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An Albian demise of the carbonate platform in the Manín Unit (Western Carpathians, Slovakia)

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Abstract: The production of platform carbonates of the Manín Unit (Manín Straits, Central Western Carpathians) belonging to the Podhorie and Manín formations and formed by remains of rudists and benthic foraminifers (Urgonian-type carbonates), was previously assumed to terminate during the Aptian. First, we show that these deposits were primarily formed on the upper slope (Podhorie Formation) and in a fore-reef environment (Manín Formation). Second, biostratigraphic data indicate that the shallow-water production persisted up to the Albian, just as it did in another succession of the Manín Unit. The Podhorie Fm contains colomiellids (*Colomiella recta*, *C. mexicana*) and calcareous dinoflagellates (*Calcisphaerula innominata)* that indicate the Albian age. It also contains planktonic foraminifers (*Ticinella roberti*, *Ticinella* cf. *primula*, *Ticinella* cf. *madecassiana*, *Ticinella* cf. *praeticinensis*) of the Albian Ticinella primula Zone. The Podhorie Formation passes upwards into peri-reefal facies of the Manín Fm where we designate the Malý Manín Member on the basis of rudists shell fragments and redeposited orbitolinids. Microfacies associations share similarities with the Urgonian-type microfacies from Mediterranean Tethys and allow us to restrict the growth and the demise of the carbonate platform. $\delta^{13}C$ and $\delta^{18}O$ isotopes change over a broad range of both formations: $\delta^{13}C$ is in the range +1.03 to +4.20 ‰ V-PDB and $\delta^{18}O$ is in the range −0.14 to −5.55 ‰ V-PDB. Although a close correlation between $\delta^{13}C$ and $\delta^{18}O$ indicates diagenetic overprint, a long-term increase of $\delta^{13}C$ can indicate a gradual increase in the aragonite production and/or increasing effects of oceanic water masses in the course of the Albian, prior to the final platform drowning. Carbonate platform evolution was connected with submarine slumps and debris flows leading to redeposition and accumulation of carbonate lithoclasts and bioclastic debris on the slope. Our study confirms that the growth of carbonate platforms in the Central Western Carpathians was stopped and the platform collapsed during the Albian, in contrast to the westernmost Tethys. A hardground formed during the Late Albian is overlain by Albian−Cenomanian marls of the Butkov Formation with calcisphaerulid limestones characterized by planktonic foraminifers of the Parathalmanninella appenninica Zone and calcareous dinoflagellates of the Innominata Acme Zone.

Keywords: Lower Cretaceous, Urgonian, Manín Fm, Podhorie Fm, planktonic foraminifers, rudists, C isotopes.

Introduction

Cretaceous carbonate platforms contain important information on biotic changes, depositional facies, diagenesis, climatic events, eustatic sea level fluctuations and terrigenous sediment influx, and provide clues to platform growth and demise during the Early Cretaceous Tethys (Simo et al. 1993). During the Late Jurassic and Early Cretaceous, several shallow marine carbonate platforms evolved on both sides of the Penninic Oceanic and on the southern Tethyan margins. During the Barremian and Early Aptian, the northern Tethyan area was covered by a shallow sea where carbonate “Urgonian”-type sediments were deposited (Arnaud-Vanneau 1980; Arnaud et al. 1995; Peybernès et al. 2000; Masse & Fenerci-Masse 2011, 2013; Clavel et al. 2013).

In the western Tethys, shallow-water Urgonian-like carbonates, including inner- and outer carbonate platform sediments and biotas (Masse et al. 1992), were deposited mainly during the Barremian and Early Aptian (Bedoulian). Their drowning occurred repeatedly at multiple steps and was connected to climatic and oceanographic changes, replacement of photozoan carbonate producers by heterozoan producers, and to oceanic anoxic crises in deeper basins (Masse 1989a,b; Föllmi 2008; Erba et al. 2015). Analyses of Urgonian carbonate platforms significantly contributed to the understanding of paleogeographical, paleoecological and paleoclimatic changes throughout the Early Cretaceous (Godett et al. 2006; Föllmi & Gainon 2008; Föllmi 2012; Föllmi & Godet 2013). Biostratigraphic, sedimentological and chemostratigraphical methods, in particular distribution of P and isotopic composition of C and O are used for characterization of nutrient support, C cycling and definition of paleoceanic proxies but also for anoxic conditions in basins, which acquired a global character during Oceanic anoxic events (OAEs, see Föllmi & Godet 2013; Huck et al. 2013).

The Urgonian-type limestones have been identified in several areas of the Western Carpathians (Mišík 1990; Michalík 1994). In the Outer Carpathians, they occur exclusively as exotic pebbles in younger deposits. In the Central Carpathians, they are preserved in the Tatric Zone, in the Manín Unit, and in the peripheral units of the Krížna Nappe (Michalík 1994; Michalík et al. 2012, 2013). Firstly, in these units, the input of clasts in platform carbonates indicated that the platform growth was still active during the Late Aptian–Albian, suggesting that the carbonate factory production in the Western Carpathians terminated later than in other Tethyan regions (Boorová 1990; Mišík 1990; Michalík et al. 2012). Second, Michalík (1994) and Michalík et al. (2012) showed that the carbonate production probably persisted up to the Early Albian in the Manín Unit at Butkov. It remains poorly known whether this late timing of the carbonate demise also applies to other successions in the Western Carpathians.

Our aim is to document biostratigraphy and facies development of platform carbonates of the Manín Unit outcropping in the Manín Straits, previously assigned to the Barremian–Aptian–"Urgonian" sequence in the Western Carpathians (Köhler 1980; Rakús 1984; Michalík & Vašíček 1984; Boorová 1991; Boorová & Salaj 1996) (Fig. 1). Integrating sedimentological, biostratigraphic and chemostratigraphical research data allowed us to better constrain the environmental development of carbonate platform in the Central Western Carpathians.

Geological setting

The Western Carpathians represent a part of the extensive Alpine–Carpathian mountain system with very complicated geological structure, composed of imbricated crustal segments covered by differentiated sedimentary sequences (Plašienka et al. 1997; Plašienka & Soták 2015). The Manín Unit is situated at the Central Western Carpathian nappe front on the left side of the Middle Váh Valley (Fig. 1A). It is partially involved in a collisional accretionary wedge (Michalík & Žítt 1988; Michalík et al. 2013). The paleogeographical position of the Manín Unit and its relations to the Tatric and the Fatric units or to the Pieniny Klippen- and Peri-Klippen zone are not resolved. The Lower Cretaceous sequence (consisting of Valanginian to Barremian pelagic limestones, covered by Urgonian-type limestones) of the Manín Unit is similar to marginal Central Carpathian units, whereas the Upper Cretaceous sequence is composed of shales unlike in the Central Carpathians, where the sedimentation was broken by strong space reduction due to Alpine folding and nappe formation (Michalík et al. 2012, 2013).

The Urgonian-like limestones in the Manín Unit are divided into slope facies of the Podhorie Fm and platform facies of the Manín Fm. The Podhorie Fm, defined in the Butkov Quarry by Borza et al. (1987), begins with a 4–5 m thick breccia member formed by markedly gradational strata rhythms. Clasts consist

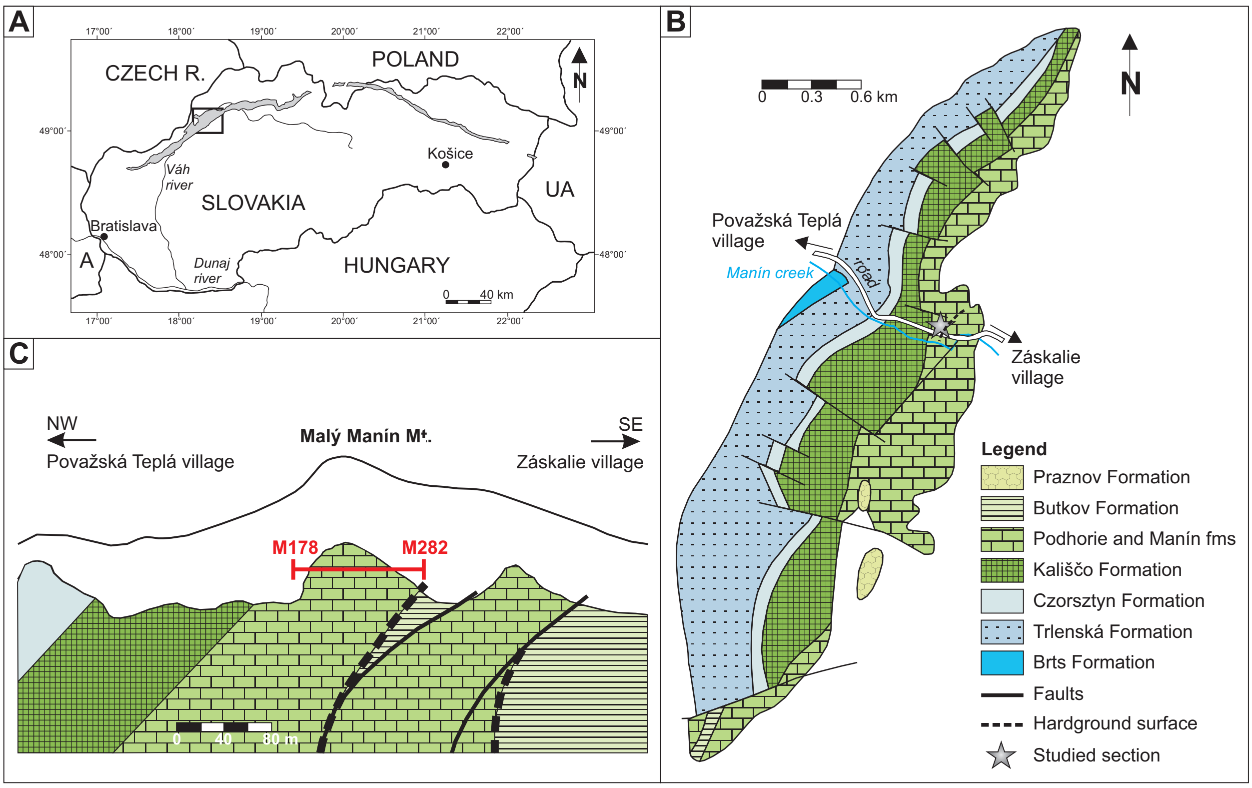

Fig. 1. A — Geographical map of Slovakia showing the Pieniny Klippen Belt and the location of the study area. **B** — Simplified geological map of the area showing studied section (modified from Mello 2005). **C** — Schematic section through the Middle Jurassic (blue)–Lower Cretaceous (green) formations of the Manín Straits with the examined section.

of bioclastic as well as of micritic limestones, cherts, rarely of fragments of basic extrusive clasts and tuffs. The clasts are of Barremian to Early Aptian age. The upper member is formed by bedded bituminous organodetritic limestones with blackish grey cherts. They change upwards into the massive pale organogenic limestone sequence of the Manín Fm (in the sense of Michalík & Soták 1990). They are of biomicritic-microsparitic character with fine-grained biogenic debris, crinoid columnals, bivalve shells and large benthic foraminifers, rare planktonic foraminifers and colomiellids. The sequence is terminated by a hardground surface and covered with dark grey spotted marls of the Butkov Fm (Kysela et al. 1982), with glauconitic grains in the basal part, containing Upper Albian foraminifers.

The Manín Straits, exposing a sequence of Jurassic–Cretaceous beds of the Manín Unit (Fig. 1B,C) is situated in the area of the Strážovské vrchy Mts., northeast of the Považská Teplá village (49°8’23.80” N, 18°30’30.80” E). The first observation from this site came from Štúr (1860), he described dark grey limestones with cherts and light grey limestone conglomerates as an equivalent of the Štramberk-type limestones. Andrusov (1945) examined a sequence of Mesozoic rocks within a geological research of the Pieniny Klippen belt. The first detailed section in the Manín Straits was produced by Mišík (1957). More detailed investigations of later authors (e.g., Köhler 1980; Michalík & Vašíček 1984; Rakús 1984; Boorová 1991; Boorová & Salaj 1996) brought new findings considering lithostratigraphy, fossil assemblages and competed with its interpretations within the Manín Unit.

Material and methods

The more than ninety-metre-thick sequence of the Podhorie- and Manín formations (Urgonian facies s. l.) and the so called “calcisphaerulid limestone” (Borza et al. 1983) was sampled in the Manín Straits. The rock samples were taken at metre intervals and have been analysed for microfacies, microfossils, nanofossils, cathodoluminescence, stable C- and O-isotope composition, total organic carbon, total carbon content and magnetic susceptibility.

Sedimentological and paleontological investigations have been supported by analyses of 92 thin-sections. Microfacies and biostratigraphically important markers have been documented in thin sections under optical microscopes Zeiss Axio Scope. a1, Zeiss-JENAPOL, using an Olympus Camedia C5060 and Axiocam 105 colour cameras. Volumetric contributions of five main microcomponents, including micrite, sparite, lithic clasts, heterozoans (i.e., large benthic foraminifers, brachiopods, molluscs, including rudists, echinoderms), and photozoans (calcareous algae, including algal microborings) were quantified. The microfacies characteristics with environmental attributions are adopted from microfacies types (F0 to F11) distinguished for the Lower Cretaceous Urgonian platforms in SE France by Arnaud-Vanneau (1980). Generic attributions of foraminiferal taxa are based on the classifications of Longoria (1974, 1984), Robaszyński & Caron (1979, 1995), Loeblich & Tappan (1988) and Premoli-Silva & Verga (2004). The carbonate classification follows the scheme of Dunham (1962) and Folk (1959, 1962). Current facies classifications are based on recent carbonate sediments and generalized models of carbonate platforms (e.g., Wilson 1975; Arnaud-Vanneau 1980; Masse & Fenerci-Masse 2011).

The calcareous nanofossils were processed by the decantation method adapted from Švábenická (2001), adjusted according Bom et al. (2015). We collected and studied 30 samples from the Podhorie and Manín formations using a Zeiss light microscope with 1500× magnification. Due to very poor preservation, 11 samples were taken from underlying beds of the section (interval M179–M189) in order to obtain calcareous nannofossils. Perch-Nielsen (1985), Bown & Young (1997) and Bown (1998) were used for their classifications.

Cathodoluminiscence records were carried out by a Neuser HC-2 microscope (hot cathode) at the Department of Geological Sciences of the Masaryk University in Brno using a polished thin section from sample No. M261, coated with carbon.

92 bulk rock samples from the M190–M 282 interval of the section were selected for geochemical analyses. Contents of total carbon (TC) and total inorganic carbon (TIC) were detected in rock-powder samples on the C-MAT 5500 device of the Ströhlein firm. Total organic carbon (TOC) content was obtained as the difference between TC and TIC (TOC=TC−TIC), and $CaCO_3$ contents recalculated from TIC are plotted in the scheme.

Isotope ratios of oxygen and carbon were analysed in CO_2 after standard decay of rock samples in 100 % phosphoric acid. Analyses of carbonate samples were generated on the Mass Spectrometer MAT253 equipped with the Gasbench device (Thermo Scientific Samples). These data are given in standard del-notation (δ) in promile (‰) with respect to the Vienna International Isotopic Standard (V-PDB) with 0.01 ‰ accuracy. Geochemical analyses were carried out in the Laboratories of the Earth Science Institute of the Slovak Academy of Sciences (Centre of excellence for integrated research of the Earth’s geosphere) in Banská Bystrica.

Mass normalized magnetic susceptibility (MS) was measured with MFK-1 kappabridge (AGICO, Brno) in the Paleomagnetic Laboratory of the Polish Geological Institute — National Research Institute. Small cubic samples of ca. 8 cm^3 volume were prepared for magnetic analyses.

Lithology

The carbonate platform sequence in the Manín Straits starts with upper slope facies of organodetrital limestones and passes upwards into peri-reef facies, with lateral replacement of these two to a considerable extent coeval parts of one area of sedimentation (carbonate platform and its slope). The thickness of these Urgonian-like facies attains around 100 m.

Their basal part (up to 45 m) is represented by mainly grey to darker grey, thick bedded to massive limestones with cherts in lower parts of the section (M178–M183) (Fig. 2). Based on their position in the sequence (emerging in the basement of the Manín Fm) and lithological character, we assign them to the upper part of the Podhorie Fm although they do not completely coincide with the original definition of the formation allocated in the Butkov Quarry. Three major faults (Fig. 2) cut through the limestones with no influence on the sequence succession.

The Podhorie Fm passes upwards continuously into the light grey, massive, strongly recrystallized limestones of the Manín Fm (around 55 m thick). The formation contains rudist shell fragments typical for the section studied. The Manín Fm is terminated by a hardground surface, which is covered by marls and marlstones of the Butkov Fm. A thin layer of calcisphaerulid limestone occurs in the basal part of the Butkov Fm.

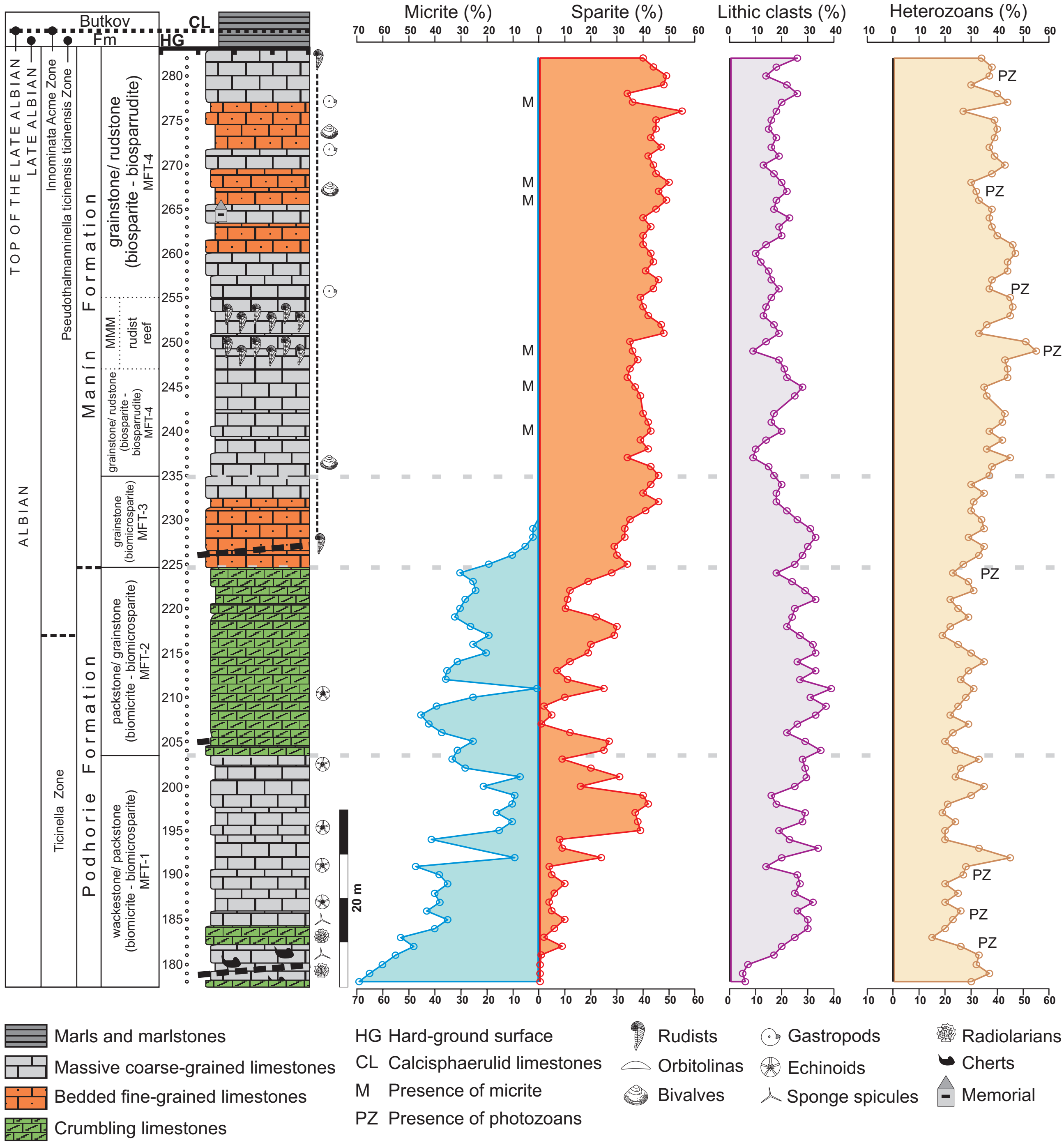

Fig. 2. A scheme of stratigraphic division of the Manín and the Podhorie fms in the Manín Straits section. Left: chronostratigraphic division, lithostratigraphy and microfacies following the scheme of Folk (1959, 1962). Right: Curves showing representation of constituents of the Podhorie- and Manín formations.

Microfacies and microfossils

We have identified four dominant facies types within the Manín and Podhorie fms (Urgonian facies s. l.) in the Manín Straits section, each of them pointing to a specific depositional environment (Figs. 2, 3). They are represented by bioclastic and peloidal wackestones and packestones (MFT-1), packstones and grainstones (MFT-2), bioclastic grainstones (MFT-3), and bioclastic grainstones and rudstones (MFT-4) (Fig. 2).

MFT-1: Wackestones and packstones (biomicritite/biomicrosparite)

They form the basal part of the section represented by the Podhorie Fm (interval M178–M203). This hemipelagic facies deposited in circalittoral environments was formed under calm conditions with weak currents (Arnaud-Vanneau 1980). A spiculite-radiolarian microfacies in the lower horizons (interval M178–M181) represents a more distal environment with fine-grained debris of echinoderms, sponge spicules of various morphotypes, rare thin- and thick walled filaments, radiolarians of the Spumellaria type, *Ostracoda* div. sp. and fragments of echinoid spines. Upwards, they completely disappear and sedimentary environment becomes shallower. The matrix is composed of micrite, replaced by secondary sparite in some places (Fig. 2). The proportion of micrite matrix in lower horizons (interval M178–M185) is basically the same as at the type locality of this formation at the Butkov Quarry, with a slight decrease (10–15 %) upwards (Fig. 2). Reef-building organisms derived from the carbonate platform do not occur in the limestones.

Planktonic foraminifers are represented by high arched globular chambered trochospiral forms. Some specimens can be determined as *Ticinella roberti* (Gandolfi) (Fig. 4A–C), *Ticinella* cf. *primula* Luterbacher (Fig. 4E–F), *Ticinella* cf. *madecassiana* (Sigal) (Fig. 4G–H), *Ticinella* cf. *praeticinensis* (Sigal) (Fig. 4D) of the Ticinella primula Zone (Premoli-Silva & Verga 2004) mark the Middle Albian interval (Figs. 2, 3). Rare colomiellids *Colomiella mexicana* Bonet (Fig. 4L), *Colomiella recta* Bonet (Fig. 4M), *Colomiella* sp. and calcareous dinoflagelates *Calcisphaerula innominata* Bonet (Fig. 4N), *Colomisphaera gigantea* (Borza) (Fig. 4O), and *Cadosina semiradiata olzae* (Nowak) also occur. Benthic foraminifers are represented by *Bolivinopsis* aff. *capitata* Yakovlev (Fig. 5A), *Glomospirella gaultina* Berthelin (Fig. 5B), *Turriglomina? anatolica* Altiner, Peybernès & Rey, 1968 (Fig. 5C), *Meandrospira favrei* (Charollais, Bronnimann & Zaninetti) (Fig. 5D), *Akcaya minuta* Hofker (Fig. 5E), *Dentalina* sp. (Fig. 5F), *Haplophragmoides* aff. *vocontianus* Moullade (Fig. 5G), *Spirillina* sp. (Fig. 5H), *Anomalina* sp., *Frondicularia* sp., *Patellina* sp., *Lenticulina* sp., *Gaudryina* sp. and *Meandrospira* sp. Redeposited calpionellids, *Crassicollaria parvula* Remane, *Calpionela alpina* Lorenz, *Lorenziella hungarica* Knauer & Nagy are present. Calcareous nannofosils are rather rare and their preservation ranges from moderate (only in a few samples) to extremely poor. We found calcareous nannoplakton in samples No. M179, M180, M182, M192 and M194. It is represented by *Watznaueria barnesiae* (Black in Black & Barnes, 1959) Perch-Nielsen (Fig. 6A–D), *Watznaueria biporta* Bukry, 1969 (Fig. 6E–F), *Watznaueria cynthae* Worsley, 1971 (Fig. 6I–J), *Cyclagelosphaera* sp. (Fig. 6K), *Cretarhabdus* sp. (Fig. 6 L) and by reworked *Micrantholithus obtusus* Stradner, 1963 (Fig. 6G) and *Nannoconus bucheri* Brönnimann, 1955 (Fig. 6H). The last stratigraphic occurrences of *Micrantholithus obtusus* and *Nannoconus bucheri* occur in the Late Aptian (Perch-Nielsen 1985; Bown 1998). *Didemnoides moreti* (Durand Delga) and *Globochaete alpina* Lombard (Fig. 3) are also rarely present. Limestones contain quartz clasts, muscovite leaflets and sporadic glauconite grains.

MFT-2: Packstones and grainstones (biomicrite/biomicrosparite)

They form the upper part of the Podhorie Fm in the section studied (interval M204–M224). They originate in calm circalittoral depositional environments (Arnaud-Vanneau 1980). Limestones contain intraclasts and moderate- to well-sorted peloids with rounded morphologies. Abundant bioclasts are represented mostly by fragments of echinoids, bivalves, planktonic foraminifers such as *Hedbergella trocoidea* (Gandolfi) (Fig. 4J) and *Ticinella primula* Luterbacher, *Ticinella roberti* (Gandolfi), *Ticinella* sp. (Fig. 4I–J), *Globigerinelloides bentonensis* (Morrow) of the Ticinella primula Zone indicate the Middle Albian by Premoli-Silva & Verga (2004) (Figs. 2, 3). From benthic foraminifers, *Turriglomina? anatolica* Altiner, *Haplophragmoides* aff. *vocontianus* Moullade, *Dentalina* sp. and *Valvulineria* sp. can be observed.

MFT-3: Grainstones (biomicrosparite)

They represent the basal part of the Manín Fm (interval M225–M235). These microfacies types, containing less diverse assemblages of microfossils were assigned to the shallower infralitoral environments with a constant, moderate to strong hydrodynamism (Arnaud-Vanneau 1980). Bioclasts reach larger sizes and are usually recrystalized. First occurrences of bivalves, partially rudist shell fragments and damaged orbitolinids occur in association with small benthic foraminifers (textularids, miliolids).

MFT-4: Grainstones and rudstones (biosparitic/biosparruditic)

They form the upper part of the Manín Fm in the Manín Straits section (interval M236–M282). This facies zone corresponds to sediments deposited in infralittoral environments of the inner platform domain which indicate high hydrodynamics, and shallow water with reworking of bioclasts (Arnaud-Vanneau 1980). Fragments of rudist shells of Caprinidae type are dominant and associated with bivalves and gastropods. The typical foraminiferal associations of these caprinid bearing

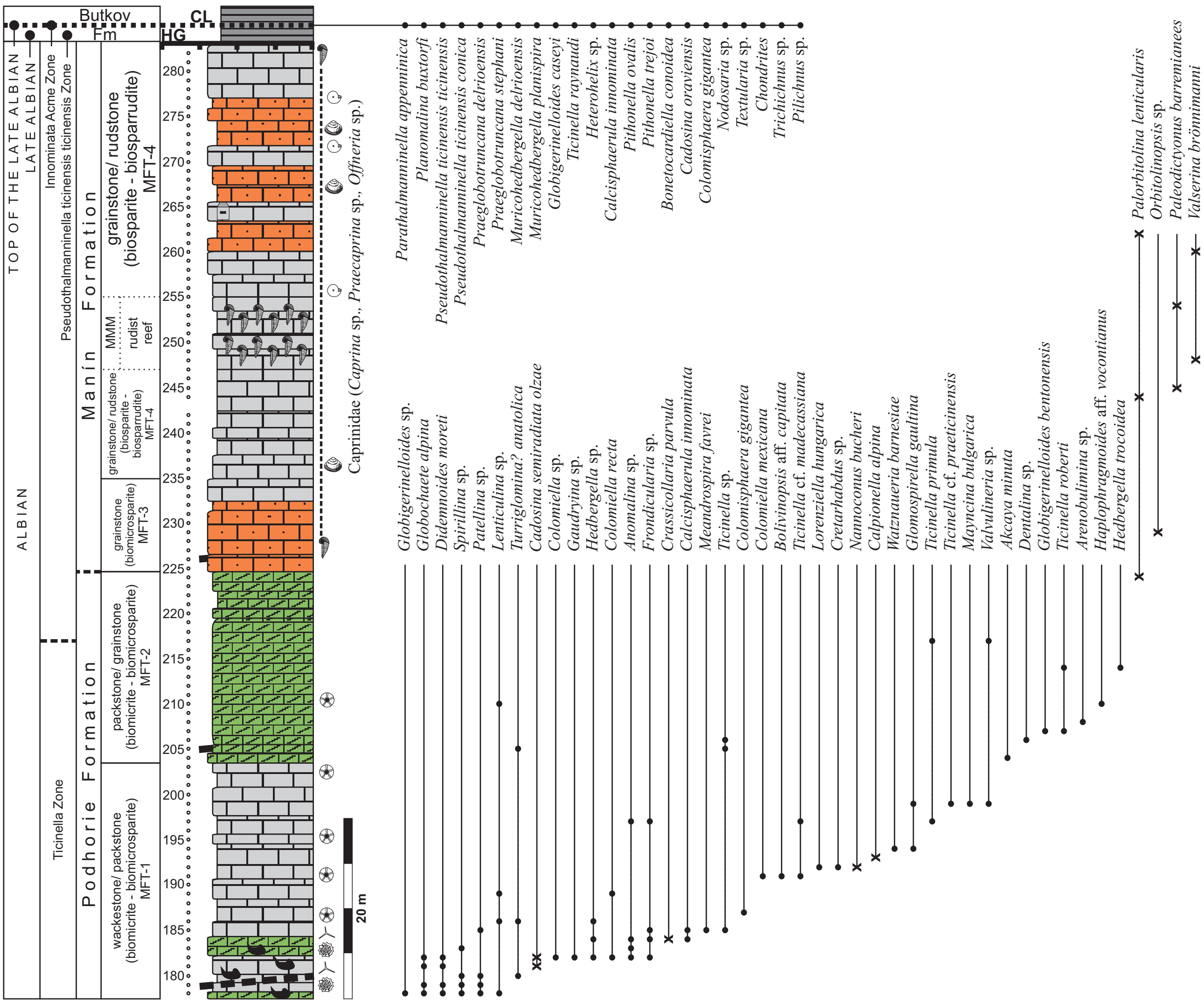

Fig. 3. Litho- and biostratigraphy of the the Manín and Podhorie fms (for legend, see also Fig. 2). Crosses — redeposited microfossils, dots — autochthonous microfossils.

beds consist of well-rounded orbitolinids (Fig. 7A–D). Less frequent constituents are represented by fragments of gastropods, crinoids, bryozoans, small benthic foraminifers (*Miliolida* sp., *Textularia* sp.) and rare planktonic foraminifers.

The orbitolinid fauna determined and assigned to the Barremian by E. Köhler, was probably redeposited as indicated by the fact that they are present in clasts (Fig. 7E,F).

In the Manín Fm, several successive generations of carbonate cement (Fig. 8), were identified with cathodoluminescence. The common types are dark red, orange and yellow (Fig. 8B,B'). Dark red cement predominates and represents the oldest generation that crystallized in intergranular pore spaces and replaced dissolved parts of detrital grains. Orange carbonate cement is younger and precipitated in the remaining pore spaces, within interboundary pores separating the brown cement sparite crystals, and in dissolved contact zones between detrital grains and dark red cement (Fig. 8B,B'). Both dark red and orange generations are represented by calcite assigned by Boggs & Krinsley (2006) to eogenesis. Yellow cement (Fig. 8B,B') is the brightest and the youngest generation of carbonate, which crystallized at the stage of telogenesis (Boggs & Krinsley 2006) in pores that remained after precipitation of the two older cement generations. Carbonates are affected by selective dolomitization (facies selective dolomitization, cf. Soreghan et al. 2000), typical of peritidal and shallow neritic facies zones.

Rudist assemblages

The entire corresponding beds (M237–M282) belong to the Manín Fm and formed part of a reef to peri-reef facies zone. The richest accumulations (beds M247–M255, about 2–4 metres thick) of rudist shell fragments (1–2 cm) represented by Caprinidae (*Caprina* sp., *Praecaprina* sp., *Offneria* sp.)

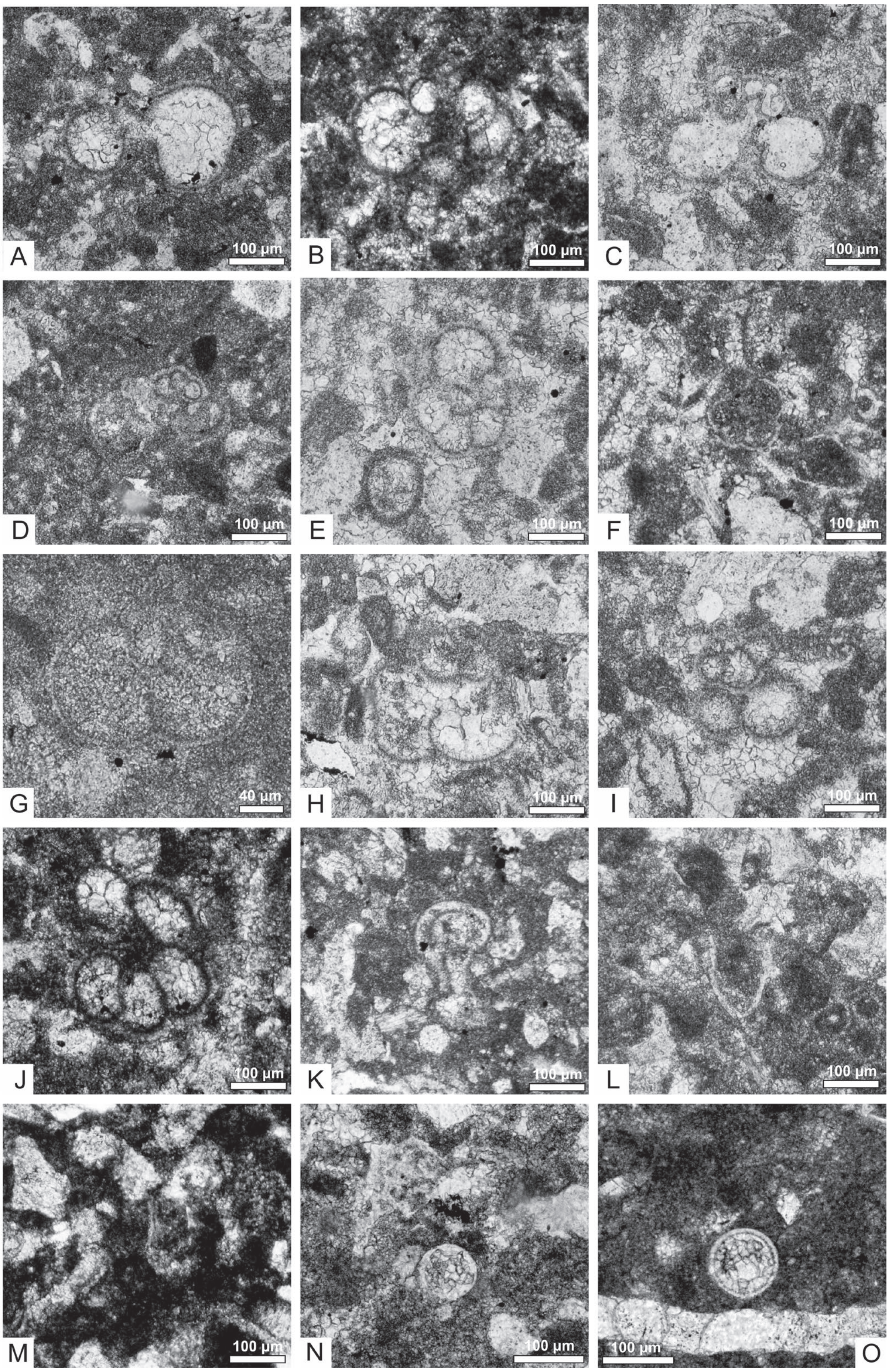

Fig. 4. Foraminiferal, tintinid and calcareous dinoflagellates microfauna of the Podhorie Fm limestones from the Manín Straits section; **A–C:** *Ticinella roberti* (Gandolfi) group, A — M207, B — M197, C — M214; **D** — *Ticinella* cf. *praeticinensis* (Sigal), M199; **E–F:** *Ticinella* cf. *primula* Luterbacher, E — M217, F — M197; **G–H:** *Ticinella* cf. *madecassiana* Sigal, G — M191, H — M197; **I** — *Ticinella* sp., M205; **J** — *Hedbergella trocoidea* (Gandolfi), M214; **K** — *Globigerinelloides bentonensis* (Morrow), M207; **L** — *Colomiella mexicana* (Bonet), M191, M194; **M** — *Colomiella recta* (Bonet), M190; **N** — *Calcisphaerula innominata* Bonet, M187; **O** — *Colomisphaera gigantea* (Borza), M184.

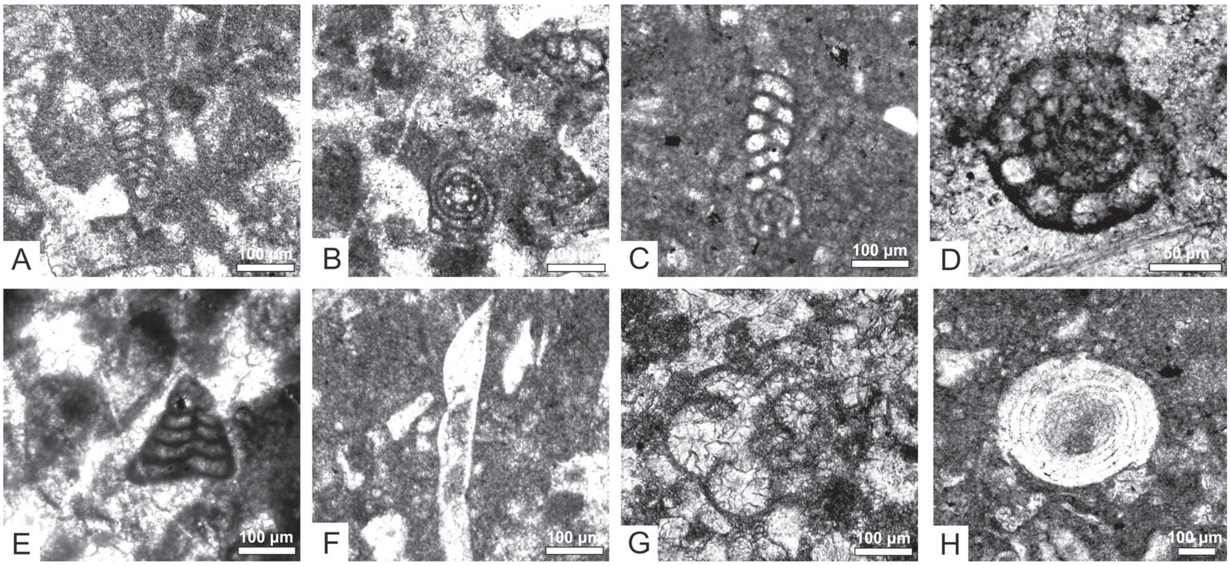

Fig. 5. Benthic foraminiferal microfauna of the Podhorie Fm limestones from the Manín Straits section; **A** — *Bolivinopsis* aff. *capitata* Yakovlev, M191; **B** — *Glomospirella gaultina* Berthelin 1880, M194; **C** — *Turriglomina? anatolica* Altiner, M192; **D** — *Meandrospira favrei* (Charollais, Bronnimann & Zaninetti), M185; **E** — *Akcaya minuta* (Hofker), M204; **F** — *Dentalina* sp., M206; **G** — *Haplophragmoides* aff. *vocontianus* Moullade, M210; **H** — *Spirilina* sp., M179.

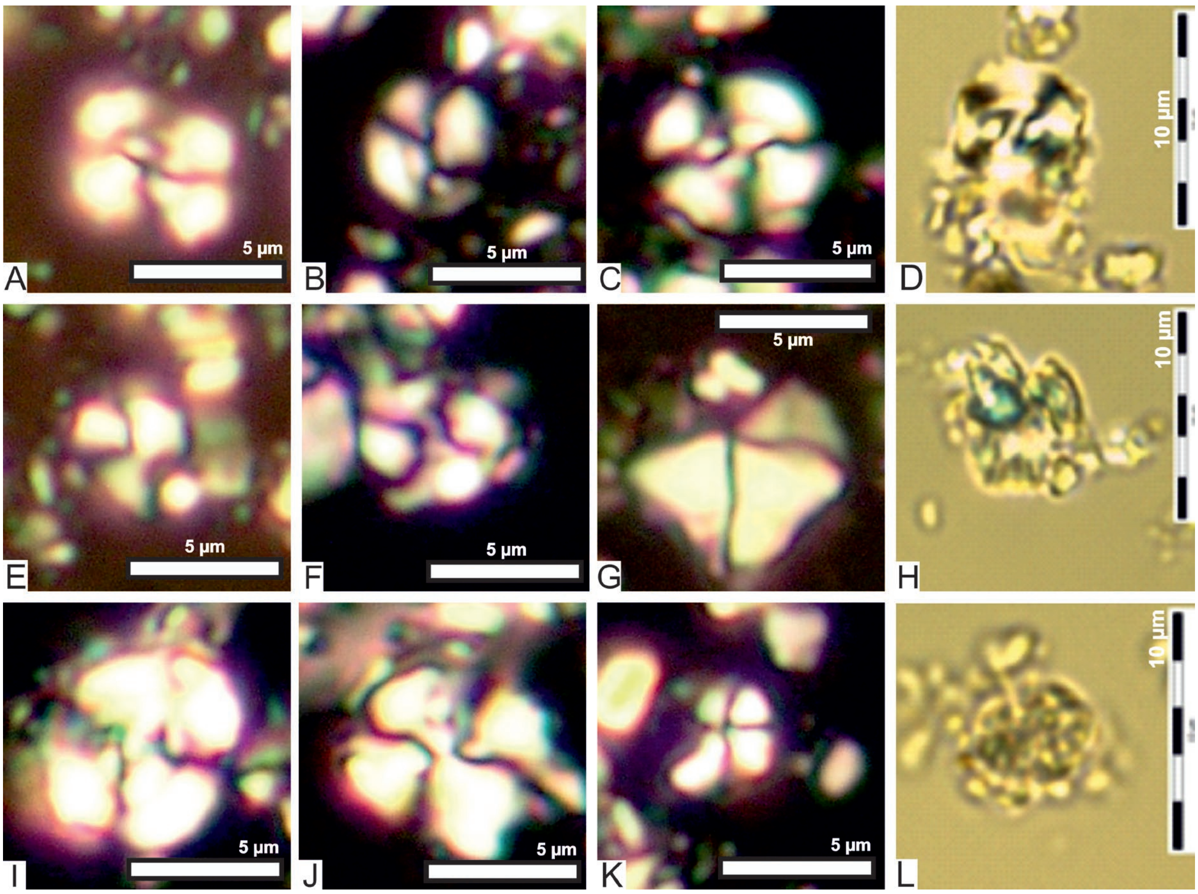

Fig. 6. Calcareous skeletal particles of nannoplankton from the Podhorie Fm limestones in the Manín Straits; **A–D:** *Watznaueria barnesiae* (Black in Black & Barnes, 1959) Perch-Nielsen, 1968, A — M179, B–C — M180, D — M194; **E–F:** *Watznaueria biporta* Bukry, 1969, E — M179, F — M182; **G** — *Micrantholithus obtusus* Stradner, 1963, M179; **H** — *Nannoconus bucheri* Brönnimann, 1955, M191; **I, J** — *Watznaueria cynthae* Worsley, 1971, M182; **K** — *Cyclagelosphaera* sp., M180; **L** — *Cretarhabdus* sp., M194.

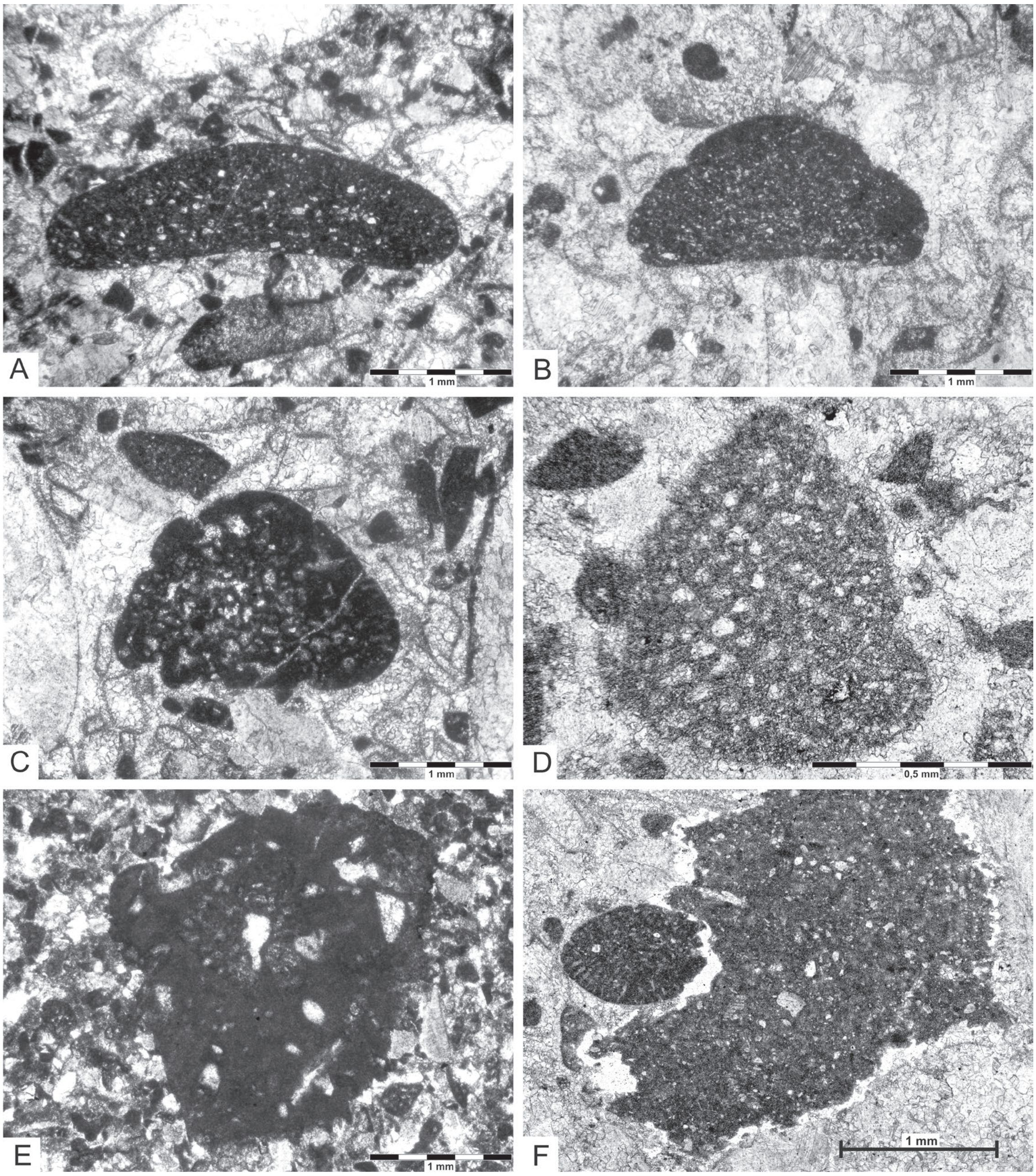

Fig. 7. Large benthic foraminifers from limestones of the Manín Fm in the Manín Straits section (determined by E. Köhler): **A** — ?*Palorbitolina* aff. *lenticularis* (Blumenbach), M224, M244, M262; **B** — ?*Valserina* aff. *brönnimanni* Schroeder et Conrad, M248, M260; **C** — ?*Paleodictyonus* aff. *barremianees* (Moullade), M246, M254; **D** — *Orbitolinopsis* sp., M229. Evidence of redeposition of large foraminiferal microfauna found in the Manín Fm limestones: **E** — Sample No. M236; **F** — Sample No. M256.

allow us to designate the Malý Manín Member. Fragments are visible on the weathered surface (Fig. 9A,B) and in polished sections (Fig. 9C,D). Inner and outer shell layers, the ligamental ridge, the cardinal apparatus and the accessory cavities are poorly preserved. A single row of pyriform canals can be observed in thin sections (Fig. 9E,F).

The foraminiferal association of these caprinids bearing beds consists predominantly of well-rounded orbitolinids and rare benthic foraminifers ascribed to miliolids which indicate reworking of these faunal remnants.

Calcisphaerulid limestones

A thin layer (3–5 cm) of a so-called calcisphaerulid limestone occurs in the basal part of the Butkov Fm. It has a pale grey and rusty-brown colour caused by enrichment of Fe minerals, and contains cross-sections of *Chondrites* (Sternberg 1883) filled with high-contrast dark sediment (Fig. 10K). This trace represents a system of tree-like branching, downward penetrating tunnels, 0.5–1.0 mm in diameter, assumed to be formed by chemosymbiotic organisms (Fu 1991). *Chondrites*

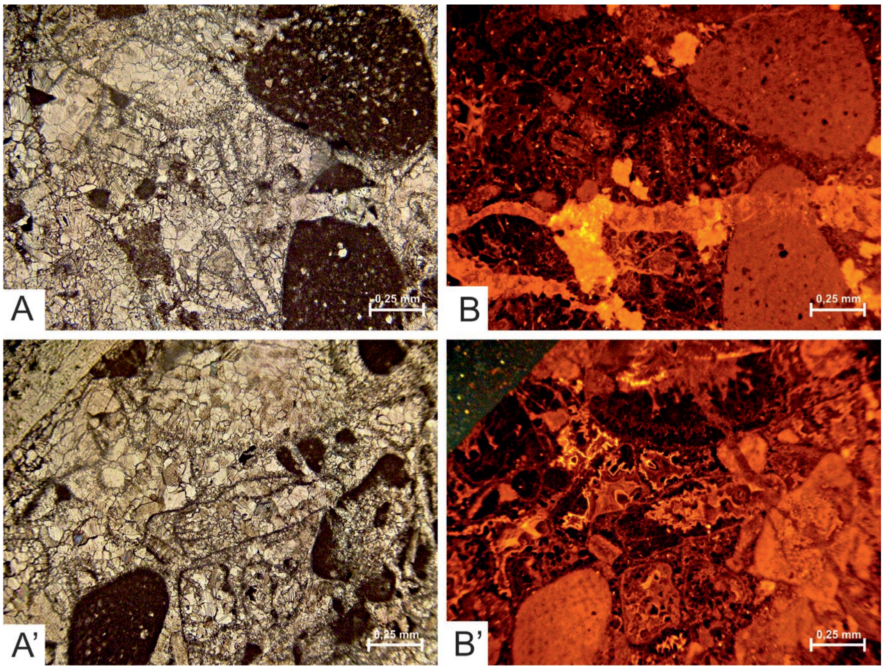

Fig. 8. Microfacies of the Manín Fm in optical (**A, A'**) and in cathodoluminiscence microscope (**B, B'**). Photos are taken from sample No. M261.

rare, represented mostly by *Nodosaria* sp. and *Textularia* sp.

Calcareous dinoflagellates are represented by abundant *Calcisphaerula innominata* Bonet (Fig. 10E) and by less frequent *Pithonella ovalis* (Kaufmann) (Fig. 10J), *Pithonella trejoi* Bonet (Fig. 10E) and *Bonetocardiella conoidea* (Bonet) (Fig. 10F). *Cadosina oraviensis* (Borza) and *Colomisphaera gigantea* (Borza) of the Innominata Acme Zone (assigned to Late Albian by Reháková (2000) are rare. Other fossil remains are represented by fragments of echinoids as well as filaments, thick-walled bivalves and bioclasts. Phosphate minerals, pyrite, rare authigenic quartz (with undulose extinction) and glauconite grains are present, sometimes filling shells and chambers of foraminifers.

can originate in the deeper parts of the substrate in an environment with very low or without oxygen content that fosters sulphate reduction (Bromley 1996). The calcisphaerulid layer also contains thin (about 1 mm) rusty-brown burrows of *Trichichnus* (Frey, 1970) and *Pilichnus* (Uchman, 1999). They are branched or unbranched, hair-like, cylindrical, straight to sinuous trace fossils, oriented at various angles (mostly vertical) with respect to the bedding, and filled by pyritized material. The producers of *Trichichnus* and *Pilichnus* were probably also chemosymbionts that harboured small filamentous bacteria in deeper portions of very poorly oxygenated sediments. (Kędzierski et al. 2015).

According to microstructure, the studied limestones represent calcisphaerulid–foraminiferal micrite (calcisphaerulid–foraminiferal wackestone/packstone). The microfacies is calcisphaerulid or calcisphaerulid–foraminiferal. Allochems are for the most part directed.

Based on abundant microfossils, the age of the calcisphaerulid limestone corresponds to the top of the Late Albian. Planktonic foraminifers of the Parathalmanninella appenninica Zone (e.g., Premoli Silva & Verga 2004) are represented by the index form *Parathalmanninella appenninica* (Renz) (Fig. 10A). In addition, *Planomalina buxtorfi* (Gandolfi) (Fig. 10F), *Pseudothalmanninella ticinensis ticinensis* (Gandolfi) (Fig. 10D), *Pseudothalmanninella ticinensis conica* (Gašpariková et Salaj) (Fig. 10B), *Praeglobotruncana delrioensis* (Plummer), *Praeglobotruncana stephani* (Gandolfi) (Fig. 10C), *Muricohedbergella delrioensis* (Carsey), *Muricohedbergella planispira* (Tappan), *Globigerinelloides caseyi* (Bolli, Loeblich et Tappan) (Fig. 10H), *Ticinella raynaudi* (Sigal) (Fig. 10I) and *Heterohelix* sp. (Fig. 10J) were identified. Benthic foraminifers are

Geochemistry and magnetic susceptibility

The $CaCO_3$ content in the section ranges from 79.15 to 99.82 % (Fig. 11). In limestones of the Manín Fm (interval M225 to M282), it remains constant and above 95 wt. %. The $CaCO_3$ content decreases locally (99.80 % to 79.15 %) in the Podhorie Fm. The $CaCO_3$ depletion could be connected with a rise of silicate content (quartz, micas, glauconite) in the sediments due to local tectonic processes. The TOC content also slightly increased (by an average of 0.05 wt. %) in some beds of the Podhorie Fm where $CaCO_3$ decreased (Fig. 11). Generally, the TOC content is lower than 0.1 % in the samples of the Manín Fm and documents nutrient pure regime on the carbonate platform.

Both C and O isotopes of bulk-rock samples show a relatively high variation: $\delta^{13}C$ is in range +1.03 to +4.20 ‰ V-PDB and $\delta^{18}O$ is in range −0.14 to −5.55 ‰ V-PDB (Fig. 11). The $\delta^{13}C$ isotope data suggest shallow water realm and more or less continuous diagenesis under marine conditions. Values are comparable with other platform carbonates, especially with Urgonian ones (Immenhauser et al. 2003; Godet et al. 2006; Föllmi & Godet 2013; Huck et al. 2013). The trends in stable isotopes mirror the separation of the succession into three intervals to some degree (the lower and upper parts of the Podhorie Fm and the Manín Fm) (Fig. 11). The correlation between $\delta^{18}O$ versus $\delta^{13}C$ trends indicate that a diagenetic signal may dominate especially in the beds with significant amount of sparite in the upper part of the sequence (Fig. 2). In spite of diagenetic effect, isotope ratios of shallow-water carbonates have a potential to record climatic changes and changes in the burial of inorganic carbon in the platform realm

(Godet et al. 2006; Föllmi & Gainon 2008; Föllmi & Godet 2013).

The $\delta^{13}C$ values in the range +2.19 to +2.68 ‰ are typical of the lowermost part of the section (M190–M203) formed by bioclastic limestones with a relatively high content of micrite matrix (wackstones), (Fig. 2). The wide range (−3.26 to −0.14 ‰) and bed to bed shifts of $\delta^{18}O$ values (Fig. 11) indicate local changes in the composition of sedimentary and/or early diagenetic fluids. Less negative $\delta^{18}O$ values indicate that a saline water occasionally penetrated into and/or was stored in the platform sediment, which later sourced sediments on the slope.

Thick-bedded and coarse-grained packstones and grainstones of the Podhorie Fm (M204–M224) are characterized by initially decreasing (+1.03 ‰) and later increasing (up to +4 ‰) $\delta^{13}C$ trends. In this part of the section, $\delta^{18}O$ vary between −1.61 and −5.55 ‰ but generally shift to more negative values. Highly negative $\delta^{18}O$ values could indicate fresh water input to the sediment and/or meteoric character of diagenetic fluids, and possibly a more humid climate (Lackie et al. 2002; Föllmi 2012).

In contrast to the Podhorie Fm, $\delta^{13}C$ values are higher and relatively uniform (+3.52 to +4.20 ‰) in the Manín Fm formed by bioclastic grainstones and rudstones (Figs. 2, 3). The $\delta^{13}C$ decreased (+3.19 to +3.17 ‰) just below the hardground surface in beds M281 and M282. The $\delta^{18}O$ values shifted to moderately negative values (−1.83 to −4.31‰) and vary less than in the Podhorie Fm. This indicates that the major volume of the rock is formed by calcareous matter derived from a platform and that primary spary-cements precipitated from fluids with isotopic composition similar to that of marine water. An increase in humid conditions with freshwater input may have preferentially reduced the signature of $\delta^{18}O$ on the platform (Poulsen et. al. 2007; Föllmi 2012).

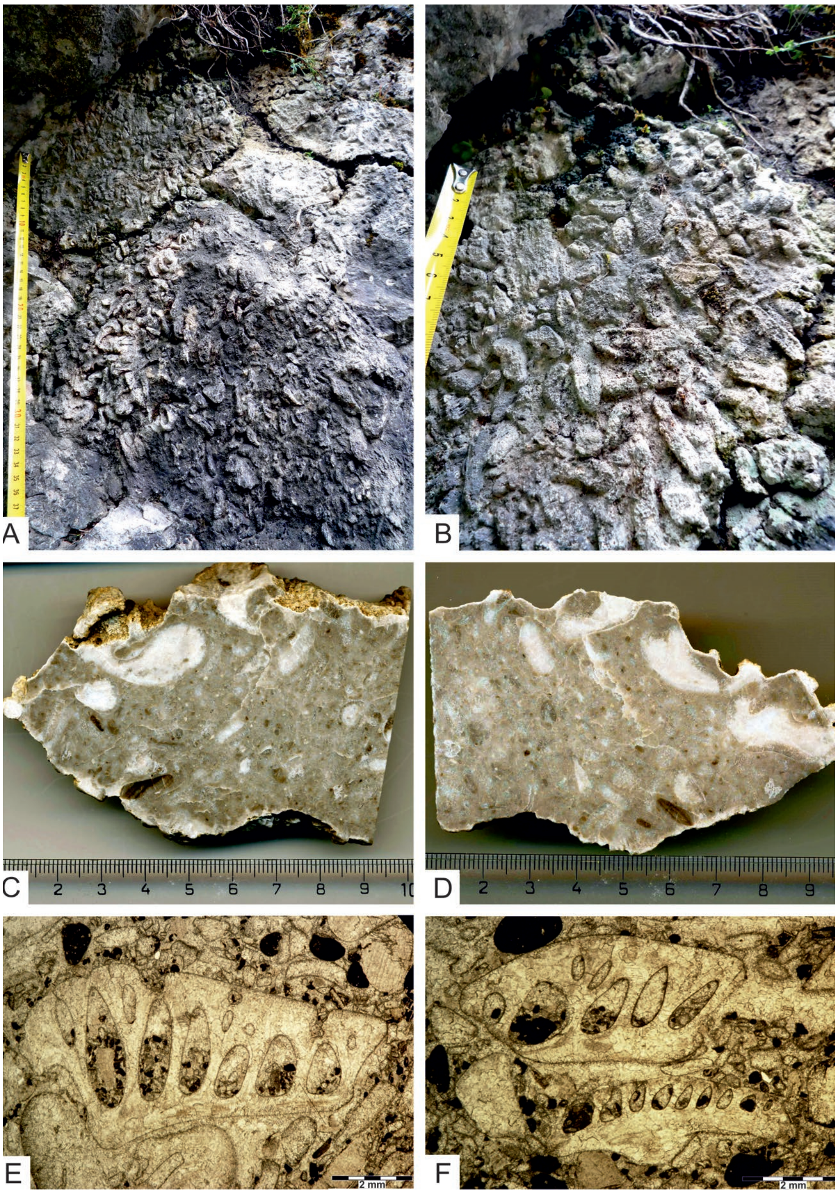

Fig. 9. Manín Fm limestones. **A–B:** field photos — bed No. M254; **C–D:** Polished section. The inner shell layer — white parts (primarily aragonitic) — is usually re-crystalized, dark spots of prismatic calcite belong to the outer shell layer; **E–F:** microscopic photos — coarse-grained organodetritic grainstone composed of poorly preserved caprinid rudists with a single row of pyriform canals associated with large benthic foraminifera, samples No. M256, M258.

MS values are mostly negative, between 0 and -6×10^{-9} m^3/kg, indicating predominant influence of diamagnetic carbonate rock matrix (Fig. 11). Exceptionally high values (54.7×10^{-9} m^3/kg) are observed only in a fault zone within the Podhorie Fm (sample 205) and are most probably related to tectonic phenomena. MS reveals a long term decreasing trend, from occasionally positive values in the lower part of the Podhorie Fm through −2 to -4×10^{-9} m^3/kg in the upper part of Podhorie and lower part of the Manín Fm, to almost constant low values of -4×10^{-9} m^3/kg in the upper part of the Manín Fm.

Discussion

Carbonate platform growth on Tethyan shelves has been controlled by major eustatic and climatic fluctuations (Arnaud-Vanneau 1980; Wissler et al. 2003; Weissert & Erba 2004). During the Late Barremian to Early Albian, these shallow carbonate platforms were affected by major drowning episodes

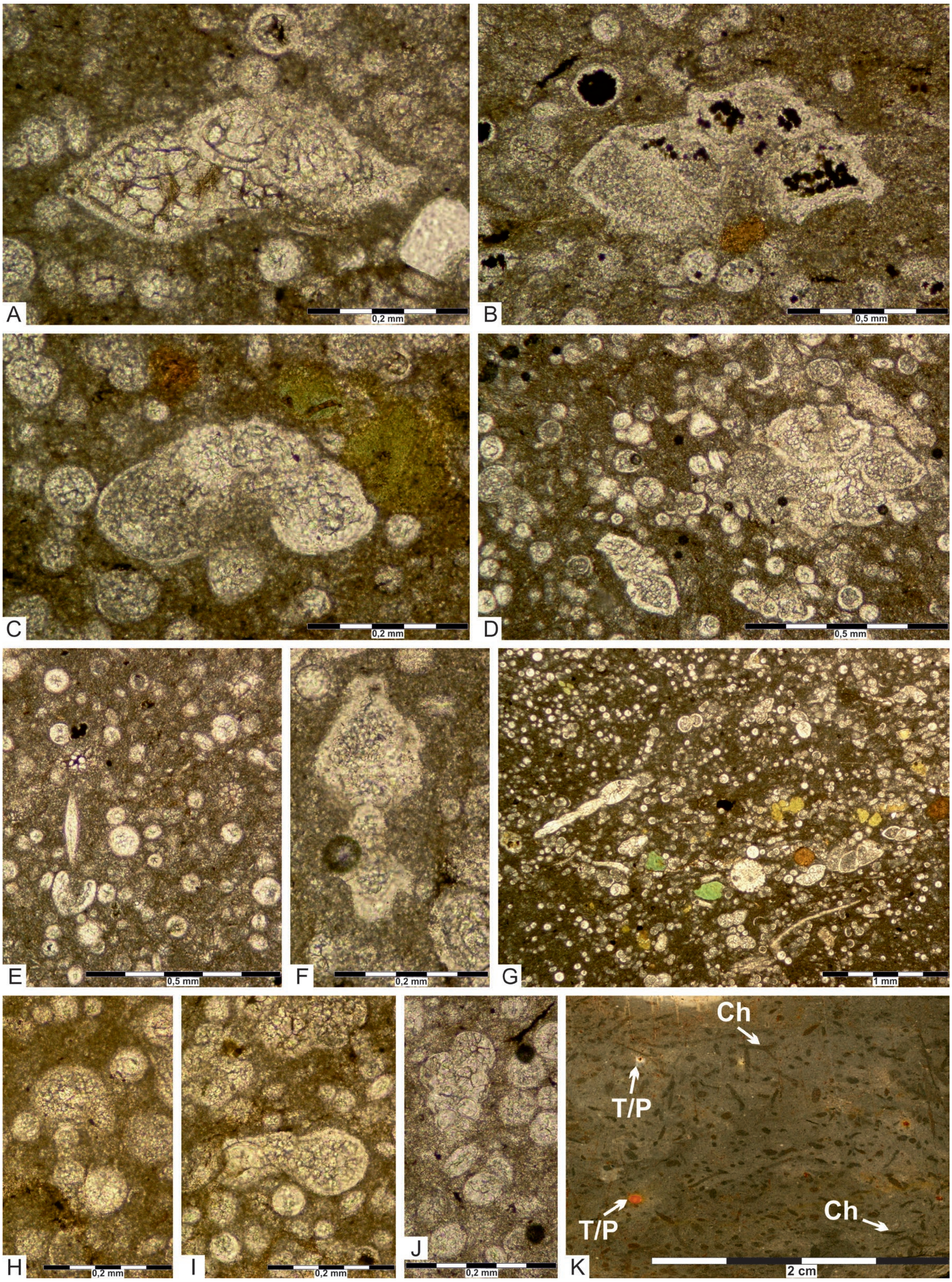

Fig. 10. Calcisphaerulid limestone. **A** — *Parathalmanninella appenninica* (Renz); **B** — *Pseudothalmanninella ticinensis conica* (Gašpariková et Salaj); **C** — *Praeglobotruncana stephani* (Gandolfi); **D** — *Pseudothalmanninella ticinensis ticinensis* (Gandolfi); **E** — Calcisphaerulid microfacies: *Calcisphaerula innominata* Bonet, *Pithonella trejoi* Bonet (approximately at the centre on the left); **F** — *Planomalina buxtorfi* (Gandolfi), *Bonetocardiella conoidea* (Bonet) (on the left below *Pithonella trejoi*); **G** — Calcisphaerulid foraminiferal biomicrite (calcisphaerulid foraminiferal wackestone/ packstone), locally directed allochems; **H** — *Globigerinelloides caseyi* (Bolli, Loeblich and Tappan); **I** — *Ticinella raynaudi* (Sigal); **J** — *Heterohelix* sp., just below it *Pithonella ovalis* (Kaufmann); **K** — Fossil traces in polished section (dark spots) of calcisphaerulid limestones.

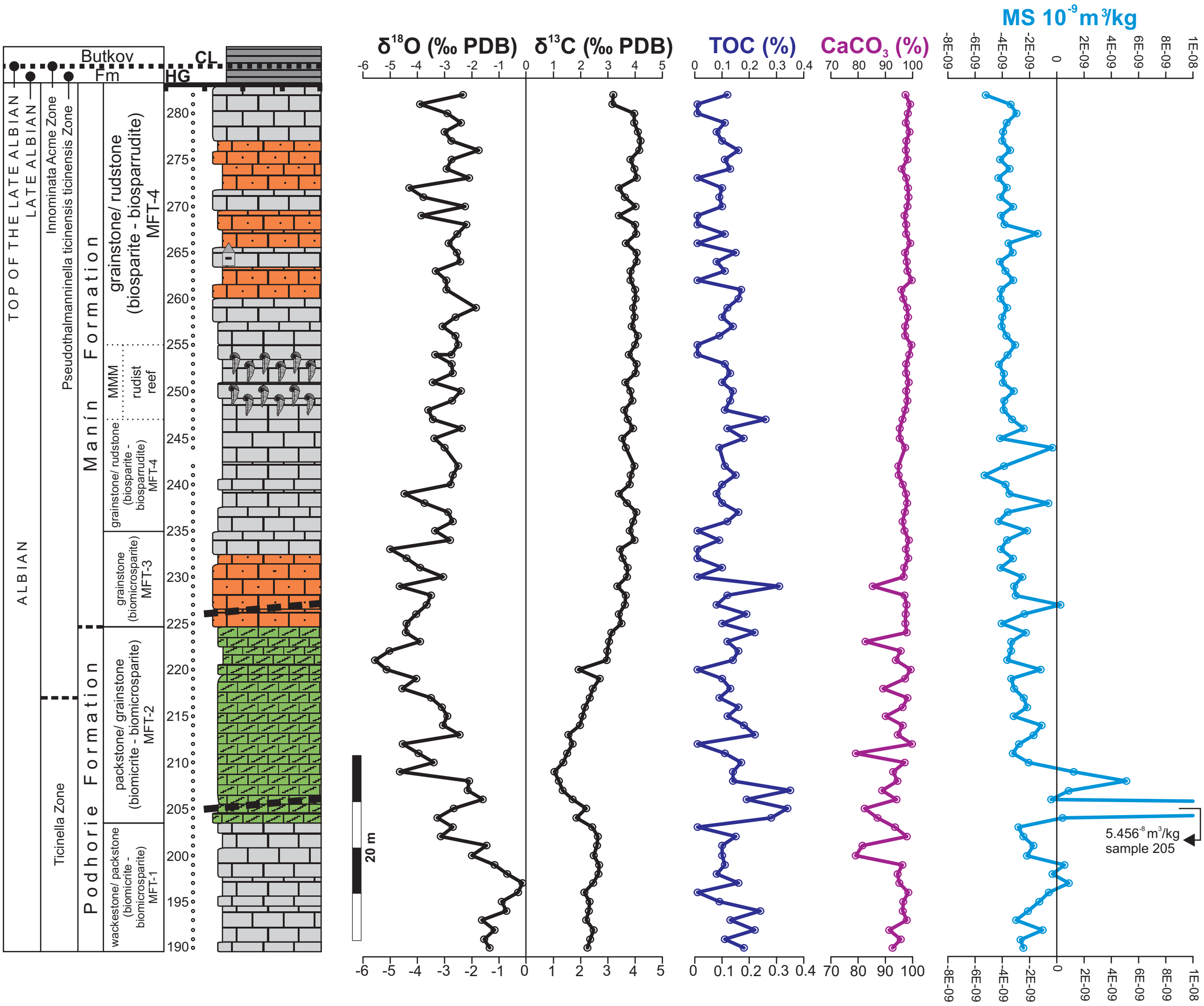

Fig. 11. A scheme of stratigraphic division of the Manín and Podhorie fms in the Manín Straits section with fluctuation curves of $\delta^{13}C$ and $\delta^{18}O$ isotopes, organic carbon content (TOC — Total Organic Carbon), calcium carbonate ($CaCO_3$) and magnetic susceptibility.

(Föllmi et al. 1994; Rosales 1999; Lehmann et al. 2000; Bièvre & Quesne 2004; Yilmaz 2006). Collapse of the platforms was accompanied by extensive submarine erosion and sliding of extensive blocks (Ferry & Flandrin 1979; Michalík & Vašíček 1984; Schöllhorn & Schlagintweit 1990, etc.). Although the age of platform carbonates of the Manín Unit outcropping in the Manín Straits was assigned to the typical "Urgonian", Barremian–Aptian sequence in the Western Carpathians mainly on the basis of orbitolinid and rudist assemblages (Köhler 1980; Michalík & Vašíček 1984; Rakús 1984; Boorová 1991; Boorová & Salaj 1996), we show that the Podhorie and Manín formations were deposited during the Albian.

Biostratigraphy and platform development

Biostratigraphic study of platform carbonates and associated basinal sediments show that the age estimates and lithology of the platform sequence in the Manín Straits determined in previous studies were inaccurate. Microfacies analyses and age assignments based on distinctive assemblages of planktonic foraminifers, calpionellids and calcisphaeres allow us to restrict the demise of the carbonate platform to the Albian and provide a schematic model displaying lithofacies architecture and platform development similar to that proposed by Gili et al. (2016), (Fig. 12). It can be assumed that the platform margin and upper slope sediments of the "Urgonian", Barremian–Aptian sequence, originally forming the higher highstand platform have been eroded and their former slope was overlain by lowstand platform exhibiting somewhat similar platform margin and upper slope facies of the older highstand platform.

The lowstand carbonate platform sequence in the Manín Straits starts with upper slope facies of the Podhorie Fm with cherts in the basal part. Based on planktonic foraminifers, *Calcisphaerula innominata* which is known to occur in the Albian (Borza 1969), *Colomisphaera gigantea*, tintinids

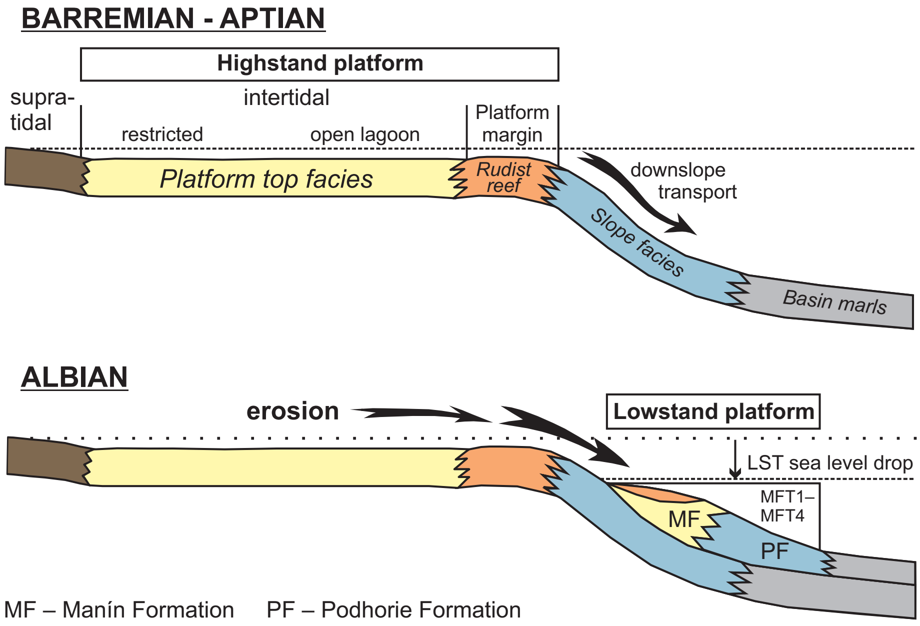

Fig. 12. Schematic model displaying lithofacies architecture and platform development in the Manín Straits. Based on Gili et al. (2016).

Colomiella recta and *C. mexicana*, these deposits correspond to the Albian Ticinella primula Zone.

The Podhorie Fm passes upwards continuously into peri-reef facies of the Manín Fm with significant accumulations of rudist shell fragments, which can indicate renewed platform progradation. With the exception of the study based on rudist findings of Masse and Uchman (1997) from the High Tatra Mts (Giewont, Wysoka Turnia, Hala Gąsienicowa) and from the Muráň limestone named as the "Caprotinenkalk" by Uhlig (1897 in Lefeld 1974), detailed taxonomic and biostratigraphic studies of the Lower Cretaceous rudist faunas of the Central Western Carpathians are absent. Investigations in the Manín Straits document the existence of caprinid rudist shell fragments. Their special status, uniqueness and character allow us to designate the Malý Manín Member (beds M247–M255) which has not been previously recognized and which has not been defined at other localities of the Manín Unit. The foraminiferal association of these caprinid-bearing beds consists predominantly of well-rounded orbitolinids. Some of them occur in clasts from which they were "separated" by transport into the limestones of the Manín Fm. Similar occurrences of orbitolinid association were documented from other localities in the Manín Unit (Boorová 1990, 1991). Signs of redeposition are also documented by the presence of rare pre-Albian calpionellids and calcareous nannoplankton.

A sudden bathymetric collapse of the Manín carbonate platform occurred during the Late Albian (Boorová 1990; Boorová & Salaj 1992) and the environment has been affected by subsequent low-rate sediment deposition. A hardground surface described by Rakús (1984) probably originated in deeper marine conditions with a minimum contribution of sediment. This surface is overlain by marls and marlstones of the Butkov Fm with an association of rare benthic and current planktonic foraminifers of the Late Albian Thalmanninella ticinensis ticinensis Zone (Boorová 1990). In the Manín Straits, as well as on the other localities of the Manín Unit (Borza et al. 1983) a thin layer (3–5 cm) of grey calcisphaerulid limestone occurs just in the basal part of the Butkov Fm. Based on rich microfossil community, this limestone was deposited during the latest Albian.

Geochemistry

The $\delta^{13}C$ record may be influenced by different biological fractionation of different groups of calcareous plankton, different types of mineralogy of pelagic and benthic producers, by quantity of organic carbon recycled, and by diagenetic processes (Föllmi & Godet 2013). The $\delta^{13}C$ and $\delta^{18}O$ values shift along the section in a close relation with changes in the composition of microfacies and their tight correlation suggests that they were subjected to diagenetic alteration. However, the trend towards higher $\delta^{13}C$ values within the Manín Fm can suggest enrichment in the aragonite production and/or isotopic composition of seawater dissolved inorganic carbon (due to aragonite dissolution, higher nutrient enrichment, and/or changes in the contribution of open oceanic water mass and platform-top water masses). However, local (tectonic) controls cannot be ruled out interpreting the beginning and demise of carbonate depositional systems (Ruberti et al. 2013; Sames et al. 2016).

The high $\delta^{13}C$ values of the Manín Fm indicate that the main amount of (sparitic-coarse) biodetrite comes from carbonate platform and its edge, containing shells and mud with original aragonite mineralogy. Input of non-carbonatic components in the Manín Fm was generally low and identifiable by higher values of MS. MS might have been influenced also by dispersed ferromagnetic and clay minerals that reside in the micrite. A long term MS decrease is generally concordant with upward-increasing $CaCO_3$ and sparite content (Figs. 2 and 11). This trend most probably reflects a relative decrease of lithogenic input. It is interesting that MS roughly follows the same decreasing trend reflected in TOC (Fig. 11). Similarly as in the case of the Urgonian facies of the Barremian–Early Aptian age, the production of aragonite can be essential for a source of the ^{13}C-heavy carbonate derived from the platform and adjacent (peri-platform) basins (Föllmi et al. 2006; Godet et al. 2006; Föllmi & Gainon 2008). In deep-water pelagic carbonates, positive shifts of $\delta^{13}C$ resulted from enhanced burial of the isotopically light sedimentary organic C (Weissert et al.

1998; Immenhauser et al. 2003, etc.). According to Immenhauser et al. (2003), a positive shift in $\delta^{13}C$ (and $\delta^{18}O$) recorded in lithified shallow-marine carbonates reflects a superposition of environmental and diagenetic effects. During the transgression, the impact of isotopically light meteoric fluids on carbonate geochemistry is much reduced as indicated by higher isotope values of shallow-water carbonates. Therefore, the trend towards higher $\delta^{13}C$ and $\delta^{18}O$ can also reflect a decreasing contribution of platform-top water masses towards the top of the Manín Fm. In summary, the geochemical and sedimentological trends within the Manín Unit suggest an overall deepening at the site of sedimentation.

In the Manín Fm (peri-reef facies), sedimentary $\delta^{13}C$ values were affected by diagenesis as indicated by smooth trends of the $\delta^{13}C$ curve, and by high positive correlation (R^2=0.75) between $\delta^{18}O$ and $\delta^{13}C$. Non-identifiable recrystallized bioclasts and lithoclasts are cemented by calcite (spary calcites — Fig. 2) that probably precipitated from pore waters of marine origin. Variable $\delta^{18}O$ values (−0.14 to −5.55 ‰, Fig. 11) but low correlation between $\delta^{18}O$ and $\delta^{13}C$ (R^2=0.01) in limestones of the lower part of the section (M191–M224, Podhorie Fm) indicate differences in depositional and diagenetic conditions between the Podhorie and Manín fms.

Frequent black shales in the mid-Cretaceous pelagic sequence have been linked with anoxic bottom-water conditions during Ocean Anoxic Events (1a–d), (Weisert et al. 1998; Heimhofer et. al. 2008; Leckie et al. 2002; Kennedy et al. 2014; Giorgioni et al. 2015). Large fluctuations of the $\delta^{13}C$ signal were indicated in the pelagic sequences and local factors such as productivity variations of surface water had an impact on the carbon isotopic composition of deep water limestones (Giorgioni et al. 2015; Ruberti et al. 2013). The local factors are important in the sequence of shallow-water and temporally isolated realm and global changes — for example, OAEs recorded as C cycle perturbations may be specifically recorded there (Föllmi et al. 2006; Godet et al. 2006; Föllmi & Gainon 2008; Ruberti et al. 2013).

The hardground indicates a demise of the mid-Albian carbonate production. The basinal black shale with variable carbonate and TOC contents were deposited over large areas of the Mediterranean and the Atlantic Tethys (Ruberti et al. 2013). In this study, dysoxic conditions probably characterized the deposition of marls, as indicated by trace fossils preserved in the calcisphaerulid limestone in the basal part of the pelagic sequence. The demise of the mid-Albian platform may be correlated with OAE 1c or OAE 1d (Leckie et al. 2002; Ruberti et al. 2015).

Conclusions

The Albian carbonate platform sequence of the Manín Straits exhibits peri-reef to upper slope facies of the older destroyed Barremian–Aptian highstand platform. The sequence starts with dark grey, thick-bedded to massive bioclastic limestones of the Podhorie Fm, with cherts in the basal part. Albian age is indicated by: (1) planktonic foraminifers of the Ticinella primula Zone, colomiellids, *Colomiella recta* and *C. mexicana,* and (2) calcareous dinoflagellates, *Calcisphaerula innominata*, *Colomisphaera gigantea* and calcareous nannoplankton. The Podhorie Fm passes upwards continuously into light grey, massive, platform limestones of the Manín Fm with abundant caprinid rudist shell fragments and a trend towards more positive $\delta^{13}C$ where we designate the Malý Manín Member (beds M247–M255). Their foraminiferal association consists of well-rounded, redeposited orbitolinids.

Four dominant microfacies associations: bioclastic and peloidal wackestones and packestones (MFT-1), packstones and grainstones (MFT-2), bioclastic grainstones (MFT-3), bioclastic grainstones and rudstones (MFT-4), (sensu Arnaud-Vanneau 1980) allow us to restrict the growth and the demise of the carbonate platform.

Isotopes in both formations change within wide intervals ($\delta^{13}C$ is in range +1.03 to +4.20 ‰ V-PDB and $\delta^{18}O$ is in range −0.14 to −5.55 ‰ V-PDB). Stratigraphic changes in $\delta^{13}C$ in the section indicate temporal changes in aragonite production and/or in the isotopic composition of seawater dissolved inorganic carbon, possibly due to reduced contribution of top-platform water masses.

Carbonate platform evolution was connected with submarine sliding, redeposition from older deposits, and carbonate clast accumulation on the toe of the slope. After a stabilization and aggradation stage, the carbonate platform collapsed just prior to the Late Albian. A hardground surface was formed, overlain by Albian–Cenomanian pelagic beds of the Butkov Fm with a thin layer of calcisphaerulid limestone characterized by planktonic foraminifers of the Parathalmanninella appenninica Zone (top of the Late Albian) and calcareous dinoflagellates of the Innominata Acme Zone.

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