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FACIES OF THE UPPER JURASSIC–LOWER CRETACEOUS DEPOSITS FROM THE SOUTHERN PART OF THE CARPATHIAN FOREDEEP BASEMENT IN THE KRAKÓW–RZESZÓW AREA (SOUTHERN POLAND)

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Abstract: A comparative sedimentological analysis of the Upper Jurassic–Lower Cretaceous deposits carried out on drill-cores from the southern part of the Carpathian Foredeep allowed us to distinguish thirteen main microfacies types. The results of microfacies analyses and stratigraphical data made it possible to propose a lithological subdivision of the southern part of the Upper Jurassic and Lower Cretaceous sediments of the Carpathian Foredeep basement between Kraków and Rzeszów. In the analysed wells, three main sedimentary complexes were distinguished, embracing the following intervals: (i) Callovian–Oxfordian, (ii) Kimmeridgian and (iii) Tithonian–Berriasian–Valanginian. The Oxfordian, Kimmeridgian and Tithonian deposits represent the outer – mid homoclinal ramp facies, whereas the Berriasian and Valanginian deposits belong to the inner homoclinal ramp facies.

Complexes of microbial-sponge reefs, with a distinct relief, could be recognised in the Upper Oxfordian sediments only. The development of these buildups took place in a basin typified by diversified morphology, determined by the block-type structure of the Palaeozoic basement and synsedimentary tectonics, which brought about substantial variability in thickness of the Oxfordian sediments. At the end of the Oxfordian, large complexes of the reef facies were replaced mainly by microbial-sponge and microbial-coral biostromes developed during the Kimmeridgian and Tithonian. In the principal part of the studied area (except the western part of the described fragment of the Carpathian Foredeep; Kraków area) during the Kimmeridgian, Tithonian, Berriasian and Valanginian, sedimentation occurred in a basin typified by homogeneous morphology, which resulted in a wide extent and comparable thicknesses of the distinguished facies types.

In the studied sections, indications of partial or complete dolomitization were observed in a large part of the sediments. Four generations of dolomite document a complex diagenetic history with multiple episodes of dolomite formation: from early diagenetic environment to late burial conditions.

Key words: facies, microfacies, dolomitization, Upper Jurassic, Lower Cretaceous, Carpathian Foredeep basement, southern Poland.

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INTRODUCTION

In the Polish part of the Carpathian Foredeep basement, between Kraków and Rzeszów (Fig. 1), the Mesozoic sediments form three complexes represented by the: (i) Triassic, (ii) Middle Jurassic–Lower Cretaceous, and (iii) Upper Cretaceous strata. Since decades, the studies of the Mesozoic sediments have been mostly inclined towards the questions of petroleum industry (*e.g.*, Karnkowski, 1999; Gliniak *et al.*, 2005; Gutowski *et al.*, 2006; Kotarba *et al.*, 2011). The results of these investigations have been presented in numerous publications as well as unpublished reports. They fragmentarily document the geological structure and the development of ideas about the lithology and stratigraphy of the Mesozoic sediments in the Carpathian Foredeep. Long-term researches allowed for distinguishing sediments of the Oxfordian, Kimmeridgian, Tithonian, Berriasian, Valanginian, and Hauterivian age (Fig. 2; *e.g.*, Morycowa & Moryc,

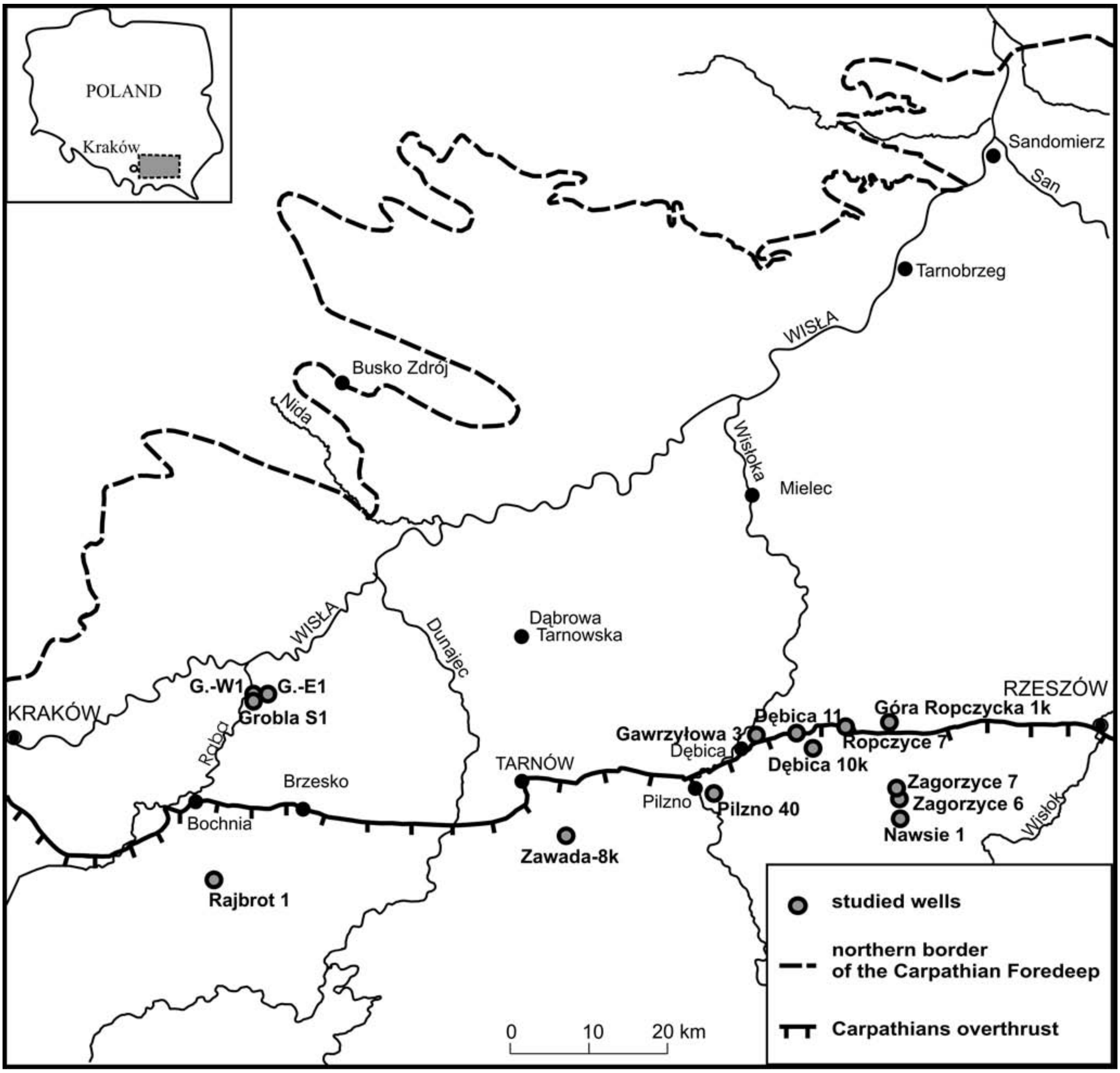


Fig. 1. Location of the studied area and investigated wells. The northern border of the Carpathian Foredeep is outlined by the extent of marine Miocene strata

1976; Golonka, 1978; Król, 2004; Gutowski *et al.*, 2007; Matyja, 2009; Urbaniec *et al.*, 2010). Detailed microfacies analyses were published only rarely and most often they concerned wells, in which the coring frequency allowed for precise microfacies observation, particularly of the Lower Cretaceous deposits (Zdanowski *et al.*, 2001; Gutowski *et al.*, 2007). In effect, in spite of extensive literature, the general outline of the facies development and stratigraphy of the Carpathian Foredeep basement is often non-cohesive (Fig. 2).

The main goal of sedimentological studies, the results of which are presented in this paper, is the characterization of facies and microfacies types and the diagenetic processes, particularly dolomitization, of the Upper Jurassic and Lower Cretaceous sediments from the southern part of the Carpathian Foredeep basement. On such a base, some ordering and general characteristics of the lithology was attempted.

GEOLOGICAL SETTING

The Carpathian Foredeep basin was formed basically in the Neogene (*e.g.*, Oszczypko, 2006); however, older, Palaeozoic and Mesozoic tectonic evolution of the basement exerted an important control as well (*e.g.*, Krajewski & Matyszkiewicz, 2004; Gutowski *et al.*, 2006; Matyszkiewicz & Olszewska, 2007; Buła & Habryn, 2010, 2011;

Jachowicz-Zdanowska, 2011). The southern border of this basin is marked by the Carpathian frontal thrust, the northern one is outlined by the extent of marine Middle Miocene strata. The Polish part of the Carpathian Foredeep basin is about 300 km long, whereas its width varies from a dozen or so kilometres near Kraków, up to about 100 km in the vicinity of Rzeszów (Fig. 1). Its basement is built up by the epi-Variscan platform and the Permian–Mesozoic cover. The Mesozoic sediments appear in the foredeep basement in two zones, separated by the Lower San Horst Structure. These are: the western zone, extending between Kraków and Ropczyce (Fig. 1), and the eastern zone in the area of Lubaczów. These zones differ in their facies development, sediment thickness, profile completeness, and also in the structural plan of the Mesozoic deposits.

The oldest Mesozoic sediments in the study area belong to the Triassic. The oldest Triassic strata are represented by a thick terrigenous and carbonate complex, which is preserved in the form of relatively frequent patches (Moryc, 2006; Buła & Habryn, 2008).

In the study area, Middle Jurassic (Upper Bajocian–Callovian) sediments are represented by sandstone and clay-silty sediments with abundant plant detritus, bearing also carbonate intercalations in the upper part of the section (Moryc, 2006). The total thickness of the Middle Jurassic deposits usually varies from a dozen or so up to several dozen metres, exceeding 100 m in a few wells only.

Upon the Middle Jurassic or Triassic and Palaeozoic deposits, a thick complex of the Upper Jurassic–Lower Cretaceous carbonate sediments occurs. At present, due to erosional cut, the state of preservation of these strata is diversified. In the vicinity of Kraków, this complex is about 300 m thick, while in the Rzeszów area its thickness amounts to even 1,300 m. The investigations conducted for years permitted to distinguish Oxfordian, Kimmeridgian, Tithonian, Berriasian, Valanginian and Hauterivian sediments, which are subdivided into numerous informal lithostratigraphic units. Recently, new Upper Jurassic (Matyja & Barski, 2007; alternatively Gutowski *et al.*, 2007) and Lower Cretaceous (Urbaniec *et al.*, 2010) lithostratigraphic subdivisions have been presented (Fig. 2).

The Upper Cretaceous complex begins with the Cenomanian glauconitic sandstones (Heller & Moryc, 1984; Moryc, 2006). The thickness of these sediments amounts to *ca*. 150 m. The Turonian–Maastrichtian is represented by sandy and marly limestones and marls. The present thicknesses and development of the Triassic, Middle Jurassic–Lower Cretaceous and Upper Cretaceous complexes are determined by the pre-Jurassic (Late Triassic) and Palaeogene erosion, as well as polyphase, mainly Cretaceous/Palaeogene block tectonics.

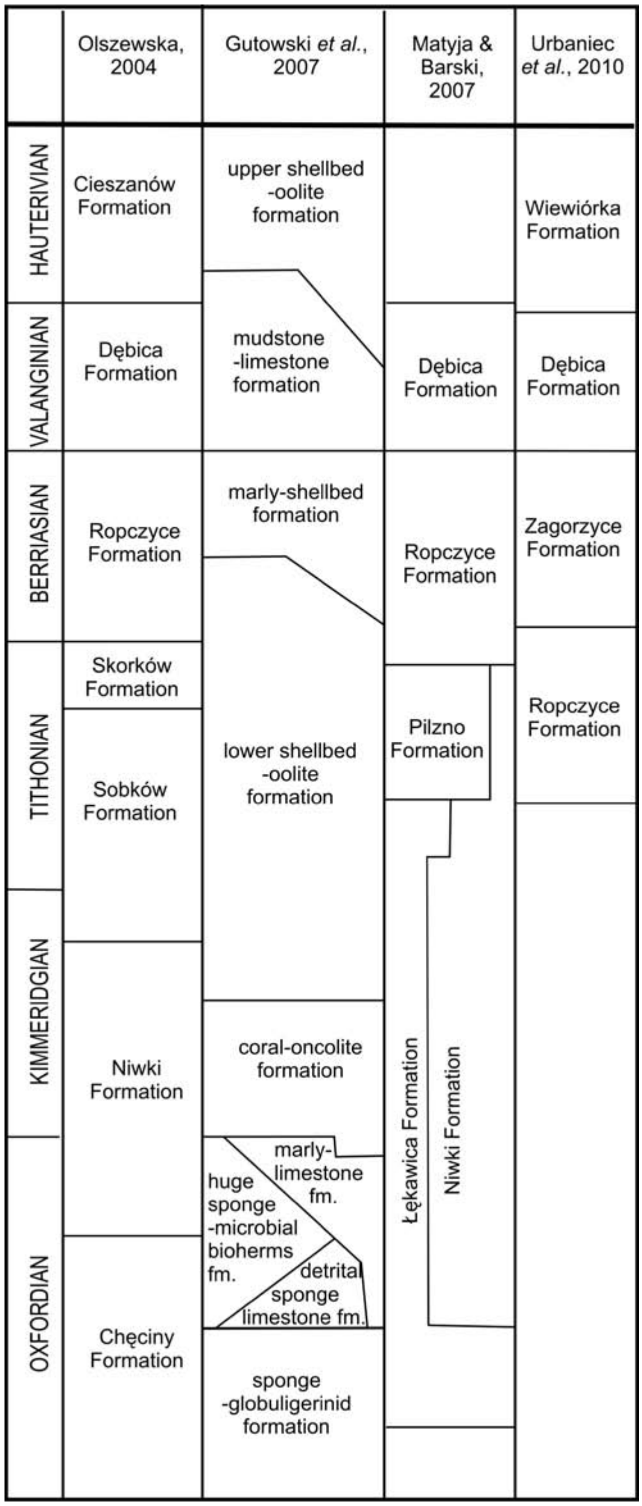


Fig. 2. Overview of the Upper Jurassic–Lower Cretaceous lithostratigraphic subdivisions of the Carpathian Foredeep basement

METHODS AND SCOPE OF INVESTIGATION

The basic research method was the analysis of cores drilled within the southern part of the Carpathian Foredeep, between Kraków and Rzeszów. The detailed microfacies analysis was carried out for the following, selected wells: Dębica 10k, Dębica 11, Gawrzyłowa 3, Góra Ropczycka 1k, Grobla E1, S1, W1, Nawsie 1, Pilzno 40, Rajbrot 1, Ropczyce 7, Zagorzyce 6, 7, and Zawada 8k (Fig. 1). The most complete well sections are presented in Fig. 3. On account of diversified frequency of the coring, some geophysical data (well logs) were examined, making it possible to determine approximately the extent of particular lithological complexes in individual wells. Part of the examination was made on cores drilled from wells, which were presented in earlier publications (wells: Nawsie 1, Pilzno 40, Zagorzyce 6, 7; *e.g.*, Zdanowski *et al.*, 2001). In addition, the characteristic of facies extent was also based on abundant published data (Morycowa & Moryc, 1976; Golonka, 1978; Zdanowski *et al.*, 2001; Król, 2004; Moryc, 1997, 2006; Gutowski *et al.*, 2007; Urbaniec *et al.*, 2010). Stratigraphical position of the studied wells was determined based on biostratigraphical studies of foraminifers examined in thin sections (Olszewska, 1999, 2004 and unpublished data).

STRATIGRAPHY

Oxfordian

The (predominantly Middle) Oxfordian sediments occur in the lower part of wells: Nawsie 1, Pilzno 40, and Zagorzyce 6. Moderately diversified microfossil assemblages are composed mostly of foraminifera and calcareous cysts of dinoflagellata (calcdinocysts). The age of the encountered assemblages is determined by the occurrence of foraminifera: *Eomarssonella paraconica* Levina, *Miliammina olgae* Bielecka, *Cornuspira eichbergensis* Kübler & Zwingli, *Ophthalmidium pseudocarinatum* Dain, *Spirillina andreae* Bielecka, *Spirillina tenuisssima* (Gümbel), *Paalzowella turbinella* (Gümbel), *Rumanolina seiboldi* (Lutze), *Ammobaculites irregularis* (Gümbel), *Ophthalmidium strumosum* (Gümbel), *Ophthalmidium oxfordianum* (Deecke), *Siphovalvulina variabilis* Septfontaine, and *Haghimashella arcuata* (Haeusler). Characteristic is the persistent, sometimes numerous, occurrence of representatives of *Globuligerina oxfordiana* Grigelis suggesting an age older than the Late Oxfordian of the majority of faunas. Foraminifera are accompanied by calcdinocysts: *Colomisphaera lapidosa* (Vogler), *Comittosphaera czestochowiensis* Řehanek, *Orthopithonella gustafsonii* Bolli, and *Crustocadosina semiradiata* (Wanner). The presence of the latter species, with the first occurrence connected with the Late Oxfordian, suggests that the investigated sections reach that age. This suggestion is supported by the presence of rare *Saccocoma*.

Kimmeridgian

The thickness of sediments assigned to the Kimmeridgian is relatively small. They were studied in wells: Nawsie 1, Pilzno 40 and Zagorzyce 6. Microfossil assemblages from the above mentioned depth intervals are rather poor. They are composed of rare representatives of foraminifera, calcdinocysts, ostracods, bryozoans, fragments of green algae *Globochaete alpina* Lombard, and planktic crinoids of the genus *Saccocoma* Agassiz.

The Kimmeridgian age of the assemblage is based on foraminifera: *Textularia depravatiformis* Bielecka & Kuznetsova, *Verneuilinoides kirillae* Dain, *Mesoendothyra izjumiana* Dain, *Rumanoloculina verbizhiensis* (Dulub) and calcdinocysts *Carpistomiosphaera borzai* (Nagy), *Colomisphaera pieniniensis* (Borza), and *Colomisphaera lapidosa* (Vogler). Among foraminifers, the presence of the long ranging species *Crescentiella morronensis* (Crescenti), *Glomospira variabilis* Kübler & Zwingli and *Mohlerina basiliensis* (Mohler) is noteworthy.

Tithonian

The Tithonian sediments were studied in wells: Nawsie 1, Pilzno 40, Zagorzyce 6 and Zagorzyce 7. A typical microfossil assemblage contained calpionellids, foraminifers, calcdinocysts and charophyta. The foraminiferal assemblage was composed, among others, of: *Buccicrenata primitiva* BouDagher-Fadel, *Charentia evoluta* (Gorbatchik), *Lituola ? baculiformis* Schlagintweit & Gawlick, *Verneuilinoides kirillae* Dain, *Melathrokerion spirialis* Gorbatchik, *Nautiloculina oolithica* Mohler, *Paleogaudryina magharaensis* Said & Bakarat, *Pseudocyclammina lituus* (Yokoyama), *Textularia depravatiformis* Bielecka & Kuznetsova, *Protopeneroplis striata* Weynschenk, and *Siphovalvulina variabilis* Septfontaine. Representatives of the family Involutininae: *Andersenolina alpina* (Leupold), *Andersenolina histeri* Neagu, *Neotrocholina molesta* (Gorbatchik) and *Ichnusella burlini* (Gorbatchik) were common. Among frequent miliolids, *Decussoloculina barbui* Neagu, *Decussoloculina mirceai* Neagu, *Scythiloculina confusa* Neagu and *Rumanoloculina mitchurini* (Dain) were recognised. Orthostratigraphic calpionellids were represented by the middle Tithonian *Praetintinopsella andrusovi* Borza. The rare calcdinocysts assemblage included *Comittosphaera pulla* (Borza), whose first occurrence marks the beginning of the Tithonian (Reháková, 2000). Charophyta are represented by sections of stems of the family *Clavatoracea*, known predominantly from the Jurassic/Cretaceous transition.

Lower Cretaceous

Sediments related to the Early Cretaceous (Beriassian–Hauterivian) were studied in wells: Nawsie 1, Pilzno 40, Ropczyce 7, Zagorzyce 6 and Zagorzyce 7.

Foraminiferal assemblages assigned to the Berriasian are composed of: *Protomarssonella kummi* (Zedler), *Protomarssonella hechti* (Dieni & Massari), *Paleotextularia crimica* Gorbtachik, *Siphovalvulina variabilis* Septfontaine, *Dobrogelina ovidi* Neagu, *Haplophragmoides joukovskyi* Charollais, Brönnimann & Zaninetti), *Nautiloculina bronnimanni* Arnaud-Vanneau & Peybernes, *Charentia evoluta* (Gorbatchik), *Protopeneroplis ultragranulata* (Gorbatchik), *Neotrocholina infragranulata* (Noth), and *Scythiloculina confusa*. The increase in the number of species and specimens was observed also in the calcdinocyst assemblage, containing, among others: *Cadosina fusca* Wanner, *Colomisphaera fortis* Řehanek, *Colomisphaera tenuis* (Nagy), *Crustocadosina semiradiata* (Wanner) and *Stomiosphaera moluccana* Wanner.

The Valanginian–Hauterivian foraminiferal assemblages commonly contained: *Verneuilinoides neocomiensis* (Majtliuk), *Praedorothia praehauteriviana* (Moullade), *Meandrospira favrei* (Charollais, Brönnimann & Zaninetti), *Mayncina bulgarica* Laugh, Peybernes & Rey, *Epistomina caracolla* (Roemer) and *Feurtilia frequens* Maync. Among rare calcdinocysts, stratigraphically significant *Carpistomiosphaera valanginiana* (Borza) and *Stomiosphaera wanneri* Borza were identified.

MICROFACIES DESCRIPTIONS AND FACIES INTERPRETATION

The results of microfacies analysis of cores presented in this study, together with geophysical data, allowed us to propose a general lithological outline of the Upper Jurassic and Lower Cretaceous strata in the Carpathian Foredeep basement. The thin-section analyses made it possible to distinguish thirteen basic microfacies types (MF-1–MF-13) occurring in different stratigraphical intervals (Figs 4–8). Considerable parts or some intervals of the analysed sections were subject to total dolomitization (Figs 9, 10), which sometimes makes recognition of the primary sedimentary textures impossible. Below, the most important microfacies types together with their stratigraphic positions are presented.

MF-1 Mudstones and bioclastic wackestones (Lower Oxfordian, Kimmeridgian)

The sediments developed as mudstones (Fig. 4A) and burrowed bioclastic wackestones (Fig. 4B) contain: spicules, planktonic foraminifera, polychaetes *Terebella lapilloides*, thin shells of brachiopods, filaments, calcified radiolaria, *Saccocoma*, and ostracods. Poorly structured thrombolites and leiolites (*cf.* Braga *et al.*, 1995) were rarely observed in wackestones, presumably stabilizing the sediments.

This microfacies was most often observed in marly limestones, mainly appearing in the Lower Oxfordian and Kimmeridgian strata (Fig. 3), where they frequently form thin-bedded marly-calcareous alternations. They represent the deep-water outer homoclinal ramp facies.

MF-2 Peloidal-tuberoid wackestones-floatstones (Oxfordian, Kimmeridgian, Lower Tithonian)

In this microfacies, abundant peloids and fauna represented by numerous tuberoids, fragments of calcified siliceous sponges, as well as shells of brachiopods and echinoid spines are observed (Fig. 4C). The sediment is sometimes stabilized by layered leiolites or poorly structured thrombolites. Spicules of sponges and other small bioclasts are also ubiquitous. In the presented wells, this microfacies type contains numerous oncoids. Relatively little, elliptical oncoid forms (<0.2 cm), with poorly legible internal structure, are most common (*cf.* Dahanayake, 1977). Moreover, the sediments consist of irregular oncoids, which are encrusted by serpulids (Fig. 4D) and numerous *Crescentiella morronensis* (Fig. 4C).

This microfacies type appears in the examined wells in the Oxfordian, Kimmeridgian and Lower Tithonian bedded limestones. Like MF-1, this microfacies represents the outer homoclinal ramp facies.

MF-3 Thrombolitic-sponge and microbial-peloidal boundstones (Upper Oxfordian, Upper Kimmeridgian, Lower Tithonian)

Sediments representing the microbial-sponge microfacies type are characterized, among others, by a rigid framework, documented with numerous geopetal filled growth cavities and the presence of microborings (Fig. 4E, F; *cf.* Pratt, 1982; Matyszkiewicz, 1997). The basic components are layered thrombolites (*cf.* Schmid, 1996), which developed on the surfaces of dish-shaped calcified siliceous sponges and in intraskeletal spaces. Peloidal stromatolites were observed considerably more rarely, usually on the surfaces of calcified siliceous sponges (Fig. 4F). Besides thrombolitic-sponge boundstones, laminated peloidal bindstones are commonly observed (Fig. 5A), which consist of peloids and microbial laminae typical for the carbonate buildups of the so-called microbial-peloid sand-mud mounds (Koch *et al.*, 1994; Leinfelder *et al.*, 1994).

Boundstones are the dominant microfacies in the strongly lithified, massive limestones representing the so-called microbial-sponge (Fig. 4E, 5C) and microbial facies (Fig. 5B), forming bioherms, reef complexes or thick-layered biostrome limestones known from many settings in Europe (*e.g.*, Leinfelder *et al.*, 1994, 1996; Matyszkiewicz, 1997). This microfacies type was most often observed in massive limestones of the Upper Oxfordian, more rarely in the Kimmeridgian marly complex and in the intervals representing the Lower Tithonian (Fig. 3). In the Oxfordian and Kimmeridgian, the thrombolitic-sponge massive limestone facies are usually limited laterally and in the vertical section by the facies of pelitic, detrital, or marly limestones (MF-1, 2). In the Tithonian, thrombolitic-sponge facies passes upwards into the facies bearing abundant corals and calcareous sponges. The microbial-sponge reef facies represents the outer-mid homoclinal ramp environments.

MF-4 Microbial-Crescentiella boundstones (Upper Oxfordian, Lower Tithonian)

This microfacies contains abundant detrital material bound by microbialites with ubiquitous fragments of *Crescentiella morronensis* (former *Tubiphytes morronensis* – Senowbari-Daryan *et al.*, 2008; Fig. 5D). The *Crescentiella morronensis* incorporated fine bioclasts and peloids. The most often observed grain components are small intraclasts, peloids, fragments of brachiopod shells, echinoderms, siliceous sponges and corals. The interskeletal spaces are commonly filled with the sparite cement. Massive accumulations of *Crescentiella morronensis* form sometimes the so-called microframework documented by geopetal filled growth cavities with internal sediment (*cf.* Flügel, 2004; Krajewski, 2008; Schlagintweit & Gawlick, 2008).

This microfacies type limestones represents the so-called *Tubiphytes* reefs (*e.g.*, Matyszkiewicz, 1997; Krajewski, 2000), typical for the upper parts of large complexes of the carbonate buildups, which are mainly represented by microbial-sponge reef facies occurring in mid ramp environments. In the study area, such buildups are characteristic for the Upper Oxfordian and Lower Tithonian.

MF-5 Coral-sponge-microbial boundstones and floatstones (Tithonian)

The coral-sponge floatstones are mainly formed by platy corals of diversified sizes, as well as by sponges and bioclasts. Amongst the corals, a relatively poor association has been recognised, represented mainly by Montivaltiidae, Microsolenidae and Stylinidae (*cf.* Morycowa & Moryc, 1976). In many cases, determination of the corals was im-

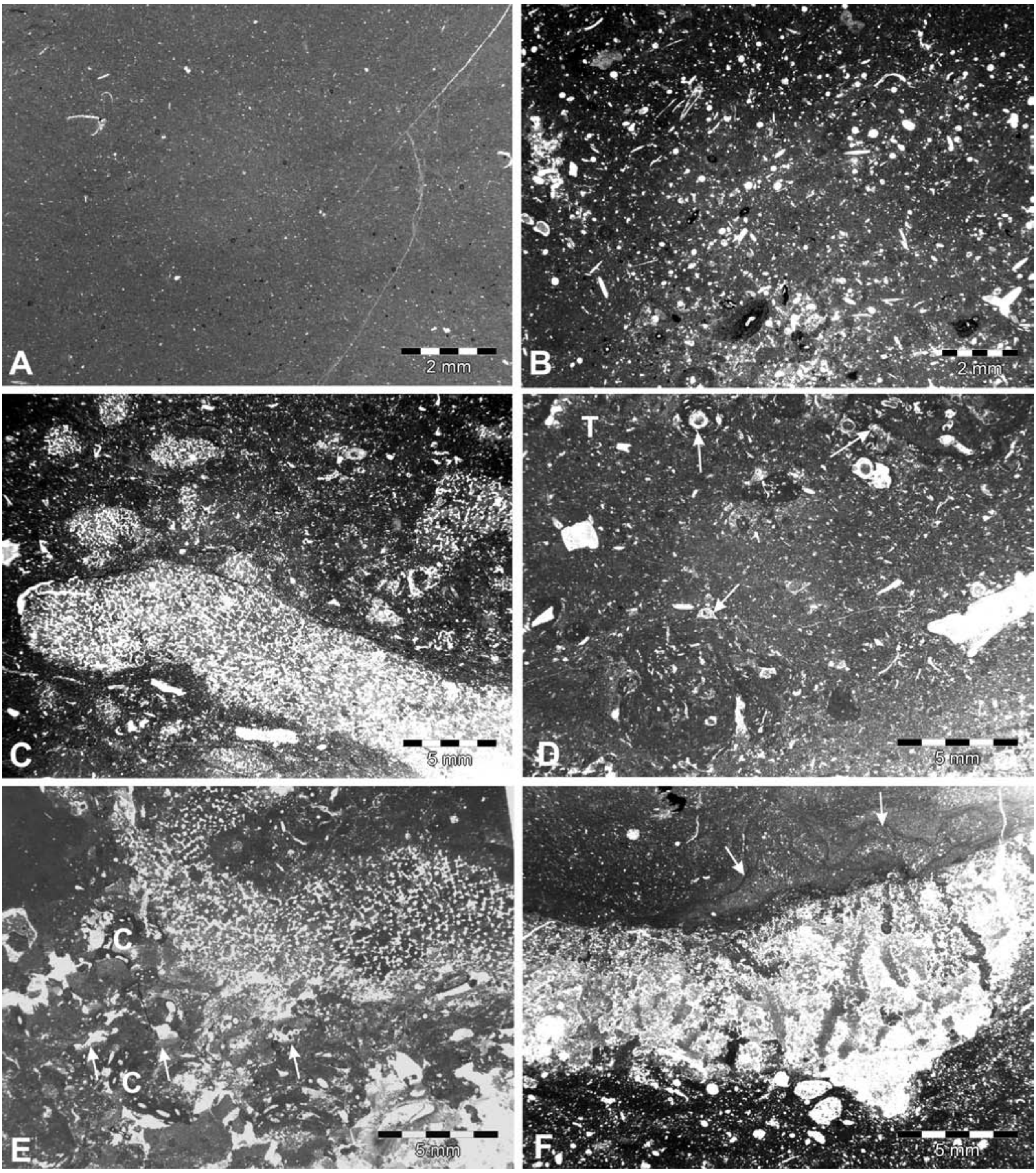


Fig. 4. Microfacies of the Oxfordian to Lower Tithonian deposits from the Kraków–Rzeszów Carpathian Foredeep basement. **A** – mudstone with rare thin shells MF-1. This microfacies is most often observed in the deep-water marl/marly limestone alternations. Grobla E1 well, interval 1,013–1,022 m; **B** – wackestone with micritized sponge; in micritic matrix numerous sponge spicules and foraminifers including *Globuligerina oxfordiana* occur; the lower part bears examples of *Crescentiella morronensis* and *Terebella lapilloides*. Grobla W1 well, interval 558–563 m MF-1; **C** – sponge floatstone with numerous tuberoids in the upper part. Góra Ropczycka 1k well, interval 3,149–3,158 m MF-2; **D** – bioclastic-oncoid wackestone bearing irregular oncoids with serpulids (arrows) and *Crescentiella morronensis*; in the upper left part poorly structured thrombolite (T) occurs. Grobla E1 well, interval 1,013–1,022 m MF-2; **E** – microbial-sponge boundstone with numerous borings and growth cavities (arrows) in the lower part, documenting the presence of the rigid framework. Most of them have geopetal infillings. In the lower part – *Crescentiella* (*C*), in the upper part – pure clotted thrombolite. Grobla W 1 well, interval 552–558 m MF-3; **F** – microbial-sponge boundstone with calcified siliceous sponge overgrown with layered thrombolite (arrowed). Góra Ropczycka 1k well, interval 3,149–3,158 m MF-3

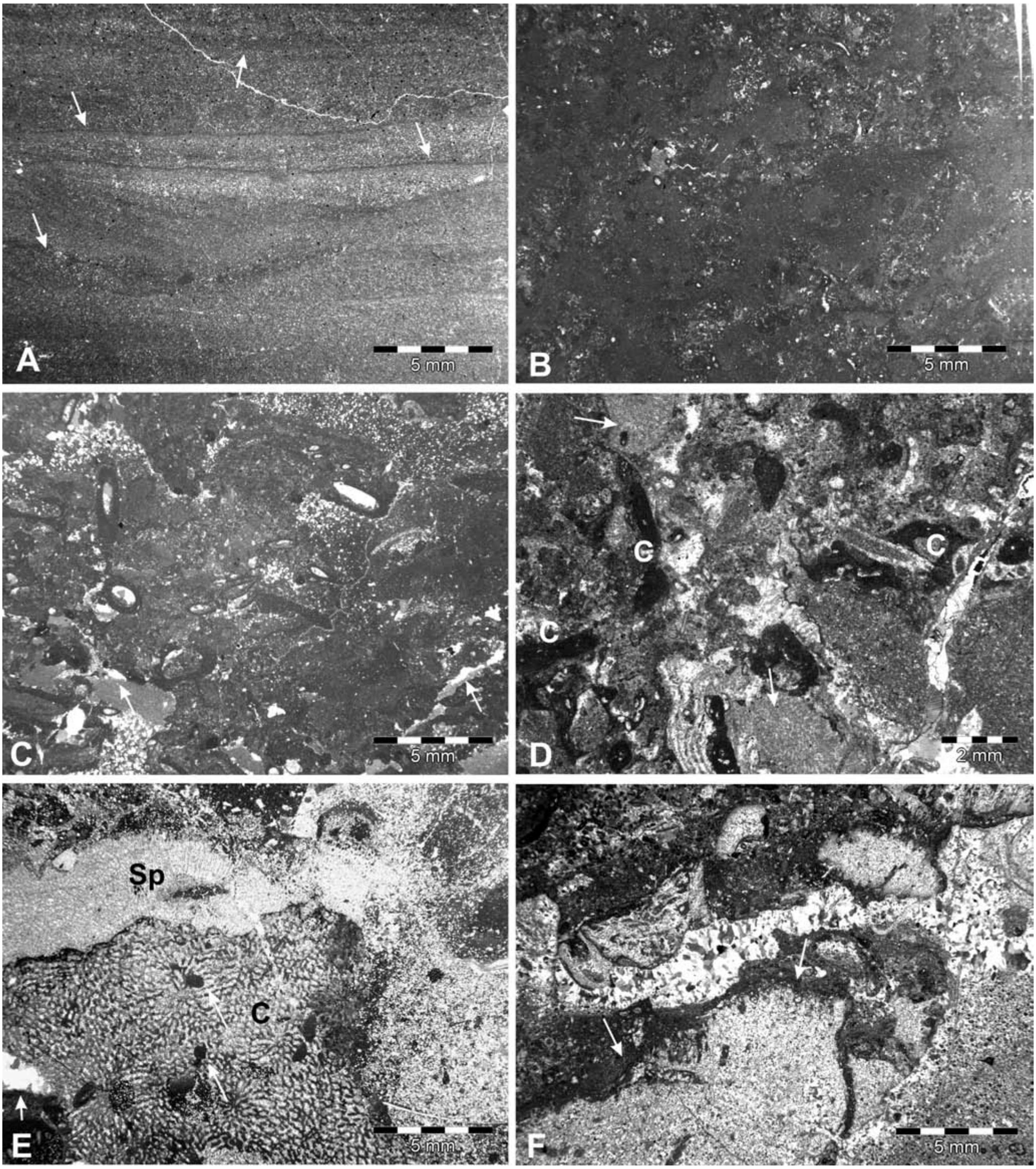


Fig. 5. Microfacies of the Oxfordian to Lower Tithonian deposits from the Kraków–Rzeszów Carpathian Foredeep basement. **A** – bindstone, peloidal deposits in mud mounds are trapped by microbial laminae (arrows). Grobla W1 well, interval 558–563 m MF-3; **B** – poorly structured thrombolite boundstone. Pilzno 40 well, interval 2,860–2,879 m MF-3; **C** – partly dolomitized thrombolite boundstone with numerous *Terebella lapilloides* and geopetal infilled growth cavities (arrows). Grobla S 1 well, interval 702–707 m MF-3; **D** – microbial-*Crescentiella* (C) boundstone representing micro-framework, *Crescentiella* (C) and microbial crusts trapping fine-bioclastic and peloidal deposits, in the lower and upper part micritized relics of macrofauna (arrowed). Nawsie 1 well, interval 3,335–3,340 m MF-4; **E** – coral (C), sponge (Sp) boundstone with numerous borings (arrows), in the lower left corner boring is geopetal filled with internal sediment. Zawada 8k well, interval 2,686–2,695 m MF-5; **F** – coral-microbial boundstone with thin boring sponge *Entobia* (arrowed); in the upper part thrombolites, in the right lower part fine peloid sediments. Pilzno 40 well, interval 2,409–2,412 m MF-5

possible because of total recrystallization of their skeletons, which obscured the internal structures. Moreover, considerable part of the sediments assigned to this microfacies type was subject to dolomitization, dedolomitization, and recrystallization processes, so the facies extent was assessed on the basis of geophysical logs. The corals are commonly accompanied by calcareous sponges. Intraskeletal spaces are generally filled with grains, particularly bioclasts or lime mud.

The coral-sponge-microbial boundstones are mainly created by recrystallized corals and calcareous sponges and thrombolites (Fig. 5E, F). Sediment bound by microbialites was subject to early lithification forming a rigid framework, documented by the presence of growth cavities and borings. In most cases, the recrystallization hinders the identification of the fauna. Like in the case of the coral-sponge floatstone facies, Microsolenidae are predominating. Sometimes, on surfaces of the corals and sponges, thin microorganisms are observed representing probably the boring sponges (ichnogenus *Entobia* Bronn; Fig. 5F; *cf.* Schlagintweit, 2010). It is possible that many of these forms, frequently described from Mesozoic sediments of the Carpathian Foredeep basement, were formerly incorrectly identified as *Lithocodium aggregatum*. It should be noted, however, that in the study area these forms appear together with corals and sponges considerably more rarely than in other areas of appearance of the coral facies (*e.g.*, Helm & Schülke, 1998; Dupraz & Strasser, 1999; Roniewicz, 2008). In the upper part of the interval bearing abundant corals, both in the bedded and massive limestones, beside corals and sponges the grains include numerous ooids, gastropods, echinoids, bivalves, *Crescentiella morronensis*, and algae.

In the studied wells, this microfacies is typical for the Tithonian (Fig. 3). The inspection of the drill cores and the microfacies analysis indicate that coral-microbial-sponge boundstones formed thin massive limestones representing biostromes or relatively small patch-reefs facies.

Poor taxonomical diversification of corals, as well as scarce presence of microorganisms typical for shallow water coral reef facies point to deposition of this sediment in an environment shallower than that of the microbial-sponge facies, probably within the mid-inner homoclinal ramp.

MF-6 Intraclastic-bioclastic grainstones-rudstones (Upper Oxfordian, Tithonian)

This microfacies is characterized by abundant intraclasts, bioclasts, including tuberoids, brachiopods, echinoderms, bivalves, fragments of calcareous sponges, corals and *Crescentiella morronensis* (Fig. 6C) and also, in the Upper Tithonian–Lower Berriasian, by ooids and cortoids (Fig. 6B, D). Poor sorting of grains predominates in most cases. Locally, the grain components are stabilized by leiolites.

Intraclastic-bioclastic grainstones were mainly observed in the intervals with massive facies, representing reef complexes, biostromes and patch-reefs occurring mainly in the Upper Oxfordian (M-3) and Tithonian (M-5). This microfacies corresponds to peri-reefal deposits of microbial-sponge, microbial-*Crescentiella* or microbial-coral-sponge reefs facies typical for the mid-homoclinal ramp environments.

MF-7 Peloid wackestones-floatstones, microbial bindstones and mudstones (Berriasian)

This type is represented by several microfacies varieties. They are built of numerous small laminae of mudstones, peloidal stromatolites, micrite stromatolites (*cf.* Schmid, 1996), and peloidal wackestones with abundant bivalves (Fig. 7A) and floatstones with gastropods, (Fig. 7B), algae *Clypeina* sp., *Salpingoporella* sp., *Actinoporella* sp. and foraminifera. Ubiquitous are crab coprolites represented by *Favreina* sp. (Fig. 6E). Small caverns, representing fenestral structures and rhizolithes, could be commonly observed in microbial bindstones and mudstones (Fig. 6F).

This microfacies could be observed exclusively in the Lower Berriasian. It represents shallow subtidal and intertidal facies of the inner homoclinal ramp.

MF-8 Porostromate cyanobacteria-algal-peloidal rudstones-bindstones (Berriasian)

Basic components of the microfacies are skeletal porostromate filamentous cyanobacteria represented mainly by *Cayeuxia*, foraminifera, algae, gastropods, aggregate grains and peloids, which are in most cases bound by microbialites (Fig. 7C–E). There occur numerous small fenestral cavities and irregular voids, filled by several generations of cements represented by blocky, isopachous and drusy cements, documenting the late diagenetic conditions, as well as meniscus cements pointing to subaerial uplift during the early diagenesis. Fenestral structures and caverns filled with crystal silt are also common.

This Berriasian microfacies type represents the low-energy inner homoclinal ramp facies within a restricted environment. In the studied wells, this type of microfacies occurs in similar intervals as MF-7 and represents a shallowing-upward sequence.

MF-9 Charophyta wackestones-microbial bindstones (Berriasian)

This microfacies type is composed of wackestones with bioclasts represented by fragments of *Clavator* sp. (Charophyta), thin-shell bivalves, peloids and gastropods. Locally a microbial crust can be observed in this sediment (Fig. 7F).

The above described microfacies type occurs most often in the same intervals as MF-8, representing Berriasian deposit. Monotonous character of the sediment, the presence of Charophyta as well as lack of typical marine fauna point to the brackish lagoon or lacustrine facies.

MF-10 Ooid-bioclastic grainstones (Upper Tithonian and Valanginian)

Predominating ooids, cortoids, bivalves, gastropods and echinoderms are observed in this facies (Fig. 8C). In most cases, the interval with ooids begins with characteristic grainstones, mostly built of bivalves and oysters (Fig. 8B; Zdanowski *et al.*, 2001). The ooidal microfacies, rare in the studied wells, form irregular horizons in the Upper Tithonian strata. Only at the top of the Lower Cretaceous sequence, represented by the Valanginian sediments, ooidal complexes of higher thicknesses were observed (Fig. 3). Moreover, this microfacies contained numerous vadoids and caverns filled with vadose crystal silt. In the studied

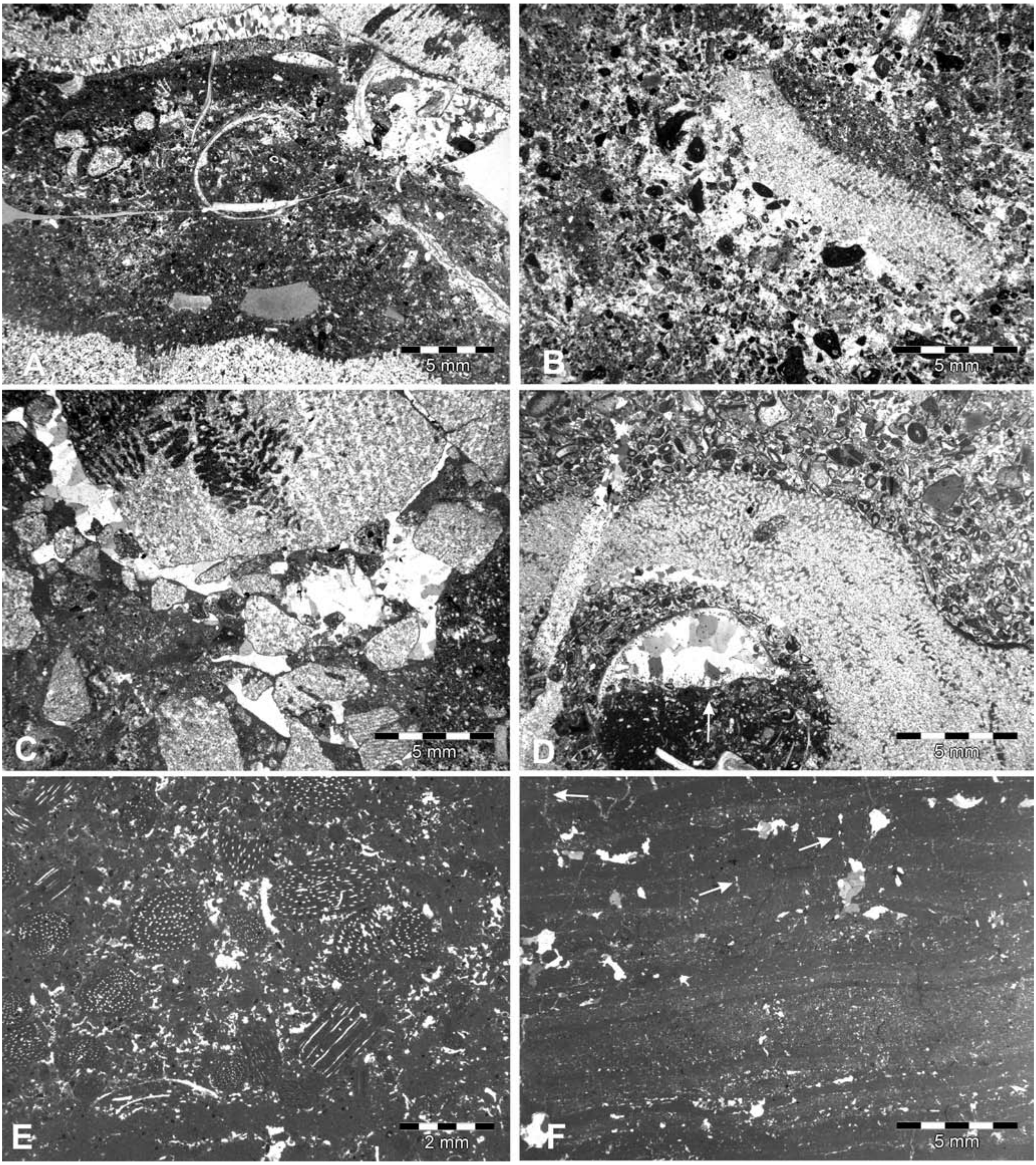


Fig. 6. Microfacies of the Tithonian to Lower Berriasian deposits from the Kraków–Rzeszów Carpathian Foredeep basement. **A** – platy coral-bioclastic floatstone; the interskeletal spaces are filled by fine peloidal and bioclastic detrical sediment. Pilzno 40 well, interval 2,409–2,412 m MF-5; **B** – coral-bioclastic grainstone-packstone, among grains numerous intraclasts occur, *Crescentiella morronensis* and bioclasts are observed as well. Nawsie 1 well, interval 3,365–3,371 m MF-6; **C** – coral floatstone-rudstone with numerous clasts of recrystalized corals. Nawsie 1 well, interval 3,335–3,340 m MF-6; **D** – ooid-bioclastic grainstone, in the central part fragment of partly recrystallized coral with borings, in the lower part geopetal (arrow) filled by small bioclasts and blocky cement, in the upper part numerous ooids, echinoderms and small bioclasts. Ropczyce 7 well, interval 2,700–2,708 m MF-6; **E** – lagoonal coprolite wackestone with *Favreina* sp. Zagorzyce 6 well, interval 2,824–2,829 m MF-7; **F** – microbial bindstone with fenestral structures and rhizolithes or small vertical desiccation cracks (arrows) indicating supratidal part of the peritidal cycle. Zagorzyce 7 well, interval 2,826–2,844 m MF-7

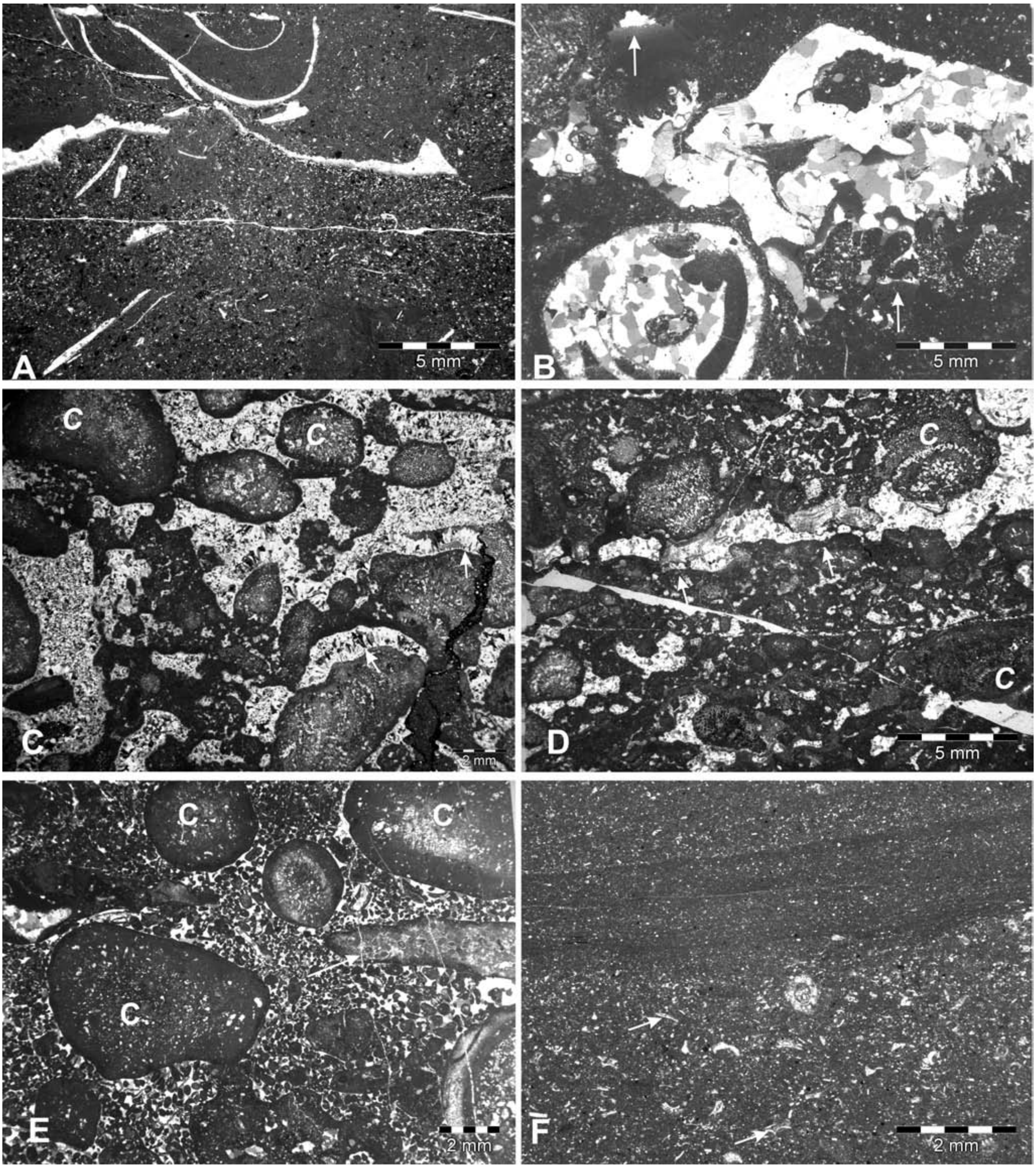


Fig. 7. Microfacies of the Berriasian deposits from the Kraków–Rzeszów Carpathian Foredeep basement. **A** – burrowed wackestone with bivalve shells and foraminifers and geopetal infilled small caverns. Zagorzyce 6 well, interval 2,829–2,838 m MF-7; **B** – floatstone-bindstone with recrystallized gastropod shells and geopetal infilled borings (arrowed). Zagorzyce 6 well, interval 3,040–3,042 m MF-7; **C** – rudstone with calcified "porostromate" cyanobacteria (C) and fibrous vadose cement (arrows) and microcrystalline (micritic), microbially induced precipitation cement. Pilzno 40 well, interval 2,315–2,317 m MF-8; **D** – rudstone with "porostromate" cyanobacteria (C). Pilzno 40 well, interval 2,315–2,317 m MF-8; **E** – coated bioclastic-peloid packstone-rudstone, nuclei of the oncoids consist of cyanobacteria (C) and ooids (arrowed). Zagorzyce 7 well, interval 2,826–2,844 m MF-8; **F** – bioclastic wackestone with fragments of charophyte, thin-shelled ostracods (arrows), in the upper part microbial crusts. Zagorzyce 6 well, interval 2,829–2,838 m MF-9

sediments, vadoids are usually similar to ooids, but have considerably bigger dimensions (usually about 1–2 mm). They are characterized by irregularity with characteristic very densely spaced lamination around the nucleus (Fig. 8A).

The occurrence of this microfacies type is mostly limited to the Valanginian. The ooidal deposits represent high-energy inner homoclinal ramp shoals.

MF-11 Gastropod floatstones to rudstones (Valanginian)

The sediment is composed of well-preserved shells of gastropods which, in individual wells, are observed at different levels. Besides gastropods, the grain components consist of numerous micritized ooids, cortoids, bivalves and foraminifers (Fig. 8D). Geopetal fillings inside gastropod shells are observed as well.

Grainstones with gastropods and ooids form in similar environments of the inner platform high-energy shoals like ooidal facies (MF-10), most probably in their back areas. In the studied sections, a gastropod coquina was observed also in Berriasian deposits within the microbial mats (MF-7) representing the tidal flat facies (Zdanowski *et al.*, 2001).

MF-12 Bioclastic-bryozoan grainstones-packstones (Valanginian)

In the highest parts of some sections (Ropczyce 1 and Zagorzyce 7 wells), within the ooidal facies, grainstones built mainly of bioclasts of crinoids and bryozoans were encountered, while ooids were observed more rarely (Fig. 8E). Quartz grains and peloids occur in these sediments as well.

Bioclastic-bryozoan grainstones represent the youngest deposits of the Lower Cretaceous in the studied area. They rest directly upon ooidal facies and represent the inner platform open-marine facies in an environment of moderate energy, probably connected with the sea level rise in the Valanginian.

MF-13 Lithoclastic rudstones-floatstones (Berriasian, Valanginian)

In different intervals of the Berriasian and Valanginian, particularly in Zagorzyce 7 well (Fig. 3), characteristic, partially dolomitized breccias were observed, developed in the form of residual lithoclastic rudstones-floatstones (Fig. 8F). The basic components are several centimetres large sharp-edged angular lithoclasts.

Dolomitization

At least four generations of dolomites appear in the studied material: (i) early diagenetic matrix dolomite type A, (ii) early diagenetic matrix dolomite type B, (iii) early burial matrix dolomite type C, and (iv) late burial saddle dolomite.

The matrix dolomite type A (Figs 9A–F, 10A–D) appears in boundstones as well as in grainstones, packstones and wackestones in the form of isolated crystals, irregularly distributed in the micritic matrix or grain components. Abundant, isolated dolomite crystals form together a porphyrotopic fabric (Fig. 9A). This type of dolomite was also observed in zones in between leiolites, accentuating their lamination (Fig. 9B), in micrite filling intergranular spaces in the fenestral grainstones-packstones (Figs 9C, 10B), and in fillings of borings in coralites (Fig. 9D). The matrix dolomite type A is developed in the form of euhedral crystals, from below 0.05 mm up to about 1 mm in diameter. Locally, crystal zoning is visible, with the crystal core and outside parts without inclusions. Concentrations of the matrix dolomite type A appear sometimes in a dense mosaic of the matrix dolomite type B crystals (Fig. 10C). The dolomitization in the form of the matrix dolomite type A is selective and at the preliminary stage it did not touch some grain components of type *Crescentiella morronensis*, fragments of echinoderms, shells of bivalves, and calcified siliceous sponge spicules. Sometimes the total matrix is dolomitized, which stresses the granular character of the rock.

The matrix dolomite type A is connected with the earliest stage of dolomitization, probably at the end of the early diagenesis. Selective replacement of the matrix at simultaneous omission of the grain elements points out that, at the beginning, the dolomitization process embraced only incompletely lithified parts of the sediment. The probable source of Mg^{2+} ions could have been pore waters, squeezed out from compacted bedded facies, which migrated towards the sponge-coral facies that were lithified earlier (*cf.* a model of Reinhold, 1998). Laboratory investigations on mechanical compaction of sediments simulating with their grain composition the Upper Jurassic, fine-detrital, bedded limestones from the Kraków area indicate that they were subject to compaction not lower than about 28% (Kochman, 2010), which is similar to the results of Ricken (1986). According to Reinhold (1998), flows of pore waters in deposited carbonate complexes could have taken place even within a distance of about 70 km.

The matrix dolomite type B, the most common variety of dolomite, forms a dense mosaic of subhedral to anhedral dolomite crystals (Fig. 10B, E, F). Crystals of the dolomite type B create xenotopic texture. Recrystallization rims are locally developed on some grains (Fig. 10F). Spaces filled with the matrix dolomite type B are larger than the thin sections analysed. Oval voids, several millimetres in diameter, which could be observed in them, presumably formed due to dissolution of bioclasts or other skeletal grains. They correspond to the moldic porosity.

The presence of recrystallization rims may suggest that this dolomite type formed due to recrystallization of the matrix dolomite type A. Stylolites penetrating into the matrix of the dolomite type B indicate that the dolomitization process took place before the chemical compaction stage.

The matrix dolomite type C appears along stratiform stylolites in zones about several millimetres thick. The dolomite occurs in the form of subhedral or anhedral crystals replacing matrix along the stratiform stylolites (Fig. 10A, B).

Explicit relationship of the matrix dolomite type C with the stratiform stylolites points out that the dolomitization occurred in the shallow burial conditions. The solutions dolomitizing the limestones penetrated along the stylolites (*cf.* Braithwaite, 1989; Matyszkiewicz, 1994). The process of dolomitization was preceded by the development of pressure dissolution, which started at a depth of about 250–300 metres (Schlanger & Douglas, 1974; Garrison, 1981), but it

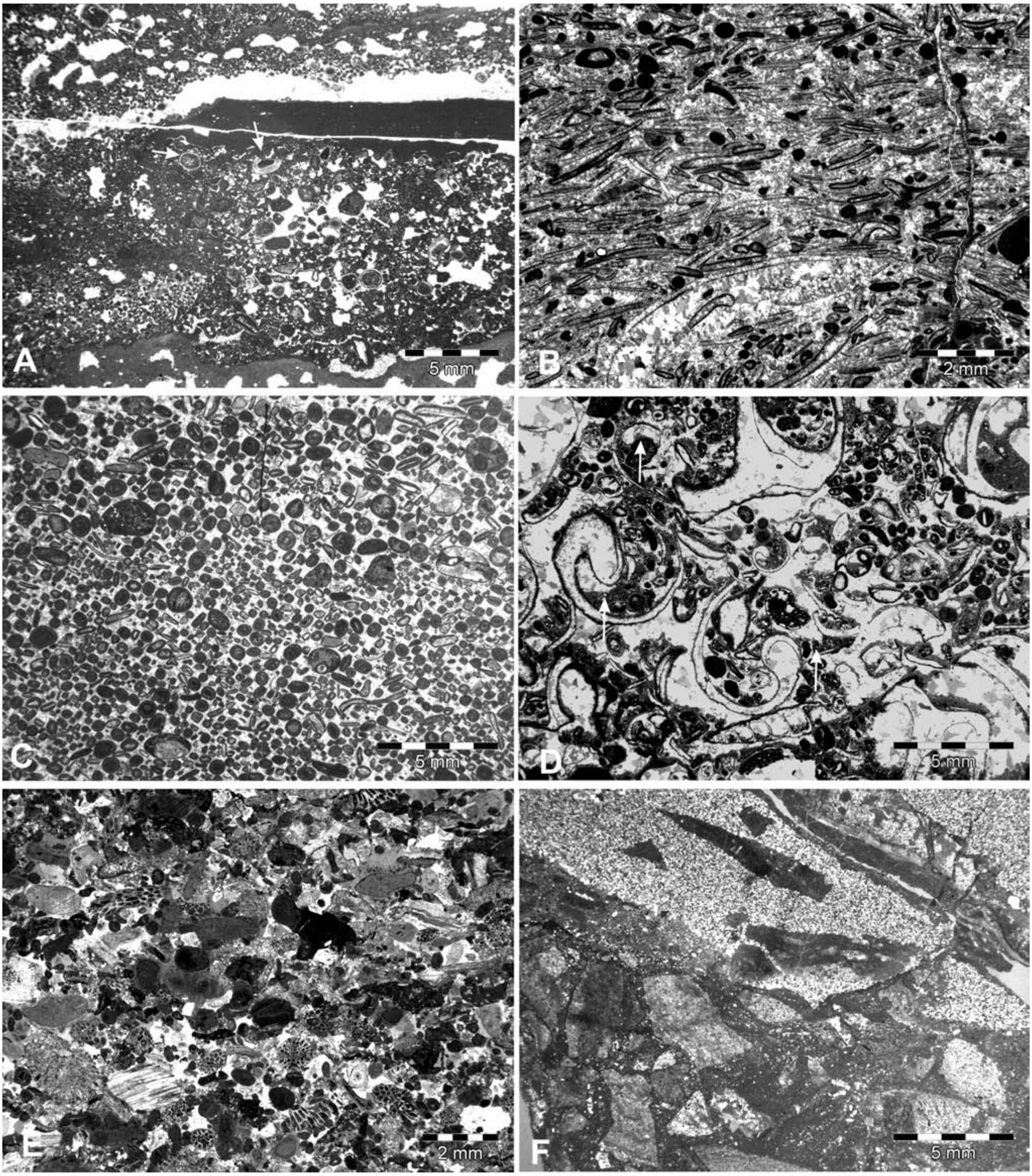


Fig. 8. Microfacies of the Upper Berriasian–Valanginian deposits from the Kraków–Rzeszów Carpathian Foredeep basement. **A** – karstified grainstone with numerous ooids, vadoids (arrowed), in the central part cavern geopetal filled by vadose internal sediment. Pilzno 40 well, interval 2,315–2,317 m MF-10; **B** – bivalve grainstone with numerous micritized ooids. Zagorzyce 6 well, interval 2,810–2,819 m MF-10; **C** – high-energy shoals ooid-cortoid grainstone. Nawsie 1 well, interval 3,108–3,111 m MF-10; **D** – oolitic-gastropod-bivalve grainstone-rudstone, numerous shells and caverns are geopetal filled with internal sediments and grains (arrows); the grains include micritized ooids, bivalves and foraminifers. Zagorzyce 6 well, interval 2,810–2,819 m MF-11; **E** – crinoid-bryozoan packstone. Ropczyce 7 well, interval 2,183–2,186 m MF-12; **F** – intraclastic breccia; Pilzno 40 well, interval 2,409-2,412 m MF-13

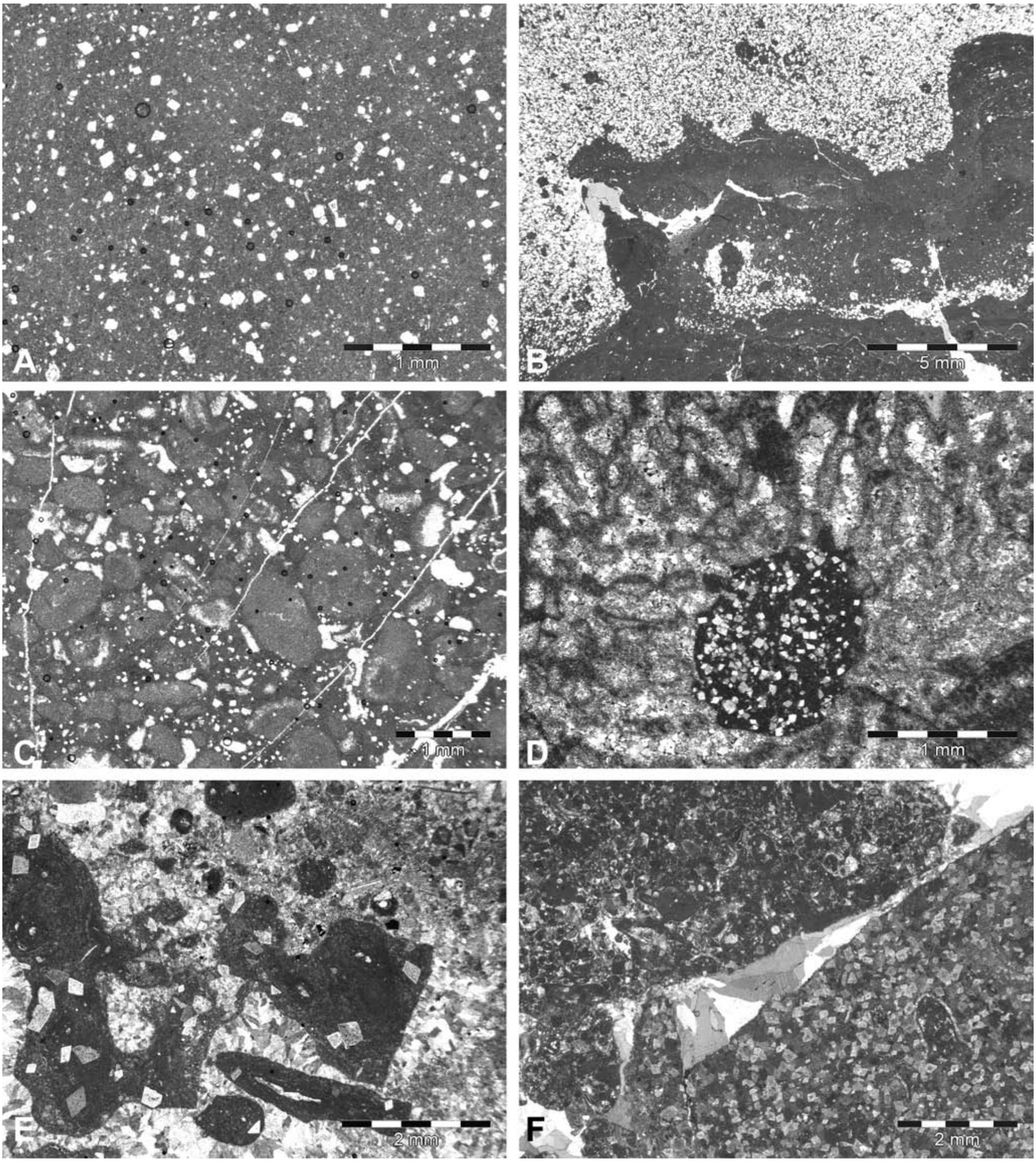


Fig. 9. Microphotographs of dolomitization processes from the Kraków–Rzeszów Carpathian Foredeep basement. **A** – mudstone-wackestone with small, isolated crystals of the matrix dolomite type A. Zagorzyce 7 well, interval 2,826–2,844 m; **B** – microbial boundstone. Microbialites are represented by poorly structured thrombolite and layered leiolites. Poorly structured thrombolite (below) divided from layered leiolite, overgrowing it, by a stratiform stylolite. In the layered leiolite, abundant crystals of the matrix dolomite type A developed on presumable contact of the layered leiolite laminae are visible. At the top, numerous crystals of the dolomite type A almost wholly replace micritic matrix. Dębica 10k well, interval 3,071–3,079 m; **C** – fenestral grainstone-packstone built of numerous oval grains cemented with micrite. In places, in which micrite does not wholly fill intergranular spaces, fenestral structures appear being partly filled with sparite carbonate cement. Isolated crystals of the matrix dolomite type A occur in micrite only, between grains. Zagorzyce 7 well, interval 2,844–2,862 m; **D** – boring in coralite filled with micrite with abundant crystals of the matrix dolomite type A. Zawada 8k well, interval 2,686–2,695 m; **E** – boundstone with abundant *Crescentiella morronensis*. Most of the micritic matrix is replaced by several generations of carbonate cements. Single crystals of the matrix dolomite type A present only in *Crescentiella morronensis*. Nawsie 1 well, interval 3,410–3,419 m; **F** – packstone with fissure filled with late diagenetic carbonate cement. Very abundant zoned crystals of the matrix dolomite type A appear below the fissure only; above the fissure only single, isolated dolomite crystals occur. Nawsie 1 well, interval 3,281–3,285 m

substantially affected the carbonate sediments at the depths exceeding 300 m (Czerniakowski *et al.*, 1984).

The saddle dolomite (Fig. 10B), observed in cracks filled with blocky calcite and poikilotopic cements and considered as late-diagenetic, sometimes co-occurs with microquartz. The saddle dolomite is developed in the form of crystals up to about 0.5 mm in diameter, with slightly arched surfaces, arranged stepwise and with scarce inclusions. Sometimes, they grow syntaxially on crystals of the matrix dolomite type B.

The saddle dolomite is interpreted as a product of precipitation from hydrothermal, hypersaline solutions (Machel, 1987; Soussi & M'Rabet, 1991; Reinhold, 1998).

DEVELOPMENT OF THE UPPER JURASSIC–LOWER CRETACEOUS DEPOSITS FROM THE SOUTHERN PART OF THE CARPATHIAN FOREDEEP BASEMENT

In the basement of the Carpathian Foredeep, the Middle and Upper Jurassic deposits, together with those of the Berriasian and Valanginian, form one complex of carbonate sediments separated from the under- and overlying ones by discordances. Allowing for certain simplification, this complex can be subdivided into three main sequences: (i) Callovian–Oxfordian, (ii) Kimmeridgian and (iii) Tithonian–Valanginian (Fig. 11; *cf.* Kutek, 1994; Gutowski *et al.*, 2005; Krajewski *et al.*, 2011). On account of the subsequent erosion and fault tectonics in particular areas of the Carpathian Foredeep, the thickness of the Upper Jurassic and Lower Cretaceous sediments is relatively highly diversified. In the western part of the area, exclusively the Oxfordian and partly Kimmeridgian sediments could be encountered. To the east, however, a complete section of the Upper Jurassic sediments appears, including the Tithonian (Fig. 3). The Upper Jurassic sediments pass into the Lower Cretaceous ones in the area of Dębica and Pilzno, and are represented by the Berriasian and Valanginian (*e.g.*, Fig. 3).

Oxfordian

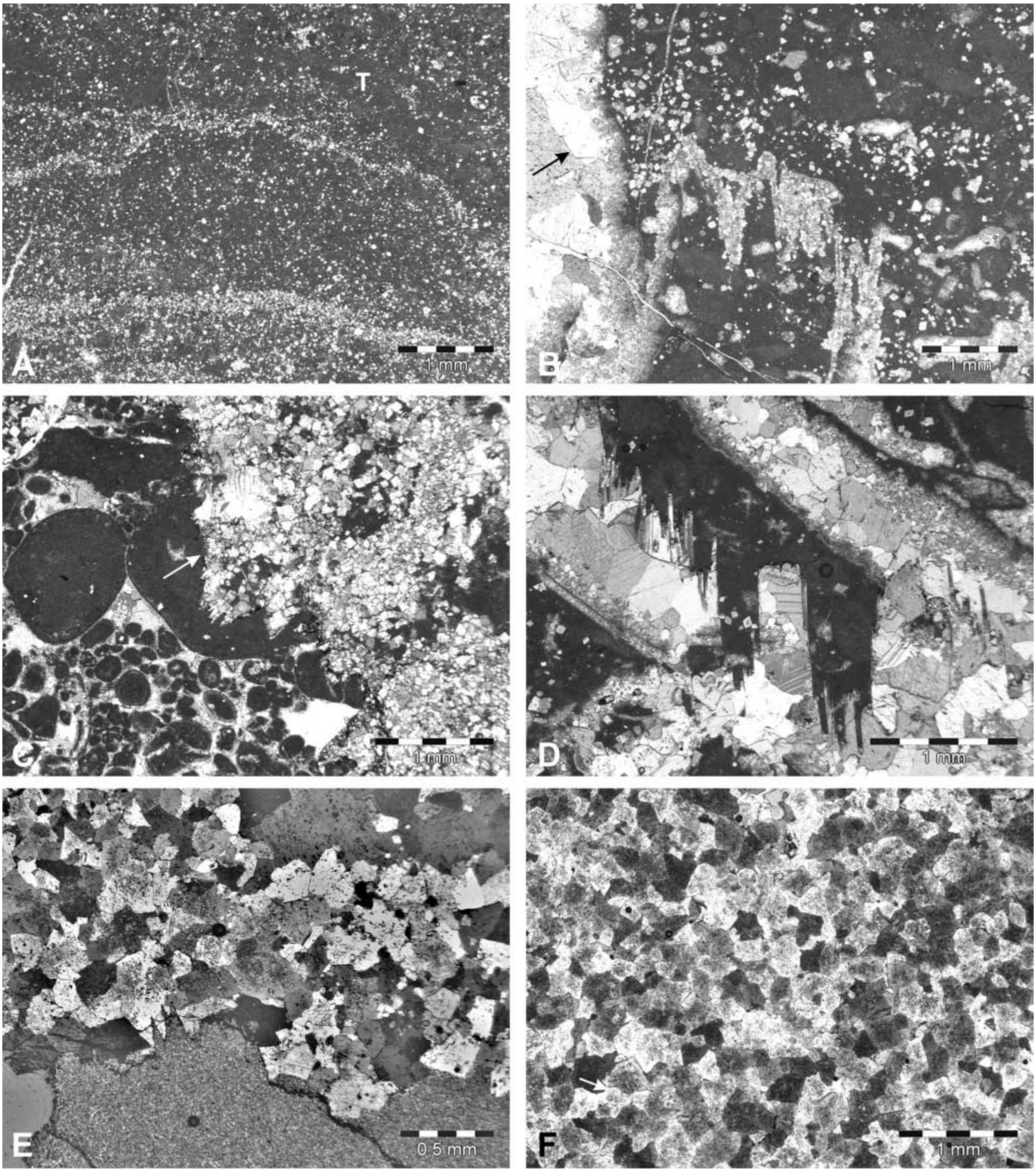
The literature dedicated to the Oxfordian sediments in the Polish part of the Carpathian Foredeep basement is extensive (*e.g.*, Morycowa & Moryc, 1976; Golonka, 1978; Matyszkiewicz, 1989; Olszewska, 1999; Maksym *et al.*, 2001; Król, 2004; Moryc, 2006; Gutowski *et al.*, 2007; Matyja, 2009). In the area in question, Oxfordian sediments rest on the Callovian ones, or directly upon various complexes of the Triassic and Palaeozoic rocks (Figs 3, 11; Moryc, 2006). These sediments are assessed to reach 800 m in thickness, based on the assumption that the Oxfordian constituted the fundamental part of the Upper Jurassic sediments in the study area (*e.g.*, Maksym *et al.*, 2001; Król, 2004; Gutowski *et al.*, 2007). However, recent data point out that the thickness of the Oxfordian sediments is considerably lower, amounting to about 200 m, so the Oxfordian complex would be the least thick complex of the Upper Jurassic in the Polish part of the Carpathian Foredeep basement (Figs 3, 11; Matyja & Barski, 2007).

In the investigated wells, considerable differences in thicknesses of the Oxfordian could be observed: from 100 m up to 250 m (Fig. 3). This phenomenon is mostly related to the intensive development of reef complexes, and partly also to differential compaction of the massive and bedded facies (Matyszkiewicz, 1999; Kochman, 2010). Between Kraków area, where the Oxfordian sediments of the Carpathian Foredeep are outcropping, and the eastern part of the study area, their thicknesses may differ by about 150 m (Fig. 3). Variable thickness values correspond to the facies diversity of sediments. The data from wells and their analogues from the Kraków Upland allow us to state that the maximal sediment thicknesses could be observed in cases of domination of the massive facies, developed as the microbial-sponge and microbial reef complexes (Figs 3, 11). Considerably lower thickness figures were noted in those areas, in which pelitic bedded facies and marly complexes were more common. In the study area, like in the adjacent ones, the intensive development of the massive facies was probably controlled by the diversified morphology of the Palaeozoic basement and the synsedimentary tectonics (*e.g.*,

Fig. 10. Microphotographs of dolomitization processes from the Kraków–Rzeszów Carpathian Foredeep basement. **A** – microbial boundstone with layered thrombolite (T – at the top); below wackestone-packstone. In microbial boundstone, isolated crystals of the matrix dolomite type A are visible. In wackestone-packstone, along two horizontally stretching stratiform stylolites, intensive dolomitization in the form of the matrix dolomite type C. Ropczyce 7 well, interval 2,374–2,383 m; **B** – grainstone-packstone with fenestral structures. Along stratiform stylolite (in the middle) abundant crystals of the matrix dolomite type C occur. In fenestral grainstone-packstone, on both sides of the stylolite visible are isolated crystals of the matrix dolomite type A, mainly in micrite surrounding the grains. On the left – fissure in the limestone filled with the saddle dolomite with characteristic slightly arched, stepwise crystal edges (arrowed). Zagorzyce 7 well, interval 2,844–2,862 m; **C** – grainstone. On the mid-left a contact of two micritized grains with single isolated crystals of the matrix dolomite type A is visible. On the left – grain deformed by compaction, on the right – the matrix dolomite type B replacing grainstone. In not fully dolomitized fields crystals of the matrix dolomite type A are visible. The border of the field occupied by the matrix dolomite type B is marked by a stylolite (arrow). Ropczyce 7 well, interval 2,503–2,507 m; **D** – boundstone in gross part replaced by late burial blocky and poikilotopic calcite cements. A stratiform stylolite crosses through the middle. In the boundstone fragments not replaced by the late burial cements isolated zoned crystals of the matrix dolomite type A occur. Zagorzyce 7 well, interval 2,844–2,862 m; **E** – matrix dolomite type B (at the top) separated from mudstone (below) by a stylolite. Cutting of the matrix dolomite type B crystals by the stylolite indicates that this type of dolomitization took place before formation of the stylolites. Dębica 10k well, interval 2,571–2,572 m; **F** – matrix dolomite type B consisting of crystals forming xenotopic mosaic. Crystal core with abundant inclusions locally surrounded with rim devoid of inclusions, formed through recrystallization (arrow). Zagorzyce well 7, interval 2,844–2,862 m

Kutek, 1994; Matyszkiewicz, 1997; Krajewski & Matyszkiewicz, 2004, 2009; Matyszkiewicz *et al.*, 2006a, b; Złonkiewicz, 2006; Olchowy, 2011).

The Oxfordian sedimentary sequence begins with a complex of marly limestones, the thickness of which usually does not exceed several metres (Fig. 3; *e.g.*, Dżułyński, 1952; Morycowa & Moryc, 1976; Golonka, 1978; Matyszkiewicz, 1997). This complex represents the outer homoclinal ramp facies (open shelf; *cf.* Burchette & Wright, 1992; Flügel, 2004). In some of the wells, the marly intervals were not cored, but their presence could be deduced from geophysical logs. Most often, they form finely bedded, marls – marly limestones alternations with abundant sponges. Calcified siliceous sponges and ammonites are commonly observed in these sediments (*e.g.*, Morycowa & Moryc, 1976; Golonka, 1978; Trammer, 1989; Matyszkiewicz, 1997; Król, 2004; Gutowski *et al.*, 2007). As far as microfacies are concerned, bioclastic wackestones, mudstones, more rarely packstones with abundant tuberoids, foraminifera and brachiopods are most common. The spon-



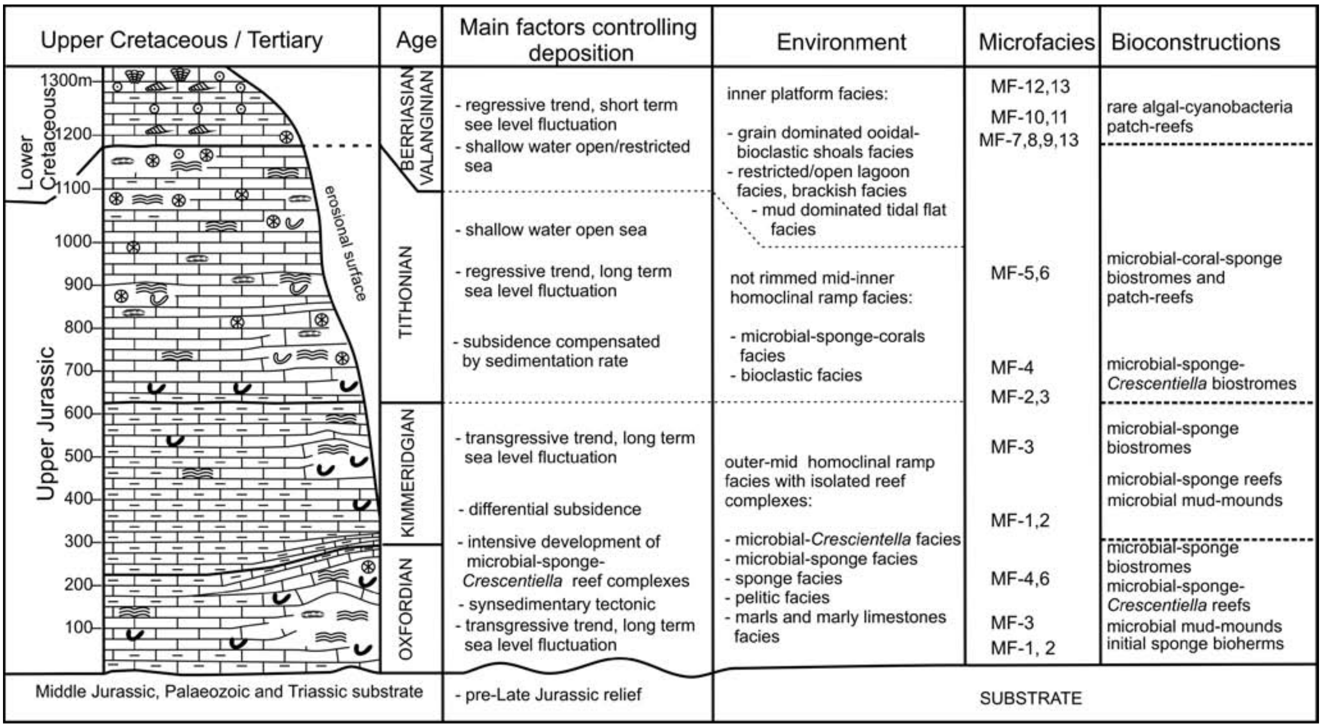


Fig. 11. Development and main factors controlling the Upper Jurassic–Lower Cretaceous sedimentation in the Carpathian Foredeep basement between Kraków and Rzeszów. The Tithonian, Berriasian and Valanginian sequence is representative for the Tarnów–Ropczyce area only

ges are always accompanied by layered thrombolites and leiolites. The epifauna is also common, mostly in the form of serpulids. Based on the analogy with the Kraków area, the marly facies could presumably represent the Lower and Middle Oxfordian (*e.g.*, Dżułyński, 1952; Trammer, 1982; Matyszkiewicz, 1997).

The marls and marly limestones are overlain by a complex of bedded and massive limestones, which represent the mid homoclinal ramp facies. The thickness of this complex in Pilzno 40 or Nawsie 1 wells does not exceed 100 m, while in Zagorzyce 6 well it amounts to about 150 m, and in the area of Grobla well and in the vicinity of Kraków it is *ca*. 200 m (Fig. 3).

The bedded limestone facies are mainly represented by pelitic limestones, detrital, most often bioclastic wackestones and packstones with numerous peloids, tuberoids, spicules, and brachiopods, and by microbial-sponge biostromes as well. Variable amounts of redeposited detrital grains could be observed in these sediments; common intraclasts and bioclasts point to the presence of elevations connected with the development of carbonate buildups.

The massive limestone facies in lower parts of the Oxfordian sections appear irregularly in the form of rather small microbial-sponge bioherms. Similar bioherms are known from the Kraków–Częstochowa Upland (Dżułyński, 1952; Trammer, 1989; Matyszkiewicz, 1997), being characterized by an initial rigid framework, as well as mud mounds, mainly built of detrital material stabilized by the microbialites. In the examined wells, the occurrence of sponge-microbial bioherms is manifested by hardly cemented limestones with densely packed sponges within intervals of pelitic or marly limestones. Large complexes of the microbial-sponge carbonate buildups in the Carpathian Foredeep basement are characteristic for the Upper Oxfordian (*e.g.*, Gutowski *et al.*, 2007). Sediments with rigid frameworks, typical of the carbonate buildups, were mostly observed in wells in the vicinities of Kraków, Tarnów, Pilzno, and Ropczyce (Figs 3, 11). In other areas, larger reef structures of this type were confirmed by wells and geophysical data only occasionally (Gliniak *et al.*, 2005). Results of geophysical investigations permitted for outlining zones, in which greater complexes of the carbonate buildups could appear. Most often they form the NW–SE stretching belts (Gliniak *et al.*, 2005; Gutowski *et al.*, 2006), like in the Kraków–Częstochowa Upland (Matyszkiewicz *et al.*, 2006a, b). Based on seismic data, larger reef bodies were reported sometimes from the areas of Tarnów, Dębica, and Ropczyce (*e.g.*, Gutowski *et al.*, 2007). It should be noted, however, that any individual microbial-sponge reef bodies larger than several dozen metres could not be observed, neither in the cores from the studied area, nor in the outcrops in Poland and Germany, which represent similar lithological complexes (*e.g.*, Keupp *et al.*, 1990, 1993; Koch *et al.*, 1994; Leinfelder *et al.*, 1994; Matyszkiewicz, 1997; Krajewski, 2000). Such structures, most often of considerable lateral extent, are characterized by relatively low though distinct relief, documented by the presence of gravitational flow deposits in their surroundings. The biggest structures of this type, reaching the stage that can be best characterized as *Crescentiella*-cement reef, display complicated and heterogeneous internal structures, formed by a row of small buildups and detrital sediments (*Tubiphytes* reefs; *e.g.*, Matyszkiewicz & Felisiak, 1992; Krajewski, 2000). At present, *Crescentiella* are assigned more and more importance as the constructors during formation of the so-called microencruster-cement reefs (*e.g.* Krajewski, 2008; Schlagintweit & Gawlick, 2008; Senowbari-Daryan *et al.*, 2008). In the drill cores, on account of variable frequency of coring, it is less clearly visible and the extent of the buildups is evaluated on the basis of geophysical logs. Investigations of the drill cores and equivalent deposits in the natural outcrops from the Kraków–Częstochowa Upland allow us to suppose that the complexes of the so-called huge sponge-microbial bioherms (*e.g.*, Gutowski *et al.*, 2007) build, in fact, systems of several levels of massive limestones. The complexes representing abundant microbial-sponge reefs are separated by bedded limestones, representing detrital sediments or microbial-sponge biostromes. Together they create complexes, which are several square kilometres in size and are separated by the areas with predominating pelitic bedded limestones and marly limestones, developed mainly as bioclastic wackestones. These complexes could correspond to several ranges of the rocks built up of massive limestone from the Kraków–Częstochowa Upland (Matyszkiewicz, 2006a, b). At the beginning, small microbial-sponge buildups predominated; in a later phase they passed into the microbial and microbial-*Crescentiella* buildups, in which detrital sediments bound by microbialites prevailed (Matyszkiewicz, 1997; Krajewski, 2000). In the vicinity of Kraków, such buildups usually pass laterally and upwards into microbial-sponge biostromes of the thick-bedded limestones (Matyszkiewicz, 1989; Krajewski, 2001). In spite of irregular, sometimes rare coring, similar sequences could be observed in the drill cores studied (Fig. 3).

The analysis of sedimentary sequences, stratigraphy, and microfacies development allow us to state that the best stratotype area for the Oxfordian in the part of the Carpathian Foredeep basement stretching from to Kraków to the east, that is to the Dębica and Ropczyce area, is the Kraków Upland, the southern part of which belongs tectonically to the Carpathian Foredeep (*e.g.*, Dżułyński, 1952; Krokowski, 1984). A higher proportion of the massive facies and submarine flow deposits in the Kraków region is probably the only difference compared to the Oxfordian sediments from the surroundings of Tarnów and Ropczyce. In the case of the Jurassic sediments of the Carpathian Foredeep from the vicinity of Kraków, intensive development of the massive facies could be explained by the existence of Palaeozoic elevations, on which the intensive development of bentonic fauna took place, and by synsedimentary tectonics, indicated by commonly appearing mass movement deposits and neptunian dykes (Krajewski & Matyszkiewicz, 2004, 2009; Matyszkiewicz *et al.*, 2006a, b). The supposed NW–SE orientation of reef structures in the study area (Gliniak *et al.*, 2005) also points to the block structure of the Palaeozoic basement (*cf.* Gutowski *et al.*, 2006; Złonkiewicz, 2006; Buła & Habryn, 2008, 2010).

The beginning of the marly sediment sequence probably overlaps with the end of the Oxfordian and the beginning of the Kimmeridgian. Such sequences could be observed in the Kraków area (Matyszkiewicz, 1997; Ziółkowski, 2007; Matyszkiewicz & Olszewska, 2007), in the areas of Tarnów, Dębica, and Ropczyce (Matyja & Barski, 2007; Olszewska, unpubl. data), as well as in other areas of Europe (*e.g.*, Keupp *et al.*, 1990; Koch *et al.*, 1994; Óloriz *et al.*, 2003; Reolid *et al.*, 2005). This, in turn, points to the regional extent of the Oxfordian/Kimmeridgian border in the zone of the transition from calcareous to calcareous-marly sequences.

Kimmeridgian

The sedimentary sequence of the Kimmeridgian is mainly represented by pelitic marly limestones and marls (Figs 3, 11). In previous studies, these sediments were included into the Oxfordian (Morycowa & Moryc, 1976; Król, 2004; Gutowski *et al.*, 2007). Recently published data clearly indicate a Kimmeridgian age of the marly complex (Matyja, 2009) in the study area. The thickness of this complex may reach up to about 550 m (Nawsie 1 well, depth interval 3,800–4,350 m); however, most often it does not exceed 300–400 m (Figs 3, 11). It is a relatively monotonous series, characterized by scarce fauna, mainly foraminifers, brachiopods, and siliceous sponges. As to the microfacies, bioclastic wackestones and mudstones predominate. In some of the wells this complex contains levels with pelitic limestones, mainly represented by wackestones with tuberoids. Biolithites are clearly rarer and occur in small microbial-sponge buildups, similar to those from the Oxfordian, though of significantly lesser extent. The geophysical log data allow us to suppose that several such levels bearing the microbial-sponge facies could be distinguished. In the majority of wells, however, these sediments were not cored. A complex of such limestones with microbial-sponge biolithites can be observed, for instance, in Zagorzyce 6 well, in the interval of 3,650–3,700 m. In the marly-calcareous complex of the Kimmeridgian, like in the interval embracing the Lower and Middle Oxfordian, a gradual rise of calcareous deposits, mainly pelitic ones, with respect to the marly facies can be observed towards the top.

Tithonian

The Tithonian sediments were recognised in the eastern part of the studied area only (Fig. 3). The thickness of the Tithonian sequence exceeds 500–600 m in those areas, in which the complete sequence of the Tithonian deposits was preserved (the area of Dębica and Ropczyce; Fig. 3). The boundary between the Kimmeridgian and Tithonian is not clearly noticeable, in part as an effect of relatively rare coring of the wells and also due to the lack of any substantial differences in the lithological development. Most probably, the Kimmeridgian–Tithonian boundary occurs within the upper parts of the marly-calcareous complex (Matyja & Barski, 2007), characteristic mainly for the Kimmeridgian.

At first, pelitic, marly limestones with scarce bioclasts and tuberoids predominate. Marly limestones pass vertically into pelitic and detrital limestone facies with common sponge fragments and microbiolites, mainly thrombolites. At the beginning, limestones with numerous calcified siliceous sponges, tuberoids, bioclasts, and also microbial-sponge biolithites can be observed. This confirms some previous observations (Matyja & Barski, 2007), which mentioned the presence of sponge facies between the marly complex of the Kimmeridgian and coral facies of the Tithonian in some wells in the Pilzno and Ropczyce area. We recognised the microbial-sponge facies in all studied wells, although they did not reach such considerable thicknesses as in the Oxfordian (Fig. 3).

In the majority of the studied wells, the Tithonian massive facies representing carbonate buildups could be recognised. At first, microbial-sponge, *Crescentiella* and detrital facies predominate. They generally formed reefs and biostromes, similar to the ones observed in the Upper Oxfordian. In numerous wells, coral facies appeared upon the upper parts of the microbial-sponge reefs, as well as over the bedded facies, what can be explained by a shallowing. Data from the wells and the literature seem to indicate that the coral-sponge facies occurred in the studied area approximately in the same time. This, in turn, points to a certain unification of the sedimentary conditions within the entire area and the lack of bigger irregularities of the bottom relief, which could have caused stronger facies diversity of sediments. The coral-microbial-sponge facies did not form bigger reef structures, but rather little patch-reefs and biostromes, similar to the microbial-sponge ones characteristic for the Upper Oxfordian. Most of the intervals with common corals are dominated by the detrital material. The microfacies analysis points to predomination of flat corals of low taxonomical diversity, and calcareous sponges. Relatively rare appearance of shallow-water microorganisms of the association *Lithocodium aggregatum* and *Bacinella irregularis*, typical of shallow-water oligotrophic conditions (*e.g.*, Dupraz & Strasser, 1999), and low taxonomical diversity of corals indicate that they did not develop in the environment optimal for a wider development of this group of organisms. In most cases, Microsolenidae corals were observed, typical for somewhat deeper and more trophic sedimentary environments (*e.g.*, Morycowa & Roniewicz, 1995; Insalaco, 1996; Lathuilière *et al.*, 2005; Roniewicz, 2008). Numerous horizons are entirely devoid of typical microorganisms on the surfaces of coral and sponge skeletons. This fundamentally distinguishes them from other areas, wherefrom sediments with high taxonomical diversified coral facies (*e.g.*, Roniewicz, 2008) and a broad spectrum of various typically reef-forming organisms (*e.g.*, Leinfelder *et al.*, 1996; Dupraz & Strasser, 1999, 2002; Reolid *et al.*, 2007) were reported. The microfacies analysis allows us to conclude that the platy coral-sponge-microbial facies developed in an environment similar to that of the microbial- sponge ones, though probably a little bit shallower (still between normal and storm wave base). These sediments represent the mid homoclinal ramp facies. Only in the uppermost part of coral facies intervals ooids indicating high water energy environment do occur.

Berriasian–Valanginian

A complex of carbonate sediments of the Lower Cretaceous was encountered in the eastern part of the area only (Figs 1, 3). In spite of the fact that the Lower Cretaceous deposits occur locally, they belong to one of the best recognised sedimentary complexes in terms of the facies and microfacies in the Polish part of the Carpathian Foredeep basement. This is mainly due to nearly complete coring of some of the wells and precise sedimentological analysis (*e.g.*, Zdanowski *et al.*, 2001; Gutowski *et al.*, 2007; Urbaniec *et al.*, 2010). The Lower Cretaceous deposits are about 150 m thick (Figs 3, 11) and show unusually high facies and microfacies variability throughout the section. Our studies confirmed the previous conclusions on the facies and microfacies development (*cf.* Zdanowski *et al.*, 2001).

The Tithonian coral-sponge-microbial facies representing a shallowing-upward sequence are overlain by deposits similar to the Lower Berriasian Purbeckian facies, known from many settings in Europe (*e.g.*, Strasser, 1988; Joachimski, 1994; Flügel, 2004; Krajewski, 2010). The transition from sedimentation related to the Upper Jurassic outer-mid platforms to the inner platform facies may be connected with the fall of the sea level at the end of the Tithonian (*e.g.* Haq *et al.*, 1987; Hallam, 2001).

The Lower Cretaceous depositional sequence can be divided into two fundamental types of facies: (i) the peloidal-microbial-cyanobacteria facies (Berriasian), and (ii) the ooidal-bioclastic facies (Valanginian). The Berriasian facies developed in varying marine and brackish inner ramp environments. These sediments proved to contain many small horizons formed by peloid-oncoid packstones, microbial bindstones, fenestral mudstones, or bioclastic wackestones with Charophyta, bivalves, gastropods, cyanobacteria and coprolites. Such changes correspond to minor sea level variations within the internal platform, lagoon of brackish character, and intertidal flat, and form a series of minor sedimentary sequences in the sections.

Facies typical of the ooid-bioclast shoal zones with vadoids commonly appear in the uppermost parts of the sections only, being connected with the transgressive impulse in the Valanginian (*e.g.*, Zdanowski *et al.*, 2001). Commonly appearing fenestral structures, meniscus cements, vadose crystal silt and intraclastic breccia point to an emergence of platform deposits. Ooidal facies did not form on extensive barrier zones, but rather in areas of local shallowings. The Berriasian–Valanginian sequence ends with the shallow-water ooidal-echinoderm-bryozoan facies bearing quartz admixtures and represents shallow, inner ramp open marine environments.

CONCLUSIONS

1. Sedimentological investigations allowed us to distinguish thirteen microfacies types characterizing the outer-mid and inner ramp facies. Together with geophysical log data they permitted to establish the presumable extent of the individual facies types in the studied sections and, together with the earlier published data, to refine the general lithological section of the Upper Jurassic and Lowest Cretaceous of the Carpathian Foredeep basement in the area comprised between Kraków and Rzeszów. Currently, on account of subsequent erosion and – mainly – Tertiary tectonics, the Kimmeridgian, Tithonian, Berriasian and Valanginian sediments are preserved in the eastern part of the area only.

2. The microfacies analyses make it possible to conclude that the Upper Jurassic complex is represented by three main sedimentary sequences of different thicknesses and diversified participation of the marly-carbonate facies, namely: the Oxfordian, Kimmeridgian and Tithonian–Valanginian ones. The sediments of the Oxfordian, Kimmeridgian and Tithonian correspond to the outer-mid homoclinal ramp facies, in which microbial-sponge and microbial-coral-sponge facies dominate. The Tithonian facies pass into internal platform open/restricted lagoon mostly peloidal-cyanobacteria, microbial and mudstones facies (Berriasian) and high energy ooidal-bioclastic shoals facies (Valanginian). So far, neither the investigated sections, nor the published data on this part of the Carpathian Foredeep have revealed any distinct area of appearance of the extensive ooid or reef barrier, but rather numerous open platform shoals.

3. In the studied part of the Carpathian Foredeep basement, maximal diversification of the thickness in particular areas took place during the Oxfordian, being connected with particularly intensive development of the microbial-sponge reef complexes, controlled by varying bottom relief and synsedimentary tectonics. The microbial-sponge facies formed extensive reef complexes, consisting of numerous small buildups, which only occasionally exceeded several dozen metres in thickness. Their development was particularly intensive in the western part of the studied area (Kraków region). The drilling and seismic data allow us to conclude, with a high probability, that the extent of the massive facies, like in the Kraków–Częstochowa Upland, is related to the main Variscan structural trends. At the end of the Oxfordian, facies unification marked its appearance throughout most of the areas, and the reef complexes were replaced by the biostromes with microbial-sponge facies and then by the microbial-coral facies. It is likely that, in spite of a considerable thickness of the Tithonian complex, the coral facies did not form larger reef structures, but developed on a flat bottom, together with detrital deposits forming mainly coral-sponge floatstones-grainstones and microbial-coral-sponge biostromes. On account of appearance of abundant corals, these sediments were often habitually recognised as the reef facies. However, the poorly taxonomically diversified assemblage of the coral facies cannot represent an environment of typical highly-diversified barrier reefs.

4. Considerable parts of the studied sections, especially the uppermost part of Upper Jurassic deposits, were subject to both dolomitization and dedolomitization processes. Four generations of dolomite have been distinguished. The matrix dolomite type A represents the earliest stage of dolomitization, which selectively involved only matrix and took place during early diagenesis, before the sediment became completely lithified. The second generation of dolomite – matrix dolomite type B – formed as a result of recrystallization of the first one before the chemical compaction of the sediment arose. Formation of the matrix dolomite type C was connected with pressure dissolution in shallow burial condition. The latest generation of dolomite, saddle dolomite, is a product of precipitation from hydrothermal and hypersaline solutions during late burial diagenesis.

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