



Dating the Penninic Ocean subduction: new data from planktonic foraminifera

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ABSTRACT

The Penninic Ocean was a side tract of the Central Atlantic Oceanic System intercalated between the European and the Austroalpine plates. Its closure started in the Early Cretaceous, as subduction of the oceanic crust beyond the Austroalpine plate. The sedimentary change on the Austroalpine shelf from pelagic carbonates into deep-water siliciclastics correlated with the denudation of the accretionary wedge resulting from that subduction. Within the Bajuvaric Unit of the Upper Austroalpine, this transition is reflected by the lithostratigraphic boundary between the older Schrambach and the younger Tannheim Formation. This boundary is well exposed in a newly discovered site at Sittendorf, southwest of Vienna. This new outcrop yields an extraordinarily rich planktonic foraminifera assemblage characterized by typical Aptian species belonging to *Blowiella*, *Globigerinelloides*, *Hedbergella*, *Leupoldina*, and *Praehedbergella*. A detailed biostratigraphic analysis based on thin-section investigations precisely dated the lithostratigraphic boundary within the lower part of the early Aptian *Leupoldina cabri* Acme Zone, having an approximate age of 123 Ma. Along with the biostratigraphic analyses, the gamma-log outcrop measurement was a powerful tool in interpreting the stratigraphy and the tectonic setting in the outcrop, which intersects one smaller-scale isoclinal fold.

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1. Introduction

Biostratigraphic data on the transition between the Schrambach and the Tannheim Formation of the northeastern Northern Calcareous Alps (Upper Austroalpine) are remarkable scarce (Weidich, 1990; Wägreich, 2003). This fact reflects the absence of identifiable ammonoid macrofossil faunas as well as the absence or bad preservation of relevant microfossils. The age of the boundary of the Schrambach and the Tannheim Formation is however of extraordinary importance for the reconstruction of Austroalpine geodynamics, since the Tannheim Formation marks the initial siliciclastic input into the basin reflecting the onset of subduction of the Penninic Ocean beneath the Upper Austroalpine (Wägreich, 2003). The newly discovered outcrop NW of Sittendorf in the southwestern Vienna Wood shed new light on this problem. The sediments of the Sittendorf section yield extraordinarily rich accumulations of planktonic foraminifera, which allow for the first time a precise dating of the uppermost Schrambach and lowermost Tannheim Formation.

2. Geological and paleontological background

2.1. Penninic Ocean and Austroalpine shelf

The Penninic Ocean (Fig. 1) was initiated in the Late Triassic by rifting and disjunction of the Austroalpine microcontinent from the

southern European Plate margin. It was the eastern prolongation of the North Atlantic Rift-System effecting the final disintegration of the Permian Pangea Supercontinent (e.g., Faupl, 2003). The formation of the oceanic crust and the sea floor spreading lasted from the Middle Jurassic to the Early Cretaceous, terminating with the introduction of its southward-directed subduction beneath the northern Austroalpine plate margin (Faupl and Wägreich, 2000). The active plate margin including the transpressional accretionary wedge and the northern parts of the Austroalpine microplate thereby underwent accelerated uplift and erosion; this is reflected by siliciclastic input into the southern, adjoining marine environments (Wägreich, 2003).

The Northern Calcareous Alps, originally encompassing the southern part of the Austroalpine microplate, are positioned today at the northern margin of the Austroalpine nappe complex (Faupl and Wägreich, 2000). In the Early Cretaceous the complex started to drift northwards, overriding progressively the northern parts of the Austroalpine plate (Fig. 2). At the front of the overthrust a piggyback basin developed, supplied from the north by a marine slope apron deposition (Wägreich, 2003). The pelagic carbonate sedimentation, which already started in the Late Jurassic, therefore changes within several meters of the section into a siliciclastic dominated sedimentation. The gradual convergence of the slope apron depositional front and filling of the piggyback basin is reflected by a coarsening upward sequence ending with coarse sand and conglomerate intercalations at the top of the succession.

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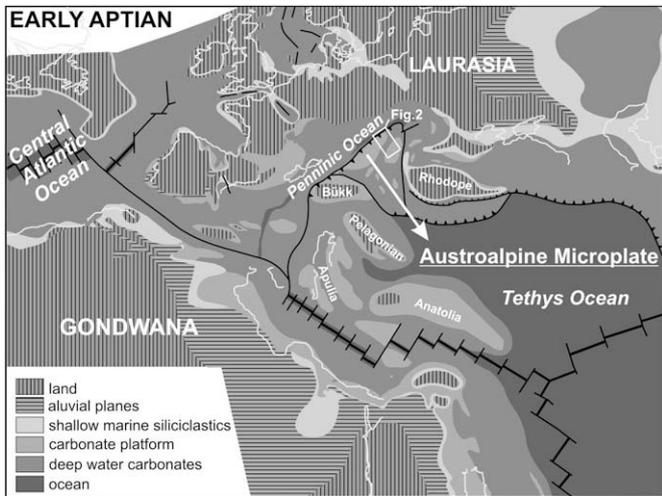


Fig. 1. Palinspastic setting and position of the Penninic Ocean subduction (modified after Masse et al., 2000).

2.2. Depositional and tectonic setting

The studied section at Sittendorf includes the slope-apron succession of the Frankenfels Nappe representing the NNE part of the Northern Calcareous Alps and the Bajuvaric Unit nappe-system. The Lower Cretaceous pelagic sediments of the Bajuvaric Unit represent its major sedimentation cycle. The significant depositional change from the carbonate to the siliciclastic depositional system is reflected in the boundary between the Schrambach and the Tannheim Formations. Accordingly, the Schrambach Formation represents the phase of autochthonous pelagic sedimentation with the light-colored, aptychi-bearing nannoconid limestones and marly limestones. The Tannheim Formation, on the other hand, features typically dark, laminated pelagic marls and marly limestones whose formation was triggered by erosion and intensive redeposition (Wagreich, 2003). The macro-invertebrate fauna of the succession is very sparse, comprising ammonoids, aptychi, belemnites, brachiopods and rare bivalves. The micro-fauna is in contrast abundant, with dominating radiolarians in the Schrambach Formation and planktonic foraminifera blooms within the Tannheim Formation.

2.3. Planktonic foraminifera patterns

The Cretaceous record of planktonic foraminifera generally shows a threefold pattern with periods of rapid diversifications

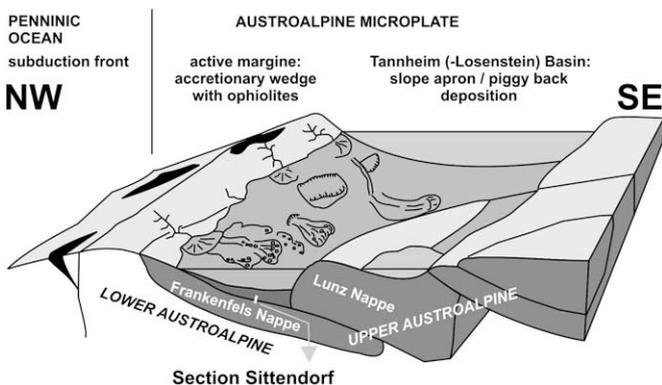


Fig. 2. Schematic paleogeographic reconstruction of the Tannheim Basin with indicated position of the Sittendorf Section (modified after Wagreich, 2003).

alternating with periods of stasis (Premoli Silva and Sliter, 1999). The investigated section represents the first diversification phase defined by the latter authors lasting from the early Valanginian to the latest Aptian. This continuous diversification is briefly interrupted only by the “Selli” event, where a smaller-scaled turnover event occurred. The diversification phase begins with the rise of the first hedbergellids in the early Valanginian followed in the early Hauterivian with the first occurrence of small planispiral *Blowiella*. Intensification of taxonomic diversification, abundance increase together with the increase of the overall test size started in the Barremian. With the Aptian the planktonic foraminifera blooms became frequent (e.g. Premoli Silva and Sliter, 1999). The assemblage prior to the Selli Event is still dominated by relatively small-sized, thin-walled and simple morphotypes (e.g. Coccioni et al., 1992). Following the Selli Event, medium-sized, clavate *Leupoldina* become typical, followed by the first occurrence of the thick-walled *Globigerinelloides*. Whereas *Leupoldina* soon retreats, *Globigerinelloides* goes through a remarkable evolution characterized by size and chamber number increase (Moullade et al., 2005). This culminated in the late Aptian, with *G. algerianus* being the first large-sized species in the evolutionary history of the genus, attaining maximum diameters of ~700 μm (Leckie et al., 2002). Synchronously, the same evolutionary trend is followed by the hedbergellids, with the remarkably large and massive *Hedbergella trocoidea* arising from the more primitive *Praehedbergella praetrocoidea* (Moullade et al., 2002). The brief global cooling (Herrle and Mutterlose, 2003; Skelton, 2003) by the end of Aptian initialized enhanced ocean mixing and thermocline destruction, triggering extinctions and the final drop in plankton diversity.

2.4. Previous investigations

The studied planktonic foraminifera of the Barremian and Aptian (Fig. 3) have a global occurrence. The ongoing investigations of depositional systems bearing *Blowiella*, *Leupoldina* and *Globigerinelloides* successions yielded data from such different parts of

AGE (Ma)	POLARITY	CHRONO-STRATIGRAPHY		BIOSTRATIGRAPHY		LITHOSTRATIGRAPHY
		Stage	Sub-stage	Tethyan Ammonites Zones	Planktonic Foraminifera Zones	Austroalpine Microplate Upper Austroalpine Deep-Bajuvaricum
115	Black	Albian	Lower	<i>L. tardefurcata</i>	<i>Hedbergella planispira</i> IZ	Tannheim Formation
				<i>H. jacobi</i>	<i>Ticinella bejaouaensis</i> IZ	
				<i>N. nolani</i>	<i>Hedbergella trocoidea</i> IZ	
				<i>P. melchioris</i>	<i>Globigerinelloides algerianus</i> TRZ	
				<i>E. sunodosocostatum</i>	<i>Globigerinelloides ferreolensis</i> IZ	
		Aptian	Upper	<i>D. furcata</i>	<i>Leupoldina cabri</i> AZ	
				<i>D. deshayesi</i>		
				<i>D. weissii</i>		
				<i>D. oglanlensis</i>		
				<i>P. waagenoides</i>	<i>Blowiella blowi</i> IZ	
120	Black	Aptian	Lower	<i>C. sarasini</i>		
				<i>I. giraudi</i>		
				<i>H. teraudianus</i>		
				<i>G. sartousiana</i>		
				<i>A. vandenheckii</i>		
125	White	Barremian	Upper	<i>C. darsi</i>	<i>H. similis</i> IZ	Schrambach Fm.

Fig. 3. Stratigraphic correlation table (modified after Ogg et al., 2004).

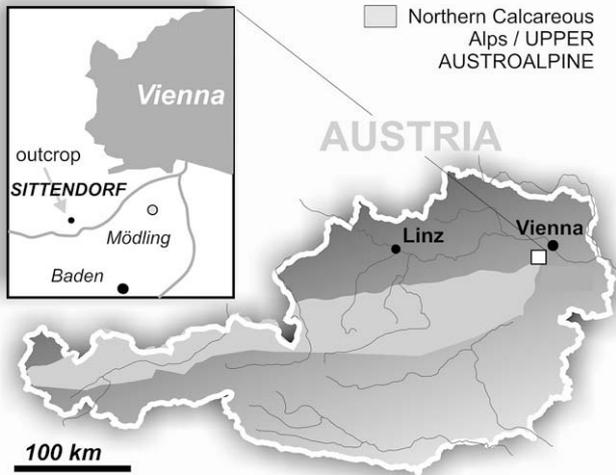


Fig. 4. Geographic position and regional geologic setting of the studied outcrop at Sittendorf.

the world like the Pacific Ocean and California (Sliter, 1989, 1999), Mexico (Longoria, 1974; Omana et al., 2005), Trinidad (Bartenstein and Bolli, 1986), Boreal Germany (Rückheim and Mutterlose, 2002), Spain (Aguado et al., 1992, 1999; Coccioni and Premoli Silva, 1994), NE France (Moullade et al., 1998, 2005), Swiss Prealps (Strasser et al., 2001), Italy (Coccioni et al., 1992), Hungary (Bodrogi and Fogarasi, 2002), Turkey (Altiner, 1991), Israel (Lipson-Benitah and Almogi-Labin, 2004), former USSR (Gorbachik, 1986) and many others.

The biostratigraphic scheme for the studied period (Fig. 3), with emphasis on the thin section approach, was introduced by Sliter (1989, 1992, 1999). The calibration of planktonic foraminifera events – combining data from epicontinental deposits with the data from the DSDP and ODP logs – was carried out by Bralower et al. (1995, 1997). The state-of-the-art recalibrations are available from Leckie et al. (2002) and Ogg et al. (2004). The most recent revisions (Boudagher-Fadel et al., 1997; Moullade et al., 2002; Verga and Premoli Silva, 2002, 2003a,b, 2005) were an important step in stabilizing the Aptian planktonic foraminiferal taxonomy, which is characterized by strongly fluctuating genus- as well as species-level concepts.

For the Early Cretaceous Austroalpine shelf, the stratigraphic data are still rather scattered and based mainly on ammonoids (Lukeneder, 2003, 2004a,b). Particularly the transition between the Schrambach Formation and the Tannheim Formation is poorly understood because it lacks ammonoid findings (Wagreich, 2003). The only available data are from Weidich (1990), based on several scattered planktonic foraminifera assemblages sieved from four sections between Vienna (Austria) and Füssen in Bavaria (Germany). The data, revealing the presence of the *Globigerinelloides ferreolensis* Zone, supported its correlation with the upper part of the Aptian stage, between 119 and 120.5 Ma (Ogg et al., 2004).

3. Material and methods

The section Sittendorf (Figs. 4 and 5) has been studied in an about 50-m-long and 5-m-high, eastward exposure at the first kilometer of the motorway from Sittendorf to Wienerwald (southwestern Vienna, Austria; GPS: 48°05'11"N, 16°09'11"E). The lithostratigraphic logging was accompanied by outcrop gamma-ray measurements to determine the variation of the mineral clay content. Subsequently, hard rock samples were taken in each meter of the section. The critical interval around the lithostratigraphic boundary was sampled in more detail – 7 additional samples were taken in the respective 2 meters of the section. Finally, bulk samples were taken from the marly interlayers.

The various bulk sample test treatments using acetic acid, hydrogen peroxide, and sodium carbonate heating failed; only one sample provided poor and massively recrystallised plankton. The oriented hard rock samples were cut into horizontal and vertical thin sections, providing the basis for the present planktonic foraminifera study. The investigation was carried out using polarized light microscopy at maximal magnification of 1000 \times .

The hard rock samples were analyzed geochemically, investigating the upsection changes in the CaCO₃, C_{org} and S contents. The C_{org} content was defined from the difference between C_{total} and C_{CaCO3}. Thus, the CaCO₃ content was determined according to the procedure outlined in ÖNORM L 1084, whereas the C_{total} content was determined by dry sample cremation (ÖNORM L 1080). The S content was detected by acidic-extraction (ÖNORM L 1085) and measurement using simultaneous ICP-AES (inductively coupled plasma-atomic emission spectrometry). The detailed ÖNORM procedures can be obtained from www.on-norm.at.



Fig. 5. Outcrop Sittendorf with indicated sample positions, including lithostratigraphic and chronostratigraphic results of the present study.

4. Lithology and facies distribution

The N-S striking section was measured from 11 m below and 12 m above the lithostratigraphic boundary between the Schrambach and the Tannheim Formation (Fig. 6). The layers dip at a very high angle toward the north (2nd section's meter: 326/70, 340/60; 16th section's meter: 000/70, 353/90).

The base of the measured section overlies a smaller-scale fault within the Schrambach Formation. Upsection, up to the 9 m mark, the Schrambach Formation exposes a monotonous series of hard, finely (at 10 cm scale), wavy bedded, micritic limestones. These mudstones to wackestones are typically light gray and contrast with the more strongly weathered and more marly portions (from 2 to 4 m, and around the 8 m mark), which are dark gray to olive green. Small-scale bioturbations are common in places, forming cm-thick horizons. Typical features include about 1-mm-thick, small, dark-colored, tube-shaped burrows unevenly distributed in the sediment.

The 9 m to 13 m level marks the transitional interval between the Schrambach and the Tannheim Formation. The boundary is defined with the top of the uppermost light gray bed at 10.9 m. The interval is characterized by a gradual upsection increase of the siliciclastic, clayey component. Nine 20- to 40-cm-thick limestone interlayers are intercalated – their boundaries show occasional minor fault structures. The lower 4 intercalations are light gray mudstones to packstones. The intervening marly intervals are light gray in the first meter, thereafter becoming dark gray laminated marls to marly limestone up to the top of the transitional interval; an exception is one 5-cm-thick dark clay horizon at 12.4 m. The other 5 micritic limestone intercalations are dark gray, laminated (first two) or homogeneous, bioturbated wackestones to packstones.

From 13 m to the top of the section, dark gray to greenish gray marls and marly limestones are present. These wackestones can be laminated or bioturbated. Between 16 m and 17 m, at 18 m and at 22 m, 40- to 100-cm-thick, more limy, less weathered intervals are intercalated. At about 14.5 m and 20 m, steep fault structures occur. Above the uppermost limestone bed the outcrop situation becomes unclear. Except for one small bivalve shell, no microfossils were found.

5. Planktonic foraminifera

5.1. Taxonomic remarks

The taxonomic concept applied here combines results by Moullade et al. (2002, 2005) and Verga and Premoli Silva (2002, 2003a,b, 2005) (Fig. 7).

Premoli Silva and Verga (2004) include in a comprehensive course manual published as well as previously unpublished results. One of the revisions – the erection of the monotypic genus *Pseudoschackoina* – was documented subsequently this year (Verga and Premoli Silva, 2005). One specimen of the tubulospine-bearing *Pseudoschackoina soundersi* was found in the sieved bulk sample 12.1.

5.1.1. Hedbergella and Praehedbergella

Hedbergella, with its type species *Anomalina lorneiana* d'Orbigny var. *trocoidea* Gandolfi, 1942, is distinguished from *Praehedbergella* according to Moullade et al. (2002, 2005). In the investigated thin sections, *Hedbergella* differs from the latter taxon by an extremely massive, macroperforate wall and large test. Moreover, whereas *H. trocoidea* shows 8 to 7 chambers in the last whorl, *P. praetrocoidea* has 6 to 7 chambers. Recognized species of *Praehedbergella* differ by the number and shape of chambers in the last whorl and by the convexity of the spiral side. *P. praetrocoidea*, *P. infractretacea* and *P. gorbachikae* have a convex spiral side, but others are rather flat. Thereby, the latter two have 5 chambers in the last whorl, being rounded in *P. infractretacea* and crescent in *P. gorbachikae*. *P. aptiana*

has 5, *P. primarae* 6 rounded chambers in the last whorl. Finally, 5 to 6 elongated chambers characterize *P. globulifera* (= *P. maslakovae*, = *P. similis*) and *P. roblesae*. The latter species already have cylindrical chambers.

5.1.2. Blowella and Globigerinelloides

The thin sections underpin well the original differential analyses for *Blowella* by Kretchmar and Gorbachik (1971), who pointed out that the latter genus never develops the massive internal dark layer in the test wall. In contrast, all three recorded representatives of *Globigerinelloides* exhibit this layer. As pointed out by Moullade et al. (2005), they form a phylogenetic succession defined by the punctual enlargement of the number of chambers in the last whorl. The lineage starts with *G. ferreolensis* (7 to 8), followed by *G. barri* (9) and ending at *G. algerianus* with more than 10 chambers.

5.1.3. Leupoldina

For the *Leupoldina* as shown by Verga and Premoli Silva (2002), the ampulae-bearing chambers, as well as the absent tubulospines and a microperforate wall, allow its distinction from *Schackoina*. Moreover, the significant time gap between their occurrences lasting from the earliest late Aptian up to the latest Albian underlines their generic level distinction.

5.2. Biostratigraphy

For the 23-m-long section in Sittendorf, five planktonic foraminifera zones were detected. The zones span the late Barremian to late Aptian interval (Gargasian sub-age in Ogg et al., 2004). The occurrence of *Praehedbergella occulta* within the first meter of the section indicates the early Aptian age (Bedoulian sub-age in Ogg et al., 2004) for the lowermost part of the section. The studied sequence therefore correlates largely with the Aptian. In the following chapter the position of the zones in the log, their definition, assemblage composition and the paleobiological character will be described in detail.

5.2.1. Blowella blowi Interval Zone (0 to 10.3 m)

Position. The zone comprises the lower and the main part of the investigated section. It corresponds to the limestone succession of the Schrambach Formation except for its very top. The additional samples from the small outcrop 15 m south of the main log also belong to the *Blowella blowi* Zone.

Definition. According to its original definition by Moullade (1974), this zone comprises the interval between the first occurrence (FO) of *Blowella blowi* (Bolli) and the FO of *Leupoldina cabri* (Sigal). The present work, however, correlates the upper boundary with the base of the *Leupoldina cabri* Acme Zone. As shown by Verga and Premoli Silva (2002), the first occurrence of the latter species is already recorded based on scattered specimens prior to the Selli Anoxic Event, but its earliest worldwide common occurrence is, however, reported only after the anoxic event (compare next section).

The correlation of the *B. blowi* FO with the early/late Barremian boundary follows Ogg et al. (2004) and the results of the DSDP and ODP research. In contrast the same datum appears in the historical stratotype at Cassis-la Bédoule (SE France), much later correlating there with the *Deshayesites deshayesi* Ammonite Zone of the early Aptian (Moullade et al., 1998). The position of the *B. blowi* FO, however, coincides in the latter section to the remarkable facies change and the deepening impulse.

Faunal character and taphonomy. The present planktonic foraminiferal assemblage is characterized by small-sized plankton foraminifera (mean size ca. 100 µm, range 50 to 250 µm). Two small-scaled pulses of upsection size increase are present. The

first one comprises the samples 0 and 1, with maximal size in the latter being about 200 μm . Within sample 2, maximal sizes return to 100 μm , increasing up to sample 8 to 250 μm . Beyond this, a small-scale general increase in size is also evident. Accordingly,

after sample 6, the maximal sizes never drop below the 200 μm mark.

The preservation is poor to moderate, often characterized by strong dissolution and recrystallization of the tests. The individuals

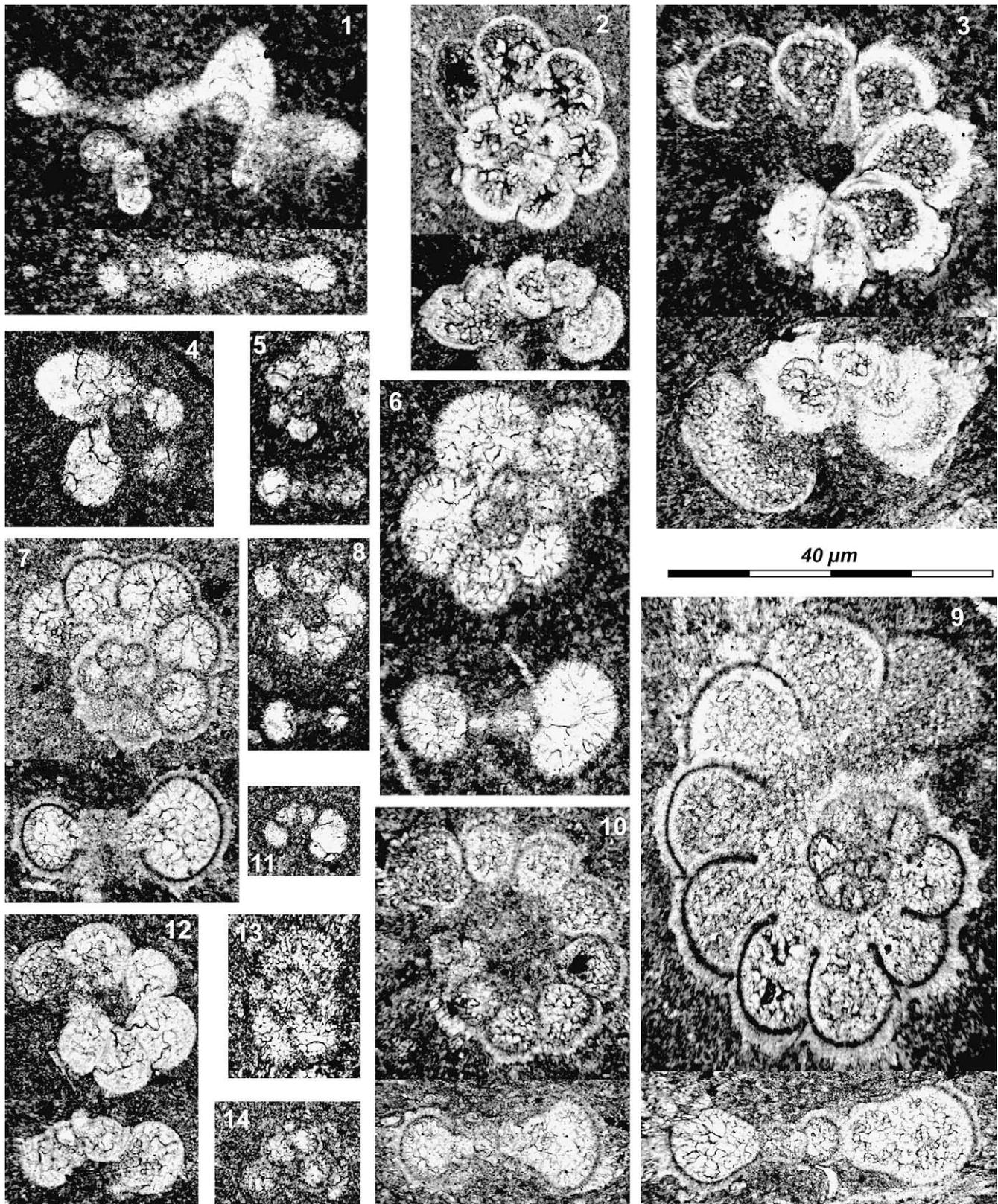


Fig. 7. 1, *Leupoldina cabri* – *pustulans* Group, Sittendorf (SI) 10.2b. 2–3, *Hedbergella trocoidea*. 2, SI 18. 3, SI 16. 4, *Blowiella duboisi*, SI 06. 5, *Blowiella aptiensis*, SI 03. 6, 8, *Blowiella blowi*, 6, SI 10.2b. 8, SI 01. 7, *Globigerinelloides ferreolensis*. 7, above, SI 13. 7, below, SI 14. 9, *Globigerinelloides algerianus*. 9, above, SI 18. 9, below, SI 19. 10, *Globigerinelloides barri*, SI 14. 11, *Praehedbergella occulta*, SI 04. 12, *Praehedbergella praetrocoidea*, SI 13. 13, *Caucasella hoterivica*, SI 13. 14, *Guembeltria cenomana*, SI 04.

are scarce. The maximal abundances are recorded from the middle part of the interval (samples 3–6), where between 12 and 20 individuals were found per 10 mm².

The assemblage is characterized by the dominance of small five-chambered hedbergellids, mostly *Praehedbergella infracretacea*. Scattered *Blowiella blowi*, and in sample 1 also *Caucasella hoterivica*, along with *Praehedbergella occulta* are present throughout the interval. Additionally, *Blowiella aptiensis* was found in sample 3 and relatively large individuals with remarkable, laterally elongated chambers – identified here as *Blowiella duboisi* – characterize samples 6 and 7. The latter morphotype strongly resembles the subspecies *Blowiella duboisi sigali*. The interval also comprises occasional findings of *Guembelitra cenomana*, *Praehedbergella aptiana*, *P. sigali*, and one possible specimen of *Leupoldina pustulans* in sample 4.

The assemblage characterizes well the upper part of the *Blowiella blowi* Zone. Hence the first occurrence of *Praehedbergella occulta* coincides with the Barremian/Aptian boundary (Premoli Silva and Verga, 2004). The first occurrence of *B. duboisi* is slightly younger but still within the *B. blowi* Zone. Conspicuously, the first occurrence of *B. duboisi sigali* has not been reported in the literature prior to the *Leupoldina cabri* Zone (e.g., Longoria, 1974; Premoli Silva and Verga, 2004; Verga and Premoli Silva, 2005).

5.2.2. *Leupoldina cabri* Acme Zone (10.7 to 12 m and 21 to 22 m)

Position. This zone occurs within two about 1-m-thick disjoined horizons of the investigated section. In the lower horizon it superimposes the *Blowiella blowi* Zone, with the boundary positioned between samples 10 and 10.2a. The interval comprises the base of the limestone/marl interbedded unit marking the gradual change from pelagic limestones to the muddy siliciclastic sedimentation. Sample 10.1 is positioned between the latter two samples; although it is rich in radiolarians, it represents the only sample in the section lacking planktonic foraminifera. The same holds true for the nannoconid plankton, which is also completely missing. The latter phenomenon probably reflects the nannoconid crisis, which corresponds to the worldwide decline in nannoconids, roughly coinciding with the base of the “Selli Level” (Bralower et al., 1999; Erba et al., 1999; Ogg et al., 2004). This interpretation is fully supported by the sudden change in nannoconid composition at that particular section’s horizon: samples below comprise both wide- and narrow-channeled nannoconid specimens, the samples above include exclusively wide-channeled specimens. Finally, as the nannoconid crisis and the Selli Event mark the uppermost part of the *Blowiella blowi* Zone, the zonal boundary must correspond to the interval between samples 10.1 and 10.2a. The horizon comprises the interval covering the very top of the Schrambach Formation and the basal part of the Tannheim Formation, represented by an intensive limestone – marl alternation. This interval, including the investigated lithostratigraphic boundary, has been intensively sampled. The zone was detected in 8 samples between 10.2a and 12. The upper boundary of the *Leupoldina cabri* Acme Zone can be tentatively placed between sample 10 and the bulk sample taken immediately above it. Thus, the bulk sample rich in primitive, seven-chambered *Globigerinelloides ferreolensis*, accompanied by *Pseudoschackoina saundersi* and *Praehedbergella infracretacea* and absent leupoldinids, already belongs to the *G. ferreolensis* Interval Zone.

The upper horizon of the *Leupoldina cabri* Acme Zone includes samples 21 and 22. The interval has a tricky position within the section: it superimposes a tectonic contact, the underlying deposits belong to the much younger *G. algerianus* Zone, and the upsection continuation is unknown due to the bad outcrop conditions. The planktonic foraminifera assemblage corresponds exactly to that of the lower horizon.

The third and last local occurrence of the assemblage was traced from samples outside the outcrop area – from a small-scale forest track outcrop located 160 m east of the *L. cabri* AZ interval at the top of the Sittendorf section.

Definition. The zone was originally defined by Bolli (1959) as the Taxon Range Zone of *Leupoldina cabri*, whereas the FO of the nominal taxon was thought to be above the Selli Level marking the Oceanic Anoxic Event 1a. Newer, more detailed investigations (Premoli Silva et al., 1999), however, also found rare specimens of *L. cabri* below the Selli Level, shifting the base of the Taxon Range Zone to the new position. As *Leupoldina cabri* is very rare prior to its originally determined FO, where it becomes relatively common, the present paper follows Premoli Silva and Verga (2004) and treats this zone, as the Acme Range Zone.

Faunal character and taphonomy. The conspicuous size increase distinguishes the planktonic foraminiferal assemblage from the underlying assemblage. Even the lowermost samples already contain up to 500 µm large leupoldinids. *Blowiella blowi*, with a radius of 300 µm, is distinctly larger than its counterparts from the previous zone. An exception is *Globigerinelloides ferreolensis*: its first primitive representatives (sample 11.2) already attain their later maximal size. In general, however, the significant increase in maximal sizes also corresponds with an increase in mean sizes from about 100 µm in the previous zone to about 150 µm. That mean size increase reflects macroevolutionary processes in praehedbergellid representatives, which provide the bulk component of the planktonic foraminifera assemblage. Together with the overall size increase, the planktonic foraminifera also become distinctly more abundant in the *Leupoldina cabri* Acme Zone. The mean densities vary between 40 and 64 individuals per 10 mm². The maximal densities within a sample range between 80 and 88 individuals per 10 mm², except for three samples ranging between 56 and 60 i.p.10 mm². The minimal densities do not fall below 20 i.p.10 mm².

The preservation is considerably better than in the previous zone, possibly reflecting the increased clay content of the matrix. The test walls are well differentiated but altered through pseudomorphosis and sometimes additionally thickened by syntaxial cement crusts. The test chambers are filled with sparite, except in several horizons in which the sediment is characterized by a stronger organic component.

The zone marks a strong species diversity increase. At least 14 species were identified throughout the zone, although one sample contained only 8 species. The stratigraphically most important feature is the presence of leupoldinids, occurring in all samples of the *Leupoldina cabri* Zone. The thin-section species-level differentiation between involute *L. cabri* and evolute *L. pustulans* is, however, tricky and requires good axial sections. Such sections prove the presence of *L. cabri* in the horizon’s lowermost and uppermost sample. The *L. pustulans* individuals were typically found in the uppermost part of the interval. *L. reicheli* with laterally elongated chambers are present throughout the interval and were also common in the samples from the neighboring forest track. *Blowiella* is conspicuously differentiated upsection: in the lower part of the interval (samples 10.2a–b) the large specimens of *B. blowi* are common, whereas within its upper part (samples 11–12) the genus is represented by *B. aptiensis* and, in the uppermost part, additionally by *B. duboisi*.

The true *Globigerinelloides* characterized by a planispiral test and dark interior wall layer could not be definitely verified in the interval, although sections of questionable representatives were observed. In contrast, the lowermost sample of the horizon already contains the low trochospiral *Praehedbergella* specimens with flattened spiral side, six chambers, thickened wall and indeed a conspicuous interior dark layer described so far exclusively for *Globigerinelloides*. The first corresponding seven-chambered

individuals, identified therefore as *Praehedbergella luterbacheri*, appear then in sample 11.1. The first *Globigerinelloides ferreolensis* was found at the beginning of the next zone. The latter phenomenon coincides with the observations of Moullade et al. (2005) from the synchronous interval at Cassis-La Bedoule (SE France). The latter authors, investigating the sieved samples from the uppermost *Leupoldina cabri* Zone, found transitional individuals between *Praehedbergella luterbacheri* and *Globigerinelloides ferreolensis*. They concluded that the trochospiral species must have given rise to the planispiral species and consequently to the genus as well. The Sitendorf samples support that theory well, providing additionally the phylogenetic basis for differentiation between the planispiral genera *Blowiella* and *Globigerinelloides* (Verga and Premoli Silva, 2003a,b, 2005). Finally, note that Moullade et al. (2005) defined a new zone named the *P. luterbacheri* Zone for the uppermost interval of the *Leupoldina cabri* Zone bearing *P. luterbacheri*. In the studied section, this new zone is a very short interval and therefore treated as a subzone including samples 11.1 to 12.

The typical praehedbergellids are represented by *P. praetrocoidea* and *P. infracretacea*. Moreover, *P. gorbachikae*, *P. occulta*, *P. primarae* and *P. globulifera* could be identified. The uppermost occurrence of *Caucasella hoterivica* in the section is recorded from sample 12. The latter species becomes extinct at the upper zonal boundary (Premoli Silva and Verga, 2004).

5.2.3. *Globigerinelloides ferreolensis* Interval Zone (12.3 to 14 m)

Position. This interval is detected from the previously described bulk sample 12.1 and thin section samples 13 and 14. It superimposes the *Leupoldina cabri* Acme Zone, with the boundary positioned beyond the last occurrence of leupoldinids in sample 12. The upper boundary is given by the tectonic contact, followed upsection by a much younger interval belonging to the *Hedbergella trocoidea* Zone.

Definition. The zone is defined by Moullade (1966) as the interval between the Last Occurrence (LO) of *Leupoldina cabri* (Sigal), coinciding with the top of the *L. cabri* Acme Zone, and the FO of *Globigerinelloides algerianus*. In the middle of the zone, *G. barri* develops from *G. ferreolensis* by increasing the number of chambers from 7–8 to 9 (Premoli Silva and Verga, 2004; Moullade et al., 2005). In the present study, the *G. barri* Zone of Moullade et al. (2005) – defined for the upper part of the *G. ferreolensis* Zone including the interval with the name-giving species – is treated as a subzone.

Faunal character and taphonomy. From the several bulk samples taken in the section, only sample 12.1 yielded scattered planktonic foraminifera. The sample, taken from the black clayey interlayer, included moderately to well-preserved specimens of *Globigerinelloides ferreolensis*, *Pseudoschackoina saundersi* and *Praehedbergella infracretacea*.

Thin sections from samples 13 and 14 are characterized by large *Globigerinelloides* representatives with sizes ranging between 250 and 450 μm . The thick-walled large praehedbergellid *P. praetrocoidea* attains sizes between 150 and 250 μm . These mean sizes are exceeded those in the previous zone by about 200 μm .

In contrast, the planktonic foraminiferal abundance remains unchanged, with maximally 84 individuals per 10 mm^2 . Mean abundance ranges between 44 and 52. With exception of tectonically affected intervals (strike/slip microstructures) the fossil preservation correspond the one of the previous zone.

The taxonomic structure is characterized by the presence of the *Globigerinelloides* species *G. ferreolensis* and *G. barri*. The occurrence of *G. barri* places both samples in the corresponding subzone. Praehedbergellids are the most common elements of the assemblage, whereby *Praehedbergella praetrocoidea* and *P. infracretacea* are particularly striking. Finally, *Blowiella aptiensis* was also detected.

5.2.4. *Globigerinelloides algerianus* Taxon Range Zone (18 to 19 m)

Position. This zone, defined by the presence of the designating taxon, was detected in samples 18 and 19. The lower boundary can be interpolated between samples 18 and 17. The latter sample lacks *G. algerianus*. The upper boundary is defined by a fault followed upsection by a much older assemblage belonging to the *Leupoldina cabri* Zone (Samples 20?, 21 and 22). Sample 20 positioned in the tectonized zone show strongly deformed sediments with microbreccia. Consequently the planktonic foraminifera are badly preserved, dominated by small praehedbergellids. Six-chambered *P. praetrocoidea* are present along with moderately large *Blowiella*. *Globigerinelloides* seems to be absent. The presumable leupoldinid presence is indicated by some morphological sections fitting at best to elongated, ampulae-bearing planktonic foraminifera.

Definition. Defined by Moullade (1966), it ranges between the FO and the LO of the nominal taxon. The recognition of the zone depends principally on the taxonomic concept of *Globigerinelloides algerianus* and its differentiation from *G. barri*. The present study follows Moullade et al. (2005) in restricting the former species to phenotypes having 10 or more chambers in the last whorl. In contrast, Premoli Silva and Sliter (1999), for example, considered the axial section and the lateral test compression to be the main distinctive characters in the two species.

Faunal character and taphonomy. With the exception of microtectonically influenced thin section portions, the planktonic foraminifera are moderately to well-preserved, similar to the previous zone. The walls are principally well differentiated, although the foraminiferal tests can be truncated through internal horizontal strike-slip movements and compaction/dissolution phenomena.

The abundances are similar to those recorded for *L. cabri* and *G. ferreolensis* Zones, with maximally 84 individuals per 10 mm^2 . *Globigerinelloides algerianus* found therein is the largest planktonic foraminifera species of the whole section, with individuals reaching up to 600 μm in sample 19 and 550 μm in sample 18. Other *Globigerinelloides* are smaller but still provide conspicuously large-sized planktonic foraminifera, with sizes ranging between 300 and 400 μm . *Hedbergella trocoidea* ranges between 250 and 300 μm .

The assemblage is characterized by the common presence of *Globigerinelloides*, including all three of its so far known species: *G. barri*, *G. ferreolensis* and *G. algerianus*. A stratigraphically striking feature is the occurrence of *Hedbergella trocoidea* with seven-chambered phenotypes, which are distinctly smaller than the eight-chambered representatives of the *H. trocoidea* Zone. *Blowiella blowi* was also identified in the interval.

5.2.5. *Hedbergella trocoidea* Interval Zone (15 to 17 m)

Position. This zone was detected based on the absence of *Globigerinelloides algerianus* and the presence of extraordinarily large, eight-chambered specimens of *Hedbergella trocoidea* in samples 15 and 16. Sample 17 has been placed in this zone based on the absence of *G. algerianus*, although the eight chambered phenotype of *H. trocoidea* is absent therein. The upper zonal boundary, placed between samples 17 and 18, bounds it from the next older zone positioned upsection. This implies that the interval including *H. trocoidea* and *G. algerianus* Zones is tectonically inverted. Thus, the *H. trocoidea* Zone interval is superimposed on the tectonic contact, bounding it from the distinctly older *G. ferreolensis* Zone.

Definition. The zone was originally defined by Moullade (1966) as the interval between the LO of *Globigerinelloides algerianus* and the FO of *Paraticinella bejaouaensis*. It is characterized by the co-occurrence of *Planomalina cheniourensis* and *Hedbergella trocoidea* (cf. Premoli Silva and Verga, 2004). The former species, however, with its first occurrence recorded in the *G. algerianus* Zone, is absent in the studied section. Nevertheless, the highly evolved, large,

eight-chambered specimens of *H. trocoidea*, absent in the previous zone, characterize well this zone.

Faunal character and taphonomy. The preservation is good to moderately good. The test walls are recrystallised by pseudomorphosis and partly overgrown by syntaxial cement.

The mean test sizes are about 200 μm , but the maximal sizes are distinctly smaller than in the previous zone. The largest individuals are hedbergellids. *Hedbergella trocoidea* specimens can reach sizes up to 400 μm . Whereas the hedbergellids apparently reached their optimum development here, the *Globigerinelloides* underwent significant size decrease. Hence not only the extinction of large globigerinelloides (*G. barri* and *G. algerianus*) is striking but also the surviving *G. ferreolensis* with a maximal size of 250 μm in investigated samples is distinctly smaller than in the previous zone.

The abundance values apparently decrease in this zone. The maximal recorded abundance never exceeds 48 individuals per 10 mm^2 , and mean abundances range between 24 and 36.

Like in all previous zones, the taxonomic structure is dominated by preahedbergellids. Typical are *Praehedbergella praetrocoidea*, *P. infracretacea* as well as *P. gorbachikae*. Large, massive, seven- and eight-chambered *Hedbergella trocoidea* is present throughout the samples. As noted above, the increase in size and number of chambers in the last whorl, relative to the counterparts in the previous zone, is interpreted to reflect macroevolution and is an evidence for this phenotype younger stratigraphic age. This correlates well with the absence of *Globigerinelloides algerianus* in the samples, supporting the placement in the *H. trocoidea* Zone. Hence, *G. ferreolensis* is the only *Globigerinelloides* representative. *Blowiella aptiensis* was also detected in the samples.

6. Geophysical and geochemical measurements

The gamma log measures the radioactivity of the rock and represents a direct function of its clay-mineral content. Increasing radioactivity reflects the increasing clay content. Gamma response (counts per second – cps) was measured using a hand-held standard gamma ray scintillometer.

The measured values range between 11 and 36 cps (Fig. 6). The gamma response allows a very good differentiation between Schrambach and Tannheim Formation. In the Schrambach Formation the gamma response generally never exceeds 20 cps, whereas the Tannheim Formation typically shows values above 20 cps. Within the *Leupoldina cabri* Zone, the gamma response gradually increases, reaching the highest values in the *G. algerianus* and *H. trocoidea* Zones. Note that the values from the lower *L. cabri* Zone horizon correlate exactly with those attained in the upper horizon, corresponding to the latter zone, only representing one tectonically inverted block (Fig. 6). The changes in the clay mineral input show, especially in the upper part of the section, a cyclic pattern within the 1 m scale.

The CaCO_3 content is distinctly higher in the Schrambach Formation than in the Tannheim Formation. Then only one sample of the Schrambach Formation fell below the 74% mark. In the lower part of the Schrambach Formation (*Leupoldina cabri* Zone) the CaCO_3 content is still punctually high, decreasing definitely in the stratigraphically younger *G. ferreolensis* and *G. algerianus* Zones. Therein it stays generally below the 70% mark, with the minimal value of 55% recorded in the stratigraphically youngest layers of the *Hedbergella trocoidea* Zone. Apparently the CaCO_3 trend acts opposite to the one of the gamma ray curve.

The results of the total carbon analyses (Fig. 6) were somewhat unexpected. The light-colored limestones of the Schrambach Formation had distinctly less total carbon than the dark marly limestones of the Tannheim Formation. The values are generally low. Except for samples 8 and 9 (maximal value 2.5%), they do not exceed the 2% mark. Moreover, in the *G. ferreolensis* Zone they never

exceed 0.5%. The peak TOC level does not correlate biostratigraphically with the AOE 1a because the nannoconid crisis is significantly above that level. The second peak in the uppermost *L. cabri* Zone is biostratigraphically too young. Consequently, another explanation must be sought for the relatively enhanced TOC level in the pelagic limestone series of the Schrambach Formation. These limestones are almost pure nannoconid limestones and therefore a product of an extraordinary calcareous phytoplankton production. This production decreased within the Tannheim Formation, where nannoconids became less frequent. Consequently, the TOC curve must reflect the changes in primary productivity of the depositional paleoenvironment.

7. Interpretation of the section

The biostratigraphic analysis proved that the lower part of the section, including the investigated lithostratigraphic boundary between the Schrambach and Tannheim Formations, is continuous. In contrast, the upper part the section shows two distinct stratigraphic discontinuities. Moreover the biostratigraphy clearly demonstrates that the package between the two faults is a tectonically inverted block with a stratigraphically older strata overlying the younger one (Fig. 8).

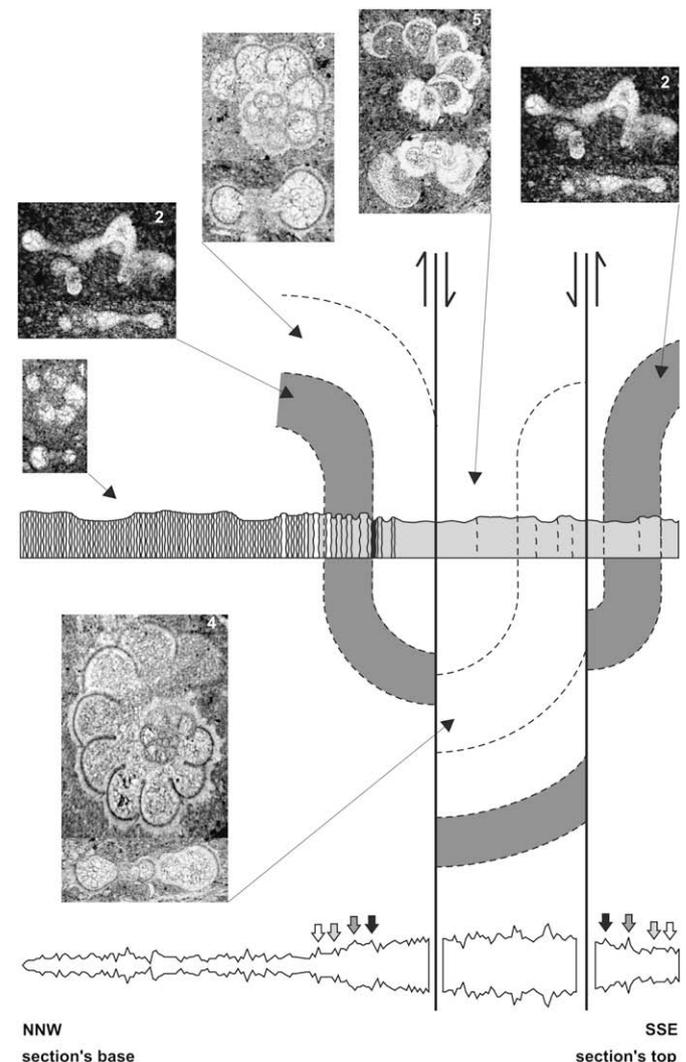


Fig. 8. Tectonic interpretation of the section Sittendorf based on the evaluation of biostratigraphic and geophysical data. Each thin section photograph represents the name-giving taxon of the indicated biozone: 1. *B. blowi* Interval Zone (IZ), 2. *L. cabri* Acme Zone, 3. *G. ferreolensis* IZ, 4. *G. algerianus* Taxon Range Zone, 5. *H. trocoidea* IZ.

The gamma-log curve supports the biostratigraphic data very well. The gamma response becomes gradually stronger in the lower, undisturbed part of the section. The inverted block from the upper part of the section shows the highest gamma responses, remaining vertically at about the same mean intensity level. The uppermost package of the section, however, shows an upsection decreasing gamma response. The curve pattern therefore shows a vertically inverted picture of the corresponding biostratigraphic interval of the lower part of the section. This strongly suggests that the package from the uppermost part of the section represents an inverted block as well.

These data allow a precise reconstruction of the tectonic setting of the studied section. Accordingly, the best fit tectonic interpretation for the section's stratigraphic pattern is a position in a laterally (N-S) compressed, isocline, slightly overturned, syncline fold as illustrated in Fig. 8. The interpolation of the successional biostratigraphic horizons beyond the large inverted package in the upper part of the section yields the most reasonable reconstruction. Therefore, the latter block must have been pushed out from the southern fold wing apex due to the pressure from progressing lateral compression. The reconstructed offset is about 5 to 6 m.

8. Conclusions

The results presented are based on thin section studies – the sieving revealed only scattered and badly preserved microfossils.

The Schrambach Formation comprises the lower 10.9 m of the section. Those pelagic limestones and marly limestones are mudstones to wackestones whose matrix is dominated by large nannoconid phytoplankton. Among the microplankton, radiolarians are often abundant, especially in the topmost portions. Planktonic foraminifera are, except for the topmost part, scattered; in the lower part they are still small sized, becoming distinctly larger upwards. The assemblage is dominated by small, five-chambered *Praehedbergella*, particularly by *P. infracretacea*. The presence of *Blowiella blowi* together with *Praehedbergella occulta* already in the lower part of the section allows the section to be placed into the upper part of the *B. blowi* Interval Zone and to be correlated with the uppermost Barremian and lowermost Aptian.

The uppermost part of the Schrambach Formation (10 m to 10.9 m) displays already marly intercalations, and therein also the C_{org} values suddenly drop from previously enhanced values (1–2%) to distinctly lower ones (<1%). Except for one sample close to the dark clay intercalation, the lowered C_{org} values persist upward throughout the Tannheim Formation. The planktonic foraminifera also undergo a radical change, not only in taxonomic composition, size and wall thickness, but particularly in abundance. From here upwards, zooplankton blooms characterize the succession up to its top. The planktonic foraminiferal assemblage is characterized by the common *Leupoldina* and large specimens of *Blowiella blowi*, defining its stratigraphic position within the *Leupoldina cabri* Acme Zone. The base of the latter Zone superimposes the early Aptian Oceanic Anoxic Event “Selli” and has an inferred age of about 124 Ma. Up to now, the presence of a planktonic foraminiferal assemblage with *Leupoldina* was unknown from the investigated depositional cycle (Schrambach – Tannheim – Losenstein Formation).

The larger part of the succession within the lower portion of the Tannheim Formation (between 10.9 m and 14 m) is characterized by the common occurrence of *Leupoldina*. For the upper part of the Acme Zone, a characteristic feature is the occurrence of *Praehedbergella luterbacheri* and *Globigerinelloides ferreolensis*. The last occurrence of *Leupoldina* in the section approximates the base of the *Globigerinelloides ferreolensis* Interval Zone, correlating roughly with the early/late Aptian boundary. The presence of the upper part of the Interval Zone is indicated by the introduction of *Globigerinelloides barri*. This species with 9 chambers in the last whorl

represents the limb in the gradual evolution from *G. ferreolensis* (7–8) to *G. algerianus* (10 to 12).

The uppermost part of the Sittendorf exposure (14 m to 23 m) follows a fault structure and comprises another fault at the 20 m of the section. Except for those two faults, the succession comprising the Tannheim Formation has been originally presumed for being principally continuous. Yet, the biostratigraphic analysis together with the analysis of the gamma-log curve trend proved clearly highly complicated tectonic setting.

Hence the samples above the fault showed distinctly younger planktonic foraminifera assemblage than the ones below the fault. The large, thick-walled *Hedbergella trocoidea* with 8 chambers in the last whorl, along with the absent *Globigerinelloides algerianus*, underpinned the late Aptian *H. trocoidea* Interval Zone.

Further upsection, up to the next fault, the reverse succession has been detected. Then not only the extremely large specimens of *G. algerianus* in that samples proved the exact correlation with the late Aptian *G. algerianus* Taxon Range Zone, but also the *Hedbergella trocoidea* has been found therein present exclusively by the distinctly smaller, primitive, 7-chambered morphotypes. Hence, this particular part of the section has been clearly proved for being a tectonically inverted block.

The latter block is delimited from the topmost part of the section by the second fault positioned at its 20 m. The reoccurrence of *Leupoldina cabri* Acme Zone in those topmost samples is highly significant. Hence it proves the stratigraphically reversed position of the uppermost section part. It proves, as well, the significant tectonic movement at the fault causing the stratigraphic gap of one planktonic foraminifera zone (i.e. *G. ferreolensis* IZ). The decreasing gamma log values together with the characteristic pattern, which is reversely symmetrical to the corresponding pattern in the lower, undisturbed part of the section, correspond well with the interpretation of that block as a tectonically inverted structure.

The presented data underpin well the rather complicated, structural geological interpretation of the section. Hence the studied exposure is apparently positioned within a slightly northwards overturned, isoclinal syncline fold. The discontinuity in the upper section is a product of the lateral pressure, block escape movements in the southern wing of the syncline.

In conclusion, the range of the section is estimated to be about 10 m.y. and to include five Aptian planktonic foraminifera zones. The terrigenous input bounded to initial subduction of the Penninic Ocean under the Austroalpine Microplate started at about 123 Ma (early Aptian). This date corresponds with that determined for the lithostratigraphic boundary between the Schrambach Formation and the Tannheim Formation. Although the section is discontinuous in its upper part (Tannheim Formation), the studied lithostratigraphic boundary is positioned within the continuous part of the section, making it suitable for the present investigation. Finally, thin section biostratigraphy of planktonic foraminifera proved, also in the Northern Calcareous Alpidic shelf, to be a powerful tool for stratigraphic dating of Aptian deep-water successions.

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References

- Aguado, R., Company, M., O'Dogherty, L., Sandoval, J., Tavera, J.M., 1992. Biostratigraphic analysis of the pelagic Barremian/Aptian in the Betic Cordillera (southern Spain): preliminary data. *Cretaceous Research* 13, 445–452.
- Aguado, R., Castro, J.M., Company, M., de Gea, G.A., 1999. Aptian bio-events – an integrated biostratigraphic analysis of the Almadich Formation, Inner Prebetic Domain, SE Spain. *Cretaceous Research* 20, 663–683.
- Altiner, D., 1991. Microfossil biostratigraphy (mainly foraminifers) of the Jurassic-Lower Cretaceous carbonate successions in north-western Anatolia (Turkey). *Geologica Romana* 27, 167–213.
- Antonova, Z.A., 1964. In: Antonova, Z.A., Schmygina, T.A., Gnedina, A.G., Kalugina, O. M.: Neocomian and Aptian Foraminifera from the Pshekh-Ubin interfluvium (northwestern Caucasus) [in Russian]. In: Egoian, V.L. (Ed.), *Stratigraphy and lithology of the Mesozoic and Cainozoic deposits of the Krasnodar area*, Trudy Krasnodarskii Filial Vsesoyuznogo Neftgazozonogo Nauchno-Isledovatel'skogo Instituta, vol. 12, pp. 3–72.
- Bartenstein, H., Bolli, H.M., 1986. The Foraminifera in the Lower Cretaceous of Trinidad, W.I. Part 5: Maridale Formation, upper Part; Hedbergella rohri Zone. *Ecologiae Geologicae Helveticae* 79/3, 945–999.
- Bodrogi, I., Fogarasi, A., 2002. New data on the stratigraphy of the Lower Cretaceous of the Gerece Mts. (Hungary) and the Lackbach section (Austria). In: Wagreich, M. (Ed.), *Aspects of Cretaceous Stratigraphy and Palaeobiogeography*. Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen 15, 295–313.
- Bolli, H.M., 1957. The foraminiferal genera Schackoina Thalmann, emended and Leupoldina, n. gen. in the Cretaceous of Trinidad B.W.I. *Ecologiae Geologicae Helveticae* 50, 271–278.
- Bolli, H.B., 1959. Planktonic foraminifera from the Cretaceous of Trinidad, B.W.I. *Bulletins of American Paleontology* 39, 257–277.
- Bolli, H.M., Loeblich, A.R., Tappan, H., 1957. The Planktonic foraminiferal families Hantkeninidae, Orbulinidae, Globorotaliidae, and Globotruncanidae. *U.S. National Museum Bull.* 215, 3–50.
- Boudagher-Fadel, M.K., Banner, F.T., Simmons, M.D., 1997. The Early Evolutionary History of Planktonic Foraminifera. *British Micropalaeontological Society Publication Series*, 269 pp.
- Bralower, T.J., Leckie, R.M., Sliter, W.V., Thierstein, H.R., 1995. An integrated Cretaceous microfossil biostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.P., Hardenbol, J. (Eds.), *Geochronology Time Scales and Global Stratigraphic Correlation*. SEPM Special Publication, 54, pp. 65–79.
- Bralower, T.J., Fullagar, P.D., Paull, C.K., Dwyer, G.S., Leckie, R.M., 1997. Mid-Cretaceous strontium-isotope stratigraphy of deep-sea sections. *GSA Bulletin* 109/10, 1421–1442.
- Bralower, T.J., CoBabe, E., Clement, B., Sliter, W.V., Osburn, C.L., Longoria, J., 1999. The record of global change in mid-Cretaceous (Barremian-Albian) sections from the Sierra Madre, northeastern Mexico. *Journal of Foraminiferal Research* 29/4, 418–437.
- Broennimann, P., Brown Jr., N.K., 1958. Hedbergella, a New Name for a Cretaceous Planktonic Foraminiferal Genus. *Journal of the Washington Academy of Sciences* 48, 15–17.
- Cocconi, R., Premoli Silva, I., 1994. Planktonic foraminifera from the Lower Cretaceous of Rio Argos sections (southern Spain) and biostratigraphic implications. *Cretaceous Research* 15, 645–687.
- Cocconi, R., Erba, E., Premoli-Silva, I., 1992. Barremian-Aptian calcareous plankton biostratigraphy from the Gorgo Cerbara section (Marche, central Italy) and implications for plankton evolution. *Cretaceous Research* 13, 517–537.
- Cushman, J.A., Ten Dam, A., 1948. Globigerinelloides, a new genus of the Globigerinidae. *Contributions from the Cushman Foundation for Foraminiferal Research* 24, 42–44.
- Erba, E., Channell, J.E.T., Claps, M., Jones, C., Larson, R., Opdyke, B., Premoli Silva, A., Riva, A., Salvini, G., Torricelli, S., 1999. Integrated stratigraphy of the Cismont Apennines (southern Alps, Italy): a “reference section” for the Barremian-Aptian interval at low latitudes. *Journal of Foraminiferal Research* 29/4, 371–391.
- Faupl, P., Wagreich, M., 2000. Late Jurassic to Eocene palaeogeography and geodynamic evolution of the Eastern Alps. *Mitteilungen der Österreichischen Geologischen Gesellschaft* 92, 79–94.
- Faupl, P., 2003. *Historische Geologie: eine Einführung*. Facultas, Wien, 271 pp.
- Gandolfi, R., 1942. Ricerche micropaleontologiche e stratigrafiche sulla Scaglia e sul Flysch cretaci dei dintorni di Balerna (Canton Ticino). *Rivista Italiana di Paleontologia. Memoria* 4, 1–160.
- Glaessner, M.F., 1937. Planktonische Foraminiferen aus der Kreide und dem Eozän und ihre stratigraphische Bedeutung. In: *Studies in Micropaleontology Vol. 1*(1) p. 27–46.
- Gorbachik, T.N., 1986. Jurassic and Lower Cretaceous Planktonic Foraminifera of the South USSR. *Nauka, Moscow*, 239 pp. (in Russian).
- Gorbachik, T.N., Moullade, M., 1973. Caracteres microstructuraux de la paroi du test des foraminifères planctoniques du Crétacé inférieur et leur signification sur le plan taxinomique. *C. R. Acad. Sci. Paris*, 227, ser. D, S. 2661, Paris.
- Herrle, J.O., Mutterlose, J., 2003. Calcareous nannofossils from the Aptian-Lower Albian of southeast France: palaeoecological and biostratigraphic implications. *Cretaceous Research* 24, 1–22.
- Kretschmar, V., Gorbachik, T.N., 1971. In: Gorbachik, T.N. (Ed.), *On Early Cretaceous Foraminifera from Crimea*. *Voprosy Mikropaleontologii* 14, 125–139 (In Russian, English abstract).
- Kretschmar, V., Gorbachik, T.N., 1986. In: Gorbachik, T.N. (Ed.), *Jurassic and Early Cretaceous planktonic foraminifera of the south of the USSR* [in Russian], p. 239.
- Leckie, R.M., Bralower, T.J., Cashman, R., 2002. Oceanic anoxic events and plankton evolution: biotic response to tectonic forcing during the mid-Cretaceous. *Paleoceanography* 17/3. doi:10.1029/2001PA000623.
- Lipson-Benitah, Sh., Almogi-Labin, A., 2004. Aptian planktonic foraminifera from Israel. *Israel Journal of Earth Sciences* 53/1, 27–46.
- Longoria, J.F., 1974. Stratigraphic, Morphologic and Taxonomic Studies of Aptian Planktonic Foraminifera. *Revista Española de Micropaleontología, Numero Extraordinario*, 107 pp., 27 pls.
- Lukeneder, A., 2003. Ammonoid stratigraphy of Lower Cretaceous successions within the Vienna Woods (Kaltenleutgeben section, Lunz Nappe, Northern Calcareous Alps, Lower Austria). In: Piller, W.E. (Ed.), *Stratigraphia Austriaca. Austrian Academy of Sciences Series, “Schriftenreihe der Erdwissenschaftlichen Kommissionen”*, 16, pp. 165–191.
- Lukeneder, A., 2004a. Late Valanginian ammonoids: Mediterranean and Boreal elements – implications on sea-level controlled migration (Ebenforst Syncline; Northern Calcareous Alps; Upper Austria). *Austrian Journal of Earth Sciences* 95/96, 46–59.
- Lukeneder, A., 2004b. Stratigraphische Erkenntnisse aus einem neuen Vorkommen von Unterkreide-Ammonoiten in der Losensteiner Mulde (Ternberger Decke, Nördliche Kalkalpen). *Jahrbuch der Geologischen Bundesanstalt* 144/2, 173–189.
- Masse, J.P., et al. (12 co-authors), 2000. Early Aptian. In: Dercourt, J., Gaetani, M. (Eds.), *Atlas Peri-Tethys, Palaeogeographical Maps Map 13, (CCGM/CGMW)* Paris.
- Moullade, M., 1966. Etude stratigraphique et micropaleontologique du Crétacé inférieur de la ‘Fosse Vocontienne’. *Documents du Laboratoire de Géologie, Faculté des Sciences, Lyon*, 15, pp. 1–369.
- Moullade, M., 1961. Quelques Foraminifères et Ostracodes nouveaux du Crétacé inférieur vocontien. *Revue de Micropaléontologie*, Paris 3 (4), 213–216.
- Moullade, M., 1974. Zones de foraminifères du crétacé inférieur mesogéen. *Comptes Rendus des Séances de l'Académie des Sciences, Paris, Serie D* 278, 1813–1816.
- Moullade, M., Bellier, J.-P., Tronchetti, G., 2002. Hierarchy of criteria, evolutionary processes and taxonomic simplification in the classification of Lower Cretaceous planktonic foraminifera. *Cretaceous Research* 23, 111–148.
- Moullade, M., Tronchetti, G., Bellier, J.-P., 2005. The Gargasian (Middle Aptian) strata from Cassis-La Bédoule (Lower Aptian historical stratotype, SE France): planktonic and benthonic foraminiferal assemblage and biostratigraphy. *Carnets de Géologie /Notebooks on Geology Brest, Article 2005/02 (CG2005_A02)*.
- Moullade, M., Tronchetti, G., Kuhnt, W., Masse, J.-P., 1998. Les Foraminifères benthiques et planctoniques du stratotype historique de l'Aptien inférieur dans la région de Cassis – La Bédoule (SE France). *Géologie Méditerranéenne* 25/3–4, 187–225.
- Ogg, J.G., Agterberg, F.P., Gradstein, F.M., 2004. The Cretaceous period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), *A Geologic Time Scale 2004*. Cambridge University Press, pp. 334–383.
- Omana, L., González-Arreola, C., Ramírez-Garza, B.M., 2005. Barremian planktonic foraminiferal events correlated with the Ammonite zones from the San Lucas Formation, Michoacán (SW Mexico). *Revista Mexicana de Ciencias Geológicas* 22/1, 88–96.
- Premoli Silva, I., Erba, E., Salvini, G., Locatelli, C., Verga, D., 1999. Biotic changes in Cretaceous oceanic anoxic events of the Tethys. *Journal of Foraminiferal Research* 29/4, 352–370.
- Premoli Silva, I., Sliter, W.V., 1999. Cretaceous paleoceanography: evidence from planktonic foraminiferal evolution. In: Barrera, E., Johnson, C.C. (Eds.), *Evolution of the Cretaceous Ocean-Clymate System*. Geological Society of America Special Paper, 332, pp. 301–328.
- Premoli Silva, I., Verga, D., 2004. *Practical Manual of Cretaceous Planktonic Foraminifera*. International School on Planktonic Foraminifera, 3^o Course: Cretaceous, Tipografia Pontefelcino, Perugia, 283 pp. + CD-ROM.
- Rückheim, S., Mutterlose, J., 2002. The Early Aptian migration of planktonic foraminifera to NW Europe: the onset of the mid-Cretaceous plankton revolution in the Boreal Realm. *Cretaceous Research* 23, 49–63.
- Sigal, J., 1952. Aperçu stratigraphique sur la Micropaléontologie du Crétacé. *XIXe Congrès Géologique International (Série 1)*, Alger Vol. 26, pp. 3–47.
- Skelton, P.W., 2003. 5 Changing climate and biota – the marine record. In: Skelton, P.W. (Ed.), *The Cretaceous World*. The Open University and Cambridge University Press, Cambridge, UK, pp. 163–184.
- Sliter, W.V., 1989. Biostratigraphic zonation for Cretaceous planktonic foraminifera examined in thin sections. *Journal of Foraminiferal Research* 19/1, 1–19.
- Sliter, W.V., 1992. Cretaceous planktonic foraminiferal biostratigraphy and paleoceanographic events in the Pacific Ocean with emphasis on indurated sediment. In: Ishizaki, K., Saito, T. (Eds.), *Centenary of Japanese Micropaleontology*. Terra Scientific Publishing Company, Tokyo, pp. 281–299.

- Sliter, W.V., 1999. Cretaceous planktic foraminiferal biostratigraphy of the Calera Limestone, Northern California, USA. *Journal of Foraminiferal Research* 29/4, 318–339.
- Strasser, A., Caron, M., Gjermeni, M., 2001. The Aptian, Albian and Cenomanian of Roter Sattel, Romandes Prealps, Switzerland: a high-resolution record of oceanographic changes. *Cretaceous Research* 22, 173–199.
- Subbotina, N.N., 1953. Fossil foraminifera of the USSR. Globigerinidae, Hantkeninidae and Globorotaliidae [in Russian]. *Trudy Vsesoyuznogo Neftyanogo Nauchno-Isledovatel'skogo Geologo-Razvedochnogo Instituta (VNIGRI), Novaya Seriya* Vol. 76 p. 1–296.
- Verga, D., Premoli Silva, I., 2002. Early Cretaceous planktonic foraminifera from the Tethys: the genus *Leupoldina*. *Cretaceous Research* 23, 189–212.
- Verga, D., Premoli Silva, I., 2003a. Early Cretaceous planktonic foraminifera from the Tethys: the small, few-chambered representatives of the genus *Globigerinelloides*. *Cretaceous Research* 24, 305–334.
- Verga, D., Premoli Silva, I., 2003b. Early Cretaceous planktonic foraminifera from the Tethys: the large, many-chambered representatives of the genus *Globigerinelloides*. *Cretaceous Research* 24, 661–690.
- Verga, D., Premoli Silva, I., 2005. Early Cretaceous planktonic foraminifera from the Tethys: the Upper Aptian, planispiral morphotypes with elongatae chambers. *Cretaceous Research* 26, 239–259.
- Wagreich, M., 2003. A slope-apron succession filling a piggyback basin: the Tannheim and Losenstein Formations (Aptian – Cenomanian) of the eastern part of the Northern Calcareous Alps (Austria). *Mitteilungen der Österreichischen Geologischen Gesellschaft* 93, 31–54.
- Weidich, K.F., 1990. Die kalkalpine Unterkreide und ihre Foraminiferenfauna. *Zitteliana* 17, 1–312.

Appendix: Cited taxa

***Hedbergella* Broennimann and Brown, 1958**

(Type species: *Anomalina lorneiana* d'Orbigny var. *trocoidea* Gandolfi, 1942)

H. trocoidea (Gandolfi, 1942)

***Praehedbergella* Gorbachik and Moullade, 1973**

(Type species: *Praehedbergella tuschepsensis* Antonova, 1964)

P. gorbachikae Longoria, 1974

P. infracretacea Glaessner, 1937

P. luterbacheri Longoria, 1974

P. occulta Longoria, 1974

P. praetrocoidea Kretschmar and Gorbachik, 1986

P. sigali Moullade, 1966

P. similis Longoria, 1974

***Globigerinelloides* Cushman and ten Dam, 1948**

(Type species: *Globigerinelloides algeriana* Cushman and ten Dam, 1948)

G. algerianus Cushman and ten Dam, 1948

G. barri (Bolli et al., 1957)

G. ferreolensis (Moullade, 1961)

***Blowiella* Kretschmar and Gorbachick, 1971**

(Type species: *Planomalina blowi* Bolli, 1959)

B. blowi (Bolli, 1959)

B. aptiensis Longoria, 1974

B. maridalensis (Bolli, 1959)

B. paragottisi Verga and Premoli Silva, 2003a

***Caucasella* Longoria, 1974**

(Type species: *Globigerina hoterivica* Subbotina, 1953)

C. hoterivica (Subbotina, 1953)

***Leupoldina* Bolli, 1957**

(Type species: *Leupoldina protuberans* Bolli, 1957 = *Schackoina cabri* Sigal, 1952)

L. cabri (Sigal, 1952)

L. pustulans pustulans Bolli, 1957

L. reicheli Bolli, 1957

***Pseudoschackoina* Verga and Premoli Silva, 2005**

(Type species: *Planomalina saundersi* Bolli, 1959)

P. saundersi (Bolli, 1959)

***Pseudoplanomalina* Moullade et al., 2002**

(Type species: *Planomalina cheniourensis* Sigal, 1952)

P. chenourensis (Sigal, 1952)