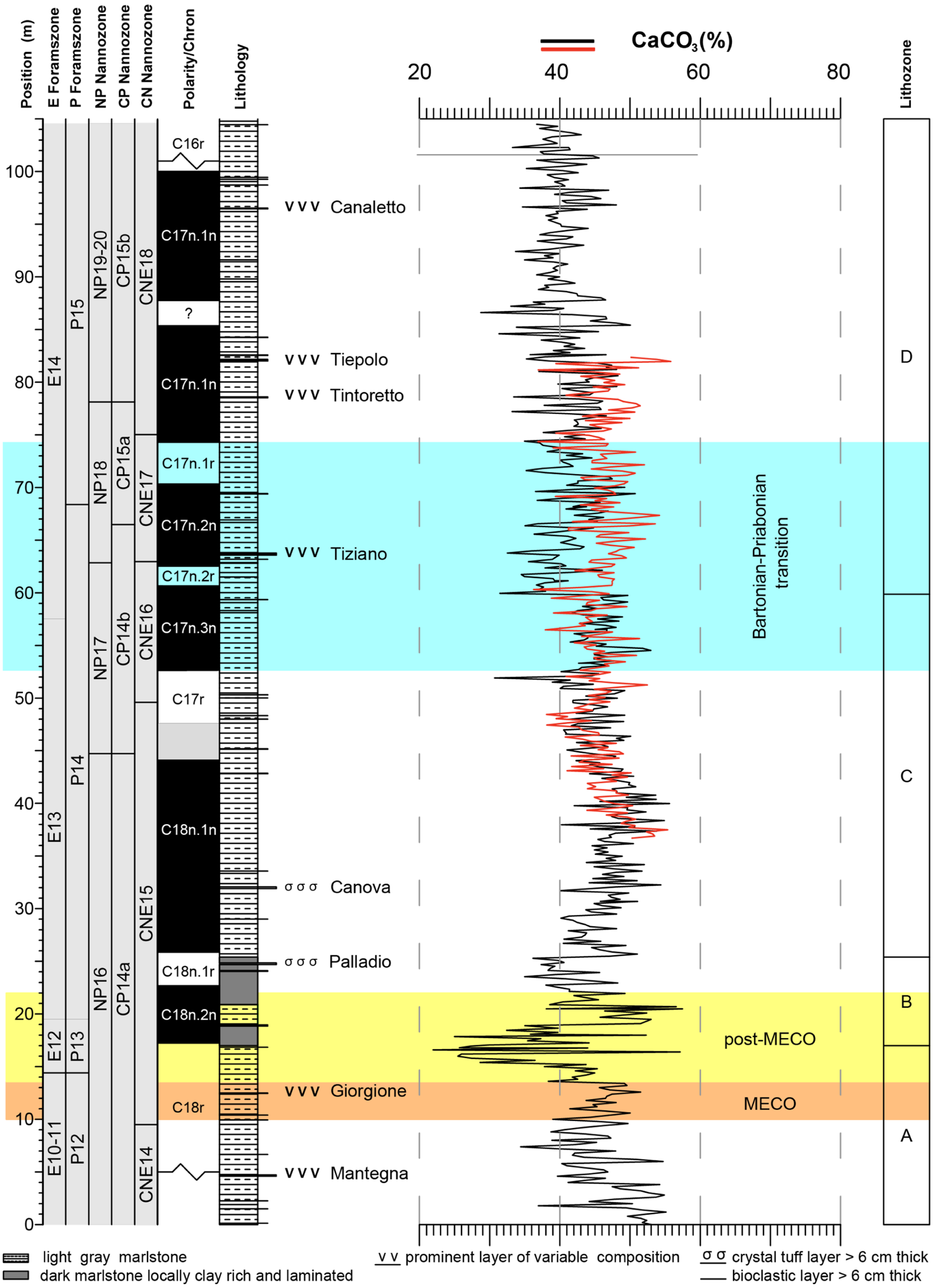

Figure 7. (modified after Agnini et al. 2011). Lithologic column of the Alano section. The main crystal tuff/bioclastic beds are positioned in the log and named after famous Venetian artists. $CaCO_3$ content throughout the section is presented in the central part of the figure (black line; Spofforth et al., 2010; red line; Galeotti et al., 2019). The total carbonate content allows the subdivision of the section into four litho-zones reported on right side. The shaded orange band indicates the MECO, the shaded yellow band marks the post-MECO interval and the light blue shaded band identifies the Bartonian-Priabonian transition, the critical interval where the Priabonian GSSP should be defined.