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FACIES OF THE UPPER JURASSIC–LOWER CRETACEOUS SEDIMENTS IN THE BASEMENT OF THE CARPATHIAN FOREDEEP (WESTERN UKRAINE)

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Abstract: The Upper Jurassic–Lower Cretaceous carbonate sediments developed in a narrow, Ukrainian part of the basement of the Carpathian Foredeep show high facies diversity. Based upon thin section studies, the authors identified eleven principal microfacies varieties. Three main stages of development of carbonate platform were distinguished: (i) Oxfordian–Early Kimmeridgian, (ii) Kimmeridgian–Tithonian, and (iii) Berriasian–Valanginian. The Oxfordian sediments are rather thin and represent both the outer and inner, distally steepened ramp facies. In the Late Kimmeridgian and, mainly, in the Tithonian, the intensive growth of rimmed platform took place with distinct zones of peritidal, margin barrier and platform slope, bearing calciturbidite facies. Development of the rimmed platform was controlled by synsedimentary tectonic movements along faults rejuvenated southwest of the Holy Cross Mts. Fault Zone. In the Berriasian–Valanginian, the dominant process was sedimentation onto not-rimmed platform controlled by small sea-level changes.

Both the facies development and literature data indicate that the Late Jurassic sedimentation in the Ukrainian part of the Carpathian Foredeep basement shows considerable differences in comparison to that of the Polish part. In the studied successions, large Oxfordian microbial-siliceous sponge reef complexes, known from the Polish part of the Carpathian Foredeep basement and other areas in Europe, were rare. In the study area carbonate buildups were encountered mainly in the intervals representing the Upper Kimmeridgian–Tithonian where small, microbial-sponge and microbial-coral biostromes or patch-reefs were formed. Their growth was presumably restricted to a narrow zone of the upper slope, close to ooidal-bioclastic margin platform facies. In the Polish part of the Carpathian Foredeep basement, the Late Jurassic sedimentation took place on a vast, homoclinal ramp while in the Ukrainian part it proceeded on a narrow, distally steepened ramp and rimmed platform with distinct marginal platform barrier. Similar platform facies distribution in both regions appeared mainly in the Early Cretaceous, although with some stratigraphical differences.

The facies distribution of the Upper Jurassic sediments was closely controlled by the block structure of the basement and by orientation of the main, transcontinental Holy Cross Mts. Fault Zone, which supports the opinion on its activity in the Mesozoic era. The Ukrainian part of the Carpathian Foredeep basement located over the Palaeozoic Kokhanivka Block, between the Krakovets and Holy Cross fault zones, includes predominantly the slope, marginal and inner platform facies. Facies observed over the Palaeozoic Rava Ruska Block (south-western part of the East-European Platform), between the Holy Cross and Rava Ruska fault zones, represents mainly the inner platform and the peri-shore deposits.

Key words: microfacies, Upper Jurassic, Lower Cretaceous, SW margin of the East-European Platform, Carpathian Foredeep basement, western Ukraine.

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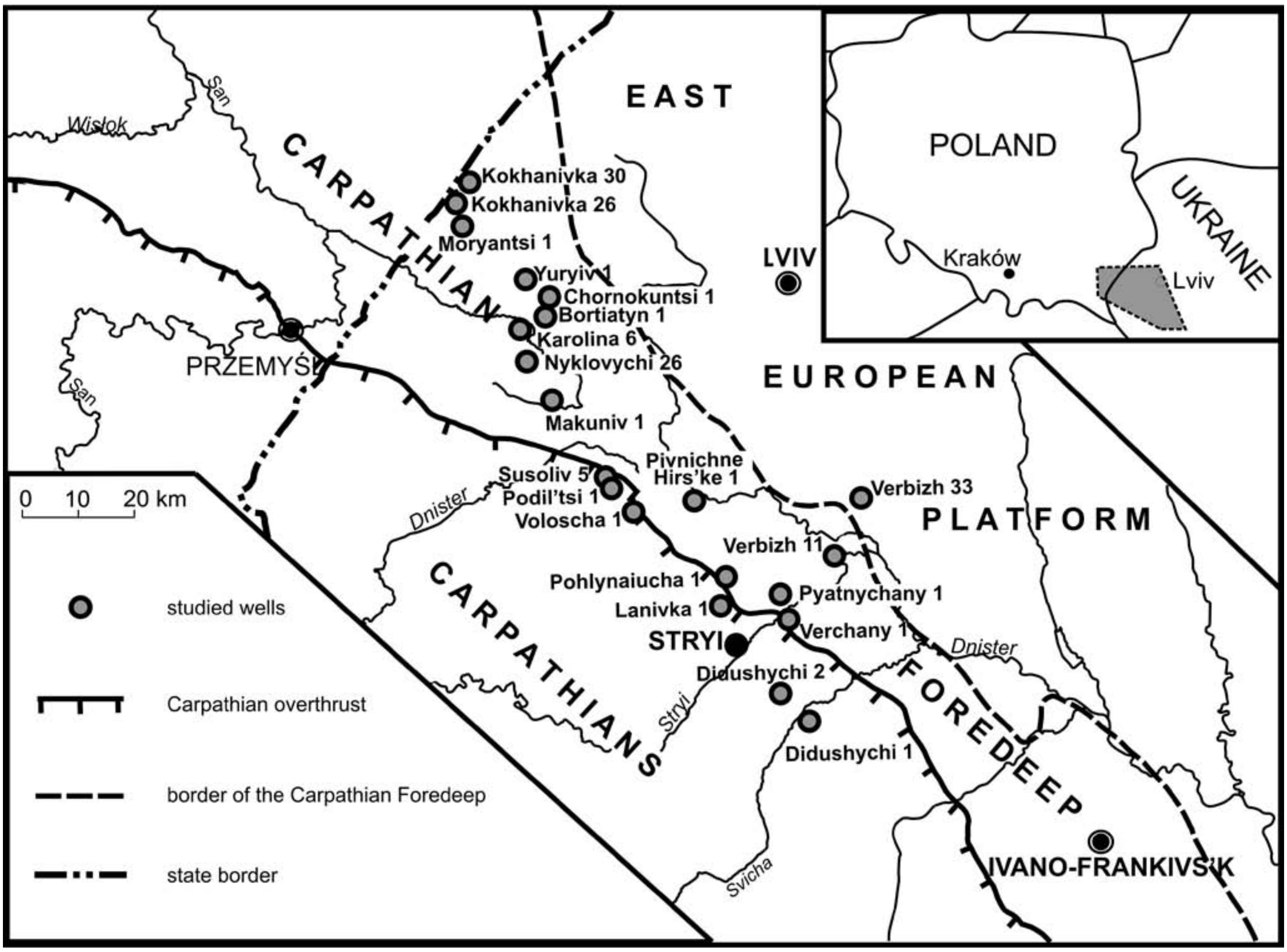

Fig. 1. Location map of the study area

INTRODUCTION

The study area is situated in the Carpathian Foredeep, mostly between the Krakovets and Holy Cross Mts. (Horodok in Ukraine) fault zones, in the narrow, so-called Bilche–Volytsya Zone (Stryi area; Fig. 1), which covers the southwestern margin of the East-European Platform (EEP). The Mesozoic sediments from that area have been investigated for a long time and with varying intensity (*e.g.*, Utrobin, 1962; Visnakov *et al.*, 1987; Dulub & Zhabina, 1999; Izotova & Popadyuk, 1996; Anikeyeva, 2000, 2004; Anikeyeva & Zhabina, 2002; Dulub *et al.*, 2003; Gutowski *et al.*, 2005a; Zhabina & Anikeyeva, 2007; Świdrowska *et al.*, 2008). The earliest studies, dated back to the end of the 19th century, were focused on sediments cropping out in the Dnister River valley, in the surroundings of Nyzhniv (*e.g.*, Gutowski *et al.*, 2005b). The research intensified in the middle of the 20th century, together with the drilling projects and resulted in recognition of Mesozoic complexes, from the uncertain Lower Jurassic to the Lower Cretaceous. Since then, in the Ukrainian part of the Carpathian Foredeep basement numerous regional lithostratigraphic suites and formations have been distinguished (Fig. 2; *e.g.*, Dulub & Zhabina, 1999; Dulub *et al.*, 2003; Anikeyeva, 2004; Zhabina & Anikeyeva, 2007), which were compared with Upper Jurassic deposits of south-eastern Poland (*e.g.*, Niemczycka, 1976; Gutowski *et al.*, 2005a, 2006; Świdrowska *et al.*, 2008; Olszewska, 2010). Most of these studies were dedicated to both the Upper Jurassic and Lower Cretaceous sedimentary complexes. Despite numerous studies, the detailed microfacies development in this part of the Carpathian Foredeep is not fully recognised (*e.g.*, Anikeyeva, 2004; Zhabina & Anikeyeva, 2007). Moreover, the microfacies data, rarely published and poorly documented, make the comparative research in this area rather difficult.

This study presents the main microfacies types of the Upper Jurassic and Lower Cretaceous carbonate sediments, which allowed the authors to identify depositional environments and to generate a general sedimentation model for the Mesozoic deposits in the narrow, Ukrainian part of the Carpathian Foredeep basement between the Krakovets and Holy Cross Mts. (Horodok) fault zones.

GEOLOGICAL SETTING

The location of the study area is peculiar: it covers the border zone of the Carpathian Foredeep and the Carpathians, the Lower San Horst Structure and the southwestern margin of the EEP (*e.g.*, Dadlez *et al.*, 1995; Stephenson *et al.*, 2003) as well as an extended tectonic zone in the vicinity of the transcontinental Holy Cross Mts. Fault Zone (HCFZ; Gutowski & Wybraniec, 2006; Buła & Habryn, 2008, 2010, 2011).

The Mesozoic sediments, which fill the studied part of the Carpathian Foredeep basement (Fig. 1), were laid down in the south-eastern part of the Mid-Polish Trough (MPT) – the Permian–Mesozoic sedimentary basin developed along the south-western border of the EEP (Dadlez *et al.*, 1995; Stephenson *et al.*, 2003). The sediments deposited at the northeastern margin of the MPT form the sedimentary cover of the south-western border of the EEP, which trends northwest-southeast, following the strike of the HCFZ. The HCFZ continues into the studied part of the Carpathian Foredeep basement where it is known as the Horodok Fault (*e.g.*, Karpenchuk *et al.*, 2006).

The south-western margin of the EEP is defined by the Trans-European Suture Zone (TESZ), the north-eastern part of which is known as the Teisseyre–Tornquist Zone. The TESZ marks the contact between Precambrian and Palaeozoic domains of crustal consolidation, running from the North Sea to the Black Sea (Pharaoh, 1999). The possible extension of the MPT along the TESZ to the southeast, under the Carpathians, as well as its origin and connections with the Tethys Ocean have been discussed in some publications (*e.g.*, Pożaryski & Brochwicz-Lewiński, 1979; Kutek, 1994; Gutowski *et al.*, 2006; Świdrowska *et al.*, 2008; Matyja, 2009), but the problem is still not fully understood. The comprehensive review of this question was presented by Świdrowska *et al.* (2008) who analysed the development of a number of sedimentary basins along the TESZ. The two outermost basins: the MPT and the Pre-Dobrogea Depression evidence their genetic independence and the lack of direct connections along the TTZ until the end of the Jurassic. Development of these basins in the Permian–Mesozoic was characterized by alternating periods of intensive deposition and uplift accompanied by erosion – the far echoes of plate tectonic events driven by geotectonic evolution of the Tethys. The Jurassic sedimentary basin in the western Ukraine was distinguished by Świdrowska *et al.* (2008) as the Stryi Depression ("*Striyskii yurskii basein*" after Dulub *et al.*, 2003).

The Mid-Polish Trough was subject to final inversion and uplift in the Late Cretaceous–Palaeogene when the Mid-Polish Anticlinorium (MPA) was formed (*e.g.*, Pożaryski & Brochwicz-Lewiński, 1979; Dadlez *et al.*, 1995; Krzywiec, 2000). In the south-eastern part of the MPA, extending from the Holy Cross Mts. (HCM) to the western Ukraine, both the uplift and erosion were most intensive, the latter reaching locally down to the Palaeozoic–Precambrian basement (*e.g.*, in the Lower San Horst Structure). Mesozoic rocks were preserved in the south-eastern part of the MPA and EEP, along the southwestern and northeastern margins of these tectonic highs, respectively. In the Miocene, the Mesozoic strata were covered with sediments filling the Carpathian Foredeep. Recently, the Miocene strata cover the Mesozoic deposits over gross part of study area, between the HCD (north-eastern border of study area) and

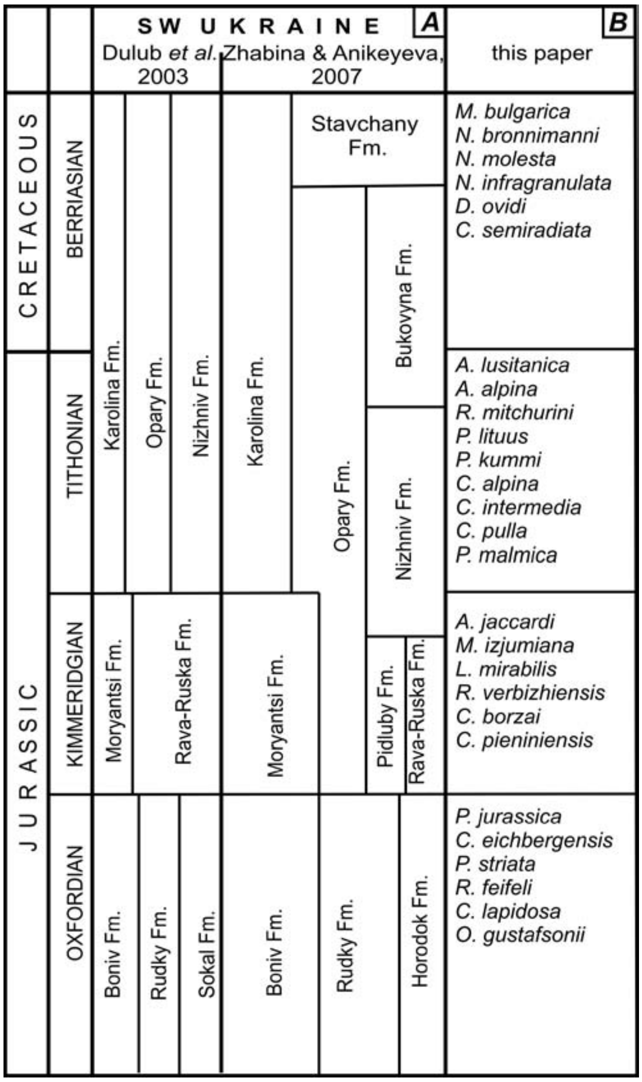

Fig. 2. Correlation of informal lithostratigraphic subdivisions of Upper Jurassic–Lower Cretaceous strata in the Ukrainian part of the Carpathian Foredeep basement (**A**) with characteristic microfossils (**B**), which were observed in the described wells (after Olszewska, unpublished data)

the Krakovets Fault (south-western border), partly plunging beneath the Carpathian Overthrust to the south and southeast in the vicinity of Stryi.

The basement of Jurassic sediments in the study area consists of Palaeozoic rocks, which build the south-western margin of the EEP. Depressions in the top surface of Palaeozoic basement are filled with Lower and Middle Jurassic clastics divided into the following units: Komarniv, Bortiatyn, Podil'tsi, Medenychi, Kokhanivka and Yavoriv (*e.g.*, Dulub *et al.*, 2003). It is worthy to note that stratigraphical and lithological studies conducted simultaneously for the Palaeozoic and Lower-Middle Jurassic clastics revealed significant (up to several hundreds of metres) differences in positioning of the Palaeozoic/Mesozoic boundary in the older literature and in some new publications (*cf.* Jachowicz-Zdanowska, 2011; Buła & Habryn, 2011). Hence, the Palaeozoic/Jurassic boundary in the study area is, in many cases, controversial and requires further detailed studies. The thickness of Lower and Middle Jurassic sediments was insufficient to level the surface left after the Variscan and Eo-Cimmerian movements. The Oxfordian sediments, which rest upon the Middle Jurassic strata (south-western part of study area) or directly upon the Palaeozoic rocks (north-eastern part of study area) were divided into three informal formations (from southwest to northeast): the Boniv, Rudky and Sokal ones (Fig. 2; Dulub & Zhabina, 1999; Dulub *et al.*, 2003). The Kimmeridgian sediments are represented by the Moryantsi and Rava Ruska formations (Zhabina & Anikeyeva, 2007). The Tithonian and Berriasian strata, which were divided into the Karolina, Opary and Nyzhniv (in some transcriptions Opory and Korolyn; T. Peryt, *pers. comm*., 2010) formations. These three units mutually interchange both laterally and vertically, and, according to some authors, deposition of both the Nyzhniv and the Opary formations has started as early as in the Kimmeridgian (Zhabina & Anikeyeva, 2007) whereas the end of this deposition is defined by the Stavchany Formation (Berriasian–Valanginian; Zhabina & Anikeyeva, 2007). Recent studies allowed some authors to distinguish basic facies of the Upper Jurassic deposits corresponding to the Wilson model (Anikeyeva, 2004; Zhabina & Anikeyeva, 2007). Hence, the Boniv Fm. and part of the Moryantsi and Karolina formations represent forereef facies, whereas the Rudky Fm. and part of the Moryantsi and Opary, as well as Sokal and Nyzhniv formations represent reef and backreef facies (Dulub & Zhabina, 1999; Anikeyeva & Zhabina, 2002; Anikeyeva, 2004).

A correlation of the above presented Upper Jurassic–Lower Cretaceous formations with lithostratigraphic units of south-eastern Poland (Niemczycka, 1976) has recently been proposed by Gutowski *et al.* (2005a) and Olszewska (2010). The subdivision of Upper Jurassic–Lower Cretaceous strata known from adjacent areas of south-eastern Poland into megasequences was accomplished by Kutek (1994), who proposed three such megasequences: Callovian–Oxfordian–Kimmeridgian, Lower–Upper Kimmeridgian and Kimmeridgian–Volgian–Berriasian. The applicability of this subdivision (with minor modifications) to the area of western Ukraine was proved by Gutowski *et al.* (2005a), who distinguished megasequences I to III, and by Świdrowska *et al.* (2008).

METHODS

The basic research method was the analysis of drill cores taken from wells drilled in the Carpathian Foredeep basement (Fig. 1). Recently, most of the drill cores are stored in Stryi. The detailed analysis was carried out on for the following, selected wells: Kokhanivka 26 and 30, Moryantsi 1, Yuryiv 1, Chornokuntsi 1, Bortiatyn 1, Karolina 6, Nyklovychi 26, Makuniv 1, Susoliv 5, Podil'tsi 1, Voloscha 1, Pivnichne Hirs'ke 1, Verbizh 11 and 33, Pohlynaiucha 1, Pyatnychany 1, Lanivka 1, Verchany 1, and Didushychi 1 and 2 (Fig. 1). Due to varying core recovery in particular wells, some poor-quality geophysical well-logs were used as a support for the studies. The most important and complete well logs are presented in Fig. 3. In addition, the analysis of facies types in the Carpathian Foredeep took advantage of abundant published data (*e.g.*, Dulub & Zhabina, 1999; Anikeyeva, 2000, 2004; Dulub *et al.*, 2003; Karpenchuk *et al.*, 2006; Zhabina & Anikeyeva, 2007).

Field studies enabled the authors to collect a set of 350 representative samples, from which oriented thin and polished sections were cut for microfacies and microfossil examinations. The results of observations were used for preparation of lithological columns, from which only the ones most characteristic for the described sequences were included into this paper (Fig. 3). The stratigraphy was based upon microfossil observations in thin sections (Fig. 2) supported by literature (Zhabina & Anikeyeva, 2007; Olszewska, 2010).

MICROFACIES DESCRIPTION AND INTERPRETATION

MF-1 Spicules-Saccocoma wackestones-mudstones (Fig. 4A–D)

This microfacies was observed only in a relatively small zone, in the south-western part of the study area, in the vicinity of the Krakovets Fault. It is represented, among others, in the Karolina 6 (2,616–3,100 m depth interval), Moryantsi 1 (2,600–3,100 m depth interval), Susoliv 5 and Nyklovychi 26 wells (Figs 1, 3). These sediments, resting on the Middle Jurassic clastics, are developed as marly limestones and dark-grey, partly dolomitized, bituminous limestones, in which dark-grey mudstones (Fig. 4B, C) and bioclastic wackestones (Fig. 4A, D) with abundant spicules, *Saccocoma*, radiolarians and thin-shelled bivalve fragments were identified. Moreover, echinoderms, numerous small bioclasts and planktonic foraminifers were observed.

Interpretation. This microfacies is typical of basinal, deep-water environment as well as of deeper shelf and outer ramp settings (*e.g.*, Flügel, 2004, p. 682). In the south-western, Ukrainian part of the Carpathian Foredeep, it can be related to the deep-water, outer platform facies. Stratigraphical observations demonstrated that this facies represents mostly the Upper Oxfordian and Kimmeridgian (excluding the Lower Kimmeridgian), and corresponds to the Boniv and Moryantsi formations known from the literature (*e.g.*, Zhabina & Anikeyeva, 2007; Olszewska, 2010).

MF-2 Intraclastic-bioclastic grainstones-rudstones (Fig. 5)

This microfacies was observed in a narrow belt located in the south-western part of the study area, in the vicinity of the Karolina 6 (2,100–2,600 m depth interval), Moryantsi 1 (2,050–2,600 m depth interval) and Podil'tsi 1 (2,400–3,000 m depth interval) wells (Figs 1, 3). The typical feature of this sediment is more or less-visible lamination formed by detrital and pelitic laminae. Detrital sediments (grainstones-rudstones) show distinct normal grading (Fig. 5B). Among grains ooids, algae, calcareous sponges and coprolites were observed, representing shallow-water environments (Fig. 5C, E). Detrital sediments grade upward into carbonate mudstones-wackestones whereas the upper surface of mudstones is sharp (Fig. 5B). Occasionally, detrital

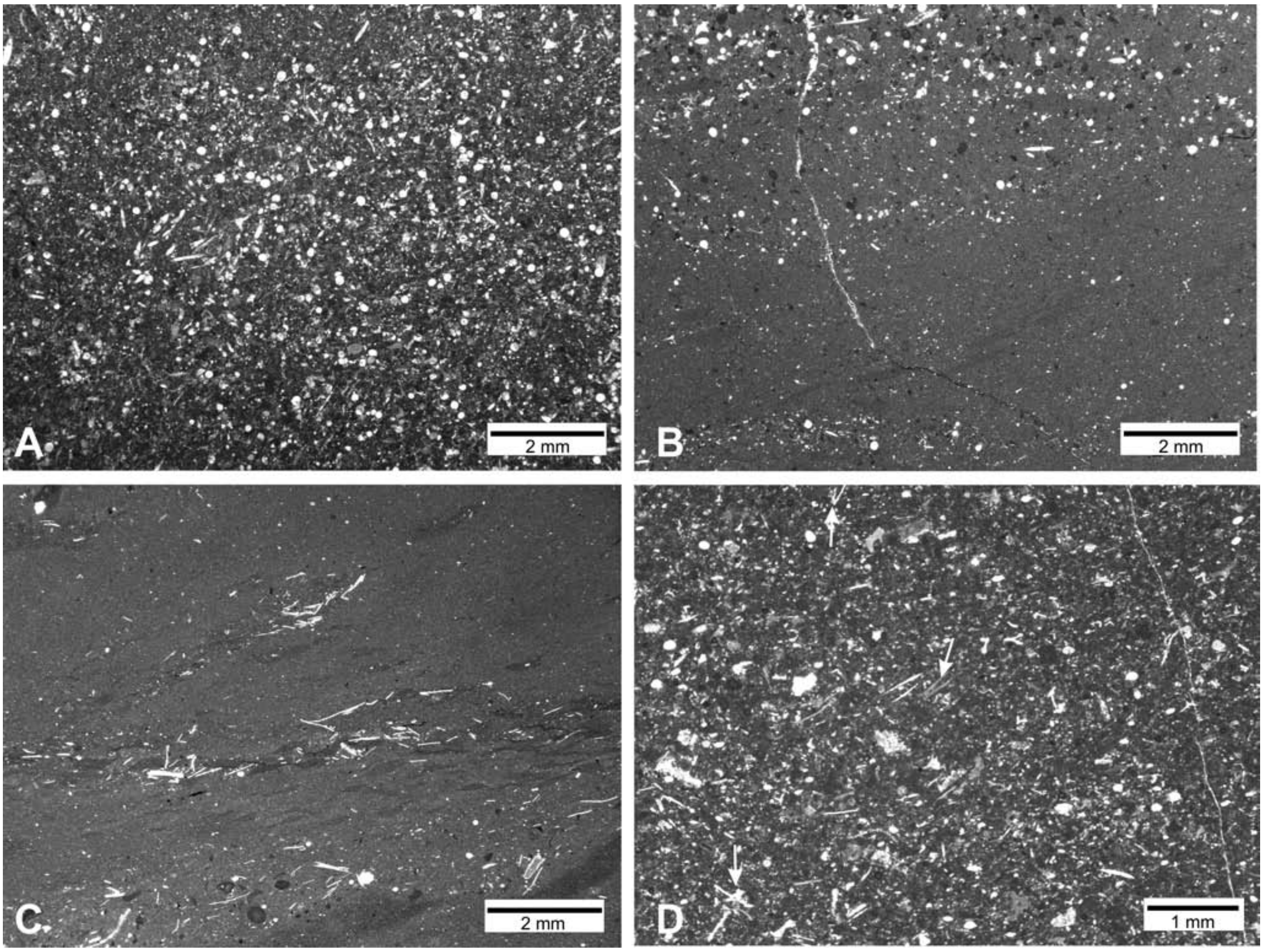

Fig. 4. Microfacies from deep-water/deep shelf and slope environments (Upper Oxfordian–Kimmeridgian–Tithonian) in the Ukrainian part of the Carpathian Foredeep basement. **A** – spiculite wackestone with numerous recrystallized radiolarians and sponge spicules (MF-1, Susoliv 5 well, depth interval 2,999–3,005 m), **B** – burrowed mudstone and wackestone with sponge spicules and pelagic foraminifers (MF-1, Karolina 6 well, 2,870 m depth), **C** – wackestone with pelagic thin-shelled bivalves (filaments) (MF-1, Karolina 6 well, 2,970 m depth), **D** – wackestone with *Saccocoma* (arrows) (MF-1, Karolina 6 well, 2,755 m depth)

sediments are stabilized by microbial crusts (Fig. 5A). Such a succession was observed many times at various depths, but up the sequences the share of detrital sediments increases. Organodetrital sediments composed of redeposited fragments of microbial-sponge and microbial-coral boundstones (Fig. 5A, D), as well as ooidal grainstones (Fig. 5F) derived from erosion of adjacent, barrier facies are common in the studied sections.

Interpretation. This microfacies was found in the south-western part of the studied fragment of the Carpathian Foredeep, along the Krakovets Fault. It represents platform slope sediments composed of numerous, fine, calciturbiditic sequences built up of allochthonous detrital material derived from erosion of the nearby, shallow-water platform marginal facies. Microfossil studies revealed that this platform slope facies belongs to the Upper Kimmeridgian and the Tithonian, and corresponds mainly to the Karolina Formation (Fig. 2; *e.g.*, Zhabina & Anikeyeva, 2007; Olszewska, 2010).

MF-3 Coral-sponge-microbial boundstones and MF-4 bioclastic grainstones-floatstones (Fig. 6)

In the analysed drill cores, these microfacies appear relatively rarely, in the form of carbonate buildups. Boundstones encountered in these wells, and in others reported in the literature (*e.g.*, Dulub & Zhabina, 1999; Anikeyeva & Machalsky, 2001; Anikeyeva, 2000; Dulub *et al.*, 2003; Zhabina & Anikeyeva, 2007), occur in a narrow, northwest–southeast-trending zone extending from the Polish-Ukrainian state border to the Stryi area (Fig. 1). Their location corresponds to the range of the so-called Opary Reef facies (*e.g.*, Karpenchuk *et al.*, 2006; Zhabina & Anikeyeva, 2007). However, in studied wells, boundstones and accompanying detrital sediments of carbonate buildup facies were observed in a few horizons only (for example, in the Bortiatyn 1 well, at a depth of 1,950 m, and in the Podil'tsi 1 well, at depths 2,300, 2,150–2,200 and 2,100 m).

Two main varieties of boundstones were distinguished: (i) microbial-sponge and (ii) microbial-coral. The micro-

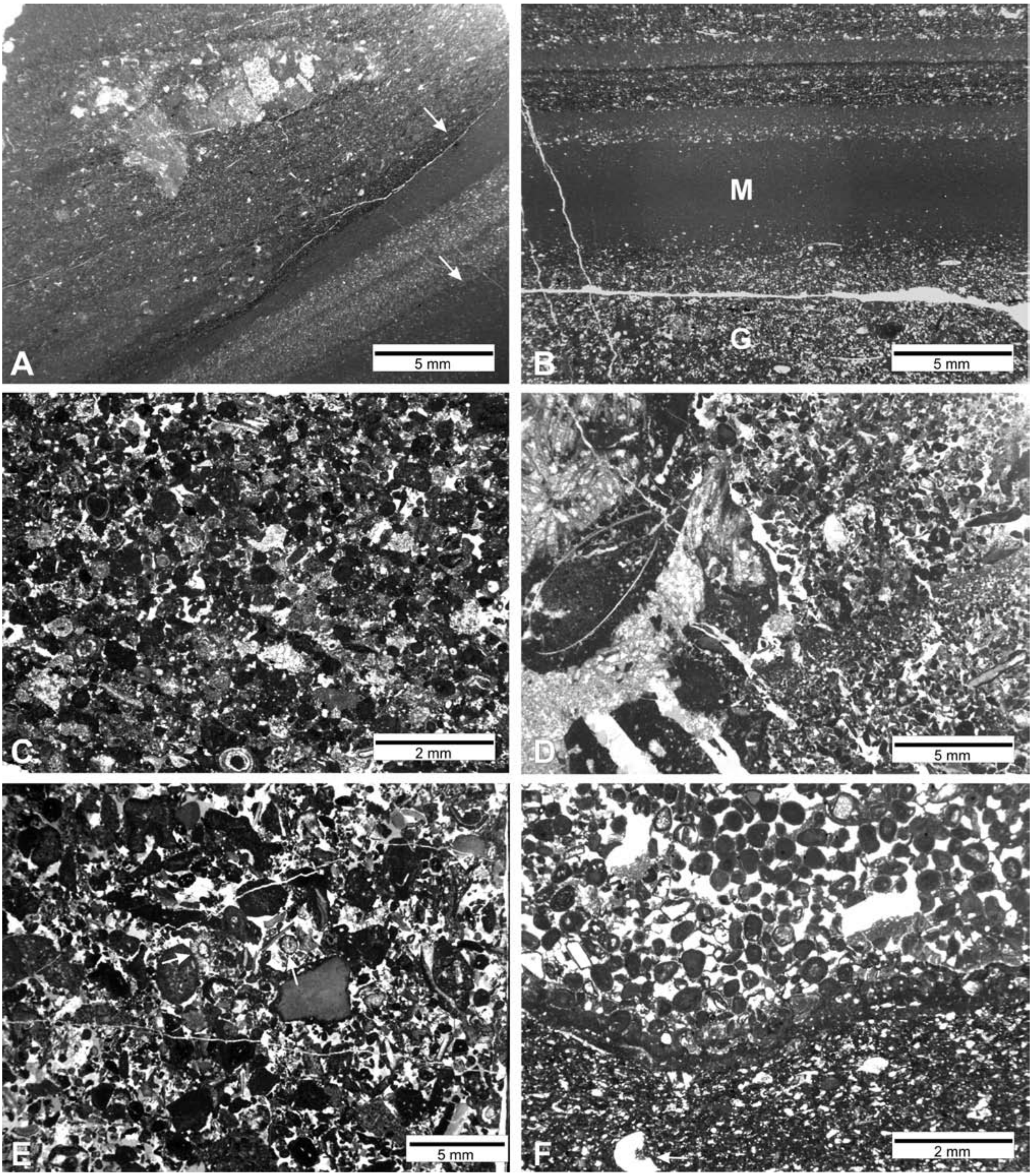

Fig. 5. Kimmeridgian–Tithonian microfacies representing allochthonous and autochthonous platform slope deposits in the Ukrainian part of the Carpathian Foredeep basement. **A** – lower part: laminated mudstone stabilized by leiolites (arrows), left upper corner: wackestone-packstone with irregular clasts derived from erosion of carbonate platform margin buildups, nuclei of clasts consist of skeletal grains (MF-1, 2, Podil'tsi 1 well, depth interval 2,405–2,410 m), **B** – laminated mudstone/packstone-grainstone representing calciturbidite sequences. The sequence starts with bioclastic packstone-grainstone (G) with parallel arranged shells. The sediment consists of bioclasts and peloids with grading reflected by upward-decreasing grain size. In the central part, packstone grades into micritic mudstone (M) (MF-1, 2, Karolina 6 well, 2,520 m depth), **C** – packstone-grainstone, close-up of turbidite sediments with numerous ooids and bioclasts redeposited from the shallow-water zone (MF-2, Karolina 6 well, 2,597 m depth), **D** – bioclastic-lithoclastic grainstone-rudstone with peri-reefal components, on the left: bioclastic packestone-grainstone, fragments of macrofauna with borings (MF-2, Bortiatyn 1 well, 2,490 m depth), **E** – microbreccia, bioclastic-lithoclastic grainstone-rudstone with numerous Dasycladacean algae (arrows), bioclast and intraclasts imported from shallow water platform (MF-2, Bortiatyn 1 well, 2,240 m depth), **F** – wackestone, upper part: fragment of a large intraclast of ooidal grainstone, lower part: wackestone with sponge spicules and small echinoderms (arrow, MF-2, Bortiatyn 1 well, 2,290 m depth)

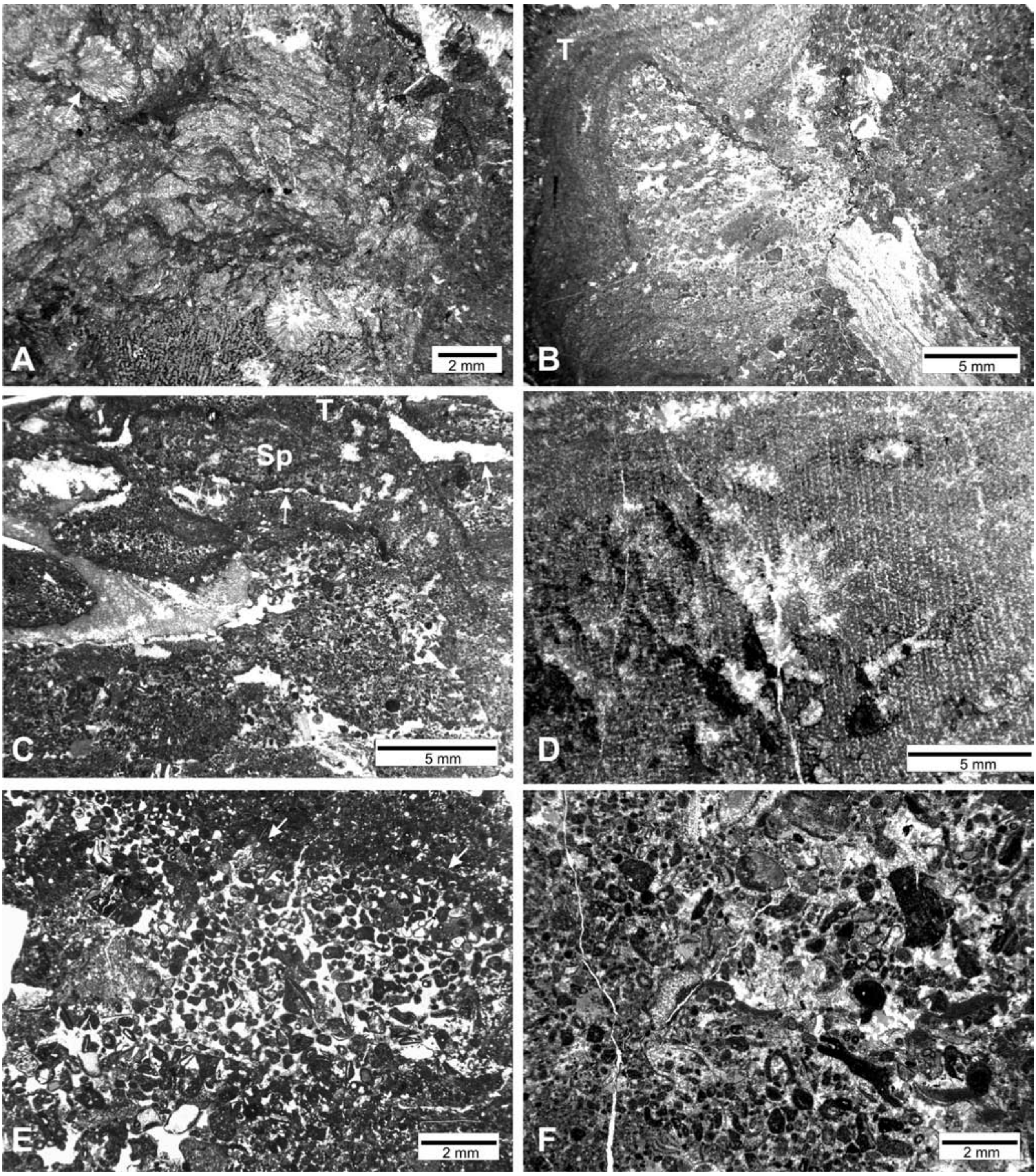

Fig. 6. Microfacies from platform margin reefs (Tithonian) in the Ukrainian part of the Carpathian Foredeep basement. **A** – coral-sponge-microbial boundstone with botryoid cement (arrow) (MF-3, Podil'tsi 1 well, depth interval 2,099–2,110 m), **B** – coral-sponge boundstone with recrystallized macrofauna and poorly structured thrombolites (T) (MF-3, Podil'tsi 1 well, depth interval 2,300–2,310 m), **C** – thrombolitic (T)-sponge (Sp) boundstone with growth cavites (arrows) (MF-3, Bortiatyn 1 well, 1,930 m depth), **D** – coral boundstone with borings (MF-3, Bortiatyn 1 well, 1,945 m depth), **E** – bioclastic-ooidal grainstone stabilized by microbial crusts (arrows) (MF-4, Bortiatyn 1 well, 2,270 m depth), **F** – bioclastic peri-reefal grainstone, grains include bioclasts, bivalves, *Crescientiella*, peloids and intraclasts (MF-4, Podil'tsi 1 well, depth interval 2,255–2,260 m)

bial-sponge boundstones are composed mostly of layered and agglutinated thrombolites, peloidal stromatolites (*cf.* Schmid, 1996) and sponges (Fig. 6C). Fine growth cavities with geopetal infillings and borings are common, which documents the existence of rigid framework. In some core intervals, only the microbialites were observed being represented by layered leiolites, which stabilize the detrital material composed mainly of peloids and small bioclasts (Fig. 6E). Similarly to microbial-sponge, the microbial-coral boundstones characterized by rigid framework were found in a few horizons only. Due to obliterated internal structure, most of coral specimens are difficult to identify (Fig. 6A, B), but among the identified corals most common were Microsolenidae (Fig. 6D). Some coral skeletons reveal common borings.

In the intervals, in which the boundstones were observed, grainstone and floatstone sediments are frequent, built up of crumbled bioclasts: mainly bivalves, gastropods, *Crescientiella morronensis* (former *"Tubiphytes" morronensis*; Senowbari-Daryan *et al.*, 2008), sponges and corals (Fig. 6F). Sediments of this microfacies most often appear in the same horizons as the reefs and products of their destruction. The ooids encountered in this facies point out that the buildups developed in the vicinity of ooidal barriers.

Interpretation. These microfacies, representing the boundstones forming the carbonate reefs or biostromes and peri-reefal deposits, were observed only in the central part of the study area. The reef facies occurs in a narrow zone, parallel to the ooidal-bioclastic facies. Analysis of data from wells and from literature did not confirm the presence of thick reef complexes with well developed, rigid framework. Instead, small buildups are present and, in the upper parts of the successions, monotonous and poorly taxonomically diversified, microbial-sponge and microbial-coral biostromes or patch-reefs occur. Their development, together with the presence of redeposited ooids and the fragments of boundstones within the slope sediments, allow us to conclude that these are deposits of the upper slope, between the ooidal-bioclastic, marginal platform barrier and the platform slope where submarine slides were encountered. The results of microfossil studies suggest the Late Kimmeridgian and Tithonian ages (Zhabina & Anikeyeva, 2007; Olszewska, unpublished data).

MF-5 Ooid-bioclastic grainstones (Fig. 7A–D)

Initially, this microfacies variety was observed in wells located in a narrow (presumably less than a few kilometres wide), northwest-southeast-trending zone between Lubaczów and Stryi (Zhabina & Anikeyeva, 2007). In the lower part of the sections, the ooidal-bioclastic facies was observed in the Upper Oxfordian–Lower Kimmeridgian succession from the Bortiatyn 1 well (Figs 3, 6C) where mixed, siliciclastic/carbonate deposits were found. Upwards, in wells from the north-eastern part of study area, this microfacies was more common. Its presence was documented also from other wells located in this zone, that is Bortiatyn 1 (1,800–2,300 and 2,500–2,550 m depth intervals) and Podil'tsi 1 (1,950–2,350 m depth interval) (Fig. 3; *e.g.*, Karpenchuk *et al.*, 2006; Zhabina & Anikeyeva, 2007). The ooidal-bioclastic microfacies is composed of small ooids, with diameters rarely exceeding 0.5 mm, and of bioclasts, which are mostly fragments of bivalves, gastropods and echinoderms (Fig. 7A, B, D).

Interpretation. In both the Kimmeridgian and Tithonian, the ooidal-bioclastic microfacies similar to MF-4 occurs mainly in a narrow zone, southwest of the Horodok Dislocation. Microfacies analysis and data from other wells drilled in the zone (*e.g.*, Karpenchuk *et al.*, 2006; Zhabina & Anikeyeva, 2007) indicate that this is a high-energy, marginal platform, ooid-bioclastic and reef facies. In the literature, these sediments were assigned to the Opary Formation (mainly the Upper Kimmeridgian–Tithonian; *e.g.*, Zhabina & Anikeyeva, 2007; Olszewska, 2010). Farther to the southwest it grades laterally into the platform slope facies (Karolina Formation). In both the Upper Tithonian and Berriasian, this facies variety was found also towards the EEP, in the Nyzhniv Formation (Fig. 3; *cf.* Dulub & Zhabina, 1999; Gutowski *et al.*, 2005b), which represents the inner, open-platform, ooidal-bioclastic shoals. Moreover, the ooidal-bioclastic facies observed in the lower parts of the successions together with siliciclastic sediments corresponds to the so-called Variegated Horizon (Lower Kimmeridgian; *e.g.*, Gutowski *et al.*, 2005a).

MF-6 Fenestral mudstones-wackestones, MF-7 microbial bindstones and MF-8 peloid-cyanobacteria packstones-wackestones (Fig. 8)

These deposits include numerous microfacies varieties with fenestral structures. An almost complete Upper Tithonian succession was observed in the Kokhanivka 26 well, which is remarkable because of full coring (Fig. 3). The microfacies varieties form numerous, alternating horizons, from a dozen or so to several dozens of centimetres thick. The most common are mudstones with abundant, irregular fenestral voids usually geopetally filled with vadose silt (Fig. 8B). Another common variety is the fenestral wackestone (Fig. 8A). This microfacies is characterized by the appearance of numerous coprolites *Favreina* sp. Common appearance of redeposited ooids indicates deposition in the vicinity of ooidal-bioclastic shoals. Peloidal packstones-grainstones (Fig. 8C) are frequent, grading up the sequence into peloid-cyanobacteria packstones (Fig. 8E, F). Regular fenestral structures are commonly observed as horizontal, microbial 'zebra-like' forms built up of a set of micrite laminae with sparite-filled spaces or of irregular caverns (Fig. 8D).

Interpretation. These microfacies varieties are common in the upper parts of the studied successions (Fig. 3). They were found northeast of the ooidal-bioclastic barrier described above. Several microfacies types represent the inner platform environment and correspond to minor fluctuations of sea level within the intertidal flat. Microfossil studies enabled the authors to assign these sediments to the Upper Tithonian (Olszewska, 2010; Olszewska, unpublished data) and perhaps, to the ?Lower Berriasian.

MF-9 Charophyta-gastropod wackestones (Fig. 9A, C, D)

In both the Kokhanivka 26 and Lanivka 1 wells, in a few horizons within the lagoonal facies (Upper Tithonian–

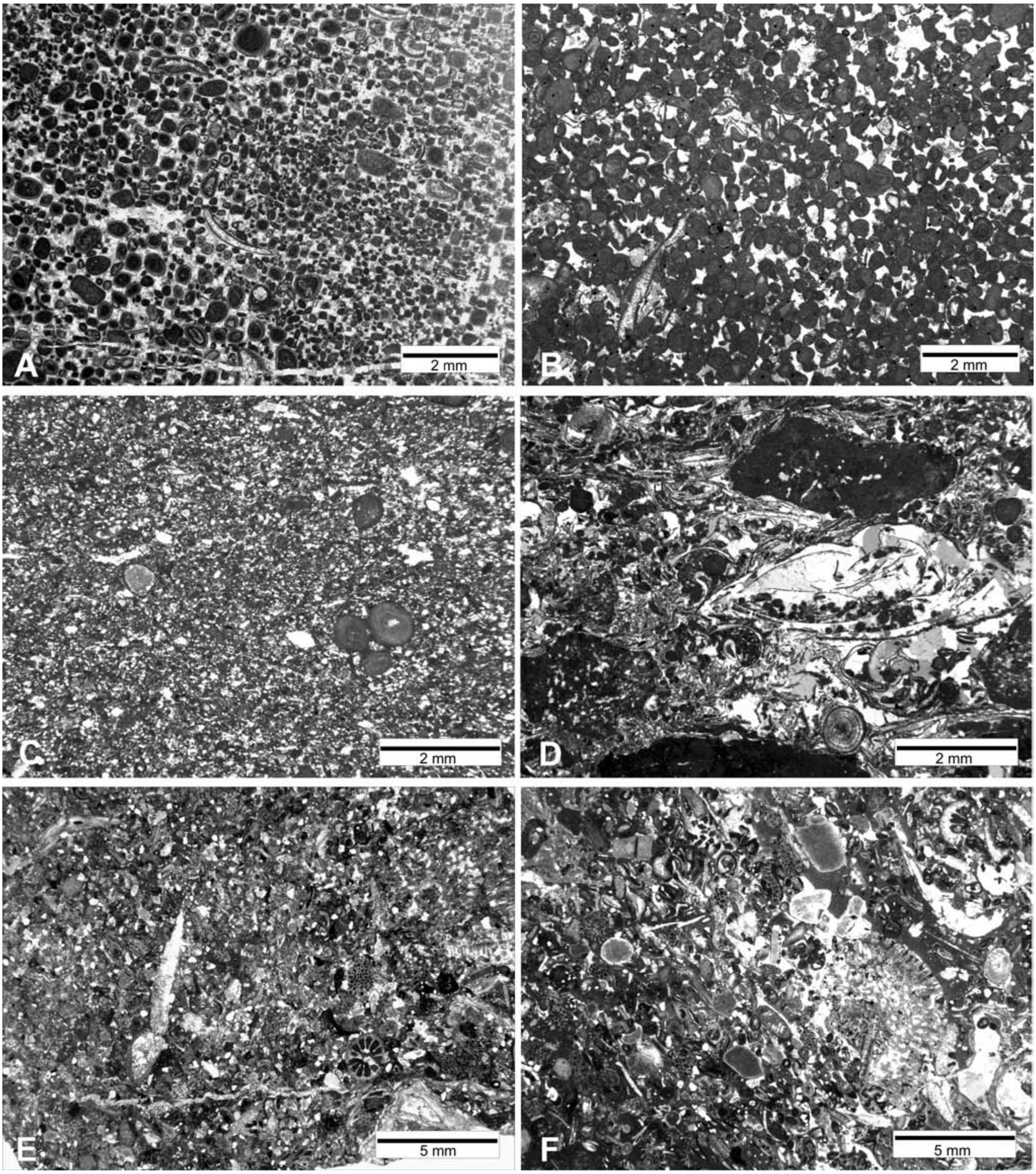

Fig. 7. Microfacies from platform margin barriers and shallow-water inner platform environments (Tithonian–Valanginian) in the Ukrainian part of the Carpathian Foredeep basement. **A** – ooidal grainstone (MF-5, Kokhanivka 26 well, depth interval 1,134–1,140.8 m), **B** – ooidal-bioclastic grainstone, most of ooids are micritized (MF-5, Susoliv 5 well, depth interval 2,999–3,005 m), **C** – bioclastic packstone-grainstone with rare micritized ooids, (MF-5, Bortiatyn 1 well, 2,480 m depth), **D** – grainstone-rudstone with numerous bivalve shells, intraclasts, lithoclasts, gastropods and concentric ooids (MF-5, Kokhanivka 26 well, depth interval 1,105.5–1,112.5 m), **E, F** – crinoid-bryozoan grainstone with numerous echinoderms, corals, bivalves and sponges (MF-10, Didushytsi 1 well, depth intervals 1,803–1,925 m)

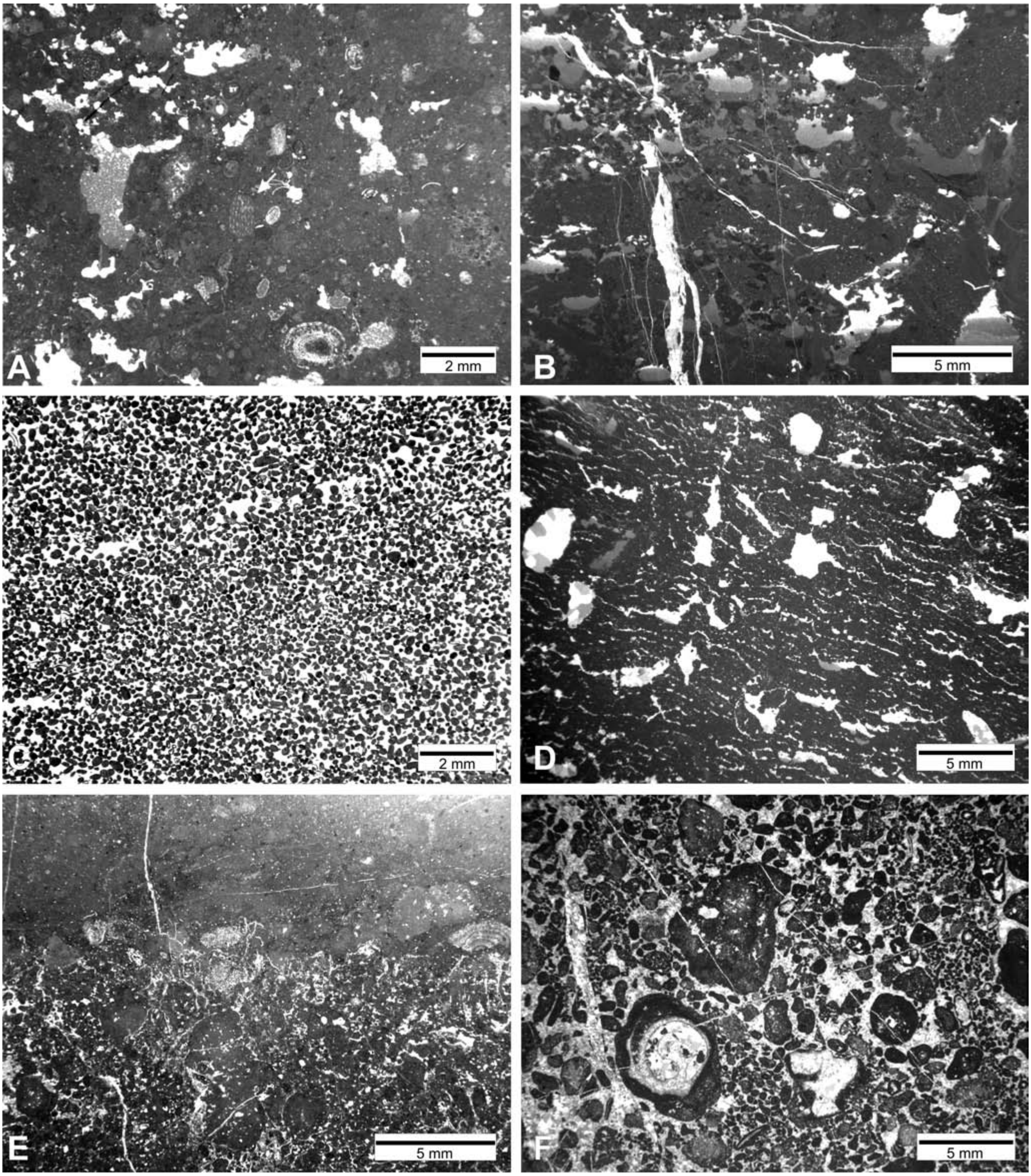

Fig. 8. Microfacies from the inner platform deposits (Tithonian–?Lower Berriasian) in the Ukrainian part of the Carpathian Foredeep basement. **A** – fenestral wackestone with coprolites (arrow) and ooids (MF-6, Kokhanivka 26 well, depth interval 1,112.5–1,119.7 m), **B** – peritidal fenestral mudstone with numerous geopetally infilled cavities (MF-6, Kokhanivka 26 well, depth interval 1,127–1,134 m), **C** – non-laminated, fine-grained peloidal grainstone (Kokhanivka 26 well, depth interval 1,193–1,201 m), **D** – regularly laminated, microbial fenestral bindstone (MF-7, Kokhanivka 26 well, depth interval 1,208–1,310 m), **E** – coated rudstone with cyanobacteria and mudstone (upper part) (Didushychi 1 well, depth interval 2,009–2,019 m), **F** – coated, bioclastic and intraclastic- bioclastic packstone-grainstone with Dasycladacea, gastropods and small oncoids (Didushychi 2 well, depth interval 2,166–2,171 m)

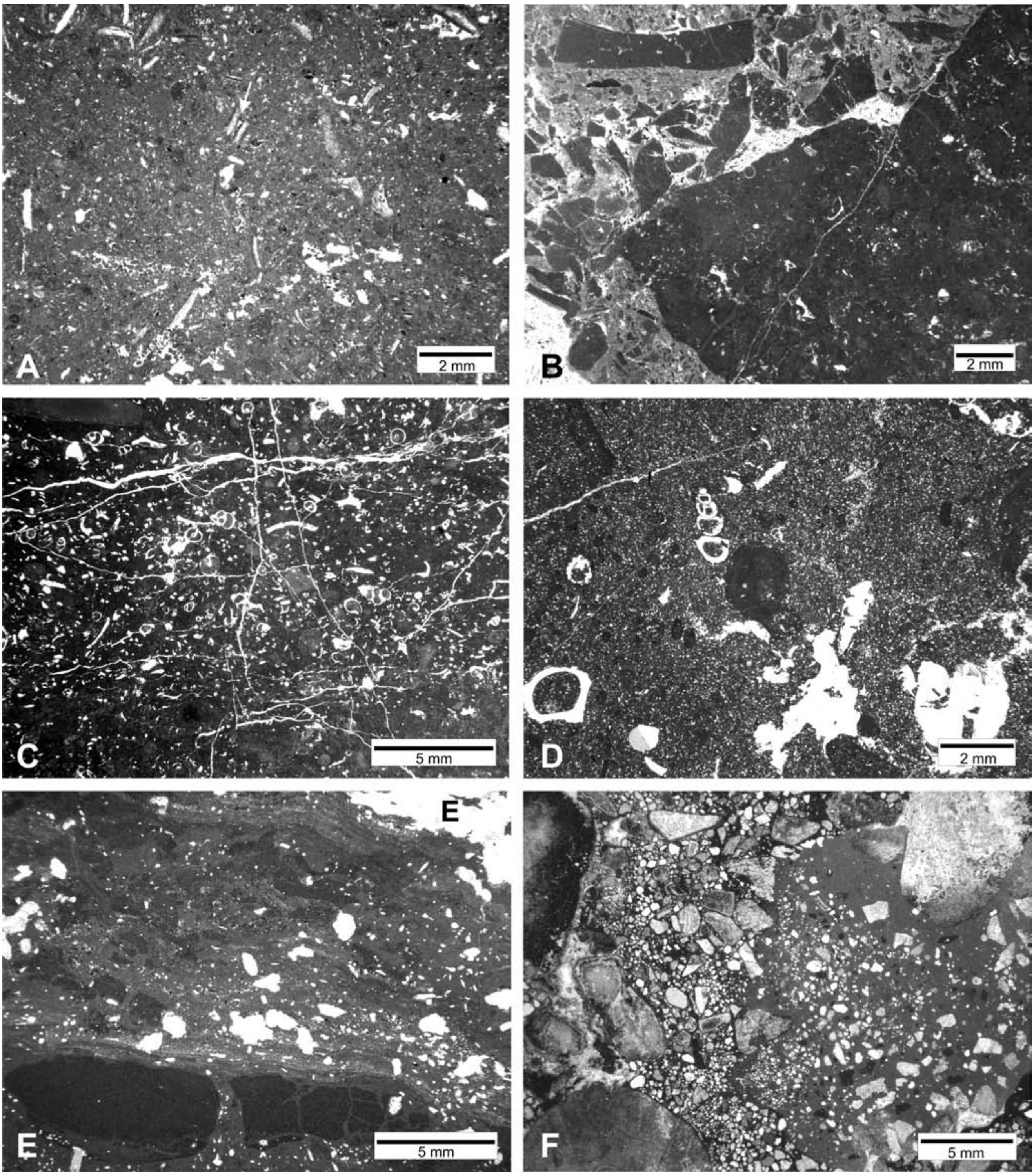

Fig. 9. Microfacies from the inner platform and peri-shore deposits (Tithonian–Berriasian) in the Ukrainian part of the Carpathian Foredeep basement. **A** – brackish, restricted lagoon/lake wackestone with fragments of Charophyta (arrow) and thin-shelled ostracods (MF-9, Kokhanivka 26 well, depth interval 1,178.6–1,185.6 m), **B** – rudstone, transgressive basal breccia, lithoclasts reflect erosion of shallow-water platform deposits (Didushychi 2 well, depth interval 1,975–1,983 m), **C** – brackish, restricted lagoon/lake gastropod wackestone (MF-9, Didushychi 1 well, depth interval 2,124–2,132 m), **D** – non-laminated, bioclastic wackestone with gastropods (MF-9, Didushychi 2 well, depth interval 2,054–2,061 m), **E** – floatstone, back-platform sabkha, in the lower part tidal intraclasts, coarse floatstone lithoclasts represented by unfossiliferous micrite clasts, in the upper part laminated, evaporatic, calcareous mudstone; irregularly distributed voids result from the replacement of evaporates (E), (MF-11, Verbizh 11 well, depth interval 866–870 m), **F** – polimictic breccia with carbonates and quartz grains (MF-11, Verbizh 11 well, depth interval 1,080 –1,084 m)

?Lower Berriasian), the peloidal wackestones were observed, with abundant fragments of Charophyta (Fig. 9A), gastropods and bivalves (Fig. 9C, D).

Interpretation. The sediments are dominated by gastropods and Charophyta representing the environment of peri-shore, brackish lakes (isolated lagoons) distributed along the shore and separating the lagoon from the land. Similar microfacies was described from the Polish part of the Carpathian Foredeep basement (Zdanowski *et al.*, 2001; Krajewski *et al.*, 2011) where it represents the Berriasian.

MF-10 Bioclastic-bryozoan grainstones (Fig. 7E, F)

The occurrence of this microfacies is limited to the north-eastern part of the study area. Up the Upper Jurassic–Lower Cretaceous succession, this microfacies becomes more common and dominated by grainstones comprising abundant bryozoans and echinoderms, whereas the number of ooids decreases, although it is still high (Fig. 7E, F). Its presence was documented from the Didushychi 1 well (1,803–1,925 m depth interval).

Interpretation. This microfacies represents the Lower Cretaceous (Berriasian–Valanginian; *cf.* Zhabina & Anikeyeva, 2007) open platform, shallow-water facies. Its presence was also described from the Lower Cretaceous (Valanginian) strata in the Polish part of the Carpathian Foredeep basement (Zdanowski *et al.*, 2001; Urbaniec *et al.*, 2010; Krajewski *et al.*, 2011) indicating a wide regional extent of the microfacies. In the Ukrainian part, this microfacies can be correlated with the Nizhniv Formation (*cf.* Dulub *et al.*, 2003; Gutowski *et al.*, 2005a).

MF-11 Lithoclastic floatstones (Fig. 9B, E, F)

In the Didushychi 1, 2 and the Verbizh 11 wells, in numerous Tithonian horizons, the lithoclasts of floatstones were observed (Fig. 9B) being characterized by micritic clasts with laminated, evaporatic calcareous mudstones (Fig. 9E). Moreover, in some horizons the polimictic breccias were noticed, composed of carbonate and quartz grains (Fig. 9F). This microfacies was observed in the north-eastern part of the study area and represents peri-shore deposits.

FACIES DEVELOPMENT OF UPPER JURASSIC–LOWER CRETACEOUS CARBONATE DEPOSITS IN THE WESTERN PART OF THE UKRAINIAN CARPATHIAN FOREDEEP BASEMENT

The results of microfacies studies combined with literature data (*e.g.*, Dulub & Zhabina, 1999; Anikeyeva, 2000, 2004; Dulub *et al.*, 2003; Karpenchuk *et al.*, 2006; Zhabina & Anikeyeva, 2007) revealed high lithological diversity of Upper Jurassic–Lower Cretaceous deposits in a narrow, strongly tectonically disturbed Ukrainian part of the Carpathian Foredeep basement (Fig. 10). Particular sediment types, indicative of sedimentary environments, show variability from the southwest to the northeast (Fig. 10). In the study area located between the Krakovets and Horodok fault zones, the stratigraphical data based on microfossil observations enabled the authors to identify Oxfordian, Kimmeridgian, Tithonian, Berriasian and perhaps ?Valanginian sediments (Fig. 3; *e.g.*, Dulub & Zhabina, 1999; Zhabina & Anikeyeva, 2007; Olszewska, 2010; Olszewska, unpublished data). The results of recent stratigraphical investigations led to correlations of several informal formations or suites distinguished in both the Polish (southeastern Poland) and the Ukrainian parts of the Carpathian Foredeep basement and farther, towards the east, over the EEP (Niemczycka, 1976; Gutowski *et al.*, 2005b; Olszewska, 2010).

In the south-western part of the study area, close to the Polish-Ukrainian state border, the Upper Jurassic carbonates rest upon the Middle Jurassic siliciclastic sediments (Karolina 6 and Podil'tsi 1 wells; Figs 3, 10). Here, the Upper Jurassic strata reach the maximum thickness, perhaps 1,000 m (Fig. 3), but to the northeast the thickness of these sediments decreases to about 500 m, as seen in the Bortiatyn 1 wells. Towards the EEP, the Upper Jurassic carbonate deposits rest directly upon the Palaeozoic rocks or upon the Oxfordian clastics of the Sokal Suite (Dulub & Zhabina, 1999). Commonly, the Upper Jurassic successions are incomplete due to post-Mesozoic tectonic activity. The biostratigraphical and facies observations enabled the authors to distinguish three main stages of sedimentation (*cf.* Kutek, 1994; Gutowski *et al.*, 2005a; Świdrowska *et al.*, 2008): (i) the Oxfordian–Early Kimmeridgian stage representing the distally steepening ramp, (ii) the Kimmeridgian–Tithonian stage representing the rimmed platform, and (iii) the Berriasian–Valanginian stage of not-rimmed, open platform (Fig. 11). Due to erosion, the last stage was recognised only in the north-eastern part of study area, in the Didushychi 1, 2 and the Verbizh 11, 33 wells.

The Upper Jurassic succession commences with the Oxfordian sediments transgressively overlaying the Middle Jurassic strata (Fig. 3). To the northeast, towards the EEP, the Oxfordian carbonates grade into siliciclastics (Dulub & Zhabina, 1999). In the studied drill cores (*e.g.*, Moryantsi 1, Karolina 6 and Podil'tsi 1 wells) the Lower and Middle Oxfordian carbonate sediments are poorly biostratigraphically documented (Olszewska, unpublished data) and their position and extent are rather doubtful, despite several publications (*cf.* Dulub *et al.*, 2003; Zhabina & Anikeyeva, 2007). The same phenomena are observed farther to the southeast, in the western part of the Crimean Upper Jurassic–Lower Cretaceous platform deposits (Krajewski & Olszewska, 2007; Krajewski, 2010). The results of this study suggest that these are mostly Upper Oxfordian strata (Fig. 3). In the analysed wells, the Oxfordian carbonate sediments show insignificant thicknesses: from about 50 m in the Bortiatyn 1 well to about 150 m in the Moryantsi 1 well (Figs 1, 3). The results of microfacies analysis suggest that in the south-western part of the study area the Oxfordian sediments are deep-water marly limestones and limestones (as in the Moryantsi 1, Karolina 6 and Podil'tsi 1 wells), represented mostly by wackestones with numerous spicules and bioclasts (Fig. 4). The microbial-siliceous sponge facies are rare in comparison with the Polish part of the Carpathian Foredeep basement and their extent is considerably smaller (*cf.* Morycowa & Moryc, 1976; Golonka, 1978; Gutowski *et al.*, 2007; Krajewski *et al.*, 2011). Although the presence of microbial-sponge buildups cannot be excluded in other

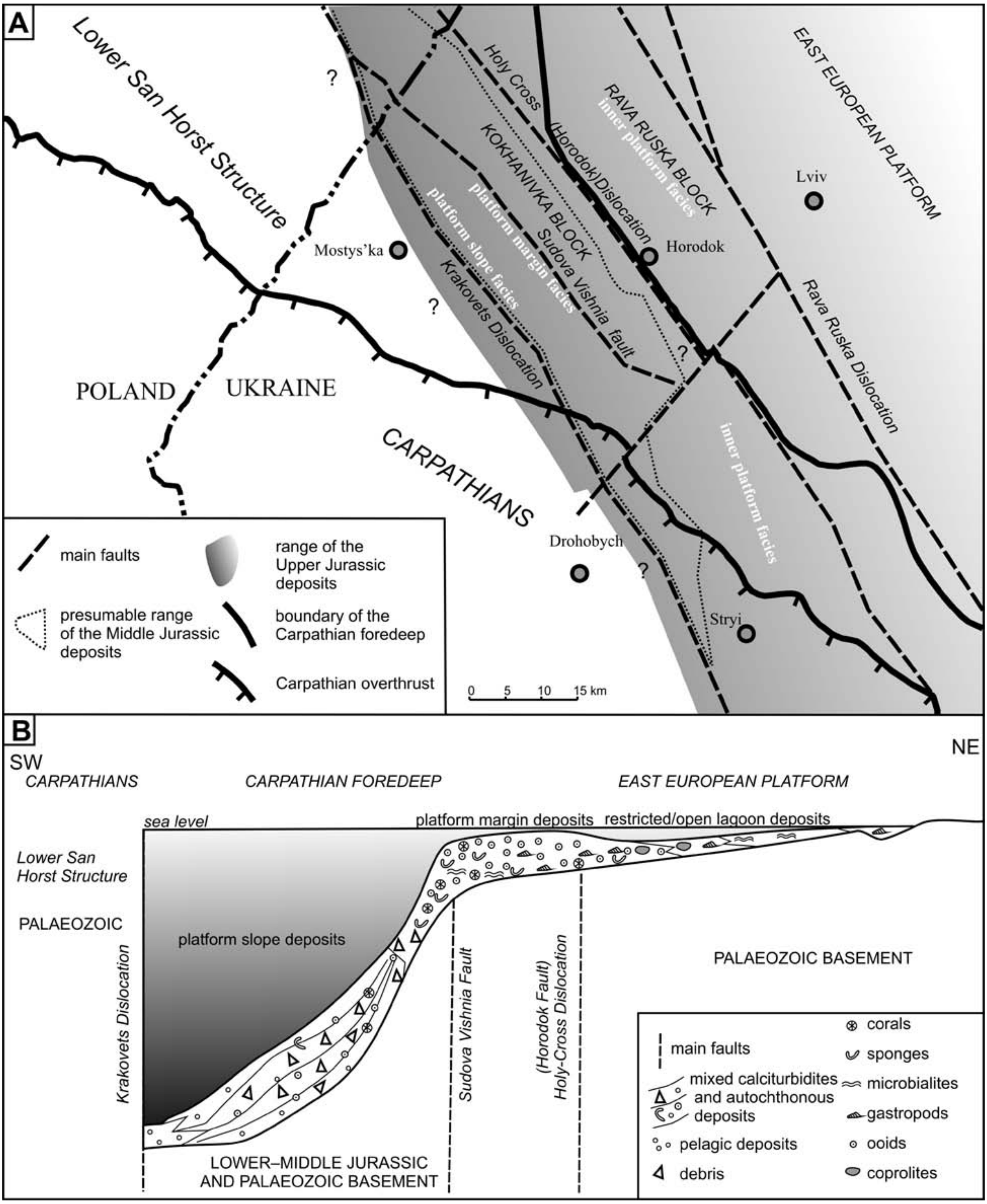

Fig. 10. **A** – Upper Jurassic (Kimmeridgian–Tithonian) facies development versus main Palaeozoic fault zones in the Ukrainian part of the Carpathian Foredeep basement (after Buła & Habryn, 2010, 2011; modified). Generally, facies distribution is parallel to the strikes of main fault zones. **B** – Idealized model of Kimmeridgian–Tithonian sedimentation and facies distribution in the rimmed platform from the Ukrainian part of the Carpathian Foredeep basement versus main tectonic units of the Palaeozoic basement (not to scale)

wells (*cf*. Zhabina & Anikeyeva, 2007), these structures have not been well-documented in the published papers. The bioherms and biostromes were described as mass occurrence of sponges with marl and clay interlayers (*e.g.*, Dulub & Zhabina, 1999; *cf*. Trammer, 1982; Olóriz *et al.*, 2003). It seems likely that such buildups do not represent larger reef complexes of massive limestone with well-developed rigid framework, which are seen in the Polish part of the foredeep basement as well as in other settings in Europe (*e.g.*, Keupp *et al.*, 1990; Leinfelder *et al.*, 1994, 1996;

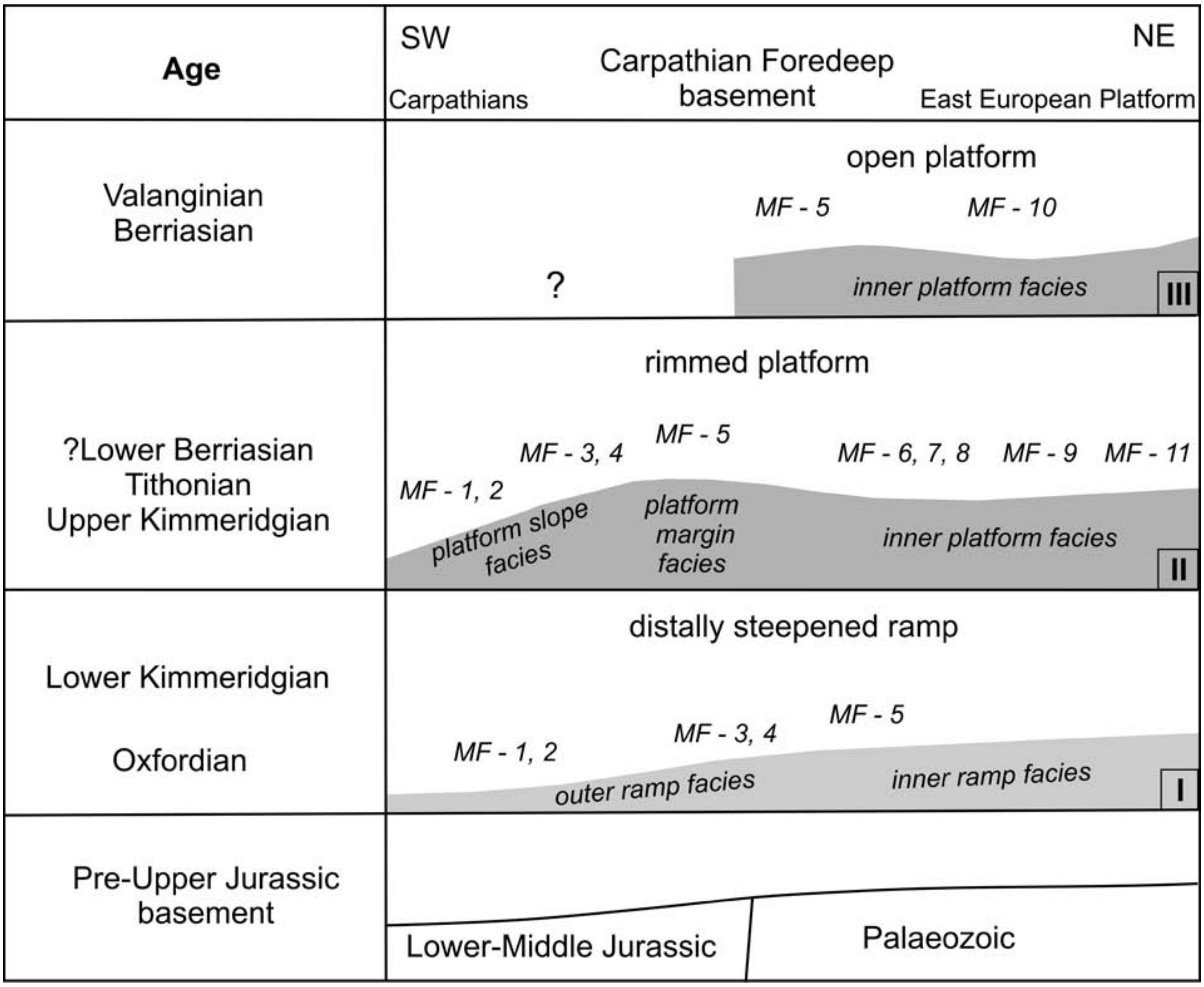

Fig. 11. Model presenting main stages of the evolution of the Late Jurassic–Early Cretaceous carbonate platform in the Ukrainian part of the Carpathian Foredeep basement with most common microfacies. (I) distally steepened ramp stage mainly corresponded to the pre-Late Jurassic morphology of the basement, (II) rimmed platform stage was connected with synsedimentary tectonics in the SW border of the East-European Platform, (III) open platform evolution stage was mainly connected with small sea level changes

Matyszkiewicz, 1997; Krajewski, 2000; Matyszkiewicz *et al.*, 2006a, b; Gutowski *et al.*, 2007) where the Oxfordian strata are thicker and form extended, microbial-sponge reef complexes. Instead, this is rather a bedded facies locally enriched in sponges. In the north-eastern part of the study area, in a narrow zone, the microbial-sponge deposits grade into the shallow-water facies with abundant corals, bioclasts and ooids (*e.g.*, in the Bortiatyn 1 well, Fig. 3). These results indicate that the transition from shallow- to deep-water environment might have proceeded over a narrow, homoclinal ramp or, what is more probable, over a distally steepened ramp controlled by the relief of the pre-Upper Jurassic basement. This may explain the narrow zone of deep-to-shallow facies transition without the distinct barrier.

The Lower Kimmeridgian succession (*e.g.*, in the Bortiatyn 1 and Podil'tsi 1 wells; Fig. 3) encompasses the facies, in which numerous bioclasts and micritized ooids are accompanied by mixed, siliciclastic-carbonate deposits: claystones, calcareous sandstones and conglomerates known from the literature as the "Variegated Horizon" (Fig. 6F; Dulub & Zhabina, 1999; Gutowski *et al.*, 2005a; Olszewska, 2010). Data from most of the studied drill cores taken in the south-western part of the area, supported by geological data from many other wells, allow the authors to conclude that this horizon occurs in the bottom parts of the Lowermost Kimmeridgian successions (Fig. 3; Gutowski *et al.*, 2005a; Olszewska, 2010).

The Lower Kimmeridgian "Variegated Horizon" is covered by a thick complex of highly diversified limestones and marly limestones (Fig. 3). The Kimmeridgian succession is locally up to 500 m thick (Podil'tsi 1 well) but usually its thickness is about 400 m (Fig. 3). Initially, in the south-western part of the study area the dominating sedimentary environment was similar to that observed in the Upper Oxfordian strata, in which spicules, *Saccocoma*, radiolarian wackestones and mudstones were abundant. The resulting limestones and marly limestones represent deep-water, outer platform facies (*e.g.*, Flügel, 2004, p. 722). Towards the platform centre, these deposits grade into bioclastic limestones, partly dolomitized and containing anhydrite; these are the inner platform facies types (*e.g.*, Didushychi 1, 2 and Verchany 1 wells; Dulub & Zhabina, 1999; Zhabina & Anikeyeva, 2007). In the study area, carbonate deposition attained full development in the Late

Kimmeridgian. In its south-western part (*e.g.*, Moryantsi 1, Karolina 1, Bortiatyn 1 and Podil'tsi 1 wells, Fig. 3) the importance of the platform slope sediments increases up the sequence. These are several layers of calciturbidites composed of allochthonous, detrital material, that is grains typical of marginal, shallow-water platform facies and autochthonous wackestones-mudstones. To the northeast, the platform slope sediments grade into platform margin facies, as observed in the Podil'tsi 1 and Lanivka 1 wells (Fig. 3), and in others. These deposits are composed of ooidal-bioclastic facies, rarely of facies with abundant corals and sponges. Data from numerous wells indicate that the barrier zone extended northwest–southeast. In the literature, this zone is called "the Opary Reef" (Dulub & Zhabina, 1999; Gutowski *et al.*, 2005a; Karpenchuk *et al.*, 2006; Zhabina & Anikeyeva, 2007). Facies of the platform margin grade towards the northeast, into the inner platform facies (Fig. 10) represented by peritidal, peloid-bioclastic wackestones-mudstones with coprolites, gastropods, bivalves, oncoids and evaporates. Taking into account the results of studies and collected data, the authors conclude that the Upper Kimmeridgian–Tithonian succession initially reflected the continuation of Oxfordian deposition in an environment of distally steepened ramp, which then evolved into the rimmed platform of the Late Kimmeridgian. The Tithonian sediments reach a thickness of about 600 m in the south-western part of the study area (Fig. 3). Generally, the Tithonian succession is a continuation of the rimmed platform deposition, which progresses to the southwest. In the south-western part of the study area the calciturbidites are observed, which (like the Upper Kimmeridgian carbonates) contain detrital sediments redeposited from the platform margin, as noticed for instance in the cores from the Karolina 6 and the Moryantsi 1 wells (Fig. 3). Some limestones show a nodular structure, typical of debris flow sediments laid down onto the platform slope. Among redeposited clasts, fragments of biolithites and oolitic facies are common, produced by erosion of marginal-platform, coral-microbial-sponge reefs and ooidal-bioclastic barriers. Towards the northeast, the platform margin facies grades into the inner platform peritidal and brackish ones (Kokhanivka 26 well). It is worth to note that these deposits correspond to the Lower Berriasian facies known from the Polish part of the Carpathian foredeep basement (*cf.* Zagorzyce 7 well; Zdanowski *et al.*, 2001; Krajewski *et al.*, 2011), which, in turn, are very similar to the Lower Berriasian Purbeckian facies known from many settings in Europe (*e.g.*, Strasser, 1988; Flügel, 2004, p. 766).

In the Berriasian and perhaps also in the Valanginian, sedimentation in the whole of the study area was dominated by ooidal-bioclastic-bryozoan facies, similar to that observed in the Polish part of the Carpathian Foredeep basement (Zdanowski *et al.*, 2001; Urbaniec *et al.*, 2010; Krajewski *et al.*, 2011). Recently, both the Berriasian and Valanginian sediments have been found mainly in the north-eastern part of the study area, for instance in the Didushychi 1, 2 and the Verchany 1 wells, whereas in the south-western part of the study area these strata were removed by erosion controlled by tectonic events. Relatively uniform development of Lower Cretaceous sediments points out that they were deposited mainly in the not-rimmed, open platform environment where synsedimentary tectonic episodes were absent.

Basing on sediment facies pattern compared to the Palaeozoic basement structure, the authors suggest that sedimentation of Mesozoic sequences was closely related to the block structure of the basement and to synsedimentary tectonics (Fig. 10; Gutowski & Wybraniec, 2006). In the Ukrainian part of the Carpathian Foredeep, numerous northwest-southeast-striking faults were indentified. Certainly, these faults of Palaeozoic provenance (Buła & Habryn, 2010, 2011) were active also in the Mesozoic, as indicated by close correspondence of the Upper Jurassic facies to the strikes of faults. This is particularly well-visible in the zone between the Krakovets and the Holy-Cross (Horodok) fault zones (Fig. 10) where a swarm of faults is developed (*e.g.*, Sudova-Vishnia Fault; Karpenchuk *et al.*, 2006; Buła & Habryn, 2011). Facies diversity observed in the Upper Kimmeridgian–Tithonian sediments of the platform slope suggests that the marine platform and the inner platform were influenced by tectonic history of the Palaeozoic Kokhanivka Block between the Krakovets and the Holy Cross fault zones (Fig. 10). Possible connections of Jurassic sedimentation with both the palaeorelief and synsedimentary tectonics were pointed out also by some Polish and Ukrainian authors (*e.g.*, Gutowski et al., 2006; Gutowski & Wybraniec, 2006; Karpenchuk *et al.*, 2006). The importance of synsedimentary tectonics for the development of rimmed platform is particularly evident in the Upper Kimmeridgian–Tithonian succession. Towards the EEP, the inner and peri-shore facies were observed over the Rava Ruska Palaeozoic Block, located between the Holy Cross and Rava Ruska fault zones (Fig. 10).

CONCLUSIONS

The results of studies enabled the authors to distinguish eleven basic Upper Jurassic–Lower Cretaceous microfacies varieties in the studied part of the Carpathian Foredeep basement. In a narrow zone of the study area, three main stages of platform development are evident: (i) distally steepened ramps, (ii) rimmed platform, and (iii) not-rimmed platform. The first stage is represented by deep-water, outer ramp and shallow-water, carbonate and siliciclastic inner ramp sediments, mostly of the Late Oxfordian age. This stage ceased with the deposition of the Lower Kimmeridgian, mixed siliciclastic/carbonate strata. The second stage includes Kimmeridgian and Tithonian sediments laid down in the rimmed platform environment. Facies diversity clearly indicates the platform slope sediments with numerous calciturbidites as well as ooidal-bioclastic, marginal platform barriers and, rarely, coral-sponge patch-reefs, and inner-platform peritidal deposits. The third stage includes Berriasian and, probably, Valanginian, mostly detrital sediments of shallow-water, open platform.

Microfacies studies combined with literature data indicate that lithology and development of the Upper Jurassic deposits in both the Ukrainian and Polish Carpathian Foredeep basement show considerable differences. In the

Polish part, vast microbial-sponge facies with well-developed, large reef complexes can be observed in the Oxfordian, rarely in the Kimmeridgian and in the Tithonian strata known from outcrops and wells, while in the Ukrainian part this facies is limited to a narrow zone only. In the Ukrainian part of the Carpathian Foredeep basement, in the Kimmeridgian and especially in the Tithonian, a distinct, narrow marginal platform barrier existed close to the EEP, while in the Polish part, in the Tithonian, sedimentation proceeded in vast homoclinal mid-ramp environments. However, similar sedimentary conditions representing the inner platform facies appeared in the Lower Cretaceous in the Polish part, and in the uppermost Jurassic–Lower Cretaceous in the Ukrainian part of the foredeep basement.

The studies revealed close relationships between the Upper Kimmeridgian–Tithonian facies distribution and the main tectonic units in the region, controlled by block structure of the Palaeozoic basement. In the area situated over the Palaeozoic Kokhanivka Block, between the Krakovets and Holy Cross fault zones, the slope-marginal and inner platform facies predominate. On the other hand, only inner platform and peri-shore facies do occur over the Rava Ruska Block, placed between the Horodok and Rava Ruska fault zones. The oolite-bioclastic barrier facies (rarely reefs), separating the platform slope from the inner platform settings, extends along a fault system discovered southwest of the Holy Cross Fault Zone. This suggests that the main fault zones were active also in the Mesozoic and closely controlled Jurassic sedimentation in the Carpathian Foredeep basement.

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