

PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY OF LATE ALBIAN-CENOMANIAN PELAGIC SEQUENCES FROM THE UMBRIA-MARCHE BASIN (CENTRAL ITALY) AND THE MAZAGAN PLATEAU (NORTHEAST ATLANTIC OCEAN)

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Abstract. Planktonic foraminifera were studied in the upper Albian to Cenomanian sedimentary sequence of the Monte Petrano and Le Breccie stratigraphic sections located in the Umbria-Marche Basin (central Italy), and of Hole 547A and Site 545 drilled by the Deep Sea Drilling Project (DSDP) on the Mazagan Plateau (offshore Morocco, northeast Atlantic Ocean). Biostratigraphic results allow the identification of a stratigraphically ordered sequence of bioevents that have proved to be reliable for regional and interregional correlations, from older to younger: the lowest occurrences (LOs) of *Tb. appenninica*, *Pl. busstorfi*, *Pa. libyca*, *Tb. brotzeni* in the Albian, and the LOs of *Tb. globotruncanoides*, *Tb. greenbornensis* and *Rt. cushmani* in the Cenomanian sediments. We remark the difficulty in the identification of the *Tb. reicheli* Zone used in the Tethyan biozonation because of the rarity and absence of the species in many low to mid-latitude pelagic sequences. To overcome the problem, we use the *Tb. greenbornensis* Zone defined as the stratigraphic interval between the lowest occurrence (LO) of *Tb. greenbornensis* and the LO of *Rt. cushmani*. The LO of *Tb. greenbornensis* is a solid bioevent with the nominal species characterized by a wide geographic distribution and occurring close to the LO of *Tb. reicheli* where the latter species is present.

The studied stratigraphic sections are compared with the coeval Mont Risou section in the Vocontian Basin and the record from Blake Nose in the western North Atlantic to verify the correlation and synchronicity of biostratigraphic and chemostratigraphic events including the Oceanic Anoxic Events 1d (OAE1d) and the Mid Cenomanian Event (MCE).

INTRODUCTION

The Albian-Cenomanian interval is a time of increased diversification in the evolutionary history of planktonic foraminifera. After the major turnover across the Aptian-Albian boundary interval, which is a dramatic event in the evolutionary history of Cretaceous planktonic foraminifera (Br  h  ret et al. 1986; Leckie 1989; Premoli Silva & Sliter 1999; Kennedy et

al. 2000; Leckie et al. 2002; Huber & Leckie 2011; Huber et al. 2011; Petrizzo et al. 2012, 2013; Kennedy et al. 2014), a progressive appearance of new lineages is observed throughout the Albian and Cenomanian. The middle-late Albian is marked by the appearance of trochospiral genera characterized by finely perforate to macroperforate shell perforations and thick (genus *Ticinella*) to muricate (genera *Muricobedbergella*, *Praglobotruncana*) wall textures, by muricate to smooth planispiral taxa (genus “*Globigerinelloides*”, see Taxonomic Remarks) with also peripheral keel (genus *Planomalina*), and by the appearance of biserial taxa

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(genus *Protobeterohelix*). In general, a high rate of evolutionary rates is observed especially within the polyphyletic rotaliporids, trochospiral taxa with sutural or umbilical supplementary aperture and a peripheral keel (Wonders 1980; González-Donoso et al. 2007), that are the major component of the assemblages until the end Cenomanian when the last representative (*Rotalipora cushmani*) disappears. In the middle to late Cenomanian the planktonic foraminiferal record is characterized by the evolutionary appearance of trochospiral and heavily muricate whiteinellids and by the double keeled *Dicarinella* and *Marginotruncana* genera in the latest Cenomanian (Premoli Silva & Sliter 1995; Fraass et al. 2015; Falzoni et al. 2018; Falzoni & Petrizzo 2020)

The diversification and high rate of planktonic foraminiferal evolution occur in a time interval that is also characterized by the deposition of organic rich sediments in the late Albian, named Breistoffer Niveau in the Vocontian Basin in southeast France (e.g., Bréhéret 1988; Gale et al. 1996) and Piali Level in the Umbria-Marche Basin in central Italy (e.g., Coccioni et al. 1987; Coccioni 2001), and by global geochemical perturbations of the carbon cycle known as the Oceanic Anoxic Events 1d (OAE 1d) in the late Albian (e.g., Erbacher & Thurow 1997; Wilson & Norris 2001; Leckie et al. 2002) and the Mid Cenomanian Event (MCE) in the middle Cenomanian (e.g., Paul et al. 1994; Jenkyns et al. 1994; Mitchell et al. 1996).

This study presents a detailed biostratigraphic and taxonomic analysis of late Albian-Cenomanian planktonic foraminiferal assemblages from Monte Petrano and Le Breccie sections located in the Umbria-Marche Basin (Fiet et al. 2001; Coccioni & Galeotti 2003; Giorgioni et al. 2015; Gambacorta et al. 2015, 2020; Gilardoni, 2017) and from Deep Sea Drilling Project Leg 79 Hole 547A and Site 545 drilled in the eastern North Atlantic Ocean, off-shore Morocco on the Mazagan Plateau (Hinz et al. 1984; Leckie 1984; Wiegand 1984; Nederbragt et al. 2001; Gilardoni 2017) (Fig. 1). The identification of a common sequence of planktonic foraminiferal bioevents is aimed to build a solid biostratigraphic framework of lowest and highest occurrences as much as possible that is reproducible at an interregional scale. Comparison of the bio- and chemostratigraphic records of the studied sections with coeval sections from the Vocontian basin (Mont Risou: Gale et al. 1996; Kennedy et al. 2004; Petrizzo et al. 2015) and western North

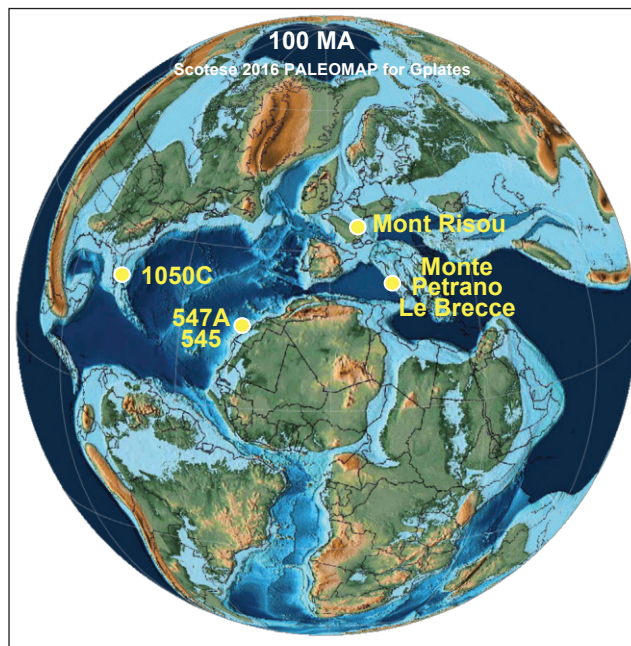


Fig. 1 - Paleogeographic reconstruction for the late Albian-Cenomanian (Scotese 2016) with locations of the Monte Petrano and Le Breccie sections (Umbria-Marche Basin, central Italy), DSDP Leg 79 Hole 547A and Site 545 on Magazan Plateau (offshore Morocco, eastern North Atlantic Ocean), ODP Hole 1050C (Blake Nose, western North Atlantic Ocean) and the Mont Risou section in southeast France.

Atlantic Ocean deep sea sediments (ODP Leg 171B Hole 1050C, Blake Nose: Norris et al. 1998; Watkins & Bergen 2003; Petrizzo & Huber 2006a, b; Petrizzo et al. 2008; Ando et al. 2009) (Fig. 1) allows evaluation of the synchronicity and reliability of the planktonic foraminiferal events and of their stratigraphic occurrences relative to the organic-rich black shales and the OAE 1d and MCE.

MATERIALS AND METHODS

The Umbria-Marche Basin is characterized by Cretaceous pelagic limestones mostly composed of calcareous nannofossil and planktonic foraminifera, cherts and marlstones deposited on a highly irregular sea floor with characteristic seamount and basin morphology (Channell et al. 1979; Lavecchia & Piali 1989; Parisi 1989; Marchegiani et al. 1999; Hu et al. 2006; Gambacorta et al. 2014). The Monte Petrano section (65 meters-thick) and Le Breccie section (20 meters-thick) (Fig. 2) cover an almost continuous stratigraphic record (Gambacorta et al. 2015, 2020) and the sedimentary succession entirely belongs to the Scaglia Bianca Formation, which consists of mainly whitish pelagic limestone resulting from lithification of nannofossil-foraminiferal oozes with chert bands, radiolarian and shale layers (Arthur & Premoli Silva 1982; Parisi 1989; Coccioni & Galeotti 2003; Gambacorta et al. 2014). Based on integrated litho-, bio-, and chemostratigraphic data Gambacorta et al. (2020) estimate a ~ 3 m gap at the Le Breccie section in a faulted interval at about 16.5 m (Fig. 2). The Monte Petrano and the Le Breccie sections record the upper Albian Oceanic Anoxic Event 1d (OAE 1d) (Erbacher & Thurow 1997) and its lithological expression, the Piali Level (Coccioni

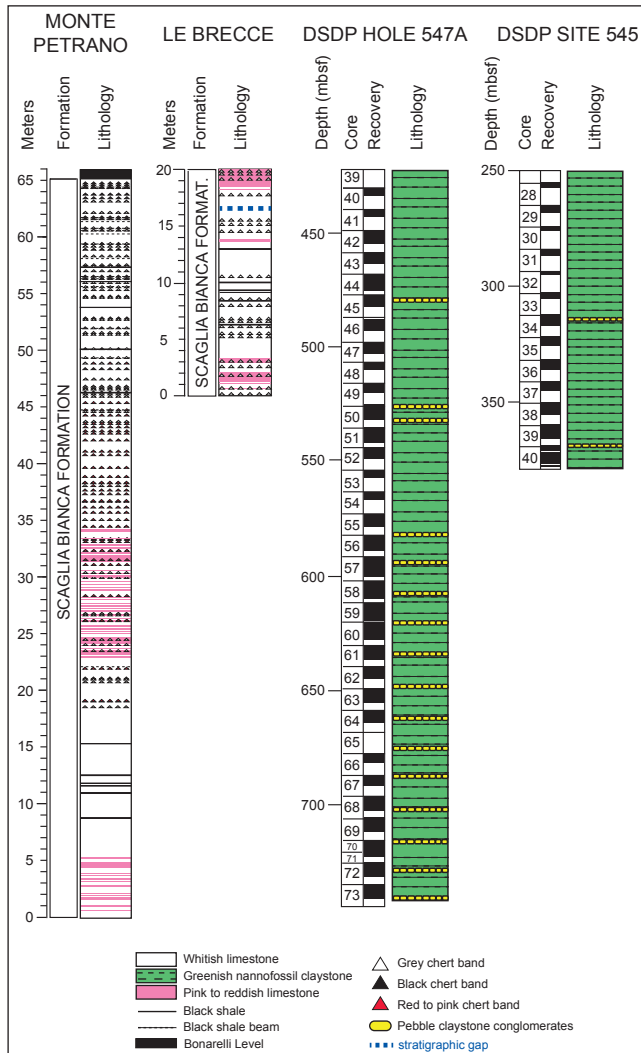


Fig. 2 - Stratigraphic columns of the Monte Petrano and Le Breccie section (after Gambacorta et al. 2015) and of DSDP Hole 547A and Site 545 (after Leckie 1984). Stratigraphic gap of about 3 m coinciding with a faulted interval in the Le Breccie section according to Gambacorta et al. (2020); mbsf = meters below sea floor.

2001), consists of six levels of black shales (Gambacorta et al. 2015, 2020). Furthermore, the Monte Petrano section also records the Mid Cenomanian Event (MCE) (Gambacorta et al. 2015). The top of the studied section is marked by the Bonarelli Level, a ~1 meter-thick interval, consisting of black shales, grey claystones and radiolarian-rich sands (Fig. 2) corresponding to the Cenomanian-Turonian boundary interval (Gambacorta et al. 2015).

DSDP Leg 79 Hole 547A (33°46.84'N; 09°20.98'W) and Site 545 (33°39.86'N; 09°21.88'W) were drilled in 1981 in the eastern North Atlantic Ocean, offshore of Morocco on the Mazagan Plateau. The upper Albian-Cenomanian stratigraphic interval is 350 m thick at Hole 547A (from core 73R to 39R) and is characterized by moderate to good recovery except for some intervals of poor recovery (Fig. 2). The dominant lithology is dark greenish grey nannofossil claystone and calcareous claystone (Hinz et al. 1984). The stratigraphic interval from core 39R to 42R (37 m) is characterized by swelling claystone, core 43R to 56R (128 m) is composed of a mixture of wavy and swelling claystone, and core 56R to 73R (185 m) lithology is mainly represented by wavy claystone. Moreover, in the lower part, intervals of planar lami-

nated dark claystone to mudstone, containing shell fragments and more quartz silt than the dominant lithology, occurs together with a pebbly claystone to mudstone and mudstone conglomerate (Hinz et al. 1984; Nederbragt et al. 2001).

At Site 545 (Fig. 2) the upper Albian-Cenomanian stratigraphic interval is 114 m-thick (from core 40R to 28R) and it is characterized by poor, slightly increasing downward, recovery. The dominant lithology is grayish olive green nannofossil claystones. A minor lithology is represented by grayish green, greenish gray, and yellow green laminated claystone rich in nannofossil; below 312.5 m grayish olive-green colors still predominate in the nannofossil rich claystones and reflect a downward increase in calcium carbonate of the sediment. In the lower part of the studied interval, two levels of claystone conglomerate composed of flat pebbles have been observed (Hinz et al. 1984).

The Monte Petrano section was sampled for planktonic foraminiferal analyses using a sampling resolution of 50 cm to 1 m and a total of 60 washed residues and 30 thin sections were analyzed. The Le Breccie section was studied using a sampling resolution between 20 cm and 60 cm and 22 washed residues were analyzed. The compactness of the lithology of rock samples belonging to the Umbria-Marche Basin (Scaglia Bianca Formation) prevented application of the standard methodology for obtaining washed residues and, consequently, samples from the Monte Petrano and Le Breccie sections were processed using a solution of acetic acid at 80% (Lirer 2000; Falzoni et al. 2016). At DSDP Hole 547A and Site 545 were studied 64 and 25 rock samples, respectively, and they were processed following the standard procedure using hydrogen peroxide to obtain washed residues for micropaleontological analyses. Biostratigraphic analyses were carried out for all the washed residues on the > 38 µm size-fraction.

Planktonic foraminiferal genera and species were identified according to holotypes and paratypes illustrated on the pforams@mikrotox Portal (Huber et al. 2016, on line taxonomic dictionary updated by the Mesozoic Planktonic Foraminifera Working Group, <http://www.mikrotox.org/pforams/index.html>) and Ellis and Messina Catalogues (Micropaleontology Press, <http://www.micropress.org/em/>). In addition, several publications were used to ameliorate the species identification (i.e., Caron & Spezzaferri 2006a, b; Petrizzo & Huber 2006a, b; Ando & Huber 2007; González-Donoso et al. 2007; Desmares et al. 2008; Lipson-Benitah 2008; Robaszynski et al. 2008; Huber & Leckie 2011; Petrizzo et al. 2015).

PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY

Several Cretaceous planktonic foraminiferal biozonations have been proposed in the last 50 years for the mid- to low latitude assemblages in the Tethyan region. For instance, Moullade (1966) defined zones and subzones for the Lower Cretaceous in the Vocontian Basin. Postuma (1971) and Sigal (1977) developed Cretaceous biozonations for the Mediterranean area. Sliter (1989) proposed a biozonation based on deep sea sediments from low-middle latitude localities using thin sections. These biozonations were further improved by Premoli Silva & Sliter (1995) and recently updated by Petrizzo et al. (2011) and Coccioni & Premoli Silva (2015) based on studies of the Bottaccione section in Italy, and by the detailed study of the

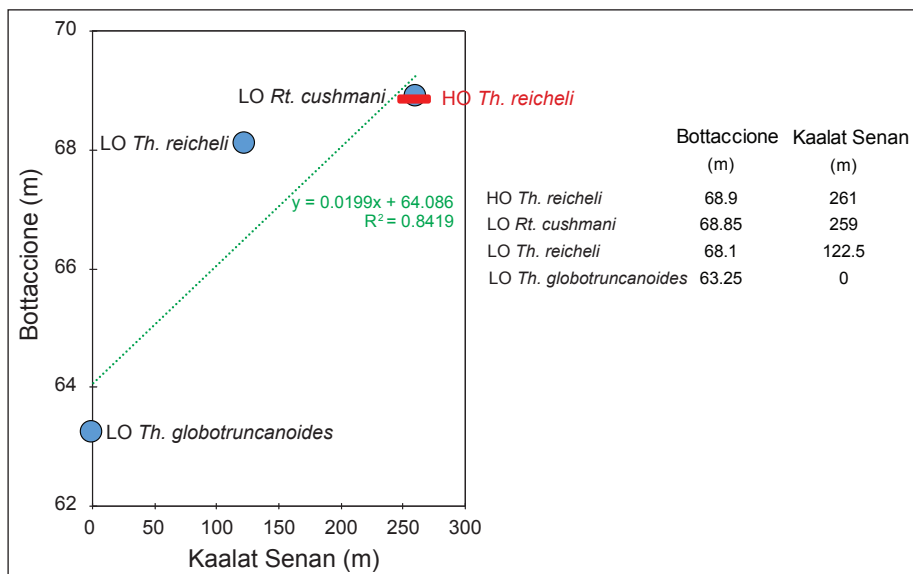


Fig. 3 - Graphic correlation of the common planktonic foraminiferal events between the Bottaccione section (central Italy) and the Kaalat Senan section (Tunisia). A best-fit regression curve (in green) is applied. LO = Lowest Occurrence, HO = Highest Occurrence.

Kaalat Senan section in Tunisia by Robaszynski et al. (1993) and Robaszynski & Caron (1995). The Tethyan biozonations by Robaszynski & Caron (1995) and Premoli Silva & Sliter (1995) are incorporated in the Geological Time Scales (Gradstein et al. 2004, 2012; Ogg et al. 2016; Gradstein et al. 2020).

The biozonations developed for the Bottaccione and the Kaalat Senan sections are very similar except for the Cenomanian interval because of the different definitions of the *Thalmaninella reicheli* and *Rotalipora cushmani* zones. At the Bottaccione section, the *Th. reicheli* Zone is defined as a Total Range Zone of the nominal taxon, and the *Rt. cushmani* Zone is defined as a Partial Range Zone between the HO (Highest Occurrence) of *Th. reicheli* and the HO of *Rt. cushmani* (Premoli Silva & Sliter 1995; Coccioni & Premoli Silva 2015). At Kaalat Senan the *Th. reicheli* Zone is defined as a Partial Range Zone between the LO (Lowest Occurrence) of *Th. reicheli* and the LO of *Rt. cushmani* while the *Rt. cushmani* Zone is a Total Range Zone (Robaszynski & Caron 1995). To verify the accuracy of correlation between the Bottaccione and the Kaalat Senan sections in the Cenomanian we have performed a graphic correlation (i.e., Sadler 2004 for review; Paul & Lamolda 2009; Petruzzo et al. 2011; Petruzzo 2019) comparing the sequences of common bioevents (Fig. 3). The correlation coefficient of the best-fit regression curve ($R^2 = 0.8419$) reveals an offset of the LO of *Th. reicheli*, that indicates it occurs either earlier in the Kaalat Senan section or is delayed in the Bottaccione section (Fig. 3). This observation calls into doubt on the reliability of the LO of *Th. reicheli* as zonal event for identifying the base of the *Th. reicheli*

Zone in both Tethyan biozonations (Premoli Silva & Sliter 1995; Robaszynski & Caron 1995). On the contrary, the HO of *Th. reicheli* seems to be isochronous between the Kaalat Senan and Bottaccione sections and is very close to the LO of *Rt. cushmani* indicating the applicability of both biozonations.

Planktonic foraminiferal bioevents

The stratigraphic distribution of the planktonic foraminiferal species identified in the sedimentary sequences in the Umbria-Marche Basin and in the Magazan Plateau are reported in Tabs. 1-4. Comparison among the four stratigraphic sections examined in this study allows identification of a stratigraphically ordered sequence of common bioevents spanning the late Albian-Cenomanian interval, including from bottom to top: the LOs of *Thalmaninella appenninica*, *Planomalina buxtorfi*, *Paracostellagerina libyca*, *Thalmaninella brotzeni*, *Thalmaninella globotruncanoides*, *Thalmaninella greenhornensis* and *Rt. cushmani*. All bioevents have been recognized in the Monte Petrano and DSDP Hole 547A, whereas at the Le Breccie section and DSDP Site 545 only the late Albian to lower Cenomanian sediments were investigated (Figs. 4 and 5).

The LOs of *Th. appenninica*, *Pl. buxtorfi* and *Pa. libyca* are documented at correlative stratigraphic positions in the Vocontian Basin (Col de Palluel section: Gale et al. 2011), western North Atlantic Ocean (Blake Nose: Petruzzo & Huber 2006a), Bottaccione section (Premoli Silva & Sliter 1995), and Libya (Barr 1972). The LO of *Th. brotzeni* is always detected below the LO of *Th. globotruncanoides* in all the studied sections in agreement with the record from the Vocontian

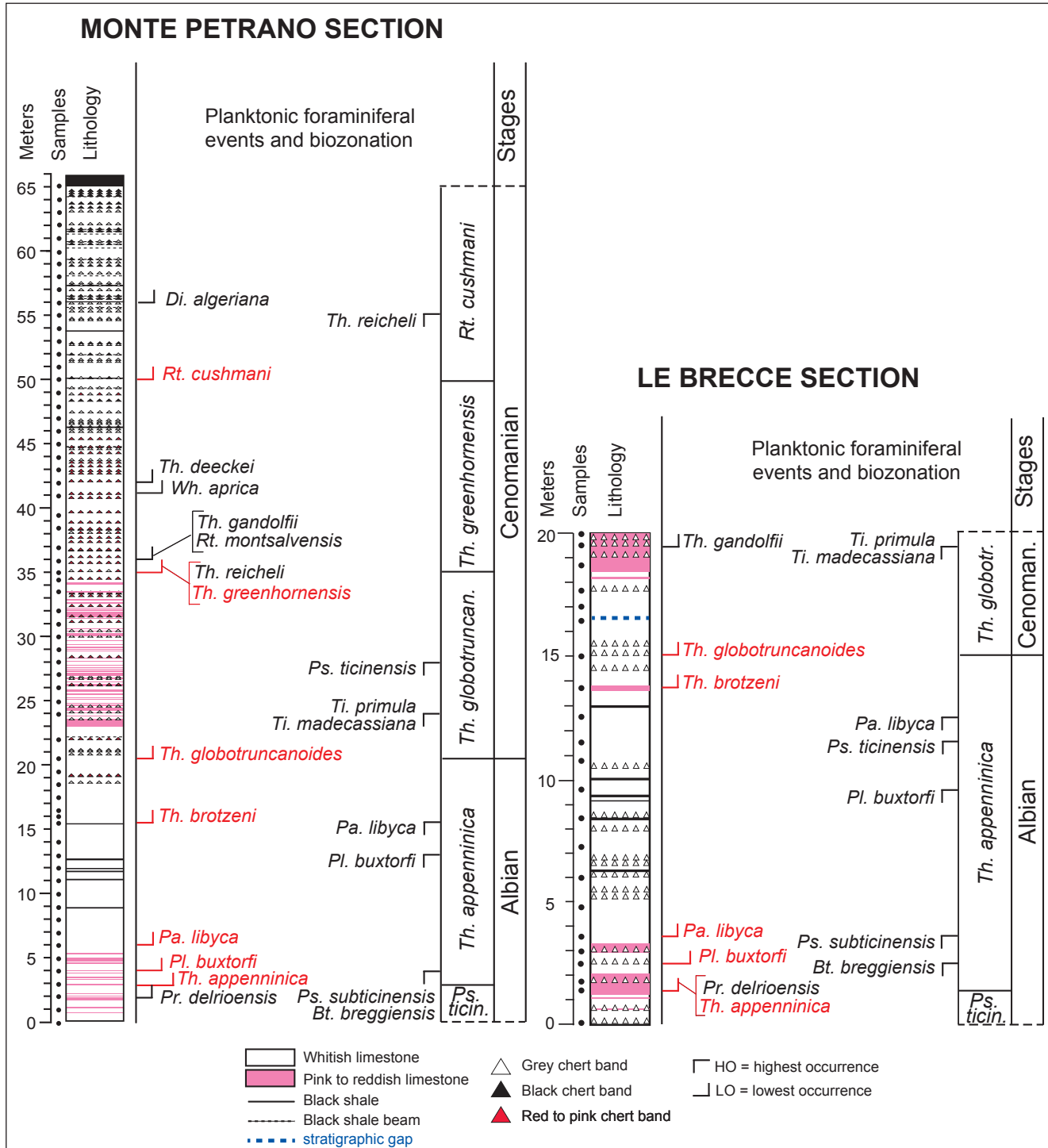


Fig. 4 - Planktonic foraminiferal biostratigraphy at Monte Petrano and Le Breccie sections. In reds are the common and stratigraphically ordered bioevents that are interpreted as reliable for regional and interregional correlation. Lithostratigraphy is from Gambacorta et al. (2015). *Ps. ticin.* = *Ps. ticinensis*; *Th. globotruncan.* and *Th. globotr.* = *Th. globotruncanoides*; Cenoman. = Cenomanian.

Basin (Mont Risou: Petrizzo et al. 2015), Bottaccione section (Premoli Silva & Sliter 1995), northern Israel (Lipson-Benitah et al. 1997), and northern Madagascar (Randrianasolo & Anglada 1989). The LO of *Th. globotruncanoides*, which is the primary criterion for the definition of the base of the Cenomanian Global Stratotype Sections and Points (GSSP) (Kennedy et

al. 2004), has been identified in all studied sections. Among the secondary criteria for the definition of the GSSP, the LO of *Pseudohalmaninella tehamaensis* was recommended to be useful (Kennedy et al. 2004), but subsequently its stratigraphic distribution was reported to be diachronous (Petrizzo et al. 2015). This observation is here confirmed as *Ps. tehamaensis* is first

LE BRECCIE samples in meters		AGE	PLANKTONIC FORAMINIFERA ZONE																																															
				Bt. subbreggiensis	Bt. breggiensis	"Gl." bentonensis	"Gl." ultramicrus	"Globigerinelloides" sp. 1	Ps. subticinensis	Ps. tichensis	Ps. tehamensis	Mu. wondersi	Pc. simplicissima	Mu. praelibyca	Mu. astrepta	Mi. cf. rischi	Ti. madecassiana	Ti. digitalis	Ti. aperta	"Gl." pulchellus	Pl. praebuxtorfi	int. Pl. praebuxtorfi - Pl. buxtorfi	Pl. buxtorfi	int. "Gl." pulchellus - Pl. praebuxtorfi	Th. appenninica	Th. balernaensis	Th. evoluta	Ti. primula	Pr. delrioensis	Mu. delrioensis (Longoria neotype)	Mu. blakensis (6 chambers)	int. Ti. aperta - Th. appenninica/balernaensis	Pa. libyca	Mu. (5 chambers)	Pr. stephani	Mu. delrioensis (Masters neotype)	Mu. blakensis (7 chambers)	Pr. delrioensis (double alignment)	int. Th. appenninica - Th. brotzeni	Th. brotzeni	int. Th. brotzeni - Th. globotruncanoides	int. Th. brotzeni - Th. globotruncanoides	int. Th. globotruncanoides - Th. greenhornensis	Th. gandolfii	Pr. gibba	Pr. stephani (double alignment)	Th. greenhornensis			
		CENOMANIAN	Th. globotrunc.				X			X	X	X			X																																		X?	
		ALBIAN	Th. appenninica	X																																														

Tab. 2 - Distribution of planktonic foraminifera in the Le Breccie section; int. = intermediate specimens. See text for complete name of genera.

above the LO of *Th. reicheli* and below the LO of *R. cushmani* (Premoli Silva & Sliter 1995). In the Gargano Promontory in southern Italy (Luciani et al. 2004) and in the Basco-Cantabrian Basin in northern Spain (Gräfe 2001) *Th. greenhornensis* precedes the LOs of *Th. reicheli* and *Rt. cushmani*. Moreover, *Th. greenhornensis* slightly precedes the LO of *Rt. cushmani* in the stratigraphic records from the U. S. Western Interior Seaway (western Kansas and Colorado: Eicher & Worstell 1970) and northern California (Douglas 1969) where *Th. reicheli* is absent. Unfortunately, the planktonic foraminiferal data from the Kaalat Senan section could not be used for comparison because none of the three morphotypes (biconvex, umbilicoconvex and evolute) of *Th. greenhornensis* documented and illustrated by Robaszynski et al. (1993) match the species concept adopted in this study according to the holotype and the emended description by Ando & Huber (2007).

Thalmaninella reicheli is a rare species characterized by a scattered stratigraphic range at Monte Petra-

no and it has not been observed at DSDP Hole 547A and Site 545. However, we cannot exclude its total absence in the Mazagan Plateau pelagic sequence because *Th. reicheli* was recorded and illustrated by Leckie (1984) in one sample from the top of DSDP Site 545 (sample 79-545-28-1, 47-49 cm) (Fig. 5). In general, *Th. reicheli* is reported to be always rare in the localities where it has been observed, and sometimes difficult to detect because of its morphologic similarity with *Th. deeckeri*. The two species show the same planoconvex lateral profile and the taxonomic features of the umbilical and spiral sides, and only differs by the geometry of the sutures on the umbilical side. Therefore, the possibility that *Th. reicheli* and *Th. deeckeri* have been misidentified and erroneously interpreted cannot be excluded.

The topmost stratigraphic distribution of *Th. reicheli* overlaps with *Rt. cushmani* at Monte Petrano (Tab. 1), in the Bottaccione section (Coccioni & Premoli Silva 2015), in Libya (Barr 1972), in northern Caucasus (Tur et al. 2001), in Spain (Gräfe 2001),

DSDP LEG 79 - HOLE 547A		CORE SECTION	INTERVAL (cm)	DEPTH (mbsf)	AGE	PLANKTONIC FORAMINIFERA ZONE		GENOMANIAN		ALBANI	
Core	Section					Interval	Depth	Zone	Subzone	Zone	Subzone
547A	40	1	30.5-33	431.8							
547A	41	1	100.5-102.5	441.51							
547A	42	2	40-42	450.4							
547A	42	3	40.5-42	453.4							
547A	42	CC	4-6	455.34							
547A	43	CC	0-15.5	463.32							
547A	44	3	51-53	472.51							
547A	44	5	47-49	475.47							
547A	45	1	17-19	478.67							
547A	45	3	16-18	481.56							
547A	46	1	60-62	488.6							
547A	46	3	60-62	491.27							
547A	47	1	52.5-54.5	498.02							
547A	47	3	52.5-54.5	501.02							
547A	47	CC	15-16.5	502.15							
547A	48	1	47.5-49.5	507.48							
547A	49	1	48-50	516.98							
547A	49	CC	11-13	519.61							
547A	50	1	83-85.5	526.83							
547A	50	3	80-82	529.68							
547A	51	1	48-50	535.98							
547A	51	3	50-52	539							
547A	52	1	52-54	545.52							
547A	52	3	47.5-50.5	548.7							
547A	53	1	50-51.5	555							
547A	54	1	82-83.5	564.82							
547A	55	1	104-106	574.54							
547A	55	CC	7-8	577.32							
547A	56	1	106-107.5	584.06							
547A	56	3	132-134	587.32							
547A	57	3	50-52	596							
547A	57	5	49-51	598.99							
547A	58	3	52-54	605.52							
547A	58	5	51-53	608.18							
547A	59	1	47-48.5	611.97							
547A	59	3	49-51	614.99							
547A	60	1	48.5-50.5	621.48							
547A	60	3	49.5-51.5	624.49							
547A	60	5	50-52	627.4							
547A	61	1	48-50	630.98							
547A	61	3	50-52	634							
547A	62	1	50-52	640.5							
547A	62	3	48-50	643.48							
547A	63	1	48-49.5	649.98							
547A	63	3	49.5-52	652.99							
547A	64	1	49-52	659.49							
547A	64	3	51-53	662.19							
547A	64	CC	5.5-7.5	663.78							
547A	65	1	36.5-38	668.86							
547A	66	2	67-69	680.17							
547A	67	2	39-41	689.39							
547A	67	CC	7-9	690.38							
547A	68	1	123-125	698.23							
547A	68	2	93-95	699.43							
547A	69	1	50-52	707							
547A	69	3	50-52	710							
547A	70	1	49.5-51.5	716.49							
547A	70	3	50-53	719.05							
547A	71	1	50.5-52	721.01							
547A	72	1	47-49	725.97							
547A	72	3	48-50	728.98							
547A	73	1	48-50	735.48							
547A	73	3	53-54.5	738.53							
547A	73	CC	23-25	740.36							

Tab. 3 - Distribution of planktonic foraminifera at DSDP Hole 547A; int. = intermediate specimens. See text for complete name of genera.

in northern Madagascar (Randrianasolo & Anglada 1989), and in the Fribourg Prealpes from where it was described (Mornod 1949; Caron & Spezzaferri 2006a). It has been reported to occur also in the Boreal Realm (Denmark: Hart 1979; South England: Hart & Harris 2012; North German Basin: Bornemann et al. 2107). Therefore, the rarity and absence of *Th. reicheli* in many Tethyan localities (northern Israel: Lipson-Benitah et al. 1997; southern Spain, central Tunisia and northern Italy: Wonders 1980; Poland: Peryt 1983; Dubicka & Machalski 2017) hamper a high resolution planktonic foraminiferal biozonation of the middle Cenomanian interval even at low latitudes and prevent detailed correlations among different depositional basins. Moreover, despite its very distinctive morphology, it has been rarely documented from outside the Mediterranean region, except in the western North Atlantic Ocean, Blake Nose (Bellier et al. 2000), and has never been identified in the U.S.

Western Interior Seaway (Pessagno 1969; Eicher & Worstell 1970; Denne et al. 2014) and northern California (Douglas 1969). On the contrary, the LO of *Rt. cushmani* is generally well recorded in upper Cenomanian sediments in the Tethyan and Boreal realms, although sometimes it has been reported as difficult to detect because of the presence of common specimens that are morphologically transitional with its ancestor *Rotalipora montsalvensis* (Ando et al. 2015; Erbacher et al. 2020).

The reliability for correlation of the bioevents identified in the studied sections is analyzed applying the graphic correlation method. Comparison between the Monte Petrano section and DSDP Hole 547A (Fig. 6) shows that all bioevents are likely reliable events as demonstrated by the significant high correlation coefficient of the linear regression curve ($R^2= 0.9666$). The sequence of bioevents observed at the Monte Petrano section is compared with those

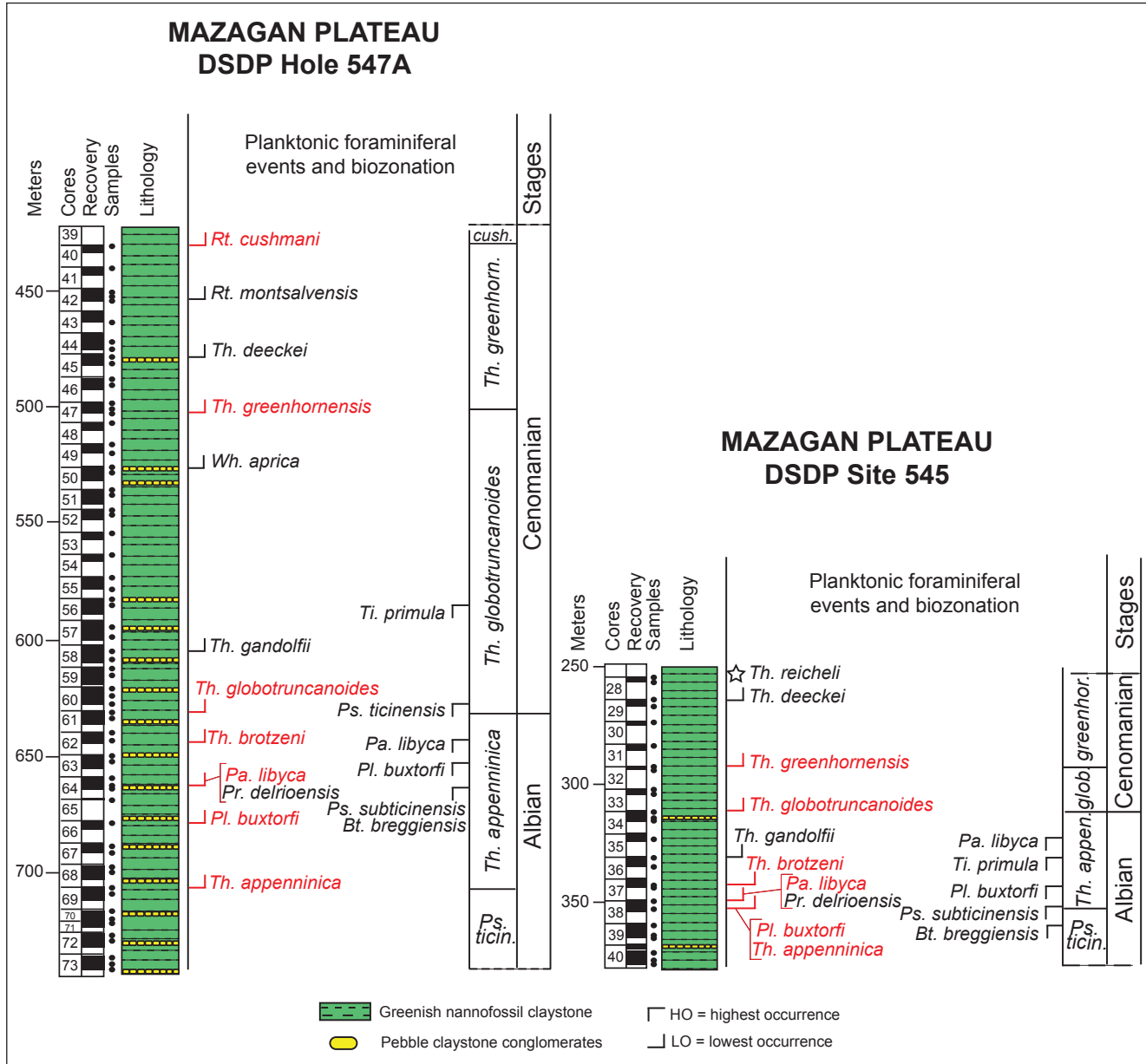


Fig. 5 - Planktonic foraminiferal biostratigraphy at DSDP Hole 547A and Site 545. In red are the common and stratigraphically ordered bioevents that are interpreted as reliable for regional and interregional correlation. Lithostratigraphy is according to the sedimentological description by Hinz et al. (1984). Star = occurrence of *Th. reicheli* according to Leckie (1984). *Ps. ticin.* = *Ps. ticinensis*; *Th. appen.* = *Th. appenninica*; *glob.* = *Th. globotruncanoides*; *Th. greenborn., greenborn.* = *Th. greenbornensis*; *cush.* = *Rt. cushmani*.

documented at the Bottaccione section in order to test the distribution of planktonic foraminifera within the same sedimentary basin. Results reveal that in the Umbria-Marche Basin the LOs of *Th. reicheli* and *Th. greenbornensis* are almost coincident and the LO of *Rt. cushmani* precedes the HO of *Th. reicheli* (Fig. 6). The very close first occurrence of *Th. reicheli* and *Th. greenbornensis* observed in the Umbria-Marche Basin is also documented from the Romandes Prealps in Switzerland (Strasser et al. 2001), in northern Israel (Lipson-Benitah et al. 1997), and Lybya (Barr 1972). The offset between the LOs of *Th. reicheli* and *Th. green-*

bornensis and the LO of *Rt. cushmani* and HO of *Th. reicheli* (Fig. 6) indicates that the latter bioevents occur either earlier at the Bottaccione section or are delayed at Monte Petrano. The possible presence of an unconformity or of an interval of reduced sedimentation rate in both sections cannot be excluded, although no lithological or bio- and chemostratigraphic evidence has been observed in the present and previous studies (e.g., Premoli Silva & Sliter 1995; Coccioni & Premoli Silva 2015; Gambacorta et al. 2015).

Based on the above observations we retain the LO of *Rt. cushmani* as a reliable zonal event defining

DSDP LEG 79 - SITE 545				AGE		PLANKTONIC FORAMINIFERA ZONE	
CORE	SECTION	INTERVAL (cm)	DEPTH (mbsf)	AGE	PLANKTONIC FORAMINIFERA ZONE		
545	28	1	10-12				
545	28	1	47-49				
545	28	CC	10-12				
545	29	1	18-22				
545	29	CC	4-7				
545	30	1	25-28.5				
545	31	1	25-27				
545	32	1	34-37				
545	32	CC	4-8				
545	33	1	99-103				
545	33	CC	7-9				
545	34	1	123-125				
545	34	3	61.5-64				
545	34	CC	1-4				
545	35	2	69-74				
545	36	1	145-150				
545	36	CC	10-13				
545	37	3	50-53				
545	37	CC	2.5-5				
545	38	1	89-91				
545	38	3	90-92				
545	39	1	96-98				
545	39	5	23-25				
545	40	5	8-10				
545	40	6	57-60				

Tab. 4 - Distribution of planktonic foraminifera at DSDP Site 545; int. = intermediate specimens. See text for complete name of genera.

the base of the *Rt. cushmani* Zone and we tentatively consider the LOs of *Th. reicheli* and *Th. greenbornensis* as interchangeable events, pending additional studies to verify their simultaneous or very close lowest occurrences from other Tethyan and Boreal localities. Therefore, with the aim to improve the planktonic foraminiferal biozonation and its applicability in different paleogeographic settings, we identify the *Th. greenbornensis* Zone following Postuma (1971) as the stratigraphic interval between the LO of *Th. greenbornensis* and the LO of *Rt. cushmani* to replace the *Th. reicheli* Zone of previous Tethyan biozonations (e.g., Premoli Silva & Sliter 1995; Robaszynski & Caron 1995).

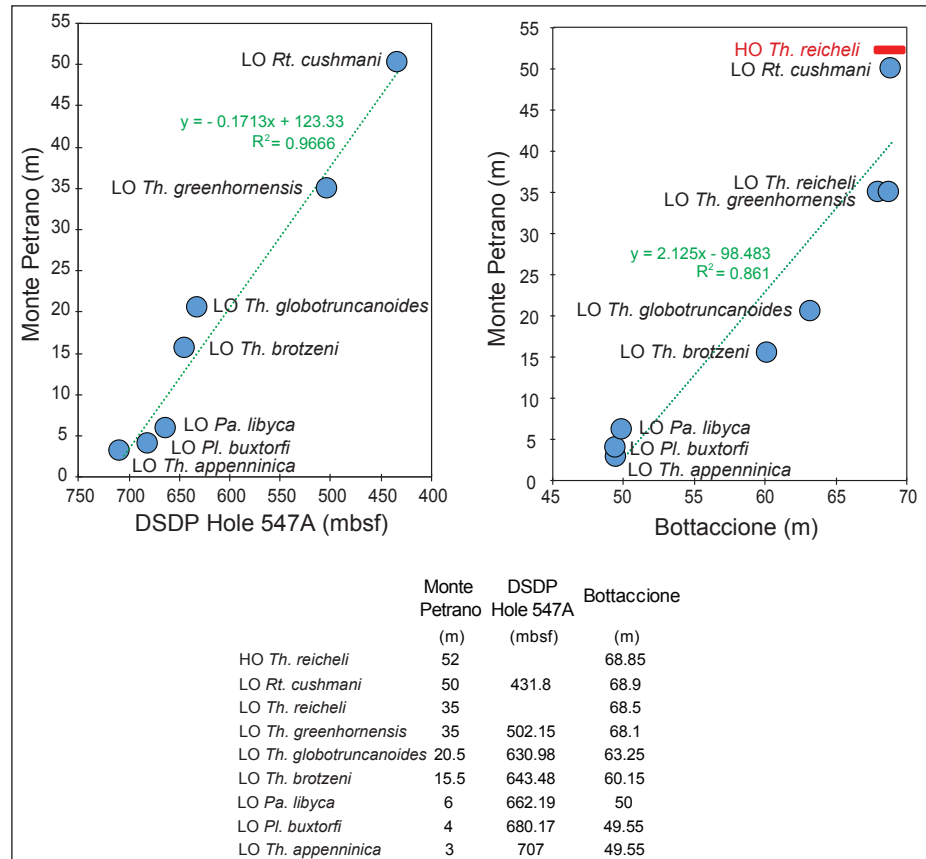
Remarks on planktonic foraminiferal events that are unreliable for correlation

Additional bioevents that occur at different stratigraphic positions in the studied sections include the HO (Figs. 4 and 5) of *Pseudothalmanninella subticinensis*, *Biticinella breggiensis*, *Pseudothalmanninella*

ticinensis, *Pl. buxtorfi*, *Pa. libyca*, *Ticinella primula*, *Ticinella madecassiana*, and the LOs of *Praeglobotruncana delrioensis*, *Thalmaninella gandolfii*, *Thalmaninella deeckei*, *Rt. montsalvensis* and *Whiteinella* species of which *Wh. aprica* is the first representative. The discrepancies in the identification of the disappearance level of these species were also observed in other stratigraphic sections located in different paleogeographic area (Umbria-Marche Basin: Bottaccione section, Coccioni & Premoli Silva 2015; Vocontian Basin: Mont Risou, Kennedy et al. 2004; western North Atlantic Ocean: Blake Nose, Petrizzo & Huber 2006a; Tunisia: Kaalat Senan, Robaszynski et al. 1993, 2008) confirming the general consensus on the unreliability of last occurrence events in biostratigraphy.

Causes of the diachroneity of the above listed Albian-Cenomanian planktonic foraminiferal events may be ascribed to mistakes in taxon identifications due to morphologic similarities between species, especially when preservation is poor (e.g., *Th. gandolfii*

Fig. 6 - Graphic correlation of the common planktonic foraminiferal events between the Monte Petrano section and Hole 547A and between Monte Petrano and the Bottaccione section. A best-fit regression curve (in green) is applied. LO = Lowest Occurrence, HO = Highest Occurrence.



and *Th. deeckeii*, both planoconvex form, Petrizzo et al. 2015; www.mikrotax.org), to taxonomic similarities between ancestor and descendant species coupled with the presence of common intermediate specimens between species that are subjectively identified at the species level (e.g., phyletic lineages from *Ps. subticinensis* to *Ps. ticinensis* and from *Rt. montsalvensis* to *Rt. cushmani*, see González-Donoso et al. 2007). Moreover, the stratigraphic distribution of species could be controlled by environmental changes that especially affect species with strict ecological preferences such as *Pa. libyca* and ticinellids that are the warmest surface dwellers species in the upper Albian - lower Cenomanian interval (Petrizzo et al. 2008). Another reason could be the different speciation timing in new evolving taxa that are thus reported to occur at different stratigraphic levels. For instance, the evolutionary appearance of *Whiteinella* species is documented either in the *Th. globotruncanoides* and *Th. reicheli* Zone (this study; Lipson-Benitah et al. 1997) or in the *Rt. cushmani* Zone (Premoli Silva & Sliter 1995; Tur et al. 2001), as well as the appearance of *Pr. delrioensis* is recorded either near the top of the *Ps. ticinensis* Zone (this study; Premoli Silva & Sliter 1995) or within the *Th. appenninica* Zone (this study; Petrizzo & Huber 2006a; Gale et al. 2011) (Figs. 4 and 5).

Description of the biozones

Our biozones definitions follow Premoli Silva & Sliter (1995) and Robaszynski & Caron (1995) except for the Cenomanian stratigraphic interval where we use the *Th. greenhornensis* Zone (Postuma 1971) as a replacement of the *Th. reicheli* Zone. The most significant planktonic foraminiferal species are illustrated in Plates 1-12 and discussed in the Taxonomic Remarks. Biozones are described below in stratigraphic order from bottom to top.

Pseudothalmaninella ticinensis Partial Range Zone

Definition: Interval between the LO of *Ps. ticinensis* and the LO of *Th. appenninica*.

Author: Bolli (1966).

Remarks: Wonders (1980) used the LO of *Pl. praebuxtorfi* as marker event for the top of the zone.

The *Ps. ticinensis* Subzone was identified by Premoli Silva & Boersma (1977) spanning the stratigraphic interval from the LO of *Ps. ticinensis* at the base and the LO of *Pl. buxtorfi* at the top.

The base of the zone is not recorded in the studied sections because *Ps. ticinensis* is already present in the lowermost sample analyzed.

Composition of the assemblages: In the Umbria-Marche Basin, *Ps. ticinensis* is quite common.

The large-size fraction is dominated by *Bt. breggiensis*, *Ticinella digitalis* and *Ticinella aperta*, while *Muricobedbergella* (*Mu. astrepta* and *Mu. praelibya*), *Pseudoclavibedbergella simplicissima* and *Ti. primula* are the most abundant species in the small-size fraction. The genus *Praeglobotruncana* first appears in the upper part of the zone.

At Mazagan Plateau, *Ps. ticinensis* is frequent in the large-size fraction and quite common in the small-size fraction. The small-size fraction is dominated by *Ti. primula* and *Ti. madecassiana*, by the genus *Muricobedbergella*, especially *Mu. praelibya*, by *Pc. simplicissima* and by common “*Globigerinelloides*” *bentonensis* and “*Globigerinelloides*” *pulchellus*. *Ticinella* (*Ti. primula* and *Ti. madecassiana*) is also among the most abundant taxon in the large-size fraction together with *Ps. ticinensis* and *Ps. tehamaensis*. The genus *Biticinella* disappears in the upper part of the *Ps. ticinensis* Zone at DSDP Site 545, whereas its HO is documented within the *Th. appenninica* Zone at DSDP Hole 547A.

Stratigraphic distribution: Monte Petrano, meter 0 to meter 3 (3 m-thick); Le Brece, meter 0 to meter 1.4 (1.4 m-thick); DSDP 547A-73R-CC, 23-25 cm to 547A-69R-1, 50-52 cm (30.36 m-thick); DSDP 545-40R-6, 57-60 cm to 545-38R-3, 90-92 cm (22.99 m-thick).

Thalmaninella appenninica Partial Range Zone

Definition: Interval from the LO of *Th. appenninica* to the LO of *Th. globotruncanoides*.

Author: Robaszynski & Caron (1995).

Remarks: Bolli (1966), Robaszynski et al. (1979), Caron (1985), Sliter (1989) and Premoli Silva & Sliter (1995) used the LO of *Th. brotzeni* as marker event for the top of the zone, whereas Postuma (1971) selected the LO of *Th. greenbornensis*. Wonders (1980) identified this zone in between the HO of *Pl. buxtoni* and the LO of *Th. globotruncanoides*. The latter species, ignored for several years by many authors, was retained valid by Wonders (1980) that instead considered *Th. brotzeni* a junior synonym of *Th. greenbornensis*. Later Robaszynski et al. (1993) regarded *Th. brotzeni* a junior synonym of *Th. globotruncanoides* and, based on this synonymy, *Th. globotruncanoides* replaced *Th. brotzeni* as marker species of the zone (Robaszynski & Caron 1995; Gale et al. 1996), and its LO was indicated as the primary criterion for identifying the base of the Cenomanian (Kennedy et al. 2004). However, because later studies have demonstrated that they are two different species (Caron & Premoli Silva 2007; Petrisso et al. 2015), the LO of *Th. globotruncanoides* is

used as marker taxon to define the top of the *Th. appenninica* Zone whereas the appearance of *Th. brotzeni* falls stratigraphically lower as confirmed by the results of this study (Figs. 4 and 5).

Composition of the assemblages: In the Umbria-Marche Basin, rotaliporids, including *Th. appenninica*, increase in abundance until the upper part of the zone and are the most common planktonic foraminifera in the large-size fraction together with the genera *Planomalina* and *Muricobedbergella*. In the small-size fraction, the genus *Praeglobotruncana* is abundant toward the top of the zone and is the most common genus together with *Planomalina* and *Muricobedbergella*. Moreover, *Bt. breggiensis* and *Pa. libyca* show a short stratigraphic distribution as the former disappears in the lowermost *Th. appenninica* Zone and the latter appears in the middle part of the zone.

At Mazagan Plateau, in both size fractions, *Th. appenninica* shows high fluctuations in abundance from common to rare and the assemblage is dominated by *Ti. primula*, *Pc. simplicissima* and “*Gl.*” *bentonensis*. In addition, in the large-size fraction, *Ps. ticinensis* and *Ps. tehamaensis* also show noteworthy abundances but in the middle and upper part of the zone, respectively, they are not present. The total stratigraphic range of *Pl. buxtoni* e *Pa. libyca* is included in this zone. At DSDP Site 545 the disappearance of *Ticinella* species are recorded in the upper part of the zone.

Stratigraphic distribution: Monte Petrano, meter 3 to meter 20.5 (17.5 m-thick); Le Brece, meter 1.4 to meter 15 (13.6 m-thick); DSDP 547A-69R-1, 50-52 cm to 547A-61R-1, 48-50 cm (76.02 m-thick); DSDP 545-38R-3, 90-92 cm to 545-34R-1, 123-125 cm (40.55 m-thick).

Thalmaninella globotruncanoides Partial Range Zone

Definition: Interval from the LO of *Th. globotruncanoides* to the LO of *Th. greenbornensis*.

Author: defined here.

Remarks: This zone was previously identified using different bioevents to mark the upper boundary. Sigal (1977) and Wonders (1980) used the LO of *Rt. cushmani*. Robaszynski & Caron (1995) and Coccioni & Premoli Silva (2015) identified the LO of *Th. reicheli* as the bioevent for the top of the zone. The marker species is frequent in the entire stratigraphic interval.

Composition of the assemblages: In the Umbria-Marche Basin rotaliporids comprise the most abundant group in the large-size fraction and reach

their maximum abundance in the middle of the zone where the number of specimens of *Praeglobotruncana* increases. The small size-fraction is dominated by *Muricobedbergella* and in the upper part of the zone by *Praeglobotruncana*, where planispirals are generally more common than in the remaining part of the section. The genus *Ticinella* disappears in the lower part of the zone.

At Mazagan Plateau, *Th. globotruncanoides* is quite rare in the small size-fraction in the lower part of the zone. It increases in abundance and size towards the upper part of the zone. The assemblage in the large size-fraction is dominated by *Th. globotruncanoides* and *Pr. delrioensis*, while the small size-fraction is dominated by *Pc. simplicissima*, *Muricobedbergella delrioensis* and by *Th. brotzeni* and “*Gl.*” *bentonensis*.

Stratigraphic distribution: Monte Petrano, meter 20.5 to meter 35 (14.5 m-thick); Le Brece, meter 15 to meter 19.97 (top of the section; 4.97 m-thick); DSDP 547A-61R-1, 48-50 cm to 547A-47R-CC, 15-16.5 cm (128.83 m-thick); DSDP 545-34R-1, 123-125 cm to 545-32R-1, 34-37 cm (19.89 m-thick).

Thalmaninella greenbornensis Partial Range Zone

Definition: interval from the LO of *Th. greenbornensis* and the LO of *Rt. cushmani*.

Author: Postuma 1971.

Remarks: This zone was used by other authors to identify intervals at different stratigraphic positions within the Cenomanian probably because of mistaken identifications of *Th. greenbornensis* being the species very similar to its direct ancestor *Th. globotruncanoides* (Ando & Huber 2007). For instance, Pessagno (1967) named the *Rt. cushmani*-*Th. greenbornensis* Subzone based on the presence of both species without defining the lower and upper bioevents. Van Hinte (1972) identified the *Th. gandolfii* - *Th. greenbornensis* Zone in between the HO of *Pl. buxtorfi* at the base and the HO of *Th. greenbornensis* at the top. The *Th. greenbornensis* Zone was identified by Premoli Silva & Boersma (1977) comprising the stratigraphic interval from the LO of *Th. greenbornensis* and the LO of *Whiteinella alpina* and within the stratigraphic range of *Rt. cushmani*. Premoli Silva & Sliter (1995) used the *Th. greenbornensis* Subzone to identify the interval from the HO of *Th. reicheli* and the LO of *Dicarinella algeriana* in the lower part of the *Rt. cushmani* Zone.

The *Th. greenbornensis* Zone, as defined by Postuma (1971), is here used to replace the *Th. reicheli* Zone of the Tethyan biozonation (Premoli Silva &

Sliter 1995; Robaszynski & Caron 1995) because *Th. reicheli* is rare and shows a scattered stratigraphic distribution in the Monte Petrano section where its LO coincides with the LO of *Th. greenbornensis*. At Mazagan Plateau *Th. reicheli* has not been observed in this study although a single specimen was reported by Leckie (1984) at the top of DSDP Site 545 (Fig. 5), moreover, we document the LO of *Th. greenbornensis* at about the same stratigraphic level as in Leckie (1984).

Composition of the assemblages: At Monte Petrano rotaliporids dominate the large-size fraction (*Th. globotruncanoides*, *Th. greenbornensis* and *Rt. montsalvensis*) together with *Praeglobotruncana* in the lower part of the zone. In the small-size fraction, rotaliporids are the most abundant group and *Praeglobotruncana* become very common in the upper part of the zone. *Thalmaninella greenbornensis* and species belonging to the genus *Whiteinella* appear at the base of the zone.

At Mazagan Plateau, the assemblage in the large size-fraction is dominated by *Thalmaninella*, particularly *Th. globotruncanoides* and to a lesser extent by *Pr. delrioensis*. On the contrary, the small size-fraction is dominated by *Pc. simplicissima*, *Mu. delrioensis*, *Th. brotzeni*, and “*Gl.*” *bentonensis*.

Stratigraphic distribution: Monte Petrano, meter 35 to meter 50 (15 m-thick); DSDP 547A-47R-CC, 15-16.5 cm to 547A-40R-1, 30.5-33 cm (70.5 m-thick); DSDP 545-32R-1, 34-37 cm to 545-28R-1, 10-12 cm (top of the section) (30.24 m-thick).

Rotalipora cushmani Total Range Zone

Definition: Interval comprising the total range of the nominate taxon.

Author: Bolli (1966).

Remarks: Van Hinte (1972), Premoli Silva & Sliter (1995) and Coccioni & Premoli Silva (2015) defined the base of the zone using the HO of *Th. reicheli*. The LOs of *Th. greenbornensis* and *Th. deekiei* were used by Premoli Silva & Boersma (1977) to mark the top of the zone.

Rotalipora cushmani is observed until the top of the stratigraphic intervals studied at Monte Petrano and at DSDP Hole 547A, therefore the upper boundary of the biozone is not recorded.

Composition of the assemblages: At Monte Petrano, rotaliporids, specifically the zonal marker species and *Th. greenbornensis* are the most frequent taxa in the large-size fraction, followed by *Praeglobotruncana*. A specimen resembling *Th. reicheli* is observed only in thin sections near the base of the zone.

The small size-fraction is dominated by *Praeglobotruncana*. The appearance of *Dicarinella* in the middle part of the zone is correlated to a decrease in abundance of *Praeglobotruncana* in both size fractions.

Stratigraphic distribution: Monte Petrano, meter 50 to meter 65 (top of the studied section; 15 m-thick). At Mazagan Plateau only the sample DSDP 547A-40R-1, 30.5-33 cm is assigned to this Zone.

IDENTIFICATION OF THE ALBIAN/ CENOMANIAN BOUNDARY, OAE 1d AND MCE

The Albian/Cenomanian boundary is defined at the Mont Risou section in the Vocontian Basin (Hautes-Alpes, southeast France) based on the lowest occurrence of *Th. globotruncanoides* which is the primary criterion for definition of the base of the Cenomanian GSSP (Kennedy et al. 2004). The planktonic foraminiferal biostratigraphy performed in this study is correlated with the calcareous nannofossil zonation and chemostratigraphic data of Monte Petrano and Le Breccie sections (Russo 2013; Giorgioni et al. 2015; Gambacorta et al. 2015, 2020) and of DSDP Hole 547A (Nederbragt et al. 2001; Chin & Watkins 2019). Moreover, the Umbria-Marche sections and DSDP Hole 547A are also compared with the Mont Risou section (Gale et al. 1996; Kennedy et al. 2004; Petruzzo et al. 2015) and the Blake Nose ODP Hole 1050C drilled in the western North Atlantic Ocean (Watkins & Bergen 2003; Watkins et al. 2005; Petruzzo & Huber 2006a; Petruzzo et al. 2008; Ando et al. 2009; Petruzzo et al. 2015) in order to establish an integrated stratigraphic framework for different paleogeographic areas and to verify the precision of the correlation between biostratigraphic and chemostratigraphic events (Fig. 7).

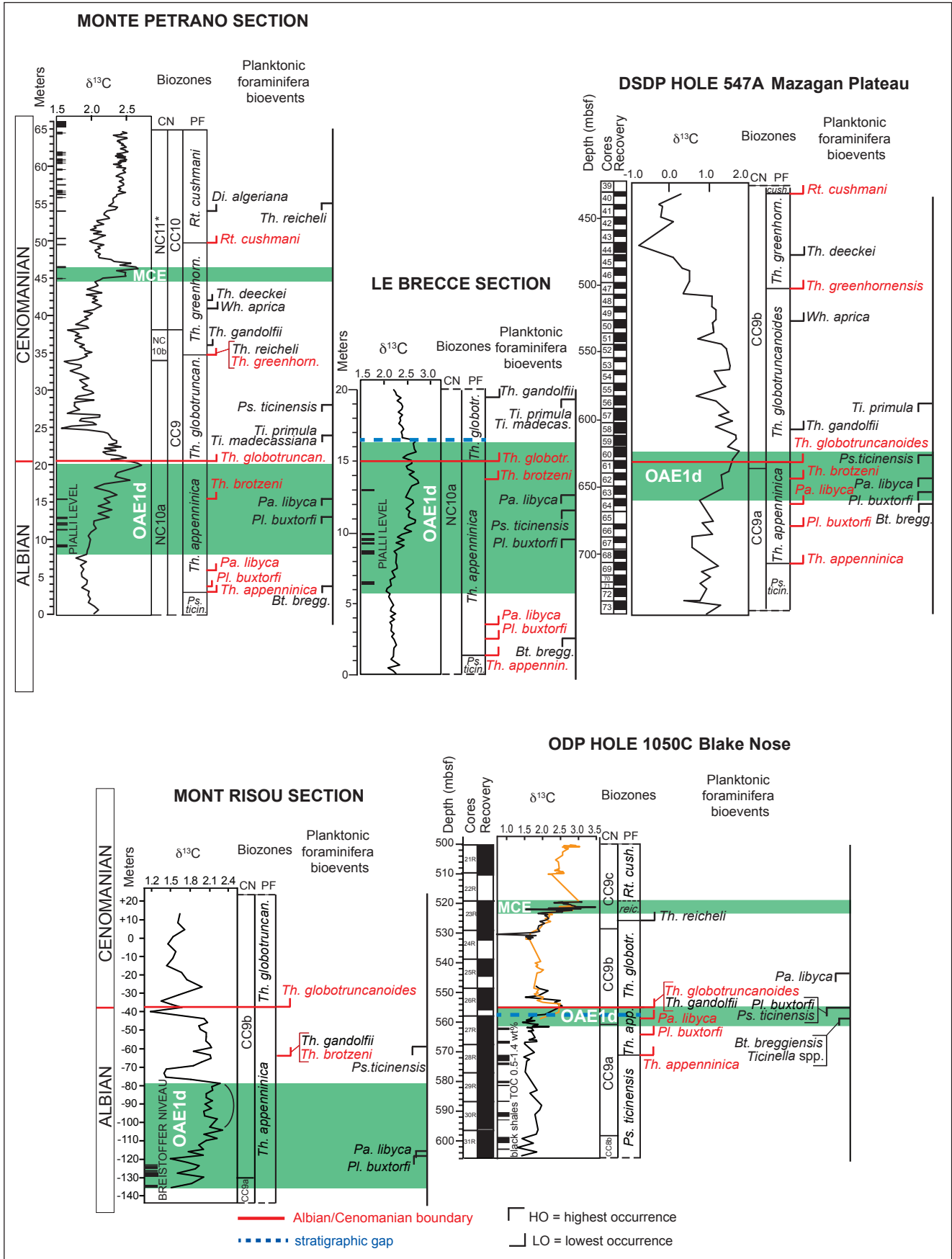
The Albian-Cenomanian boundary interval in the stratotype section at Mont Risou is marked by an extended plateau of increasing $\delta^{13}\text{C}$ values followed by a negative excursion of the carbon isotope value where the LO of *Th. globotruncanoides* is recorded. Precisely, the carbon isotope record shows a complex trend with a maximum value of 2.3‰ at -104 m, not corresponding to lithological changes, followed by a plateau of highest values that gradually decrease upward (Gale et al. 1996; Kennedy et al. 2004) (Fig. 7). A similar chemostratigraphic record characterized by increasing $\delta^{13}\text{C}$ values followed by a decreasing trend

is observed at the Monte Petrano and Le Breccie sections (Gambacorta et al. 2015, 2020), at Mazagan Plateau (Nederbragt et al. 2001) and at Blake Nose (Petruzzo et al. 2008; Ando et al. 2009).

Comparison of the bio- and chemostratigraphic events among sections highlights the following (Fig. 7): a) the base of the $\delta^{13}\text{C}$ excursion is identified within the stratigraphic range of *Pl. buxtorfi* in all sections; b) the maximum $\delta^{13}\text{C}$ value at Monte Petrano and DSDP Hole 547A falls just below and above the LO of *Th. globotruncanoides*, respectively, while at ODP Hole 1050C the maximum $\delta^{13}\text{C}$ value coincides with the LO of *Th. globotruncanoides*. At Mont Risou the positive excursion (plateau of highest values) can be correlated to an interval falling in the upper part of the *Th. appenninica* Zone, while at the Le Breccie section it falls at the stratigraphic gap in the faulted interval (Gambacorta et al. 2020).

The stratigraphic position of the LO of *Th. globotruncanoides* and the $\delta^{13}\text{C}$ maximum excursion show excellent correlation among the Umbria-Marche sec-

Fig. 7 - Integrated stratigraphy of the sections analysed in this study compared with the Mont Risou section (southeast France, Vocontian Basin) and ODP Hole 1050C (Blake Nose, western North Atlantic Ocean). Planktonic foraminiferal bioevents in red are interpreted to be reliable for correlation among sections. See text for the explanation of OAE 1d and MCE (green bands). Monte Petrano and Le Breccie: chemostratigraphy and calcareous nannofossils biostratigraphy from Gambacorta et al. (2015, 2020); planktonic foraminifera biostratigraphy from this study. DSDP Hole 547A: chemostratigraphy from Nederbragt et al. (2001); calcareous nannofossils biostratigraphy according to Chin & Watkins (2019); planktonic foraminiferal biostratigraphy from this study. Mont Risou: chemostratigraphy and calcareous nannofossil biostratigraphy from Gale et al. (1996) and Kennedy et al. (2004); planktonic foraminifera biostratigraphy from Kennedy et al. (2004) and Petruzzo et al. (2015). ODP Hole 1050C: chemostratigraphy from Petruzzo et al. (2008) and Ando et al. (2009), black curve = data based on planktonic foraminifera, orange curve = data based on coccolith fraction; calcareous nannofossils biostratigraphy from Watkins & Bergen (2003) and Watkins et al. (2005); planktonic foraminiferal biostratigraphy from Petruzzo & Huber (2006a), Petruzzo et al. (2008) and Ando et al. (2009). Blue dashed line = stratigraphic gap at the Le Breccie section according to Gambacorta et al. (2020) and at ODP Hole 1050C following Petruzzo & Huber (2006a). CN = calcareous nannofossils; PF = planktonic foraminifera; *Ti. madecassiana*; *Bt. bregg.* = *Bt. breggiensis*; *Th. appennin.*, *Th. app.* = *Th. appenninica*; *Rt. cush.* = *Rt. cushmani*; *reic.* = *Th. reichelti*; other abbreviations as in Figs. 4 and 5.



tions, the Mazagan Plateau and Blake Nose, in agreement with the record from the Bottaccione section (Sprovieri et al. 2013; Coccioni & Premoli Silva 2015), and the Calera Limestone in the Permanente Quarry in California (Robinson et al. 2008). In all these stratigraphic sections the LO of *Th. globotruncanoides* falls just above or below or is coincident with the maximum carbon isotope value. Moreover, the $\delta^{13}\text{C}$ profile throughout the Albian-Cenomanian stratigraphic interval is rather similar and with comparable amplitudes and absolute values in sections from the Boreal Realm (Speeton section, north-east England: Mitchell et al. 1996; Jarvis et al. 2006 and Anderten section, north Germany: Bornemann et al. 2017). On the contrary, in the Mont Risou section the maximum isotopic excursion values fall below the Albian/Cenomanian boundary, within the upper *Th. appenninica* Zone and above the HO of *Pl. buxtorfi*. Moreover, the sequence of bio- and chemostratigraphic events observed in the Mont Risou section is also seen in the Col de Palluel section (Gale et al. 2011) indicating that the relative positions of biotic and carbon isotope events are significantly different in the sedimentary sequences at the Hautes Alpes in southeast France compared to the other localities. Reasons are most likely a result of subtle differences in the Vocontian Basin environmental conditions, tectonic history, sedimentation rates and diagenetic history, and variable sampling density among stratigraphic sections.

In all the stratigraphic sections analysed in this study (Fig. 7) the carbon isotope positive anomaly observed throughout the upper *Th. appenninica* Zone roughly correlates with organic rich sediments named the Piali Level in the Umbria-Marche sections (e.g., Coccioni et al. 1987; Coccioni 2001; Coccioni & Galeotti 2003; Gambacorta et al. 2015, 2020; Giorgioni et al. 2015) and Breistroffer Niveau in the Vocontian Basin sections located in southeast France (e.g., Br  h  ret 1988; Gale et al. 1996; Giraud et al. 2003; Kennedy et al. 2004; Bornemann et al. 2005). However, black shales are also recorded within the *Th. appenninica* Zone in areas (Swiss Prealps: Strasser et al. 2001; Gargano promontory, Southern Italy: Luciani et al. 2004) where they are not accompanied by an obvious positive carbon isotope excursion to indicate that organic rich sediments are not necessarily the result of a perturbation of the global carbon cycle but may be related to local sedimentary conditions (F  llmi 2012).

The Piali Level and the Breistroffer Niveau represent the regional sedimentary expression of the lat-

est Albian OAE 1d (Erbacher & Thurow 1997) characterized by widespread occurrence of black shales, suggesting a possible global perturbation (e.g., Wilson & Norris 2001; Leckie et al. 2002; Bornemann et al. 2005; Gr  cke et al. 2006; Robinson et al. 2008; Jenkyns 2010; Giorgioni et al. 2015; Melinte-Dobrinescu et al. 2015). In fact, in addition to the Umbria-Marche Basin and Vocontian Basin, OAE 1d has been documented in the Boreal Realm (Speeton section in north-east England: Mitchell et al. 1996; Jarvis et al. 2006; Anderten section in north Germany: Bornemann et al. 2017), in Southern Tibet (Yao et al. 2018), in North America (U. S. Western Interior Basin: Gr  cke et al. 2006; Richey et al. 2018), in the east and west Pacific Ocean (Andean Basin, Peru: Navarro-Ramirez et al. 2015; Calera Limestone, California: Robinson et al. 2008; Yezo Group, Hokkaido, Japan: Takashima et al. 2004), and in the western and eastern Atlantic Ocean (Blake Nose: Wilson & Norris 2001; Watkins et al. 2005; Petrizzo et al. 2008; Mazagan Plateau: Nederbragt et al. 2001).

OAE 1d (Fig. 7) is identified as the interval between the starting point of the $\delta^{13}\text{C}$ excursion and the point or plateau of maximum $\delta^{13}\text{C}$ values, and the latter is often not associated with the deposition of black shales (e.g., Petrizzo et al. 2008; Gambacorta et al. 2015, 2020; Bornemann et al. 2005, 2017). The base of OAE 1d roughly coincides with the Piali Level at Monte Petrano and Le Breccie sections which consist of six dark black shales few centimeters thick interbedded with whitish limestone (Fiet et al. 2001; Giorgioni et al. 2015; Gambacorta et al. 2015, 2020). At DSDP Hole 547A the onset of OAE 1d is associated with the occurrence of compact marl and mudstone with 0.5-1.0 wt % TOC content (Deroo et al. 1984; Nederbragt et al. 2001). At Mont Risou the base of OAE 1d is equated at the Breistroffer Niveau which is composed of five relatively organic-rich, dark, laminated marl beds up to 0.7 m thick alternating with dark gray bioturbated marl across a 10 m interval (Gale et al. 1996). At Blake Nose Hole 1050C the base of OAE 1d is placed at the top of an about 40 m-thick laminated dark claystone with 0.5-1.4 wt % TOC content alternating with olive-gray nannofossil claystone (Barker et al. 2001).

The beginning of OAE 1d always falls within the stratigraphic range of *Pl. buxtorfi*, whereas the end of the event falls at different biostratigraphic levels: at the Monte Petrano section it is observed in the uppermost *Th. appenninica* Zone and very close to the base

of the *Th. globotruncanoides* Zone, at the Mont Risou sections it falls in the uppermost *Th. appenninica* Zone, at the Le Brece section and DSDP Hole 547A it is correlated to the lowermost *Th. globotruncanoides* Zone and at ODP Hole 1050C it coincides with the Albian/Cenomanian boundary (Fig. 7). Our observations may suggest that the duration of OAE 1d at the various localities depends strongly on local palaeoceanographic conditions and is likely to be somewhat dissimilar when we compare different oceanographic settings and basins.

The Mid Cenomanian Event (MCE) is a positive carbon isotope excursion frequently associated with distinctive lithological changes but not widespread formation of organic-rich sediments (Jenkyns et al. 1994; Coccioni & Galeotti 2003) that was first described by Paul et al. (1994) in sections in North West Europe. Subsequently, it has been identified in numerous sections in the Boreal Realm, in the Tethys and Atlantic Ocean (e.g. Mitchell et al. 1996; Erbacher et al. 1996; Erbacher & Thurow 1997; Mitchell & Carr 1998; Rodriguez-Lazaro et al. 1998; Stoll & Schrag 2000; Coccioni & Galeotti 2003; Voigt et al. 2004; Jarvis et al. 2006; Wilmsen 2007; Ando et al. 2009; Friedrich et al. 2009; Gertsch et al. 2010; Hardas et al. 2012; Reboulet et al. 2013; Giraud et al. 2013; Gambacorta et al. 2015).

In the Monte Petrano section, the MCE is identified according to Gambacorta et al. (2015) and falls within the stratigraphic range of *Th. reicheli* (Fig. 7) in agreement with sections from the Boreal Realm (e.g. Speeton, UK: Mitchell 1996; North German Basin: Bornemann et al. 2017), Morocco (Tarfaya: Beil et al. 2018) and Atlantic Ocean (Blake Nose ODP Hole 1050C: Ando et al. 2009). However, comparison of the biostratigraphic and carbon isotope records between the English Chalk and the Umbria-Marche Basin (Bottaccione and Gorgo a Cerbara sections) reveals apparent interregional difference in the duration of the stratigraphic range of *Th. reicheli* and thus of the stratigraphic position of the MCE. In fact, the MCE in the Boreal Realm has been recorded in the *Acanthoceras rhotomagense* ammonite Zone (Paul et al. 1994; Mitchell et al. 1996; Jarvis et al. 2006) that corresponds to the interval between the *Th. reicheli* and the lower *Rt. cushmani* zones in the Tethyan biozonation (Gradstein et al. 2012; Ogg et al. 2016), whereas the MCE is reported to fall in the middle-upper part of the *Rt. cushmani* Zone in the Umbria-Marche Basin (Coccioni & Galeotti 2003; Sprovieri et al. 2013; Coccioni & Premoli Silva 2015).

TAXONOMIC REMARKS

Foraminifera genera and species with authors and years identified in the studied sediments (Tabs. 1-4) are listed according to their stratigraphic order of appearance in the geological record. Comments are included for some genera and species to clarify the taxonomic concepts followed in this study and for taxa which taxonomic status is currently under revision. Remarks on significant morphological and evolutionary features are provided when necessary. Significant planktonic foraminiferal species are illustrated in Plates 1-12.

Genus *Ticinella* Reichel, 1950.

Type species: *Anomalina roberti* Gandolfi, 1942, pp. 100, 134, 150, pl. 2, figs. 2a-c.

Ticinella madecassiana Sigal, 1966, p. 197, pl. 3, figs. 7ab-10ab (upper Albian, Diego-Suarez well, north of Mount Raynaud, Madagascar).

Remarks. According to Huber & Leckie (2011), *Ti. madecassiana* is the intermediate species in the phyletic lineage from *Microbedbergella rischi* to *Ti. primula* based on the observation of transitional morphotypes characterized by the lack of supplementary apertures, larger size and density of pores than in *Mi. rischi*, and by the development of a ticinellid wall texture characterized by being thicker. However, in the studied sections *Ti. madecassiana* is abundant and very distinctive but no forms phylogenetically related to *Mi. rischi* were observed.

Ticinella primula Luterbacher in Renz et al., 1963, p. 1085, fig. 4 (upper Albian, western Switzerland).

Ticinella aperta Sigal, 1966, p. 200-201, pl. 6, figs. 11-13 (upper Albian, Diego-Suarez well, north of Mount Raynaud, Madagascar).

Remarks. The species characterized by the elongation of the last chamber was described as *Ti. raynaudi* var. *aperta* by Sigal (1966) and is here erected to species level.

Ticinella digitalis Sigal, 1966, p. 200-201, pl. 6, figs. 6-8 (upper Albian, Diego-Suarez well, north of Mount Raynaud, Madagascar).

Remarks. The species characterized by having chambers radially elongated was described as *Ti. raynaudi* var. *digitalis* by Sigal (1966) and is here erected to species level.

Ticinella roberti (Gandolfi, 1942), pp. 100, 134, 150, pl. 2, figs. 2a-c (Aptian or Albian, Gorge of the

Breggia River, Canton Ticino, southeastern Switzerland).

Remarks. *Ticinella roberti* is a very rare species, observed only in the Mazagan Plateau sediments.

Ticinella moulladei Premoli Silva et al., 2009, p. 136, pl. 3 fig. 1 (upper Albian, Diego-Suarez well, north of Mount Raynaud, Madagascar).

Remarks. This species differs from *Ti. primula* by having more chambers and a stronger ornamentation and from *Ti. roberti* by possessing a low and loosely coiled trochospire.

Genus *Globigerinelloides* Cushman & ten Dam, 1948.

Type species: *Globigerinelloides algeriana*, Cushman & ten Dam, 1948, p. 42-43.

Remarks. There is a general consensus among specialists on the need of taxonomic revision of the genus. Traditionally all planispiral species are included in the Albian to Maastrichtian genus *Globigerinelloides* according to the coiling mode even if there are inconsistencies in the taxonomic classification as species included in the genus possess different wall textures and are not phylogenetically-related (see explanations and discussion in Petrizzo et al. 2017). However, for the time being we include the planispiral taxa in the genus *Globigerinelloides* to avoid the usage of an informal name although we are aware of a distribution gap of the genus across the upper Aptian-lower Albian stratigraphic interval (Huber & Leckie 2011; Petrizzo et al. 2012, 2013). Specifically, the lack of planispiral taxa at the Aptian/Albian boundary clearly indicates the absence of evolutionary relationships between the Aptian *Globigerinelloides* and the planispiral taxa that first appear in the middle Albian and are characterized by a different wall texture. The definition of a new genus or genera to accommodate the polyphyletic Albian to Maastrichtian planispiral taxa is certainly needed but will require further studies to reconstruct the ancestor-descendant relationships among the various species. Therefore, the genus name is quoted in the text and figures to separate the Albian-Cenomanian from the Aptian species.

“Globigerinelloides” bentonensis (Morrow, 1934), p. 201, pl. 30, figs. 4a-b (Cenomanian, Hartland member of Greenhorn Limestone of Kansas).

“Globigerinelloides” pulchellus (Todd & Low, 1964), p. 409, pl. 1, figs. 9a-b (Cenomanian?, Puerto Rico Trench).

Remarks. The species, characterized by having a pustulose wall texture, is interpreted as the ancestor of the *Planomalina* lineage (Petrizzo & Huber 2006b). Common transitional specimens between *“Gl.” pulchellus* and *Pl. praebuxtorfi* were observed in the studied sections.

“Globigerinelloides” ultramicrus (Subbotina, 1949), p. 33, pl. 2, figs. 17-18 (Cenomanian, Kapustnaya Gorge, southern slope of Caucasus, Russia).

“Globigerinelloides” alvarezzi (Eternod Olvera, 1959), p. 91-92, pl. 4, figs. 5-7 (Campanian – Maastrichtian, well Bustos, Tumulipais, Mexico).

Genus *Biticinella* Sigal, 1956.

Type species: *Anomalina breggiensis* Gandolfi, 1942, p. 102, pl. 3, fig. 6.

Biticinella subbreggiensis Sigal, 1966, p. 193, pl. 1 figs. 1-7, pl. 2 fig. 2 (upper Albian, Gorge of the Breggia River, Canton Ticino, southeastern Switzerland; Mount Raynaud, Madagascar).

Remarks. *Biticinella subbreggiensis* is a distinctive species and is easily distinguished by its descendant *Bt. breggiensis* being low trochospiral instead of planispiral (Sigal 1966).

Biticinella breggiensis (Gandolfi, 1942), p. 102, pl. 3, fig. 6 (Albian-lower Cenomanian, Gorge of the Breggia River, Canton Ticino, southeastern Switzerland).

Genus *Muricohedbergella* Huber & Leckie, 2011.

Type species: *Globigerina cretacea* var. *delrioensis* Carsey, 1926, p. 43-44.

Muricohedbergella delrioensis (Carsey, 1926), p. 43-44 (lower Cenomanian, Del Rio Clay, Grayson Formation, Austin, TX).

Remarks. This species has been misidentified for long time because it was erected by Carsey (1926) who did not designate the repository of the type species (Pessagno 1976). Consequently, Plummer (1931) reported *Mu. delrioensis* as missing. Two neotypes were erected first by Longoria (1974) and then by Masters (1976) and both were deposited at the Smithsonian Museum of Natural History. The neotype erected by Longoria had the priority (Masters 1977) and was chosen as valid neotype, but according to Petrizzo & Huber (2006a) it has been lost and only the invalid neotype of Masters remained stored in the repository. The two neotypes mainly differs for the elevation of the trochospire that is slightly higher in the specimen by Longoria. Specimens resembling both neotypes

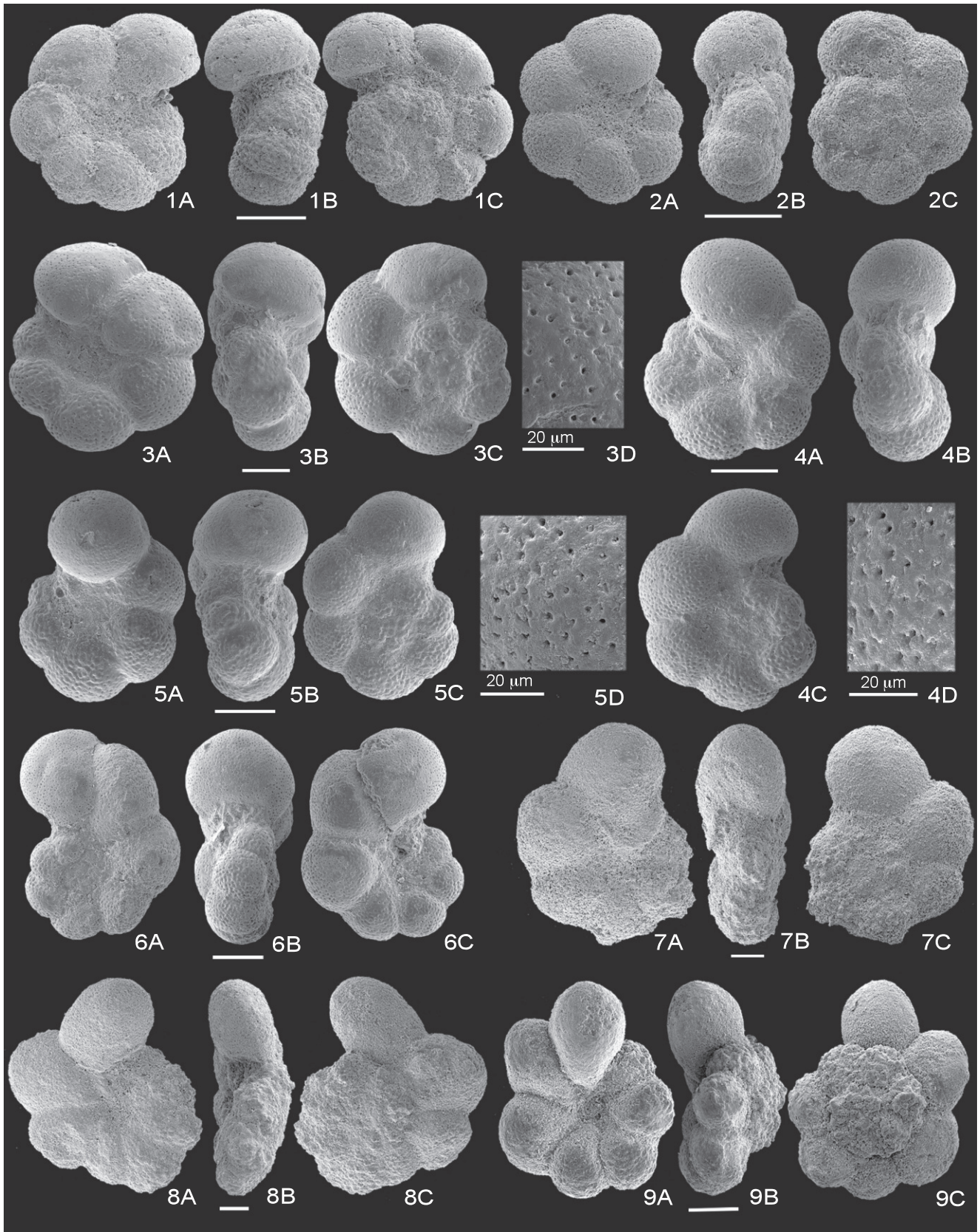


PLATE 1

1 - A-C, *Ticinella madecassiana*, Sample MP0. 2 - A-C, *Ticinella madecassiana*, Sample MP6. 3 - A-D, *Ticinella madecassiana*, Sample DSDP 79-547A-73R-3, 53-54.5 cm. 4 - A-D, *Ticinella primula*, Sample DSDP 79-547A-73R-3, 53-54 cm. 5 - A-D, *Ticinella primula*, Sample DSDP 79-547A-71R-1, 50.5-52 cm. 6 - A-C, *Ticinella primula*, Sample DSDP 79-545-39R-5, 23-25 cm. 7 - A-C, *Ticinella aperta*, Sample MP2. 8 - A-C, *Ticinella digitalis*, Sample MP2. 9 - A-C, *Ticinella digitalis*, Sample B0.01. Scale bar 100 µm unless indicated otherwise.

are included in the species concept adopted in this study. However, specimens close to the neotype by Longoria (1974) are more abundant and show a continuous stratigraphic record.

Muricohedbergella planispira (Tappan, 1940), p. 12, pl. 19, fig. 12 (Cenomanian, Grayson Formation, Denton County, TX).

Muricohedbergella wondersi (Randrianasolo & Anglada, 1989), p. 806, pl. 1, figs. 1-3 (upper Albian, Antsiranana, northern Madagascar).

Remarks. According to Petrizzo & Huber (2006b), it is considered the ancestor of the *Planomalina* phyletic lineages (*Mu. wondersi* – “*Gl.*” *pulchellus* – *Pl. praebuxtorfi* – *Pl. buxtorfi*). Transitional specimens between *Mu. wondersi* and “*Gl.*” *pulchellus* characterized by having trochospiral test, pustules concentrated at the beginning of the last whorl and slightly curve sutures are observed in the studied assemblages.

Muricohedbergella astrepta (Petrizzo & Huber, 2006a), p. 182 pl. 6, figs. 1a-c and 4a-c (upper Albian, Blake Nose Escarpment, Western North Atlantic Ocean, ODP Hole 1050C).

Muricohedbergella praelibya (Petrizzo & Huber, 2006a), p. 185, pl. 5, figs. 1a-c to 5a-c (upper Albian, Blake Nose Escarpment, Western North Atlantic Ocean, ODP Hole 1050C).

Remarks. According to Georgescu & Huber (2006), *Mu. praelibya* is regarded as the ancestor of *Pa. libya* by the developing of costellae from aligned pustules.

Muricohedbergella blakensis (Petrizzo & Huber, 2006a), p. 182, pl. 4, figs. 5a-c, 6a-c (upper Albian, Blake Nose Escarpment, Western North Atlantic Ocean, ODP Hole 1052E).

Remarks. Specimens with 5, 6 and 7 chambers in the last whorl have been observed (Tabs. 1-4).

Genus *Pseudoclavibedbergella* Georgescu, 2009.

Type species: *Hedbergella amabilis* Loeblich & Tappan, 1961, p. 274, pl. 3, figs. 1-7 and 9.

Pseudoclavibedbergella simplicissima (Magné & Sigal, 1954), p. 487, pl. 14, fig. 11 (lower Cenomanian, Rhazouane, Tunisia).

Genus *Pseudothalmanninella* Wonders, 1978.

Type species: *Globotruncana ticinensis* Gandolfi, 1942, p. 113-135, pl. 2, figs. 3.

Pseudothalmanninella subticinensis (Gandolfi, 1957), p. 59, pl. 8, fig. 1 (upper Albian or lowermost Ceno-

manian, Gorge of the Breggia River, Canton Ticino, southeastern Switzerland).

Pseudothalmanninella ticinensis (Gandolfi, 1942), p. 113-135, pl. 2, fig. 3 (upper Albian, Gorge of the Breggia River, Canton Ticino, southeastern Switzerland).

Pseudothalmanninella tebamaensis (Marianos & Zingula, 1966), p. 399, pl. 38, fig. 4 (upper Albian, Dry Creek, Beegum Basin, Chickabally Member, Sacramento Valley, California).

Remarks. Its lowest occurrence is one of the secondary criteria for the definition of the Albian/Cenomanian boundary (Kennedy et al. 2004), but according to Petrizzo et al. (2015) it is diachronous and consequently it should not be used anymore for placing the Albian/Cenomanian boundary. The present study confirms its scarce reliability for correlation among different depositional basins.

Genus *Thalmanninella* Sigal, 1948.

Type species: *Thalmanninella brotzeni* Sigal, 1948, p. 102, pl. 1, fig. 5.

Thalmanninella evoluta (Sigal, 1969), p. 637-638, pl. 1 fig. 10-12 (upper Albian, the Diego-Suarez well, north of Mount Raynaud, Madagascar).

Remarks. Transitional specimens between *Ti. digitalis* and *Th. evoluta* characterized by pinched margin and depressed spiral sutures were observed in this study.

Thalmanninella balernaensis (Gandolfi, 1957), p. 60, pl. 8, fig. 3a-c (lower Cenomanian, Breggia River, Switzerland).

Remarks. We recognize the phyletic lineage from *Ti. digitalis*, *Th. evoluta* to *Th. balernaensis*.

Thalmanninella appenninica (Renz, 1936), p. 14, fig. 2 (lower Cenomanian?, Bottaccione section, Gubbio, central Italy).

Remarks. The species concept of *Th. appenninica* has been revised several times (Luterbacher & Premoli Silva 1962; Sigal 1969; Wonders 1978; Robaszynski et al. 1979) especially because Renz (1936) erected the species from a thin section. This led to confusion in the definition of *Th. appenninica* and in its distinction from other rotaliporids. For instance, *Th. balernaensis* has been considered a junior synonym for a long time (Wonders 1978; Robaszynski et al. 1979). In this study, *Th. appenninica* is identified following the species concept of Luterbacher & Premoli Silva (1962) and the topotype illustrated in Robaszynski et al. (1979).

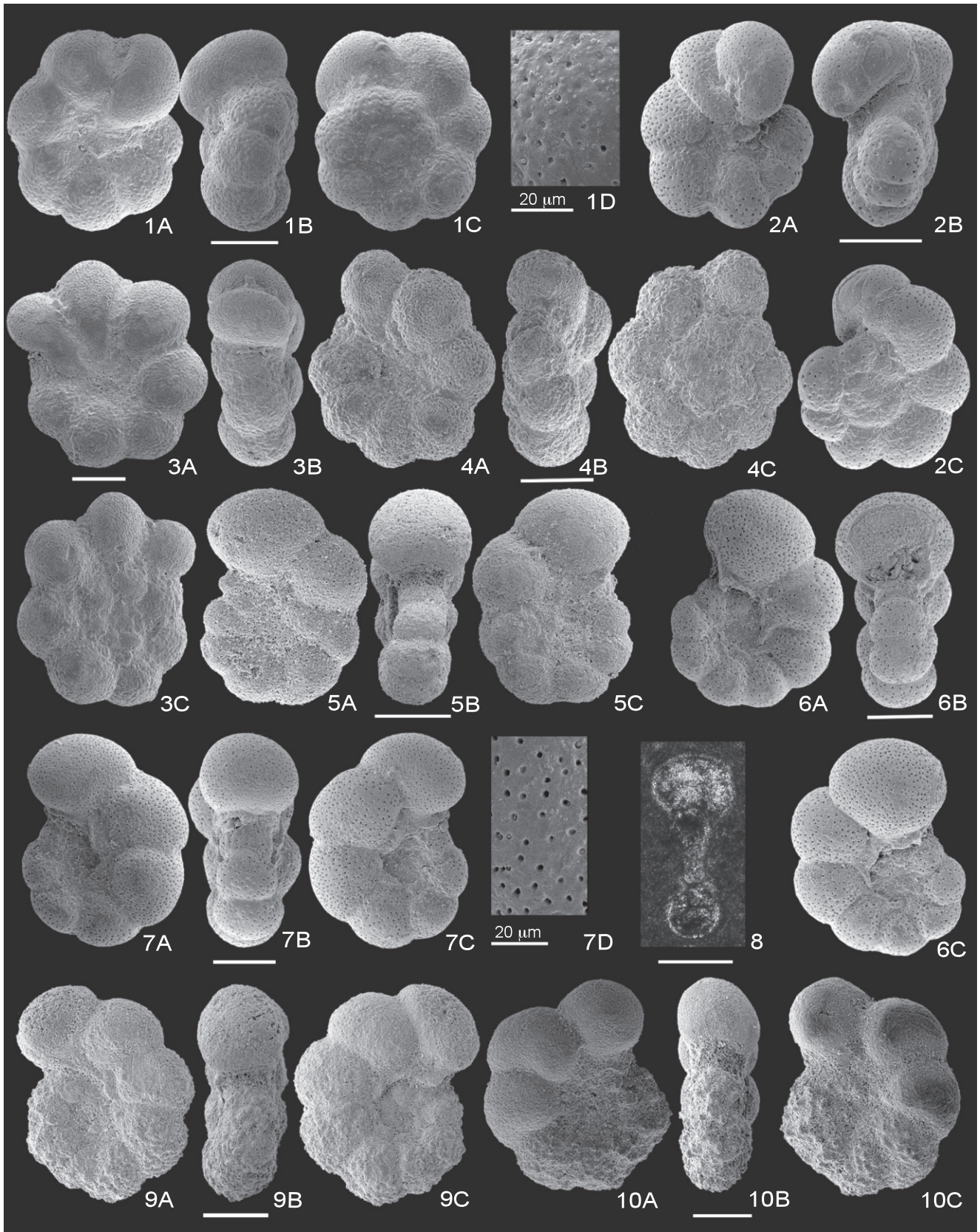


PLATE 2

1 - A-D, *Ticinella roberti*, Sample DSDP 79-547A-71R-1, 50.5-52. 2 - A-C, *Ticinella roberti*, Sample DSDP 79-547A-67R-2, 39-41 cm. 3 - A-C, *Ticinella moulladei*, Sample DSDP 79-547A-69R-3, 50-52 cm. 4 - A-C, *Ticinella moulladei*, Sample DSDP 79-545-39R-5, 23-25 cm. 5 - A-C, "*Globigerinelloides*" *bentonensis*, Sample MP24. 6 - A-D, "*Globigerinelloides*" *bentonensis*, Sample DSDP 79-547A-45R-3, 16-18 cm. 7 - A-C, "*Globigerinelloides*" *bentonensis*, Sample DSDP 79-545-34R-1, 123-125 cm. 8 - "*Globigerinelloides*" *bentonensis*, Sample MP40. 9 - A-C, "*Globigerinelloides*" *pulchellus*, Sample MP0. 10 - A-C, "*Globigerinelloides*" *pulchellus*, Sample B1.8. Scale bar 100 µm unless indicated otherwise.

Thalmaninella gandolfii (Luterbacher & Premoli Silva, 1962), p. 267 pl. 19, fig. 3 (Gorge of the Breggia River, Canton Ticino, southeastern Switzerland).

Thalmaninella brotzeni Sigal, 1948, p. 102, pl. 1, fig. 5 (middle Cenomanian, Sidi Aïssa, Algeria).

Remarks. This species has been considered a junior synonym of *Th. globotruncanoides* (Robaszynski & Caron 1995; Gale et al. 1996; González-Donoso et al. 2007; Ando & Huber 2007; Lipson-Benitah 2008; Robaszynski et al. 2008) until Caron & Premoli Silva (2007) and Petrizzo et al. (2015) demonstrate they are two distinct species.

Thalmaninella globotruncanoides Sigal, 1948, p. 100, pl. 1, fig. 4 (middle Cenomanian, Sidi Aïssa, Algeria).

Remarks. The description of the species was emended in Petrizzo et al. (2015).

Thalmaninella greenbornensis (Morrow, 1934), p. 199, pl. 31, fig. 1 (Upper Cretaceous, Colorado group, Greenhorn Formation, Hartland shale member).

Remarks. The species was emended by Ando & Huber (2007) who re-illustrated and described the holotype of *Th. greenbornensis* and highlighted the main morphological features for its identification and distinction from its ancestor *Th. globotruncanoides*. Partially raised umbilical sutures, umbilically positioned supplementary apertures and closely spaced periumbilical ridge are taken as the diagnostic features of *Th. greenbornensis*, to distinguish it from *Th. globotruncanoides* that, on the contrary, is characterized by fully raised umbilical sutures. According to Ando & Huber (2007) the crescentic numerous chambers and smooth and circular peripheral outline considered for long time diagnostic for the identification of *Th. greenbornensis* can be applied to evolved forms of *Th. globotruncanoides*. *Thalmaninella greenbornensis* is phylogenetically-related to *Ticinella* as observed in the studied assemblages and proved by the occurrence of common intermediate morphotypes indicating the gradual and progressive evolution of the *Ti. aperta* - *Th. appenninica* - *Th. brotzeni* - *Th. globotruncanoides* - *Th. greenbornensis* lineage.

Thalmaninella deeckeii (Franke, 1925), p. 88-90, pl. 8, fig. 7 (Cenomanian, Jordanshutte auf Wollin, Pommern, Germany).

Remarks. It differs from *Th. reicheli* in having more crescentic chambers and partially raised and curved umbilical sutures instead of straight and depressed sutures.

Thalmaninella reicheli (Mornod, 1950), p. 583, figs. 5(4) (upper Cenomanian, Ruisseau des Covayes, southern east slope of the Montsalvens chain, north of Cerniat, Préalpes fribourgeoises, Switzerland).

Remarks. The holotype is missing and the neotype has been described and illustrated by Caron & Spezzaferri (2006a).

Genus *Schackoima* Thalman, 1932.

Type species: *Siderolina cenomana* Schacko, 1897, p. 166, pl. 4, figs. 3-5.

Schackoima leckiei Bellier, Moullade & Tronchetti, 2003, p. 137, pl. 1, figs 1-13 (holotype under the name of *Clavibedbergella moremani* in Leckie, 1984, p. 611, pl. 8, fig. 12) (upper Albian, Mazagan Plateau, Eastern North Atlantic, DSDP Hole 547A).

Schackoima cenomana (Schacko, 1897), p. 166, pl. 4, figs. 3-5 (Cenomanian, type locality not given).

Schackoima bicornis Reichel, 1948, p. 400, figs. 4, 6-10 (Cenomanian, Gorge of the Breggia River, Canton Ticino, southeastern Switzerland).

Genus *Protobeterobelix* Georgescu & Huber, 2009.

Type species: *Guembelina washitensis* Tappan, 1940, p. 115, pl. 19, figs. 1.

Protobeterobelix washitensis (Tappan, 1940), p. 115, pl. 19, fig. 1 (Lower Cretaceous, Grayson Formation, Austin, TX).

Genus *Planomalina* Loeblich & Tappan, 1946.

Type species: *Planomalina apsidostroba* Loeblich & Tappan, 1946, p. 258, pl. 37, figs. 22-23b = *Planulina buxtorfi* Gandolfi, 1942, p. 103, pl. 3, fig.

7.

Planomalina praebuxtorfi Wonders, 1975, p. 90, pl. 1, fig. 1 (upper Albian, El Burrueco, southern Spain).

Planomalina buxtorfi (Gandolfi, 1942), p. 103, pl. 3, fig. 7 (lower Cenomanian, Breggia River near Chiasso, Canton Ticino, Switzerland).

Remarks. It is considered the last member of the phyletic lineage from *Mu. wondersi* - "*Gl.*" *pulchellus* - *Pl. praebuxtorfi* to *Pl. buxtorfi* (Petrizzo & Huber 2006b).

Genus *Praeglobotruncana* Bermudez, 1952.

Type species: *Globorotalia delrioensis* Plummer, 1931, p. 199, pl. 13, fig. 2.

Praeglobotruncana delrioensis (Plummer, 1931), p. 199, pl. 13, fig. 2 (Lower Cretaceous, Del Rio Formation, on right bank of Shoal Creek, Austin, Travis Country, TX).

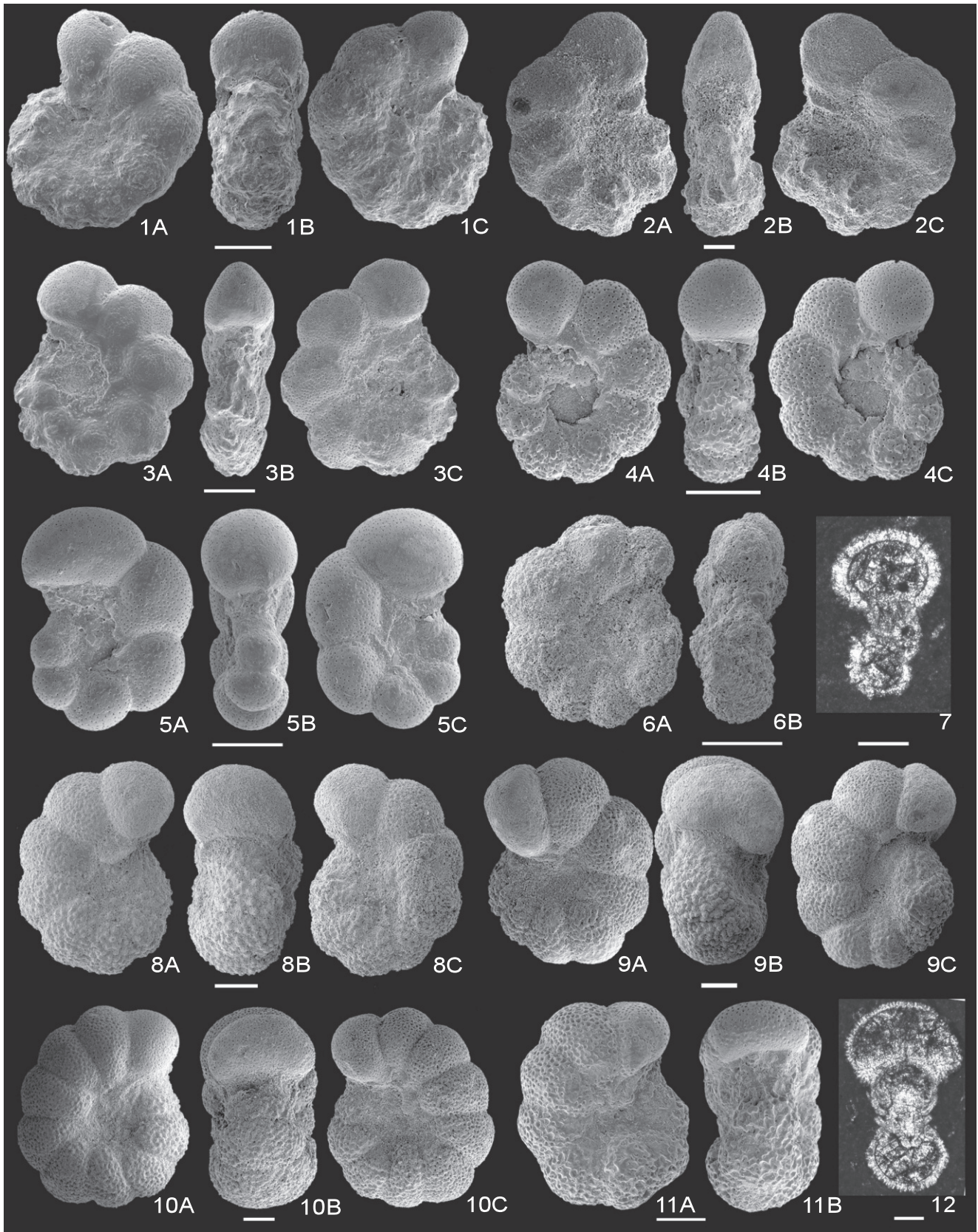


PLATE 3

1 - A-C, "*Globigerinelloides*" *pulchellus*, Sample DSDP 79-547A-71R-1, 50.5-52 cm. 2 - A-C, intermediate specimen "*Globigerinelloides*" *pulchellus* – *Planomalina praebuxtorfi*, Sample B1.8. 3 - A-C, intermediate specimen "*Globigerinelloides*" *pulchellus* – *Planomalina praebuxtorfi*, Sample DSDP 79-545-38R-3, 90-92 cm. 4 - A-C, "*Globigerinelloides*" *ultramicros*, Sample DSDP 79-547A-44R-3, 51-53 cm. 5 - A-C, "*Globigerinelloides*" cf. *alvarezii*, Sample DSDP 79-547A-64R-3, 51-53 cm. 6 - A-B, "*Globigerinelloides*" *ultramicros*, MP18.5. 7 - *Biticinella subbreggiensis*, Sample MP2. 8 - A-C, *Biticinella subbreggiensis*, Sample MP6. 9 - A-C, *Biticinella subbreggiensis*, Sample B0.01. 10 - A-C, *Biticinella breggiensis*, Sample B1.8. 11 - A-B, *Biticinella breggiensis*, Sample DSDP 79-545-39R-1, 96-98 cm. 12 - *Biticinella breggiensis*, Sample MP2. Scale bar 100 μ m.

Remarks. According to the original description by Plummer (1931), *Pr. delrioensis* is a single keeled taxon with curved and raised spiral sutures. Specimens similar to the holotype are observed only in the Monte Petrano section. The species concept adopted in this study has been enlarged following Robaszynski et al. (1979) and Petruzzo & Huber (2006a) and specimens characterized by a single to double alignment of pustules have been included.

Praeglobotruncana stephani (Gandolfi, 1942), p. 130, pl. 3, fig. 4 (Cenomanian, Gorge of the Breggia River, near Chiasso, southeastern Switzerland).

Praeglobotruncana gibba Klaus, 1960, pp. 209, 304-305, pl. 16-17, fig. 6a-c (Cenomanian, Gorge of the Breggia River, near Chiasso, southeastern Switzerland).

Genus *Paracostellagerina* Georgescu & Huber, 2006.

Type species: *Hedbergella libyca* Barr, 1972, p. 14, pl. 10, fig. 5.

Paracostellagerina libyca (Barr, 1972), p. 14, pl. 10, fig. 5 (lower Cenomanian, Cyrenaica province, Libya).

Genus *Rotalipora* Brotzen, 1942.

Type species: *Rotalipora turonica* Brotzen, 1942, p. 32, text-fig. 11-4, = *Globorotalia cushmani* Morrow, 1934, p. 199, pl. 31, fig. 4.

Rotalipora montsalvensis (Mornod, 1950), p. 584, figs. 4(1) (upper Cenomanian, Ruisseau des Covayes, southern east slope of the Montsalvens chain, north of Cerniat, Préalpes fribourgeoises, Switzerland).

Remarks. This study supports the interpretation that *Rt. montsalvensis* is the ancestor species of *Rt. cushmani* according to González-Donoso et al. (2007) as transitional specimens between the two species were observed.

Rotalipora cushmani (Morrow, 1934), p. 199, pl. 31, fig. 4 (upper Cretaceous, Hodgeman County, Kansas, U.S.A.).

Genus *Whiteinella* Pessagno, 1967.

Type species: *Whiteinella archaeocretacea* Pessagno, 1967, p. 298-299, pl. 51, figs. 22-24.

Whiteinella aumalensis (Sigal, 1952), p. 28, fig. 29 (middle Cenomanian, probably Aumale, south-east of Algiers, northern Algeria).

Whiteinella aprica (Loeblich & Tappan, 1961), p. 292, pl. 4, fig. 16 (Cenomanian, U.S. Highway 80, west of Dallas, Texas).

Whiteinella baltica Douglas & Rankin, 1969, p. 193, pl. 9, figs. A-C (lower Santonian, east of Bavnodde Pynt, Bornholm, Denmark).

Whiteinella brittonensis (Loeblich & Tappan, 1961), 1961, p. 274, pl. 4, fig. 1 (Cenomanian, Eagle Ford Group, west of Cedar Hills, Dallas County, Texas).

Whiteinella paradubia (Sigal, 1952), p. 28, fig. 28 (Cenomanian, probably northern Algeria).

Whiteinella archaeocretacea Pessagno, 1967, p. 298-299, pl. 51, figs. 22-24 (Turonian, Eagle Ford Group, west of Cedar Hills, Dallas County, Texas).

Whiteinella inornata (Bolli, 1957), p. 57, pl. 13, fig. 5 (Coniacian, Trinidad Petroleum Development well Moruga 15, Trinidad).

Whiteinella bornholmensis (Douglas & Rankin, 1969), p. 194, pl. 6, figs. A-C (lower Santonian, east of Bavnodde Pynt, Bornholm, Denmark).

Genus *Dicarinella* Porthault, 1970.

Type species: *Globotruncana indica* Jacob & Sastry, 1950, p. 267, fig. 2a-c.

Dicarinella algeriana (Caron, 1966), p. 74-75, pl. 16, fig. 8 (lower Turonian, Sidi Aïssa, Algeria).

Dicarinella imbricata (Mornod, 1950), p. 589, pl. 15, figs. 5(3) (Turonian, Ruisseau des Covayes, southern east slope of the Montsalvens chain, north of Cerniat, Préalpes fribourgeoises, Switzerland).

Dicarinella hagni (Scheibnerova, 1962), p. 225-226, fig. 6 (middle Turonian, Horné Srnie, west Carpathians, Czechoslovakia).

Dicarinella takayanagi (Hasegawa, 1999), p. 186, pl. 8, figs. 1-4 (uppermost Cenomanian, lower part of the Takinosawa Formation, Hokkaido, Japan).

Dicarinella roddai (Marianos & Zingula, 1966), p. 340, pl. 39, fig. 5 (Turonian, Dry Creek, Beegum Basin, Sacramento Valley, California).

Remarks. According to Douglas (1969) and Robaszynski et al. (1979), it is a junior synonym of *Di. hagni*, instead they are identified as distinct species in this study.

Dicarinella canaliculata (Reuss, 1854), p. 70, pl. 26, fig. 4 (upper Cretaceous, Gosau valley, Ostalpen near Salzburg, Austria).

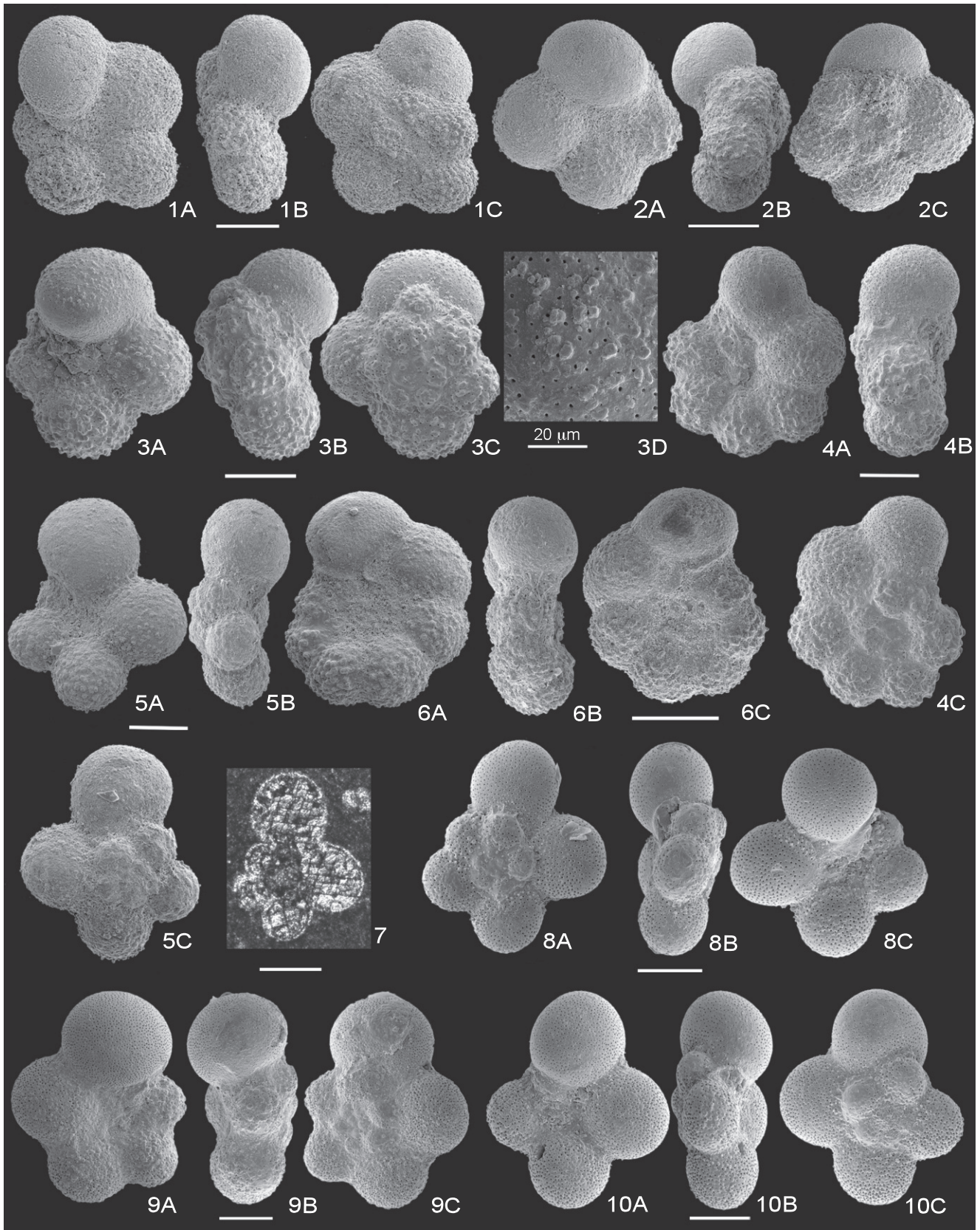


PLATE 4

1 - A-C, *Muricobedbergella delrioensis*, Sample MP0. 2 - A-C, *Muricobedbergella delrioensis*, Sample MP4. 3 - A-D, *Muricobedbergella delrioensis*, Sample DSDP 79-547A-63R-3, 49.5-52 cm. 4 - A-C, *Muricobedbergella planispira*, Sample DSDP 79-547A-65-1, 36.5-38 cm. 5 - A-C, *Pseudoclavibedbergella simplicissima*, Sample MP6. 6 - A-C, "*Globigerinelloides*" *ultramirrus*, MP 28. 7 - *Pseudoclavibedbergella simplicissima*, Sample MP30. 8 - A-C, *Pseudoclavibedbergella simplicissima*, Sample DSDP 79-547A-53R-1, 50-51.5 cm. 9 - A-C, *Pseudoclavibedbergella* cf. *simplicissima*, Sample DSDP 79-547A-63R-3, 49.5-52 cm. 10 - A-C, *Pseudoclavibedbergella simplicissima*, Sample DSDP 79-545-38R-7, 89-91 cm. Scale bar 100 µm unless indicated otherwise.

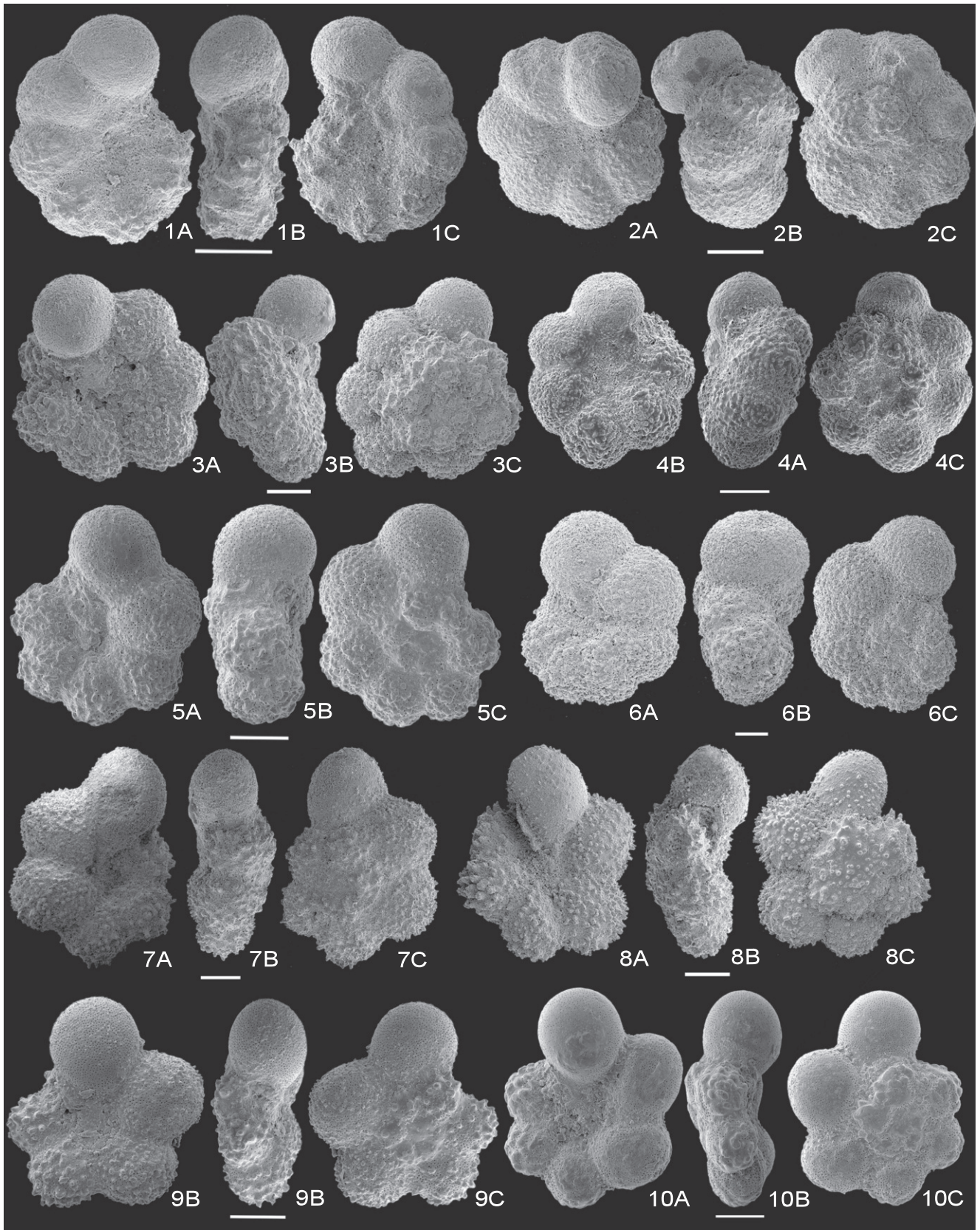


PLATE 5

1 - A-C, *Muricobedbergella wondersi*, MP2. 2 - A-C, *Muricobedbergella astrepta*, Sample MP2. 3 - A-C, *Mu. astrepta*, Sample DSDP 79-545-36R-1, 145-150 cm. 4 - A-C, *Muricobedbergella astrepta*, Sample B3. 5 - A-C, *Muricobedbergella praelibya*, Sample DSDP 79-547A-65R-1, 36.5-38 cm. 6 - A-C, *Muricobedbergella praelibya*, Sample MP0. 7 - A-C, *Muricobedbergella blakensis*, Sample MP12. 8 - A-C, *Muricobedbergella blakensis*, Sample MP13. 9 - A-C, *Muricobedbergella blakensis*, Sample DSDP 79-547A-64R-3, 51-53 cm. 10 - A-C, *Muricobedbergella blakensis*, Sample DSDP 79-545-37R-3, 50-53 cm. Scale bar 100 μ m.

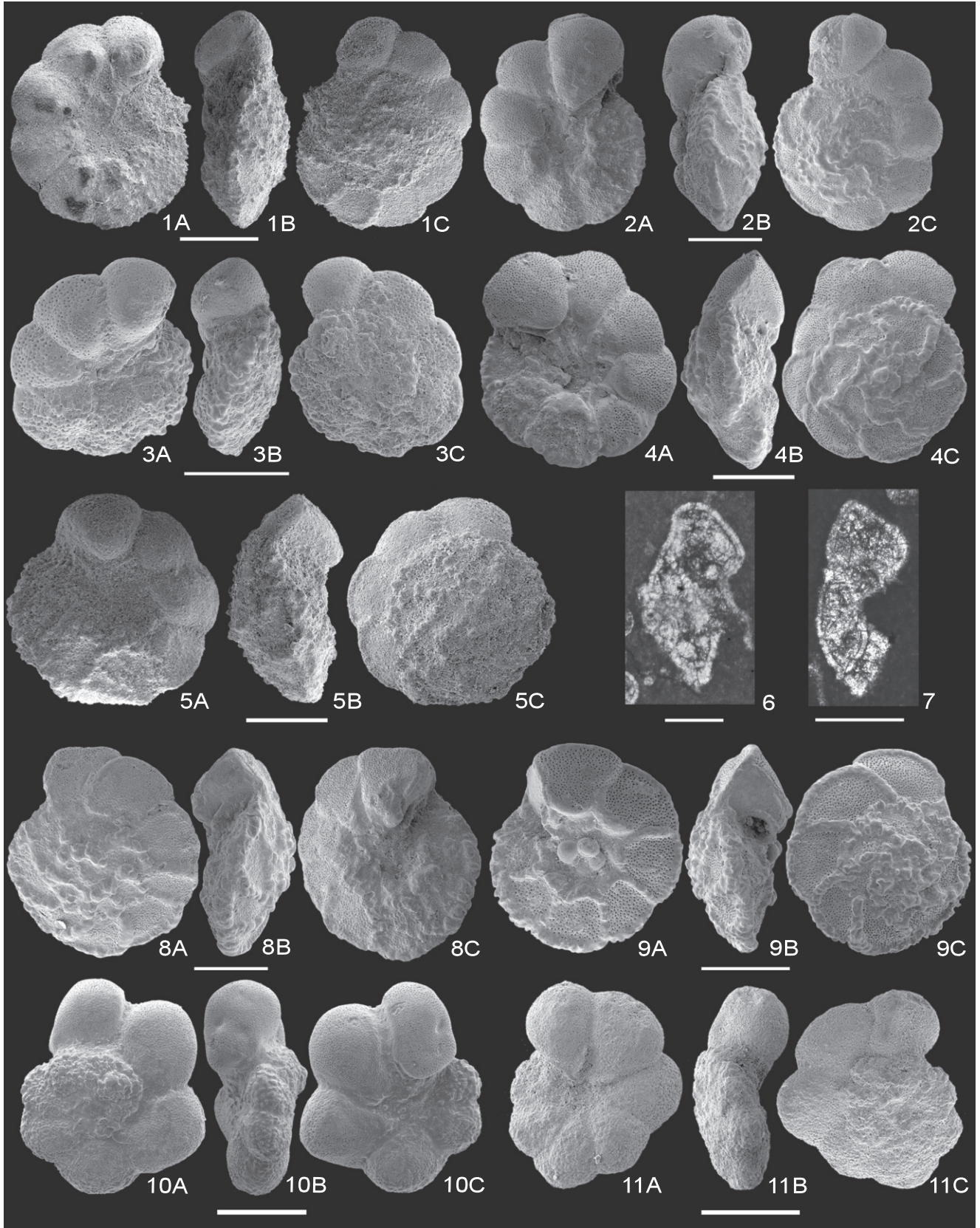


PLATE 6

1 - A-C, *Pseudothalmaninella subticinensis*, Sample B0.01. 2 - A-C, *Pseudothalmaninella subticinensis*, Sample DSDP 79-547A-65R-1, 36.5-38 cm. 3 - A-C, *Pseudothalmaninella subticinensis*, Sample DSDP 79-545-40R-5, 8-10 cm. 4 - A-C, *Pseudothalmaninella ticinensis*, Sample DSDP 79-547A-65R-1, 36.5-38 cm. 5 - A-C, *Pseudothalmaninella ticinensis*, Sample B0.01. 6 - *Pseudothalmaninella subticinensis*, Sample MP4. 7 - *Pseudothalmaninella ticinensis*, Sample MP6. 8 - A-C, *Pseudothalmaninella tebamaensis*, Sample DSDP 79-547A-65R-1, 36.5-38 cm. 9 - A-C, *Pseudothalmaninella tebamaensis*, Sample DSDP 79-547A-47R-3, 52.5-54.5 cm. 10 - A-C, intermediate specimen *Ticinella digitalis*-*Thalmaninella evoluta*, Sample DSDP 79-547A-68-2, 93-95 cm. 11 - A-C, *Thalmaninella evoluta*, Sample MP2. Scale bar 200 µm.

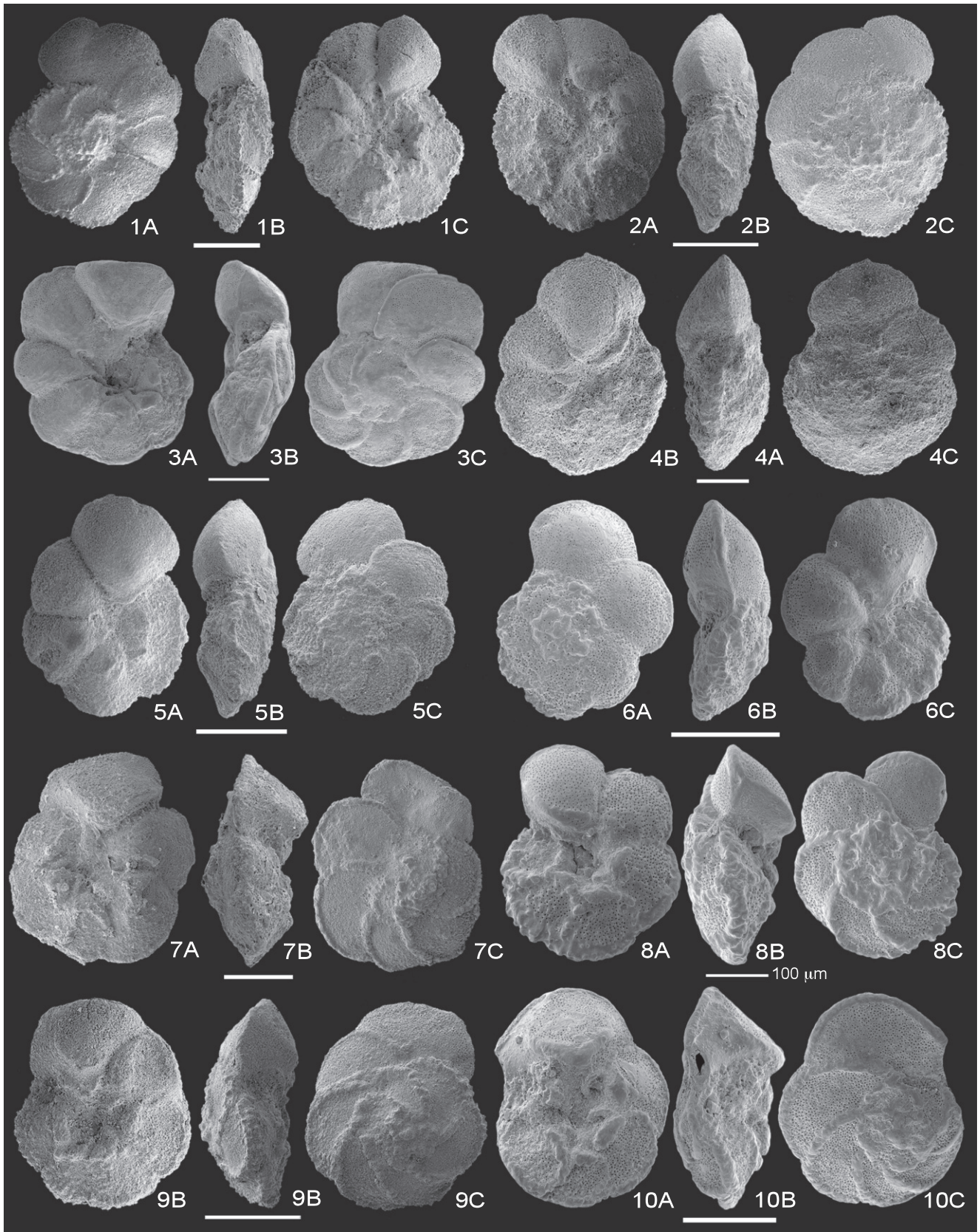


PLATE 7

1A-C, *Thalmanninella balernaensis*, Sample MP13. 2 - A-C, *Thalmanninella balernaensis*, Sample B6. 3 - A-C, *Thalmanninella balernaensis*, Sample DSDP 79-545-35R-2, 69-74 cm. 4 - A-C, *Thalmanninella appenninica*, Sample MP4. 5 - A-C, *Thalmanninella appenninica*, Sample B1.8. 6 - A-C, *Thalmanninella appenninica*, Sample DSDP 79-547A-65R-1, 36.5-38 cm. 7 - A-C, *Thalmanninella gandolfii*, Sample MP36. 8 - A-C, *Thalmanninella gandolfii*, Sample DSDP 79-547A-58R-3, 52-54 cm. 9 - A-C, *Thalmanninella brotzeni*, Sample MP19.5. 10 - A-C, *Thalmanninella brotzeni*, Sample DSDP 79-545-30R-1, 25-28.5 cm. Scale bar 200 µm unless indicated otherwise.

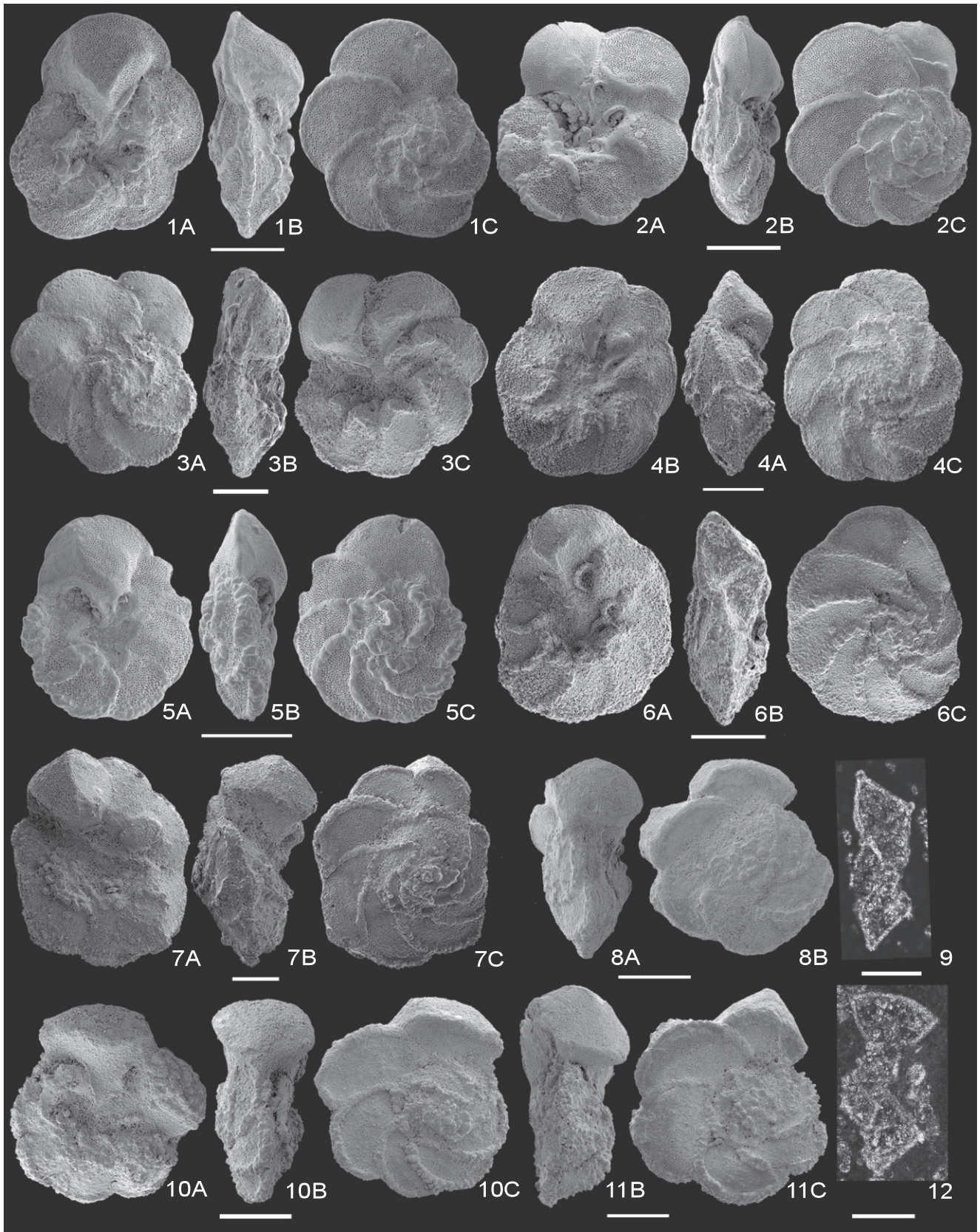


PLATE 8

1A-C, *Thalmaninella globotruncanoides*, Sample DSDP 79-545-30R-1, 25-28.5 cm. 2 - A-C, *Thalmaninella globotruncanoides*, Sample DSDP 79-547A-60R-5, 50-52 cm. 3 - A-C, intermediate specimen *Thalmaninella globotruncanoides*-*Thalmaninella greenbornensis*, Sample MP35. 4 - A-C, intermediate specimen *Thalmaninella globotruncanoides*-*Thalmaninella greenbornensis*, Sample MP50. 5 - A-C, *Thalmaninella greenbornensis*, Sample DSDP 79-547A-48R-1, 47.5-49.5 cm. 6 - A-C, *Thalmaninella greenbornensis*, Sample MP57. 7 - A-C, *Thalmaninella deeckeii*, Sample MP45. 8 - A-B, *Thalmaninella reicheli*, Sample MP35. 9 - *Thalmaninella greenbornensis*, Sample MP44. 10 - A-C, *Thalmaninella reicheli*, Sample MP44. 11 - A-B, *Thalmaninella reicheli*, Sample MP45. 12 - *Thalmaninella reicheli*, Sample MP46. Scale bar 200 μ m.

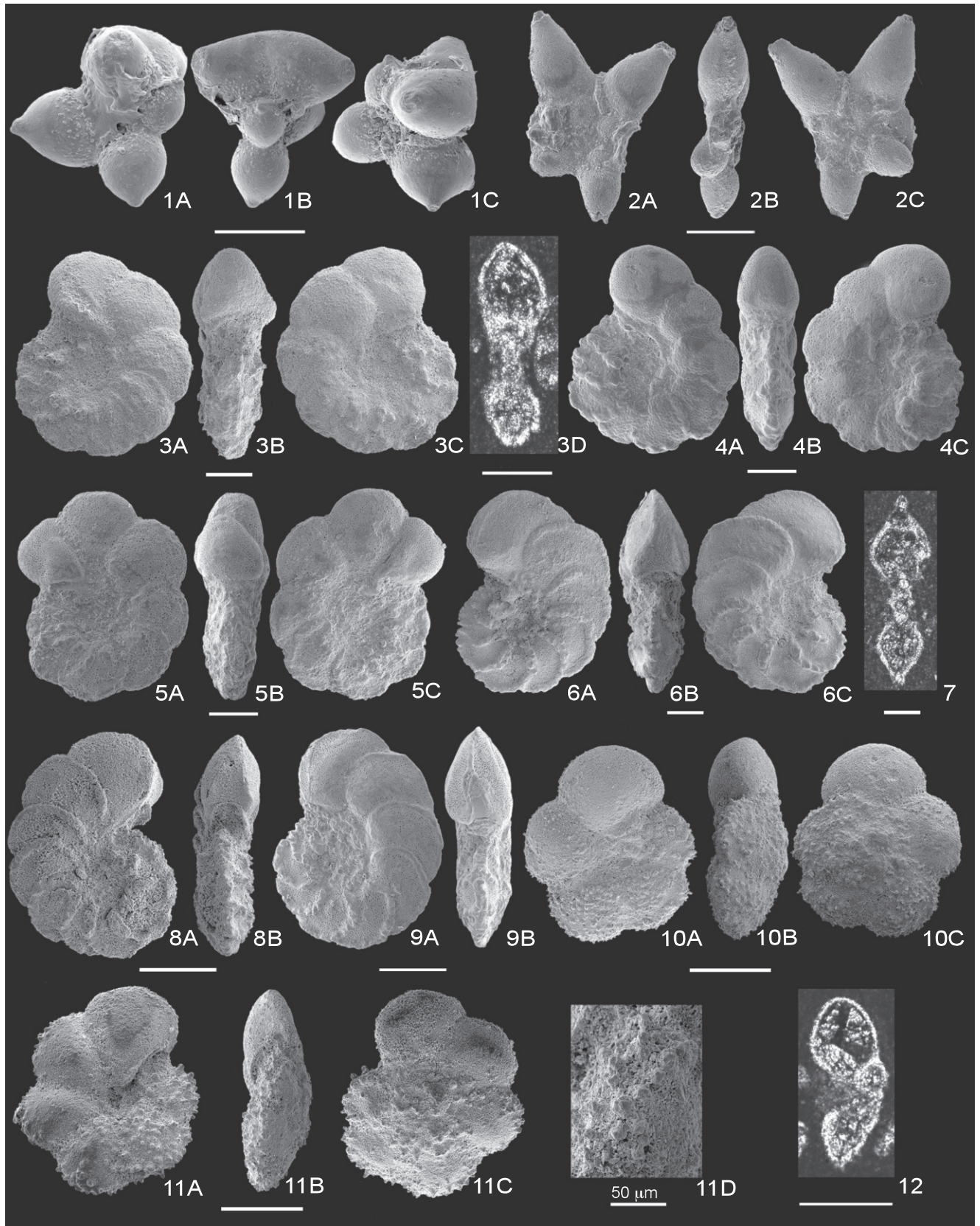


PLATE 9

1 - A-C, *Schackoina bicornis*, Sample DSDP 79-547A-44R-3, 51-53 cm. 2 - A-C, *Schackoina leckiei*, Sample DSDP 79-545-39R-1, 96-98 cm. 3 - A-D, *Planomalina pruebuxtorfi*, Sample MP4. 4 - A-C, *Planomalina pruebuxtorfi*, Sample DSDP 79-547A-67R-2, 39-41 cm. 5 - A-C, *Planomalina pruebuxtorfi*, Sample DSDP 79-545-38R-3, 90-92 cm. 6 - A-C, *Planomalina buxtorfi*, Sample MP13. 7 - *Planomalina buxtorfi*, Sample B6. 9 - A-C, *Planomalina buxtorfi*, Sample DSDP 79-545-37R-3, 50-53 cm. 10 - A-C, *Praeglobotruncana delrioensis*, Sample MP19.5. 11 - A-D, *Praeglobotruncana delrioensis*, Sample B9.6. 12 - *Praeglobotruncana delrioensis*, Sample MP14. Scale bar 100 µm.

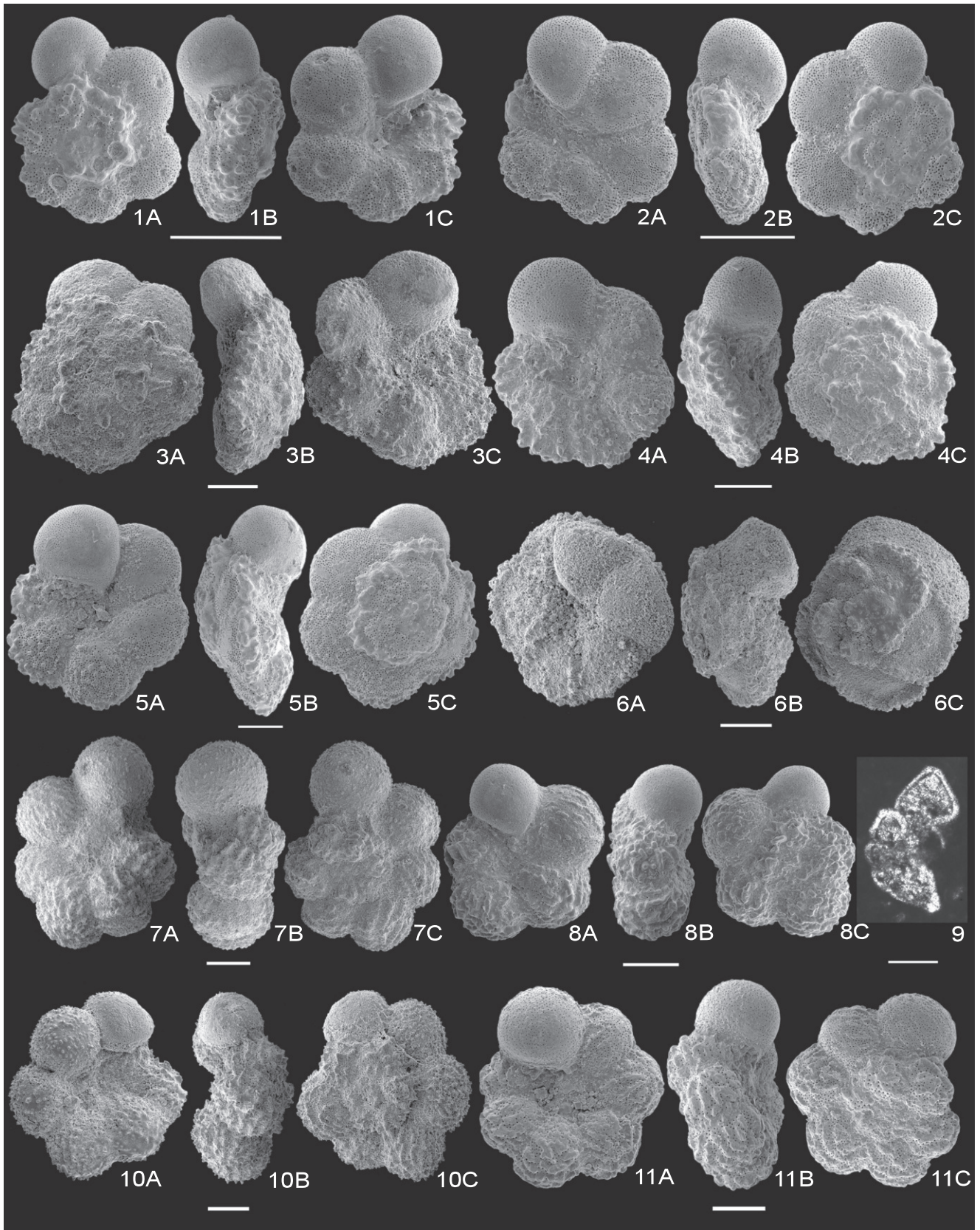


PLATE 10

1 - A-C, *Praeglobotruncana delrioensis*, Sample DSDP 79-547A-58R-3, 52-54 cm. 2 - A-C, *Praeglobotruncana delrioensis*, Sample DSDP 79-545-38R-1, 89-91 cm. 3 - A-C, *Praeglobotruncana stephani*, Sample B9.6. 4 - A-C, *Praeglobotruncana stephani*, Sample DSDP 79-547A-62R-3, 48-50 cm. 5 - A-C, *Praeglobotruncana stephani*, Sample DSDP 79-545-34R-CC, 1-4 cm. 6 - A-C, *Praeglobotruncana gibba*, Sample MP60. 7 - A-C, *Paracostellagerina libyca*, Sample MP14. 8 - A-C, *Paracostellagerina libyca*, Sample DSDP 79-547A-64R-3, 51-53 cm. 9 - *Praeglobotruncana gibba*, Sample MP64. 10 - A-C, *Paracostellagerina libyca*, Sample B11.4. 11 - A-C, *Paracostellagerina libyca*, Sample DSDP 79-545-38R-1, 89-91 cm. Scale bar 100 μ m.

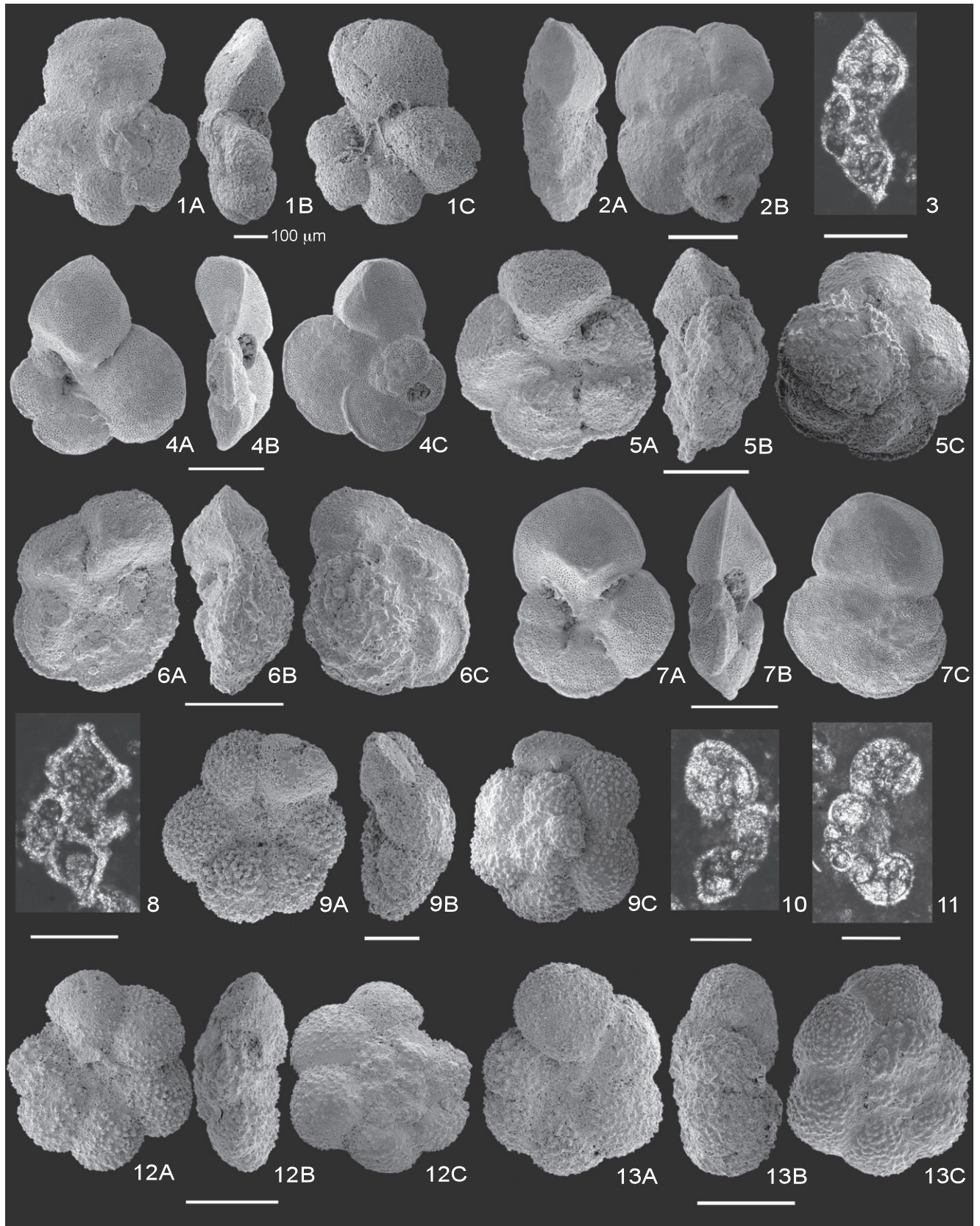


PLATE 11

1 - A-C, *Rotalipora montsalvensis*, Sample MP46. 2 - A-B, *Rotalipora montsalvensis*, Sample MP38.5. 3 - *Rotalipora montsalvensis*, Sample MP36. 4 - A-C, intermediate specimen *Rotalipora montsalvensis*-*Rotalipora cushmani*, Sample DSDP 79-547A-42R-3, 40.5-42 cm. 5 - A-C, *Rotalipora cushmani*, Sample MP59. 6 - A-C, *Rotalipora cushmani*, Sample MP65. 7 - A-C, *Rotalipora cushmani*, Sample DSDP 79-547A-40R-1, 30.5-33 cm. 8 - *Rotalipora cushmani*, Sample MP64. 9 - A-C, *Whiteinella aumalensis*, Sample MP44. 10 - *Whiteinella aumalensis*, Sample 55MP. 11 - *Whiteinella brittonensis*, Sample MP58. 12 - A-C, *Whiteinella aumalensis*, Sample MP45. 13A-C, *Whiteinella brittonensis*, Sample MP45. Scale bar 200 μm unless indicated otherwise.

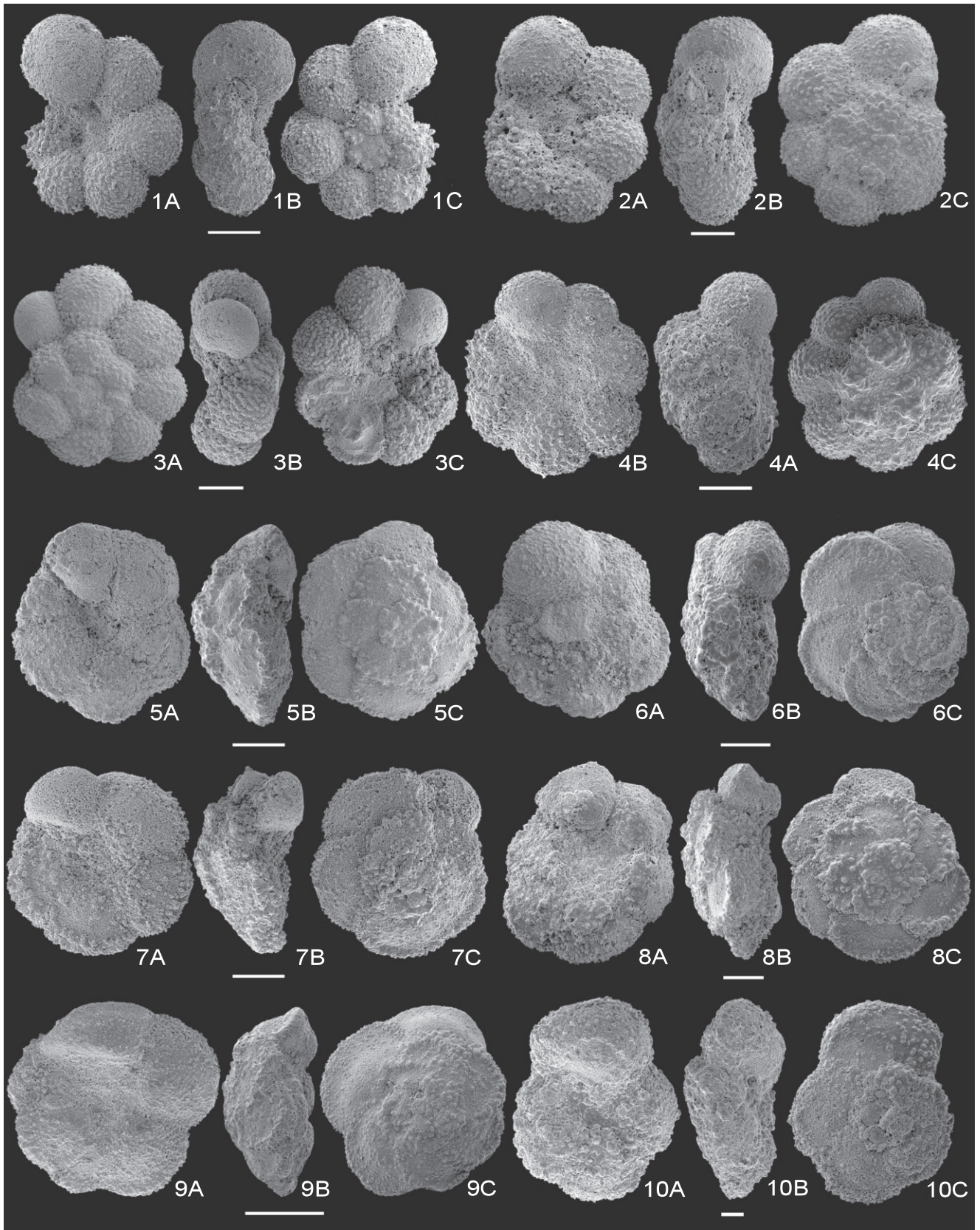


PLATE 12

1 - A-C, *Whiteinella* cf. *aprica*, Sample MP42. 2 - A-C, *Whiteinella aprica*, Sample MP44. 3 - A-C, *Whiteinella aprica*, Sample MP44. 4 - A-C, *Whiteinella paradubia*, Sample MP45. 5 - A-C, *Dicarinella algeriana*, Sample MP59. 6 - A-C, *Dicarinella imbricata*, Sample MP58. 7 - A-C, *Dicarinella imbricata*, Sample MP59. 8 - A-C, *Dicarinella hagni*, Sample MP59. 9 - A-C, *Dicarinella hagni*, Sample MP64. 10 - A-C, *Dicarinella takayanagi*, Sample MP59. Scale bar 100 μ m.

CONCLUSIONS

Results of detailed biostratigraphic analysis of the upper Albian-Cenomanian at Monte Petrano and DSDP Hole 547A and of the upper Albian-lower Cenomanian stratigraphic records at the Le Brece section and DSDP Site 545 reveal a stratigraphically ordered sequence of planktonic foraminiferal events useful for regional and interregional correlations. The lowest occurrences of *Th. appenninica*, *Pl. buxtorfi*, *Pa. libyca*, *Th. brotzeni* in the Albian and the LOs of *Th. globotruncanoides*, *Th. greenbornensis* and *Rt. cushmani* in the Cenomanian are shown to be reliable and likely synchronous bioevents at all studied localities. On the contrary, some species show occurrences that are poorly correlative among sections and thus are considered to be unreliable bioevents, they are: the HOs of *Ps. subticinensis*, *Bt. breggiensis*, *Ps. ticinensis*, *Pl. buxtorfi*, *Pa. libyca*, *Ti. madecassiana*, *Ti. primula* and the LOs of *Pr. delrioensis*, *Th. gandolfii*, *Th. deeckeii*, *Rt. montsalvensis* and *Whiteinella* species of which *Wh. aprica* is the first representative.

We confirm the applicability of the Tethyan biozonation except for the mid-Cenomanian stratigraphic interval as we replace the *Th. reicheli* Zone with the *Th. greenbornensis* Zone defined as the stratigraphic interval from the LO of *Th. greenbornensis* and the LO of *Rt. cushmani*. The use of this planktonic foraminiferal Zone introduced by Postuma (1971) is proposed because of difficulty in the identification of *Th. reicheli* Zone, which is a marker species that is rare or absent in many western and eastern Tethyan localities and in the U. S. Western Interior Basin record. On the contrary, the LO of *Th. greenbornensis* is demonstrated to be an easy identifiable bioevent as the species is characterized by a wider geographic distribution and often reported to appear in the same stratigraphic level as *Th. reicheli* when the latter species is present.

Comparison of the Umbria-Marche sections and the Mazagan Plateau sections with the Blake Nose (western North Atlantic Ocean) and Mont Risou (Vocontian Basin, southeast France) stratigraphic records highlight a similar sequence of bio- and chronostratigraphic events. An exception is the stratigraphic position of the LO of *Th. globotruncanoides* at the Mont Risou GSSP stratotype that seems to be delayed relative to the maximum values of the carbon isotope excursion and OAE 1d in the other localities. Further investigations are needed to understand this discrepancy and if the apparent diachroneity is either

an artifact of sampling resolution or is related to peculiar sedimentological, diagenetic and environmental features of the Vocontian Basin. Interestingly, the MCE is registered within the stratigraphic occurrence of *Th. reicheli* at both Monte Petrano and Blake Nose stratigraphic sections in agreement with the records from the English Chalk and the Boreal North Germany regions, and in disagreement with previous observations in other sections of the Umbria-Marche Basin where the MCE is placed stratigraphically higher and correlates with the presence of *Rt. cushmani*.

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