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Characterization of silicified fossil assemblage from upper Carnian "Amphiclina beds" at Crngrob (central Slovenia)

Značaj okremenjene fosilne združbe zgornjekarnijskih amfiklinskih plasti pri Crngrobu (osrednja Slovenija)

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Ključne besede: Slovenski bazen, Južne Alpe, zgornji trias, tuval, diageneza, roženec, okremenitev, konodonti

Abstract

The village of Crngrob (central Slovenia) is known to geologists for the silicified fossils found in the thick soil covering the "Amphiclina beds", a Carnian lithostratigraphic unit of the Mesozoic Slovenian Basin. Due to silicification, the assemblage may provide an important insight into Carnian marine life; however, the nature of the fossil assemblage, as well as the timing and mode of silicification are unknown. A detailed sedimentological section, which covers the uppermost part of the "Amphiclina beds" and their transition to the "Bača Dolomite", was recorded at one of the fossil-bearing localities. The section consists of limestone (including bioturbated filament and radiolaria-filament wackestones, laminated filament packstone, bioclast wackestone, peloid packstone, floatstone with intraclasts and bioclasts, and intraclast floatstone and rudstone), marlstone and dolomite. Chert is locally present in nodules or as dispersed silicified patches, giving a speckled appearance to the host rock. According to our interpretation, the deposition of the limestone occurred via hemipelagic settling, turbidite currents and debris flows in a slope-to-basin or outer ramp setting. The composition of the grains (which include green algae fragments, thick-shelled bivalves, corals and solenoporacean algae) clearly points to the allochthonous nature of the material, which was largely derived from shallow-water environments. Fossils, as well as the intraclasts and sometimes the matrix, are locally replaced by chalcedony and granular megaquartz. This type of silicification does not appear to be selective to particular microfacies. As the silicification occurred after the down-slope transport of shells and the deposition of the sediment, the Crngrob fossil assemblage represents a thanatocoenosis or even a taphocoenosis, and it is not representative of autochthonous Carnian associations.

Izvleček

Okolica Crngroba (osrednja Slovenija) je geologom poznana po okremenjenih fosilih, najdenih v preperini, ki prekriva karnijske amfiklinske plasti. Zaradi okremenjenosti bi fosilna združba lahko nosila pomembno paleoekološko vrednost, vendar njen izvor in značaj nista znana, tako kot nista poznani vrsta in čas okremenitve. V okviru raziskave smo na eni od lokalitet, kjer so bili najdeni fosili, posneli sedimentološki profil preko zgornjega dela amfiklinskih plasti in prehoda v baški dolomit. Zaporedje sestavlja menjavanja plasti apnenca (bioturbiranega filamentnega in radiolarijsko-filamentnega wackestona, laminiranega filamentnega packstona, bioklastičnega wackestona, peloidnega packstona, floatstona z intraklasti in bioklasti ter intraklastičnega floatstone do rudstona), laporovca in dolomita. Lokalno se pojavlja roženec v obliki večjih gomoljev ali drobnih, razpršenih zaplat. Glede na našo interpretacijo je sedimentacija potekala na zunanjem delu pobočja ali ob vznožju pobočja, kjer se hemipelagični in deloma pelagični apnenci prepletajo s sedimenti turbiditnih in drobirskih tokov. Gravitacijski tokovi so večino biogenih zrn, kot so zelene alge, debelolupinske školjke, korale in solenoporaceje, prinesli iz plitvomorskih okolij. Fosili, mestoma pa tudi mikritni intraklasti in osnova, so nadomeščeni s kalcedonom in zrnatim megakremenom. Ta vrsta okremenitve ni vezana na posamezen mikrofacies, temveč se pojavlja v vseh apnenčastih in dolomitnih plasteh. Ker je do okremenitve prišlo po prenosu materiala po pobočju navzdol, nabrana fosilna združba ne more predstavljati naravne karnijske življenjske združbe, temveč gre za primer tanatocenoze ali celo za tafocenozo.

Introduction

With the right timing, silicification may provide high-quality preservation of fossils, because it preserves fine-scale morphological details and small, fragile or otherwise rarely fossilized organisms. Silicified fossil assemblages may thus yield a valuable insight into past life (Cherns & Wright, 2009; Mergl, 2010; Butts & Briggs, 2011). A large collection of silicified and/or pyritized (limonitized) centimetre-sized cephalopods (ammonites), brachiopods, bivalves and gastropods, as well as a few large pieces of colonial corals has been assembled through almost 25 years of field work by F. Stare in the vicinity of Crngrob (central Slovenia). This site has raised considerable interest among professional geologists, but the lack of quality exposures has prevented a more detailed analysis. According to previous work (Ramovš, 1981, 1986, 1987, 1998a, b) the fossils derive from black micritic limestone of Tuvalian (Upper Carnian) age, which belongs to the "Amphiclina beds" (Grad & Ferjančič, 1968; Rožič et al., 2015), an informal lithostratigraphic unit of the Slovenian Basin, but no further account of the fossil-bearing beds has been given until now.

A well exposed succession of shale, limestone, marlstone and dolomite at one of the fossil-bearing sites near the village of Crngrob has been discovered during the geological mapping of the area. The section provided an opportunity to document the composition of the uppermost "Amphiclina beds" and to evaluate the nature of the Crngrob fossil assemblage and its potential use in palaeoecological studies of Carnian marine life. We attempted to identify the depositional environment, the diagenetic sequence, the type and relative timing of silicification and/or pyritization, and to characterize the quality of the preservation. This paper also provides the basis for future taxonomic determinations of the Crngrob fossil assemblage.

Geological Setting

The studied area is located in the vicinity of the village of Crngrob in central Slovenia (Fig 1). The geological structure of this area is covered by the Basic Geological Map of Yugoslavia, Sheet Kranj (Grad & Ferjančič, 1968, 1976). A reconnaissance of the area has been carried out by Rožič et al. (2015). Most recently, the leading author of this paper made a detailed map in order to compare the distribution of lithological units with the positions of fossil sites (Fig. 2). Two major tectonic units have been identified. The eastern part of the map belongs to the Tolmin Nappe of the eastern Southern Alps (Placer, 1999, 2008). The oldest lithostratigraphic unit here consists of alternating shale, siltstone, bedded limestone

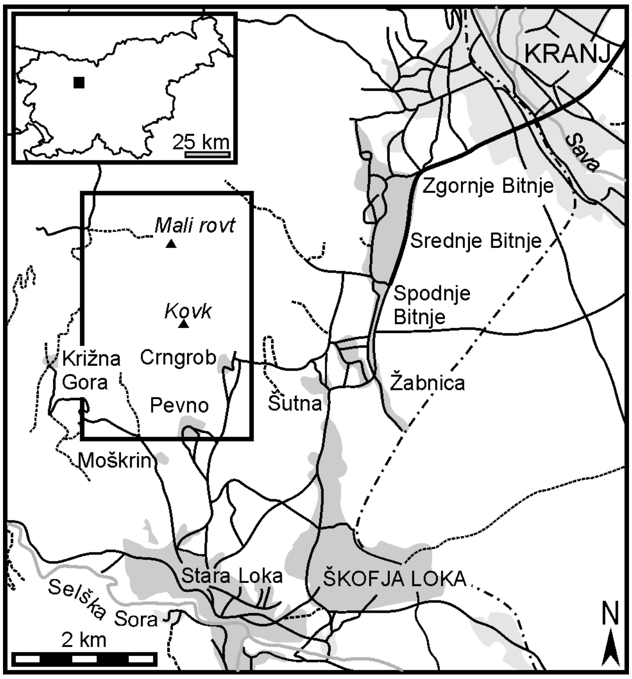

Fig. 1. Location of the studied area. Rectangle shows the area of the geological map in Fig. 2.

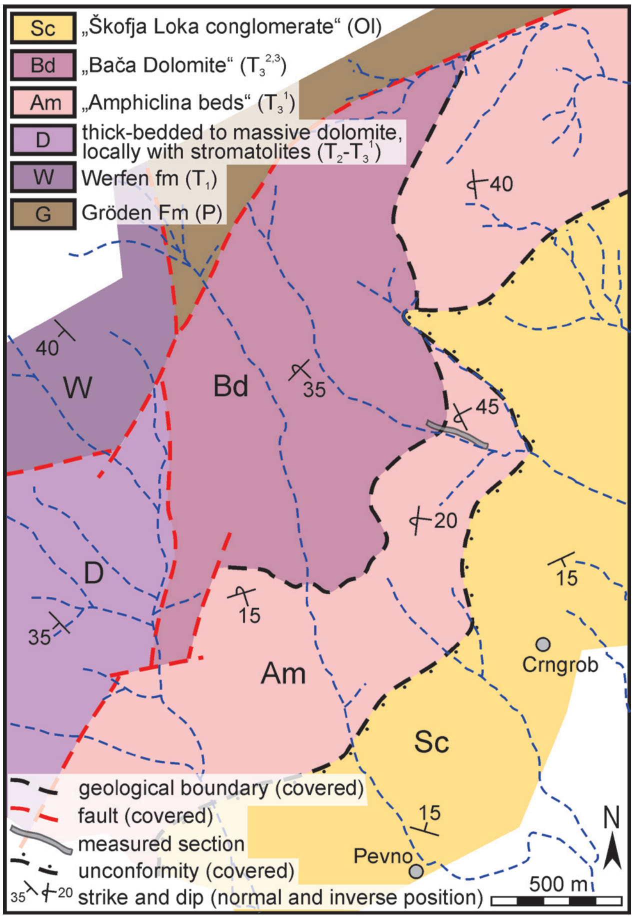

Fig. 2. Simplified geological sketch map of area E of the village of Crngrob (the mapping was performed by one of the authors, L.G.).

and black dolomite, which belong to the "Amphiclina beds" (sensu Turnšek et al., 1982; Buser, 1986). The "Amphiclina beds" grade into the Norian-Rhaetian "Bača Dolomite" (i.e., bedded dolomite with chert). Both are considered to have been deposited in the deeper marine Slovenian Basin (Cousin, 1981; Buser, 1986, 1989, 1996), a marine intraplatform trough situated at the western passive continental margin of the Neotethys Ocean (see the palaeogeographic reconstruction in Haas et al., 1995). To the east, the "Amphiclina beds" are unconformably overlain by uppermost Eocene-lower Oligocene conglomerates. To the west, the "Amphiclina beds" and the "Bača Dolomite" are in fault contacts with red quartz sandstone (the Permian Gröden Formation), marly limestone, carbonate siltstone and marlstone with mica (the Lower Triassic Werfen Formation), and Triassic thick-bedded to massive dolomite with some stromatolites, all of which belong to the External Dinarides tectonic unit (Placer, 1999, 2008). A reconnaissance of the area (Fig. 2) shows that the silicified fossils derive only from the "Amphiclina beds".

Methods

The fossil-bearing succession was recorded along a forest road (Figs. 1-2) at one of the fossil-bearing sites. From this section, 26 samples were collected. An additional 10 samples, which were silicified to various degrees, were collected from debris approximately 130 m to the SW after the lateral continuity of the beds had been verified. For optical microscope analysis, 40 thin sections of sizes 47×28 mm and 75×49 mm were prepared. Selected thin sections were stained with Alizarin Red S. Microfacies (MF) types were named according to the terminology of Dunham (1962) and Embry and Klovan (1971). The quartz terminology used here follows that of Maliva and Siever (1988). Grain proportions were determined by counting 300 random points per section using JMicroVision v.1.2.7 software (© 2002-2008 Nicholas Roduit). Cathodoluminescence (CL) was performed using a cold cathode CITLCL8200/MK4 (Technosyn, Cambridge) at a voltage of 16 kV and a current of 300-450 mA. Neither filters nor standards were used for image calibration. In addition to sedimentological samples, nine composite conodont samples with an average weight of approximately 2 kg were collected and treated with acetic acid. Following this treatment, the conodont elements were hand-picked for determination. The conodont elements were photographed with a JEOL JSM 6490 LV Scanning Electron Microscope. The Conodont Alteration Index (CAI) was determined according to Epstein et al. (1977).

Description of section

The studied section (46°12´22.59´´N, 14°18´12.68´´E) is located in the upper part of the "Amphiclina beds", and extands to the contact with the "Bača Dolomite" (Figs. 3, 4). The recorded beds are underlain by shale and siltstone, whereas the dominant lithology in the section is bedded limestone (locally dolomitized), which is interbedded with marlstone. Several MF types were identified within the limestone beds (see Table 1 for a detailed description).

Wackestone (MF 1 and 3) is bioturbated and mostly thin- to medium-bedded. Some thicker beds display amalgamation, with wavy intercalations of marl. Thin-shelled bivalves (filaments) and radiolaria are common fossils (Fig. 5.1-5.2). In a few beds, filaments form a packstone texture, with shells oriented concordant to the bedding plane (MF 4; Fig. 5.3). Small ammonites were found in larger amounts in a few beds. Wackestone containing mollusc fragments and lacking radiolarian fossils and filaments was identified among the samples from the debris (MF 2; Fig. 5.4). Thin- to medium-thick bedded peloid packstone (MF 5) is present, though less common. Some beds are normally graded and/or display parallel laminae. Bioclasts are subordinate to peloids; in addition to filaments, ammonites and *Tubiphytes*-like microproblematica, fragments of mollusc shells, geniculi of dasyclad green algae and benthic foraminifera were also found. Thin- to medium-bedded floatstone with intraclasts and bioclasts (MF 6; Fig. 5.5-5.8) is characterized by a chaotic texture, with clasts floating in a wackestone or packstone matrix containing thin-shelled bivalves and radiolaria, as well as very rare abraded ooids. Besides intraclasts that are identical in composition to those seen in MF types 1-5, rare fragments of corals, sponges, dasyclad and solenoporacean algae appear among the larger particles. Thin-shelled bivalves are oriented with their convex sides upwards. Floatstone sometimes sharply overlies filament wackestone and grades into peloid packstone. Limestone beds were subject to slumping, resulting in disrupted beds up to 120 cm thick, with angular to rounded wackestone intraclasts kneaded into the marly matrix (MF 7 in Table 1; Fig. 5.9).

Table 1. Microfacies types of the uppermost "Amphiclina beds" at Crngrob.

Microfacies type	Short description	Figures
1 - Bioturbated filament wackestone	Filaments represent 80 % of grains. Subordinate are putative calcified radiolarian, calcite sponge spicules and echinoderm plates.	Fig. 5.1
2 - Bioturbated radiolaria-filament wackestone	Radiolaria prevail over sparse filaments and very rare echinoderms plates, nodosariid foraminifers and juvenile ammonites.	Fig. 5.2
3 - Laminated filament packstone	Filaments (50 % of thin section area) are concordant with the bedding and oriented with their convex sides up or down. The space between filaments is filled with dense wackestone consisting of 40 % pellets and rare (2 %) radiolaria. Calcite cement often fills shielded sites below and between the valves.	Figs. 5.3
4 - Bioclast wackestone	Bioclasts (20 %) are randomly distributed within microsparitic matrix. Mollusc shell fragments represent 10 %, small ammonites 6 %, and echinoderms 3 % of the clasts. Gastropods and ostracods are very rare. With the exception of the ostracods, the bioclasts are replaced by drusy mosaic spar. Some larger bivalve shells show signs of bioerosion and/or endolitization. The patches of drusy mosaic spar (8 % of the area) indicate that part of the micritic matrix was probably winnowed away.	Fig. 5.4
5 - Peloid packstone	Grains are arranged in crude laminae and are sorted by size. Some laminae indicate normal grading. Elongated grains are sometimes aligned with the bedding, but this appears to be mostly due to compaction. Peloids predominate among grains. They range from 0.05 mm to over 1 mm in size. They are ellipsoidal to elongated and angular to well rounded. The smaller ones display only micritic interiors, whereas internal layering may be observed in the larger grains. Due to the presence of *Tubiphytes*-like microproblematica (1.5 % of the area), some of the peloids probably originated as microbialite intraclasts. Mollusc fragments represent 5-10 % of the area, and echinoderm plates up to 5 %. Geniculi of dasyclad green algae, gastropods, brachiopods, "spherulites", juvenile ammonites, ostracods, microproblematica *Thaumatoporella parvovesiculifera* (Raineri) and benthic foraminifera (*Decapoalina schaeferae* (Zaninetti, Altiner, Dager & Ducret), *Palaeolituonella meridionalis* (Luperto), *Duotaxis* sp., *Reophax* sp., Duostominidae, and nodosariid Lagenida) are very rare. Thin-shelled bivalves ("filaments") may be locally present. They are oriented with their convex sides upwards, and blocky spar sometimes fills the spaces beneath the valves.	
6 - Bioclast-intraclast and intraclast-bioclast floatstone	Clasts larger than 2 mm represent 30 % of the area (note that some compaction likely occurred), while wackestone or packstone matrix fills the remaining volume. The distribution of large clasts seems chaotic, although some alignment parallel to the bedding may be present that is due to compaction. Most are intraclasts with subangular edges and correspond to MF 1-5. Rrecrystallized sponges (up to 3 cm large fragments) are rarer, as are partly broken bivalve and brachiopod shells, corals, ammonites, solenoporacean algae and presumed genicules of dasyclad algae. Some large echinoderm plates and fragmented gastropods may also be counted among the largest grains. Within the wackestone matrix, some filaments, echinoderm plates, calcified or pyritised radiolaria, gastropods, and foraminifera (*Aulotortus sinuosus* Weynschenk, *Diplotremina subangulata* Kristan-Tollmann, ?*Duostomina biconvexa* Kristan-Tollmann, "*Trochammina*" *almtalensis* Koehn-Zaninetti, *Variostoma pralongense* Kristan-Tollmann, *Reophax* sp., Duostominidae, and nodosariid Lagenida) are present. A similar association of grains is present within the packstone matrix, together with peloids, microbialite aggregate grains, calcimicrobes, *Tubiphytes*-like microproblematica, fragments of *Thaumatoporella parvovesiculifera* (Raineri), ostracods, and occasional abraded ooids.	Figs. 5.5-5.8
7 - Intraclast floatstone and rudstone	Angular to subrounded clasts are up to 16 mm in size and represent up to 60 % of the thin-section area. Mudstone, "calcisiltite" (with small sparitic fragments and nodosariid lagenid foraminifera), wackestone with thin-shelled bivalves, and wackestone with microbialite fragments and echinoderm plates are seen. The interstitial space is filled with dolomitized matrix. Rarely, echinoderm plates can be found.	Fig. 5.9

Diagenesis

Although different lithologies constitute the sequence, it appears that diagenetic processes did not act selectively on the individual MF types: neomorphism, silicification, and precipitation of ferrous dolomite were detected in wackestone, as well as in floatstone. However, due to the larger number of aragonitic shells and intraclasts, these diagenetic processes seem to be most common in floatstone.

Micrite, commonly recrystallized into microspar (which shows speckled luminescence under CL), is the main supporting medium in all MF types. Early mosaic calcite in places fills vugs and intragranular spaces (Fig. 6.1) in bioclastic wackestone. Bladed spar has also been observed within a brachiopod interior in peloid packstone. Compaction of the sediment is evident from flattened peloids, sometimes wrapped around echinoderm plates, puzzle-like breakage of bivalve or other shells, and alignment of the filaments within bioturbations, as well as outside them. Pyrite crystals are present in the matrix and in micritic intraclasts. In thin section 654b (laminated filament packstone), radiolaria appear to be pyritized within a thin strip of sediment (Fig. 6.2). They preserve many details of their tests, in contrast to more common calcified specimens. In one case, pyrite also crystallized on the bivalve shell, pre-dating the precipitation of ferrous dolomite. In other cases, however, well-formed and relatively large pyrite crystals cross-cut blocky spar or calcite veins. Relatively early changes further incorporate replacement of aragonite with drusy mosaic calcite through the complete dissolution of aragonitic bioclasts (thick-shelled bivalves, gastropods, ammonites, sponges, corals) and the formation of moulds (Figs. 6.3-6.4).

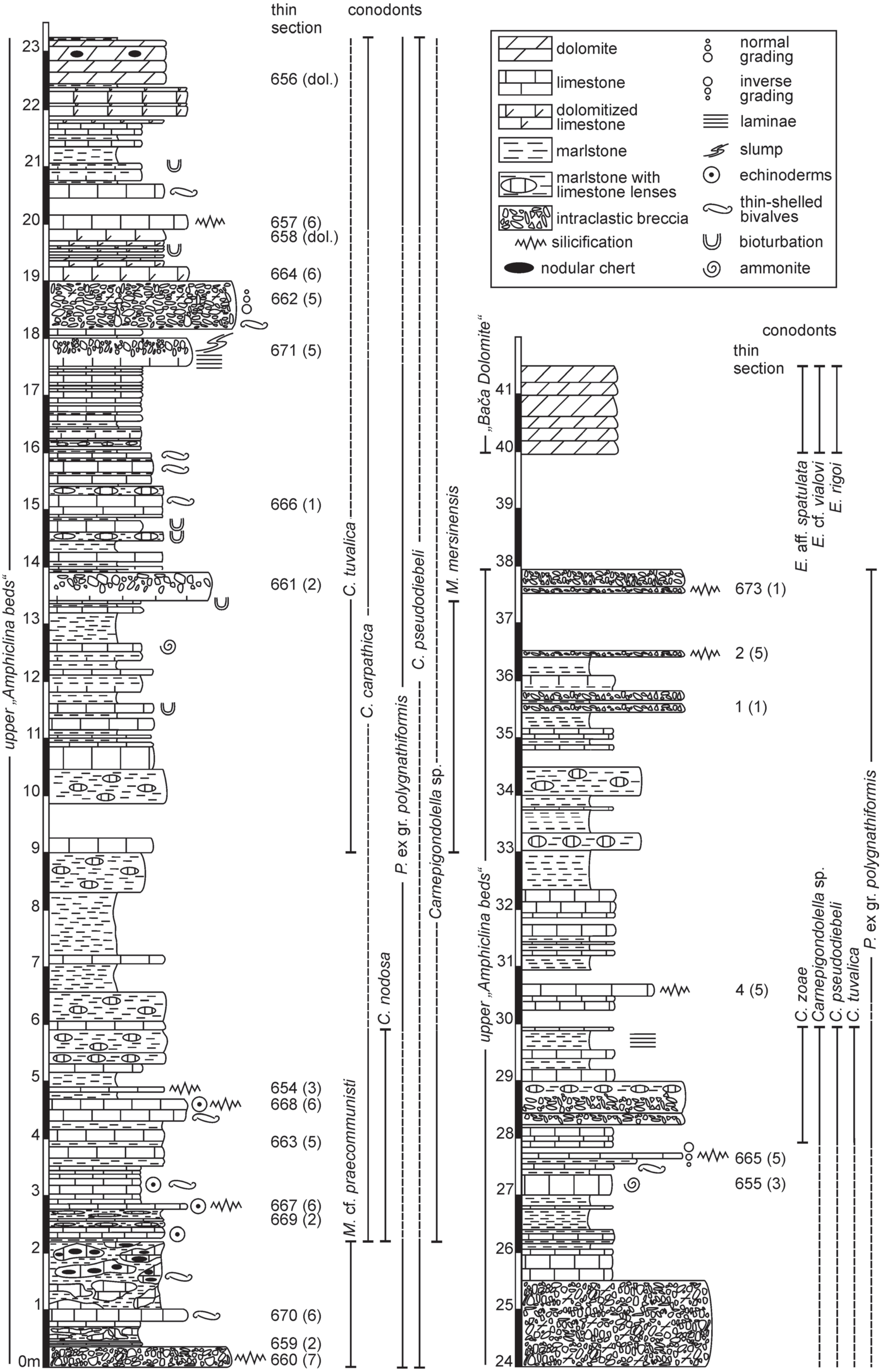

Fig. 3. Presentation of the recorded section. Numbers in brackets refer to MF type (see Table 1). Other samples (for additional study of the silicification) were collected ex situ. Abbreviations: *C- Carnepigondolella, E- Epigondolella, M- Metapolygnathus, P- Paragondolella.*

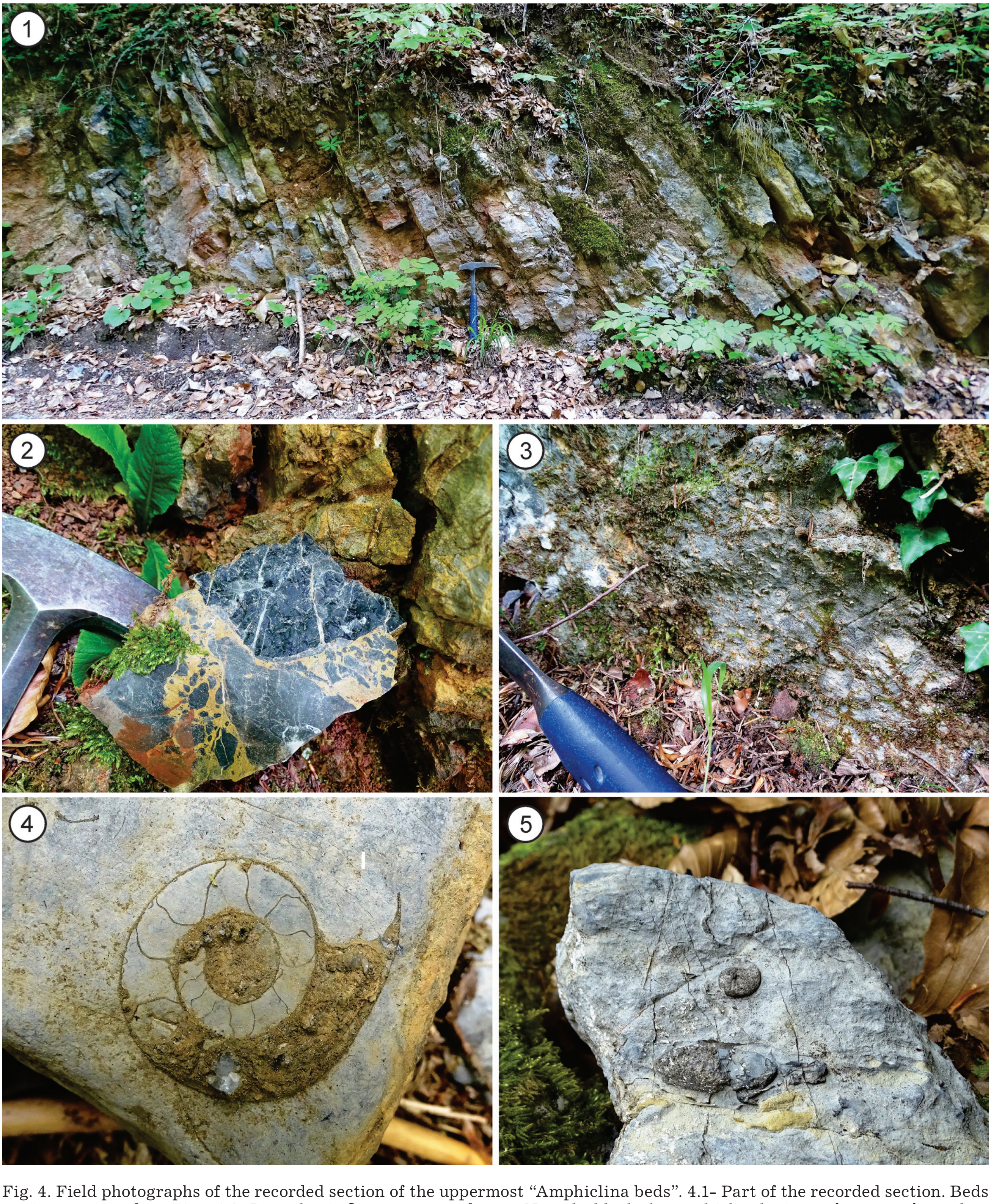

Fig. 4. Field photographs of the recorded section of the uppermost "Amphiclina beds". 4.1- Part of the recorded section. Beds are in overturned position. 4.2- Intraclastic floatstone to rudstone. Note the black chert, which substitutes for most of one clast (a thin strip of limestone remains on the outer side of the clast). 4.3- Selective silicification, giving a "mottled" appearance to the rock. 4.4- An at least partly silicified ammonite, approximately 2.5 cm in size. 4.5- Small silicified ammonites. The larger ammonite is approximately 5 cm in diameter.

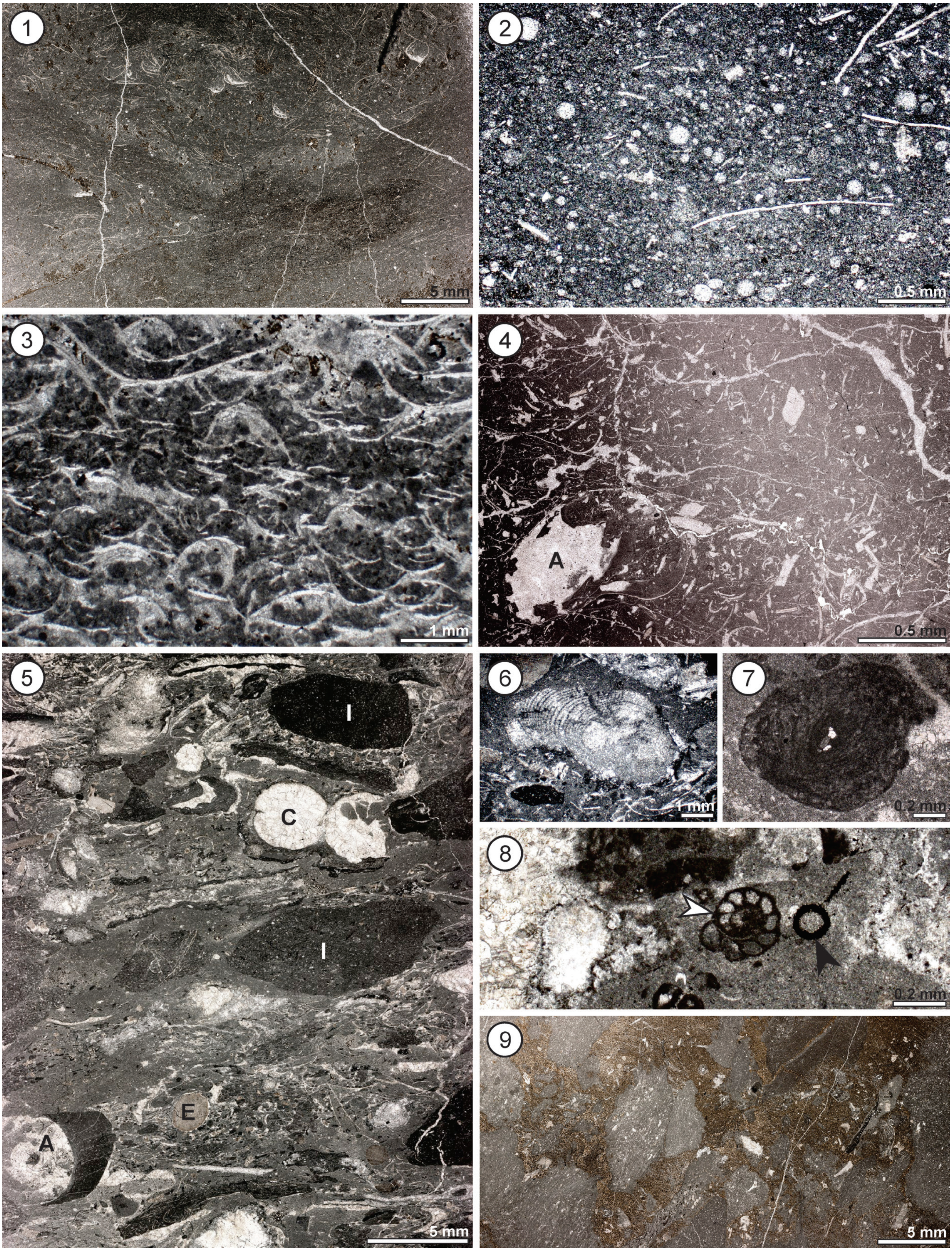

Fig. 5. Microfacies types of the uppermost "Amphiclina beds" at Crngrob.

5.1- Bioturbated filament wackestone. Thin section 666. 5.2- Bioturbated radiolaria-filament wackestone. Thin section 659. 5.3- Laminated filament packstone. Thin section 654b. 5.4- Bioclast wackestone. A: ammonite. Thin section 652. 5.5- Bioclast-intraclast and intraclast-bioclast floatstone. C: corals; E: echinoderm; A: ammonite (as part of an intraclast); I: intraclasts. Thin section 672a. 5.6- Fragment of solenoporacean red algae. Intraclast-bioclast floatstone. Thin section 672e. 5.7- *Tubiphytes* sp. Intraclast-bioclast floatstone. Thin section 672c. 5.8- Duostominid foraminifera (white arrowhead) and pyritized radiolaria (black arrowhead). Bioclast-intraclast or intraclast-bioclast floatstone. Thin section 672h. 5.9- Intraclast floatstone and rudstone. Thin section 660.

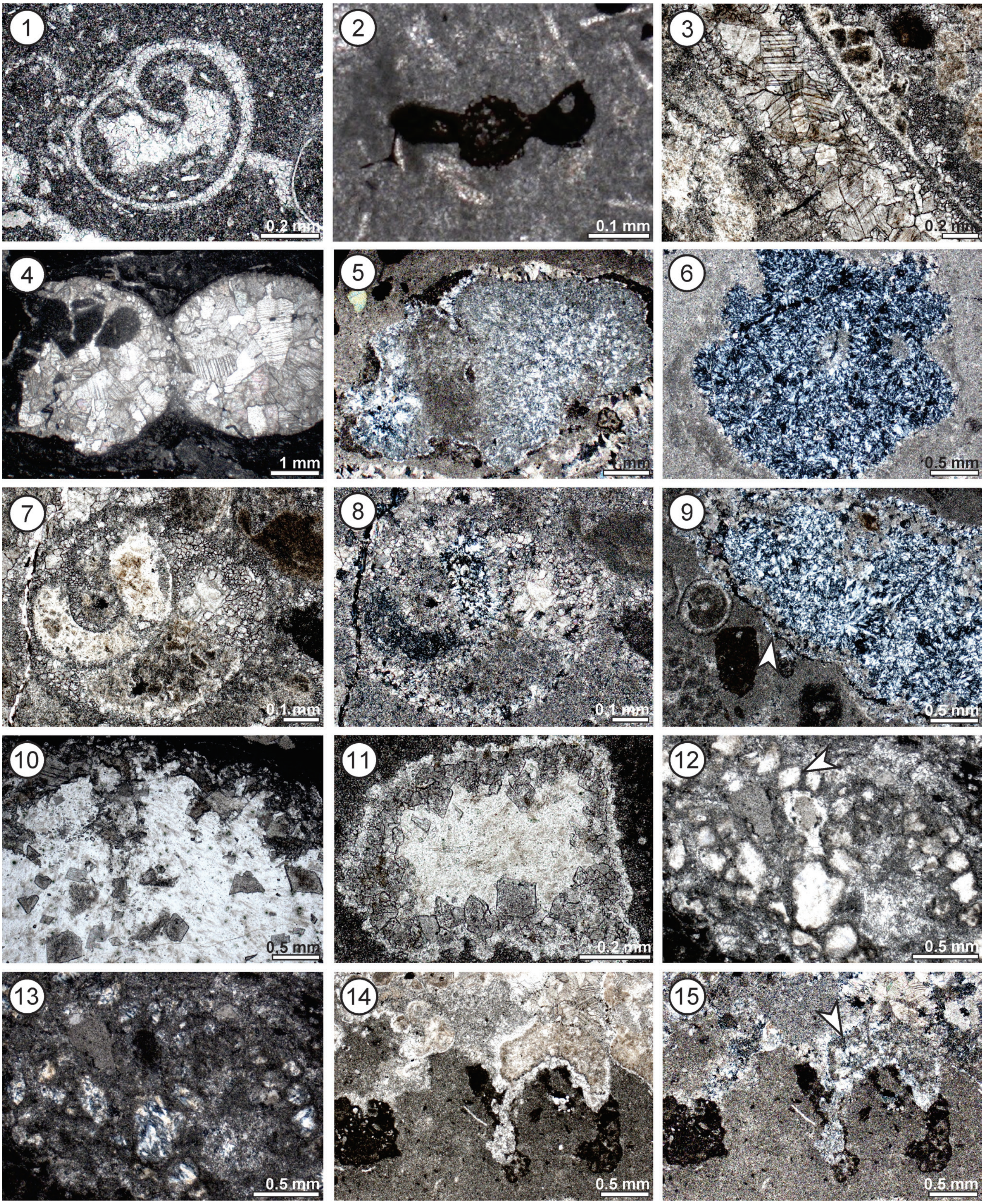

Fig. 6. Diagenetic features of the uppermost "Amphiclina beds" at Crngrob. 6.1- Mosaic spar, partly infilling the interior of a gastropod. Micrite (automicrite?) clings to the inner wall of the shell. Thin section 652. 6.2- Pyritized radiolarian and small sponge spicules. Thin section 654b. 6.3- Neomorphism of a bivalve shell. Thin section 653. 6.4- Neomorphism of corals. Thin section 672a. 6.5- Replacement of a probable micritic intraclast by chalcedony. Thin section 672h. 6.6- Silicification of an echinoderm plate. Thin section 653. 6.7- Partial silicification of a gastropod. Note that the chert infills the interior of the gastropod and partly replaces its shell. Thin section 653. 6.8- Same view under crossed Nicols. 6.9- Silicification front (arrowhead). Note the adjacent gastropod, which is not yet silicified. Thin section 653. 6.10-6.11- Void-filling chert. Note the rhombic carbonate crystals lining the wall of the void. Chips of crystals are included within the chert. Thin sections 667b and 653. 6.12- Chert, replacing some particles, including presumably rhombic crystals. Thin section 668b. 6.13- Same view under crossed Nicols. 6.14-6.15- Silicification front. Note the large rhombic crystal replaced by chalcedony that is seen under crossed Nicols (Fig. 6.15). Thin section 672h.

Spherulitic chalcedony and granular megaquartz locally replace the micritic matrix, gastropods, thick-shelled bivalves, echinoderms (excluding the surrounding syntaxial calcite cement), brachiopods, calcimicrobes, some intraclasts and even lagenide foraminifera (Figs. 6.5-6.9). Microstructure-controlled replacement of brachiopod shells by chalcedony has also been observed, while microbial crusts are often the sites of precipitation of quartz euhedra. Chalcedony may enclose rhombic carbonate crystals and/or infill the remaining internal parts of the voids, which are lined with large rhombic crystals of a carbonate mineral (Figs. 6.10-6.11). These rhombic crystals may be partly shattered, with chips incorporated into the chert. Rarely, chalcedony appears to replace the rhombic crystals (Figs. 6.12-6.15). In sample 654b, silicification has affected some or part of the laminae with higher porosity: it appears to stop at the contact with more matrix-rich lamina (Fig. 7.1). Ferrous dolomite in large crystals substitutes for the matrix between filaments in other parts of the thin section (Fig. 7.2). Ferrous dolomite locally fills gastropod (Fig. 7.3), ammonite (Figs. 7.4-7.5), and thick-shelled bivalve shells (Fig. 7.6), especially in bioclast-intraclast and intraclast-bioclast floatstone. The infill may be partial (in which case the other part of the mould is being filled by drusy mosaic calcite) or complete. Ferrous dolomite is also found within veins (Fig. 7.7). Under CL, bright orange, dull red and non-luminescent bands are seen in clearly zoned crystals. The non-luminescent clear mosaic or blocky calcite post-dates ferrous dolomite; the calcite fills the remaining space (Fig. 7.8). In one sample, the clear blocky spar forms patches within the micritic matrix (Fig. 7.9). In rare cases, the clear spar fills veins. The relationship with chert is unresolved. Another generation of megaquartz, which is reflected by crystals more than 1 mm in size, occurs rarely in veins or fills the spaces between the clear spar crystals (Fig. 7.10).

Some samples are completely dolomitized, and dolomitization may have taken place contemporary with selective replacement of fossils by ferrous dolomite (the timing of dolomitization is currently not resolved). Different types of pervasive dolomitization can be distinguished, hinting at different generations of dolomite. Sedimentary structures are sometimes still preserved, due to the different colours, shapes and sizes of the dolomite crystals. Smaller euhedral to subhedral crystals with brownish outer rims (which are enriched in Fe) seem to preferentially substitute for the micritic matrix (Fig. 7.11). Under CL, they exhibit dark red luminescence with thin bright yellow bands. The second type of dolomite is represented by lighter and larger subhedral crystals (Fig. 7.12), which emit very weak, dark red luminescence. Some veins are also filled with dolomite. Calcite veins cut through all other diagenetic phases. The exception may be the second generation of megacrystalline quartz, for which the relationship with the calcite veins could not be determined.

Age of the studied succession

Conodont biostratigraphy

The Colour Alteration Index (CAI) of the recovered conodont elements (some of which are shown in Fig. 8) is 5 and/or slightly above 5, demonstrating strong alteration and even a low grade of metamorphism (see Kovacs & Arkai, 1987; Sudar & Kovacs, 2006; Kovacs et al., 2006).

The conodont fauna from the uppermost "Amphiclina beds" is dominated by the elements *Paragondolella* ex gr. *polygnathiformis* (Budurov & Stefanov) and *Carnepigondolella* with the representatives: *Carnepigondolella* aff. *carpathica* (Mock), *C. nodosa* (Hayashi), *C. pseudodiebeli* (Kozur), *C. tuvalica* Mazza et al., *Carnepigondolella zoae* (Orchard), *Carnepigondolella* sp., in association with *Metapolygnathus mersinensis* (Moix et al.) and *M.* cf. *praecommunisti* Mazza et al. As a direct forerunner of *Metapolygnathus*, the genus *Paragondolella* can be distinguished by the terminal or subterminal position of the basal pit (Kozur, 2003). Some specimens of *Paragondolella* reveal transitional features towards the genus *Metapolygnathus*, with a prolonged keel behind the basal pit. This feature is consistent with observations of Mazza et al. (2012). The genus *Paragondolella* is confined to the Carnian, whereas *Metapolygnathus* ranges from the Late Carnian to the basal Norian. The species *M. praecommunisti* has not yet been documented from Slovenia, but its successor, *M. communisti* Hayashi has been reported from the Late Carnian-Early Norian fauna of the Martuljek Group in the Julian Alps (Celarc & Kolar-Jurkovšek, 2008). *Carnepigondolella* is characterized by a weak ornamentation on the platform margins and by a subterminal basal pit (Kozur, 2003). This genus is a marker of the Upper Carnian that also occurs rarely in the Lower Norian and is regarded as the forerunner of *Epigondolella*.

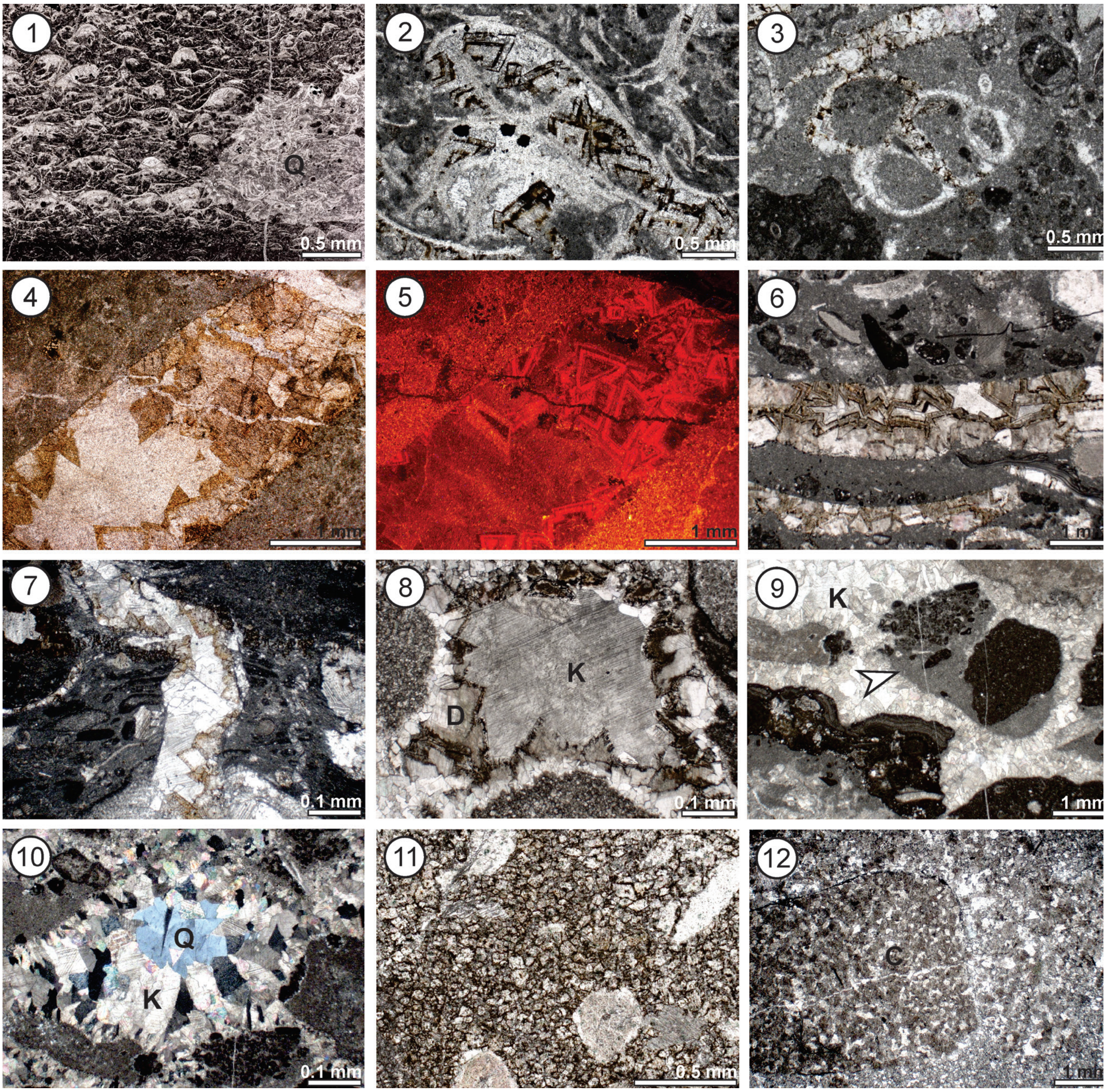

Fig. 7. Diagenetic features of the uppermost "Amphiclina beds" at Crngrob. 7.1- Partial silicification of the radiolarian-filament packstone. Note the sharp lower boundary of the chert (Q), which follows a lithological boundary with a greater amount of micritic matrix. Thin section 654b. 7.2- Ferrous dolomite between bivalves. Thin section 654b. 7.3- Replacement of a gastropod shell by ferrous dolomite. Thin section 672c. 7.4- Ferrous dolomite filling the dissolved shell of an ammonite. Thin section 667c. 7.5- Same view under CL. 7.6- Ferrous dolomite filling dissolved bivalve shells. Shells are fragmented. Thin section 672c. 7.7- Vein-filling ferrous dolomite. Thin section 667b. 7.8- Blocky calcite (K) filling the interior of the void lined by ferrous dolomite (D). Thin section 672i. 7.9- Blocky calcite (K) precipitated after partial dissolution of the matrix (arrowhead). Thin section 672h. 7.10- Megaquartz (Q) interior to the blocky calcite (K). Thin section 672h. 7.11- Subhedral to euhedral dolomite crystals. Note the brownish colour of the outer rim. Large, undolomitized grains are echinoderm plates. Thin section 660. 7.12- Subhedral dolomite. Note the ghostly image of the clast (C), suggesting a former floatstone texture. Thin section 672g.

Fig. 8. Conodont elements from the uppermost "Amphiclina beds" (8.1-8.6) and the lowermost "Bača Dolomite" (8.7-8.8). 8.1- *Carnepigondolella tuvalica* Mazza et al., sample GeoZS 5661. 8.2- *Carnepigondolella zoae* (Orchard), sample GeoZS 5661. 8.3-8.4- *Paragondolella* ex gr. *polygnathiformis* (Budurov & Stefanov), samples GeoZS 5540 and 5539. 8.5-8.6- *Carnepigondolella* aff. *carpathica* (Mock), sample GeoZS 5660. 8.7- *Epigondolella rigoi* Noyan & Kozur, sample GeoZS 5643. 8.8.- *Epigondolella* cf. *vialovi* (Buryi), sample GeoZS 5643.


1a
1b
1c
2a
2b
2c
200 µm
3a
3b
3c
4a
4b
4c
5a
5b
5c
6a
6b
6c
7a
7b
7c
8a
8b
8c

Among the *Carnepigondolella* species that were identified, the presence of *C. tuvalica* and *C. zoae* that occur in the Late Tuvalian is important. The measured uppermost part of the "Amphiclina beds" is thus Tuvalian in age.

A single sample from the "Bača Dolomite" yields a small but significant fauna. It is marked by the exclusive presence of *Epigondolella* that reveals a more reduced platform, allowing development of a free blade. This genus is characteristic of the Norian, but it had already appeared in the Late Tuvalian. Several morphogenetic lineages are recognized from the period of their rapid evolution (Orchard, 2007). The co-occurrence of the species *E.* aff. *spatulata* (Hayashi), *E. rigoi* Noyan & Kozur, and *E.* cf. *vialovi* (Buryi) defines the Lacian age of the sample. Norian epigondolellids are known to occur extensively in Slovenia (Kolar-Jurkovšek, 1991; Buser et al., 2008), and a similar fauna was recently documented from the Lower Norian strata of the Martuljek Group in the Julian Alps (Celarc & Kolar-Jurkovšek, 2008).

Foraminifera

Concerning foraminifera, the following taxa (listed alphabetically) were identified in thin sections of bioclast-intraclast/intraclast-bioclast floatstone and in peloid packstone: *Aulotortus sinuosus* Weynschenk, ?*Decapoalina schaeferae* (Zaninetti, Altiner, Dager & Ducret), *Diplotremina subangulata* Kristan-Tollmann, ?*Duostomina biconvexa* Kristan-Tollmann, *Duotaxis* sp., *Palaeolituonella meridionalis* (Luperto), *Reophax* sp., "*Trochammina*" *almtalensis* Koehn-Zaninetti, *Variostoma pralongense* Kristan-Tollmann. Undetermined Duostominidae and nodosariid Lagenida were also recognized. Neither species provides a detailed stratigraphic range. It should be noted, however, that the range of *Decapoalina schaeferae*, which was previously known from Norian and Rhaetian strata (Gale et al., 2013), should be extended to the Late Tuvalian.

Discussion

Depositional model

Concerning sedimentation, three types of sediments can be distinguished in the observed section. The bioturbated filament wackestone, radiolaria-filament wackestone and laminated filament packstone are interpreted as hemipelagic/pelagic sediments. The concordant position of thin-shelled bivalves in the latter may be due to redeposition out of suspension, compaction, or the presence of weak bottom currents (Kidwell & Bosence, 1991). Traces of bioturbation suggest oxygenated bottom conditions. The presence of radiolaria, ammonites, and thin-shelled bivalves suggests an open-marine environment (Flügel, 2004). The bioclast wackestone and peloid packstone are interpreted as distal turbidites, or as the result of some other gravitational current transport mode. This is supported by the presence of normal grading and laminae in peloid packstone and the presence of grains derived from within the photic zone (green algae, bioerosion on bivalve shells, foraminifera *Decapoalina schaeferae*, *Palaeolituonella meridionalis*).

The chaotic distribution of clasts floating in slightly convoluted (fluid) matrix suggests that the bioclast-intraclast and intraclast-bioclast floatstone formed via debris flows. Grains are again partly derived from shallow water (corals, solenoporaceans, green algae, and the foraminifera *Aulotortus sinuosus*), but some micritic intraclasts represent mud chips torn from the sea bottom, and fossils found within the matrix (radiolaria, filaments) represent open-marine biota. The intraclast floatstone to rudstone might alternatively represent a debris flow deposit with a predominance of basin-derived clasts, or a slump conglomerate/breccia.

This facies association suggests the slope to toe-of-slope setting, or the outer ramp environment (Flügel, 2004).

Timing of silicification of fossils

Although we could clearly distinguish between the megaquartz that post-dates the blocky spar from the chalcedony, which replaces fossils, we are not able to confidently assign the silicification of fossils to the early or late stages of diagenesis. The ammonites, gastropods and bivalves, which were originally made up of aragonite (Flügel, 2004), were probably already replaced by low-Mg calcite spar when silicification occurred. They are replaced alongside low-Mg calcite calcimicrobes, brachiopods and lagenide foraminifera, as well as high-Mg calcite echinoderms (Flügel, 2004). Chalcedony usually replaces only parts of fossils and is not always confined to the fossils itself. As seen in Figure 6.9, silicification did not extend to the gastropod immediately adjacent to the progressing silicification front. The silicification thus clearly post-dates deposition of the sediment. Furthermore, the presence of rhombic crystals lining some vugs filled with chalcedony, seemingly shattered and broken-off rhombic crystals, and rhombic crystals replaced by silica suggest that the chalcedony precipitated after the vug-lining spar.

The silicification in the "Amphiclina beds" might be somewhat similar to the late diagenetic silicification that selectively affected clasts in conglomerates of the Upper Jurassic Toril Formation in the Bethic Mountains of Spain (Bustillo & Ruiz-Ortiz, 1987). Bustillo and Ruiz-Ortiz (1987) additionally recorded nodule- and bed-producing early diagenetic silicification that was restricted to the Ta (partly), Tb and Tc parts of the intercalated turbidite beds. The rare nodular chert in the recorded part of the "Amphiclina beds" may indeed be early diagenetic, as shown by the presence of chert clasts in rudstone shown in Figure 4.2 (which is similar to the nodular chert in the Norian-Rhaetian "Bača dolomite"; D. Skaberne, pers. com. 2009). In the case of the silicified fossils, however, there seems to be no preference for lithology, as the same type of clasts may be silicified in both bioclast-intraclast floatstone and hemipelagic sediments. The impression that silicification is confined to certain lithologies is solely a consequence of the greater amount of calcareous bioclasts in bioclast-intraclast and intraclast-bioclast floatstone. Therefore, rather than arguing for lithological control over the silicification of fossils, we suggest that all the investigated types of limestone acted similarly during the burial diagenesis, which can be attributed to the largely homogenous permeability of the matrix-rich sediment.

Conclusions

The uppermost 38 m of the "Amphiclina beds" were sampled at Crngrob in order to define the origin of the silicified fauna, the nature of the assemblage and the timing of silicification. The section exposes limestone, dolomite and marlstone of Tuvalian age. Within the limestone, seven microfacies types were determined. Bioturbated filament wackestone, bioturbated radiolaria-filament wackestone and laminated filament packstone represent hemipelagic sediments. Peloid packstone and bioclast wackestone were deposited from distal turbidite flows. Bioclast-intraclast and intraclast-bioclast floatstone represent the debris-flow microfacies, while intraclast floatstone and rudstone are interpreted as debris-flow deposits or as slump breccias. The sediments were deposited in the slope to toe-of-slope setting or in the outer ramp setting (Flügel, 2004). A complex diagenetic history has been partly resolved. Early diagenesis involved compaction of the sediment and replacement of aragonite with drusy mosaic calcite. Local selective silicification affected the fossils, as well as some of the intraclasts and even parts of the matrix. Silicification (replacement by chalcedony and megaquartz) was detected in all of the limestone types, but it is most evident in bioclast-intraclast and intraclast-bioclast floatstone, where the majority of the larger fossils are found. Because the silicification occurred after deposition of the sediment, and because the fossils are partly derived from shallow-water environments, the Crngrob silicified fossil assemblage represents a biased thanatocenosis or even a taphocenosis, and it is not an autochthonous Carnian fossil association. Ferrous dolomite, sometimes associated with veins, locally replaces non-silicified or partly silicified fossils and matrix. Clear mosaic or blocky calcite postdates ferrous dolomite. Some samples are completely dolomitized. Two types of dolomitization are suggested by the different sizes, shapes, and colours of the dolomite crystals, and the original texture of the sediment is sometimes preserved. The timing of dolomitization has not been resolved.

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