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A LOST CARBONATE PLATFORM DECIPHERED FROM CLASTS EMBEDDED IN FLYSCH: ŠTRAMBERK-TYPE LIMESTONES, POLISH OUTER CARPATHIANS

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Abstract: Limestones designated the Štramberk-type are the most common carbonate exotic clasts (exotics) embedded in the uppermost Jurassic–Miocene flysch deposits of the Polish Outer Carpathians. About 80% of stratigraphically determinable carbonate exotics from the Silesian, Sub-Silesian and Skole units (nappes) are of Tithonian (mostly)–Berriasian (sporadically Valanginian) age. A study of these exotics revealed eight main facies types: coral-microbial boundstones (FT 1), microencruster-microbial-cement boundstones (FT 2), microbial and microbial-sponge boundstones (FT 3), detrital limestones (FT 4), foraminiferal-algal limestones (FT 5), peloidal-bioclastic limestones (FT 6), ooid grainstones (FT 7), and mudstones-wackestones with calpionellids (FT 8). Štramberk-type limestones in Poland and the better known Štramberk Limestone in the Czech Republic are remnants of lost carbonate platforms, collectively designated the Štramberk Carbonate Platform. Narrow platforms were developed on intra-basinal, structural highs (some of them are generalized as the Silesian Ridge), with their morphology determined by Late Jurassic synsedimentary tectonics. An attempt was made to reconstruct the facies distribution on the Tithonian–earliest Cretaceous carbonate platform. In the inner platform, coral-microbial patch-reefs (FT 1) grew, while the upper slope of the platform was the depositional setting for the microencruster-microbial-cement boundstones (FT 2). Microbial and microbial-sponge boundstones (FT 3), analogous to the Oxfordian–Kimmeridgian boundstones of the northern Tethyan shelf (also present among exotics), were developed in a deeper setting. In the inner, open part of the platform, foraminiferal-algal limestones (FT 5) and peloidal-bioclastic limestones (FT 6) were deposited. Poorly sorted, detrital limestones (FT 4), including clast-supported breccias, were formed mainly in a peri-reefal environment and on the margin of the platform, in a high-energy setting. Ooid grainstones (FT 7), rarely represented in the exotics, were formed on the platform margin. Mudstones-wackestones with calpionellids (FT 8) were deposited in a deeper part of the platform slope and/or in a basinal setting. In tectonic grabens, between ridges with attached carbonate platforms, sedimentation of the pelagic (analogous to FT 8) and allodapic ("pre-flysch") Cieszyn Limestone Formation took place. The most common facies are FT 4 and FT 1. Sedimentation on the Štramberk Carbonate Platform terminated in the earliest Cretaceous, when the platform was destroyed and drowned. It is recorded in a few exotics as thin, neptunian dykes (and large dykes in the Štramberk Limestone), filled with dark, deep-water limestones. Reefal facies of the Štramberk Carbonate Platform share similarities in several respects (e.g., the presence of the microencruster-microbial-cement boundstones) with reefs of other intra-Tethyan carbonate platforms, but clearly differ from palaeogeographically close reefs and coral-bearing facies of the epicontinental Tethyan shelf (e.g., coeval limestones from the subsurface of the Carpathian Foredeep and the Lublin Upland in Poland; the Ernstbrunn Limestone in Austria and Czech Republic). Corals in the Štramberk Limestone and Štramberk-type limestones are the world's most diverse coral assemblages of the Jurassic–Cretaceous transition.

The intra-basinal ridge (ridges), traditionally called the Silesian Cordillera, which evolved through time from an emerged part of the Upper Silesian Massif to an accretionary prism, formed the most important provenance area for carbonate exotic clasts in the flysch of the Silesian Series. They are especially common in the Lower Cretaceous Hradiště Formation and the Upper Cretaceous–Paleocene Istebna Formation. The Baška-Inwałd

Ridge and the Sub-Silesian Ridge were the source areas for clasts from the Silesian and Sub-Silesian units (e.g., in the Hradiště Formation), while the Northern (Marginal) Ridge was the source for clasts from the Skole Unit (e.g., in the Maastrichtian–Paleocene Ropianka Formation).

Key words: Reefs, facies, Štramberk Limestone, Silesian Ridge, Jurassic, Cretaceous, Carpathian Basin, Poland.

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INTRODUCTION

In the Polish Outer Carpathians, shallow-water carbonate sedimentation is recorded only by carbonate clasts, redeposited bioclasts, and very rare, small, unrooted, poorly exposed klippen. Clasts of limestones are exotic to the dominant siliciclastic, uppermost Jurassic–Miocene flysch deposits. They were derived from extrabasinal and intra-basinal source areas of the Carpathian rocks, which periodically emerged and were destroyed. Such rocks were described as "exotic" since the 19th century ("exotischen Graniten", "exotische Blöcke"; Morlot, 1847; Hohenegger, 1861). In the general geological literature, the term "exotic clasts" is usually used (Flügel, 2010, p. 172), whereas in the Polish geological literature, the term "exotics" (Polish "egzotyki" including also carbonate exotics), is also commonly applied. On the basis of fossils, facies and microfacies, these clasts (pebbles, rarely blocks) are mostly described as Devonian–Carboniferous (Malik, 1978, 1979; Burtan *et al*., 1983; Tomaś *et al*., 2004) and Upper Jurassic–lowermost Cretaceous (the present paper and references therein), more rarely Middle Jurassic (Książkiewicz, 1935, 1956a; Barczyk, 1998; Olszewska and Wieczorek, 2001), Early Cretaceous (Oszczypko *et al*., 1992, 2006, 2020; Krobicki *et al*., 2005), Late Cretaceous (Książkiewicz, 1956a; Gasiński, 1998) and Palaeogene in age (Leszczyński, 1978; Rajchel and Myszkowska, 1998; Leszczyński *et al*., 2012; Minor-Wróblewska, 2017).

At the beginning of these studies, the focus was on small, unrooted klippen, namely the Andrychów Klippen (called also Klippes) near Wadowice (Zeuschner, 1849; Hohenegger, 1861; Uhlig, 1904; Książkiewicz, 1935, 1971b; Nowak, 1976; Gasiński, 1998; Olszewska and Wieczorek, 2001), and in Kruhel Wielki, near Przemyśl (Niedźwiedzki, 1876; Wójcik, 1907, 1913, 1914; Bukowy and Geroch, 1956; Morycowa, 1988; Olszewska *et al*., 2009), now poorly exposed. Subsequently, exotic pebbles, much more common and providing data on more facies, were studied more frequently. The first attempt to describe exotics, including crystalline rocks, was presented by Nowak (1927). Jurassic–Cretaceous carbonate exotics at Bachowice, containing facies unknown at other localities in the Polish Outer Carpathians, were described by Książkiewicz (1956a). The preliminary results of studies, which encompassed the entire spectrum of carbonate exotics from the western part of the Polish Outer Carpathians, were presented by Burtan *et al.* (1984). Malik (1978, 1979) described both Palaeozoic and Mesozoic carbonate clasts in the Hradiště Sandstone of the Silesian Unit, but other studies were mostly concerned with the Štramberk-type limestones from selected outcrops. The studies of these limestones, if concerned with exotics at many localities, were focused on their fossil content (e.g., Kołodziej, 2003a; Bucur *et al*., 2005; Ivanova and Kołodziej, 2010; Kowal-Kasprzyk, 2014, 2018) or presented only the preliminary results of facies studies (e.g., Hoffmann and Kołodziej, 2008; Hoffmann *et al*., 2008).

Carbonate platforms, the existence of which was deciphered from detrital carbonate components, are called lost carbonate platforms (e.g., Belka *et al*., 1996; Flügel, 2010; Kukoč *et al*., 2012). Clasts and other shallow-water components are, metaphorically, witnesses to lost carbonate factories (the term is taken from Coletti *et al*., 2015). Analyses of the age and lithology of exotic clasts have been applied in the reconstruction of the provenance areas of the clasts and their palaeogeography and the development of the sedimentary sequences of the Polish Outer Carpathians (e.g., Książkiewicz, 1956b, 1962, 1965; Unrug, 1968; Oszczypko, 1975; Oszczypko *et al*., 1992, 2006; Hoffmann, 2001; Krobicki, 2004; Słomka *et al*., 2004; Malata *et al*., 2006; Poprawa and Malata, 2006; Poprawa *et al*., 2006a, b; Strzeboński *et al*., 2017; Kowal-Kasprzyk *et al*., 2020).

Štramberk-type limestones are most common among the exotics. It is a field term that refers to limestones, mostly beige in colour, that are supposed to be the age and facies equivalents of the Tithonian–lower Berriasian Štramberk Limestone in Moravia (Czech Republic; Eliáš and Eliášová, 1984; Picha *et al*., 2006). The Štramberk Limestone and the Štramberk-type limestones of both countries were deposited on platforms, attached to the intrabasinal ridges and margins of the basin of the Outer Carpathians. These platforms are collectively termed the Štramberk Carbonate Platform.

The terms "Štramberk Limestone" and "Štramberk-type limestones" have been widely used in the area of the former Austro-Hungarian Empire for the field description of shallow-water limestones of assumed Late Jurassic age, usually occurring within flysch deposits of the Outer Carpathians. Upper Jurassic–lowermost Cretaceous shallow-water limestones in Romania (commonly forming mountains or ridges, e.g., Pleş *et al*., 2013, 2016), in Bulgaria and Serbia (Tchoumatchenco *et al*., 2006), and Ukraine (Krajewski and Schlagintweit, 2018), and in Turkey (Masse *et al*., 2015) sometimes are referred to as the Štramberk-type limestones as well. In the Austrian-German literature similar limestones in the Alps are known as the Plassen Limestone (e.g., Steiger and Wurm, 1980; Schlagintweit *et al*., 2005). Biostratigraphic studies revealed that some carbonate clasts, accounting for several percent of the exotics and commonly called Štramberk-type limestones in the field, are in fact of Oxfordian–Kimmeridgian age. These limestones were generally deposited in a deeper environment than were most facies of the Štramberk-type limestones *sensu stricto* (Nowak, 1976; Olszewska and Wieczorek, 2001; Kowal-Kasprzyk, 2016; Kowal-Kasprzyk *et al*., 2020).

The Štramberk Limestone occurs as olistoliths, blocks, and as smaller clasts in breccias and conglomerates in the Cretaceous flysch deposits of the Silesian Unit of the Outer Carpathians, Czech Republic (Moravia, mostly in the Kotouč Quarry, near Štramberk; Stramberg in the older literature). They are interpreted as the deposits of a carbonate platform, developed on the Baška Ridge, in the northern part of the Outer Carpathian basin (Eliáš and Eliášová, 1984; Picha *et al*., 2006).

The Štramberk Limestone is rich in fossils, intensively studied already in the 19th century (for references: Blaschke, 1911; Vašíček and Skupien, 2004, 2005), including the world's most diversified coral fauna of Tithonian–Berriasian age (e.g., Ogilvie, 1897; Eliášová, 1975, 1978, 1981a, 2008). The results of the detailed studies of Ogilvie (1897) on these coral assemblages, unique in many respects (128 species, including many endemic taxa) were communicated to a wider scientific community in *Nature* by Gregory (1898). Some of corals described by Ogilvie (1897) came from limestone blocks in the Silesian Nappe, Cieszyn, Silesia, in the western part of the Polish Carpathians, for example at the localities Iskrzyczyn (German name Iskritschin), Skoczów (Skotschau), Ustroń (Ustron), Wilamowice (Willamowitz), and Wiślica (Wischlitz); see also Geyer (1955). Maria Ogilvie Gordon started her career with studies of corals from the Štramberk Limestone. She was one of the prolific researchers of the later 19th century, a famous researcher on the Dolomites, in the Alps (Wachtler and Burek, 1997).

The Štramberk-type limestones in Poland were the subject of papers on microfossils and rarely on macrofossils, mostly corals (Table 1; short reviews in Kołodziej, 2015a, b; Salamon and Trzęsiok, 2015; Kowal-Kasprzyk, 2018), but there are rare sedimentological contributions, mostly concerned with the microfacies of the exotic clasts at selected sites. The Štramberk Limestone was rarely studied in terms of sedimentology (Eliáš and Eliášová, 1984, 1986; Hoffmann *et al*., 2017). The limestones in the Carpathians of the Czech Republic and Poland deserve attention, because they are relatively rare examples of carbonate platforms, especially reefs, developed in the Tithonian and earliest Cretaceous. They are known mostly from the area of the earlier Tethyan domain (e.g., Steiger and Wurm, 1980; Eliáš and Eliášová, 1984; Morsilli and Bosellini, 1997; Shiraishi and Kano, 2004; Săsăran, 2006; Ivanova *et al*.,

Table 1

List of papers on micro- and macrofossils from the Štramberk-type limestones, Polish Outer Carpathians. Some palaeontological papers on the Štramberk Limestone published in the 19th century and at the beginning of 20th century (e.g., the paper on corals by Ogilvie, 1897) included descriptions of fossils from exotic clasts from the Cieszyn Silesia, western part of the Polish Outer Carpathians. These papers are not included in the list (see Blaschke, 1911).

Group of fossils	References
Algae (benthic)	Olszewska and Wieczorek (2001), Bucur *et al.* (2005)
Ammonites	Książkiewicz (1963, 1974)
Bivalves	Wójcik (1913, 1914), Książkiewicz (1963, 1974)
Brachiopods	Zeuschner (1857), Wójcik (1913, 1914), Książkiewicz (1974), Smirnova (1975)
Bryozoa	Hara and Kołodziej (2001)
Calcareous dinoflagellate cysts	Olszewska and Wieczorek (2001), Olszewska *et al.* (2011), Strzeboński *et al.* (2017)
Calpionellids and chitinoidellids	Morycowa (1964a, 1968, 1988), Geroch and Morycowa (1966), Olszewska and Wieczorek (2001), Ciborowski and Kołodziej (2001), Olszewska *et al.* (2011), Kowal-Kasprzyk (2014, 2018)
Corals	Morycowa (1964a, 1968, 1974, 2008), Kołodziej (1995, 1997b, 2003a, 2015b)
Crinoids	Salamon and Gorzelak (2010), Hess *et al.* (2011), Lach *et al.* (2015), Trzęsiok (2015)
Crustaceans	Patrulius (1966), Müller *et al.* (2000), Krobicki and Fraaije (2017)
Echinoids	Kroh (2015)
Foraminifera	Geroch and Morycowa (1966), Kołodziej (1997a), Kołodziej and Decrouez (1997), Król and Decrouez (2002), Decrouez and Morycowa (1997), Olszewska and Wieczorek (2001), Ivanova and Kołodziej (2004, 2010), Olszewska *et al.* (2011), Kowal-Kasprzyk (2016), Łapcik *et al.* (2016), Strzeboński *et al.* (2017)
Gastropods	Książkiewicz (1963)
Microproblematica	Kołodziej and Decrouez (1997), Kołodziej, (1997a), Bucur *et al.* (2005), Hoffmann *et al.* (2008), Kołodziej (2015b), Kołodziej *et al.* (2015), Kowal-Kasprzyk (2015, 2016)
Sponges (calcified sponges/ sclerosponges)	Podoba (2009)

2008, 2015; Krajewski, 2008; Schlagintweit and Gawlick, 2008; Rusciadelli *et al*., 2011; Ohga *et al*., 2013; Pleş *et al*., 2013, 2019; Chatalov *et al*., 2015; Kaya and Altıner, 2015; Hoffmann *et al*., 2017; Atasoy *et al*., 2018; Ricci *et al*., 2018a, b; Mircescu *et al*., 2019; Nembrini *et al*., 2021; and Leinfelder *et al*., 2002 for more references), in contrast to the Oxfordian–Kimmeridgian reefs of the Tethyan shelf (Leinfelder *et al*., 2002). The Oxfordian and Kimmeridgian were times of strong coral reef development (Insalaco *et al*., 1997; Leinfelder *et al*., 2002). Falling sea levels in the Tithonian and across the Jurassic–Cretaceous boundary (Haq *et al*., 1988) resulted in a marked decline in the extent of the reefs (Leinfelder *et al*., 2002; Kiessling, 2008; Tennant *et al*., 2017).

The aims of the present paper are to (1) describe the main facies represented in exotics of the Štramberk-type limestones, (2) attempt to interpret their depositional environments, (3) propose the facies distribution on the carbonate platform, and (4) discuss their palaeogeographical constraints.

GEOLOGICAL SETTING

Geological background

The exotics were collected in the Polish Outer Carpathians, known also as the Flysch Carpathians (Fig. 1). These mountains constitute part of the Western Carpathians, which belong to the Alpine-Carpathian orogenic belt. Geographically, this area is situated in southern Poland, in the Beskidian Piedmont and in the Beskidy Mountains. Tectonically, the Outer Carpathians are composed of several nappes (e.g., Książkiewicz, 1977). The Outer Carpathian nappes originated in the Miocene, as a result of continental plate collision (e.g., Ślączka, 1996; Oszczypko, 1997, 2004; Golonka *et al*., 2000, 2006b). The ridges separating the basins were buried and subducted and the deposits of mainly the central parts of the basins are preserved (e.g., Sikora, 1976; Książkiewicz, 1977; Ślączka *et al.,* 2006).

Figure 2 shows the lithostratigraphy of the Silesian, Sub-Silesian and Skole series with the locations of the sites of the exotics studied (see also Table 2). The majority of the sample locations are situated in the Silesian Nappe – the second largest Outer Carpathian nappe, which continues

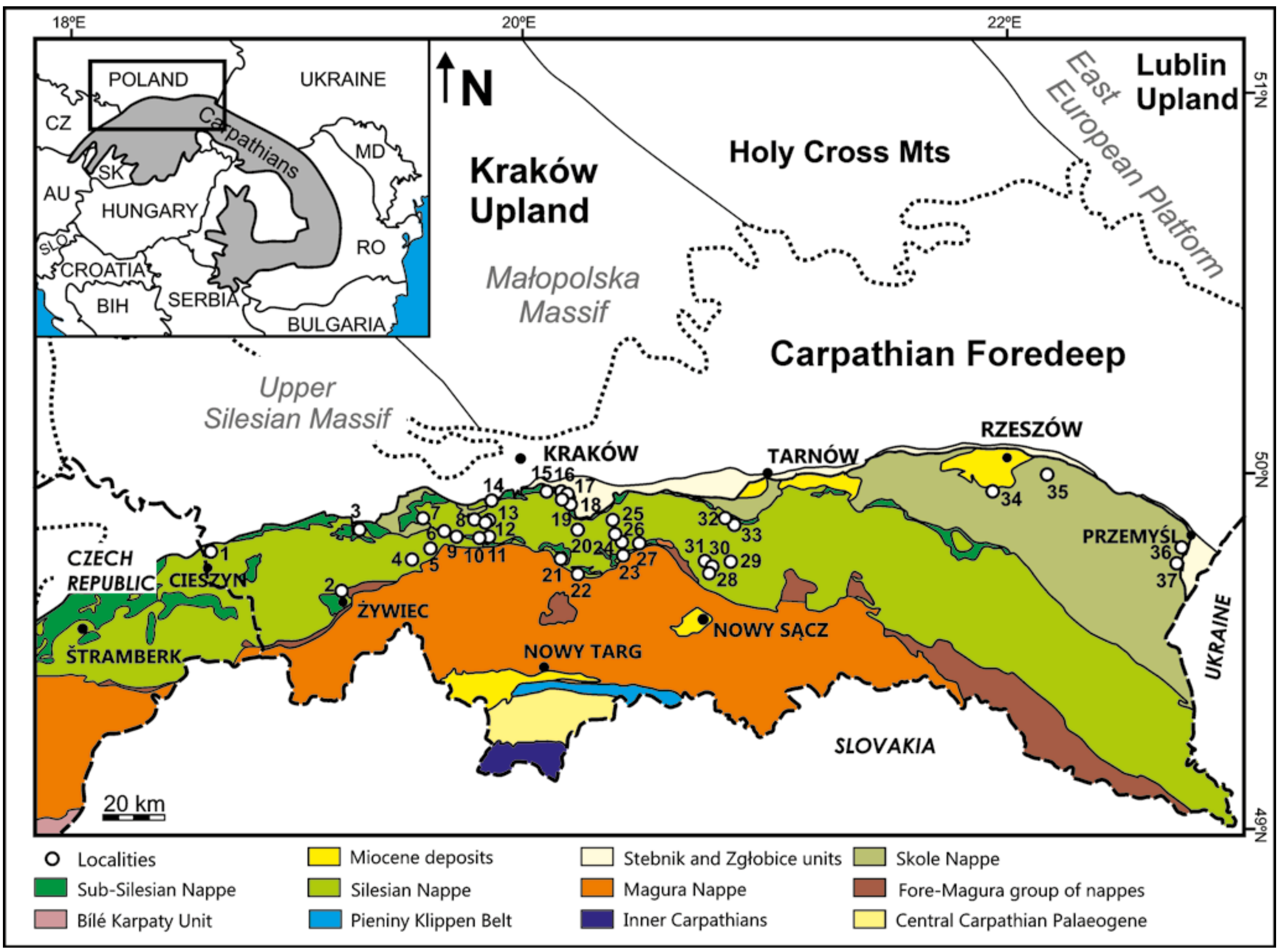

Fig. 1. Tectonic map of the Polish and part of the Czech Outer Carpathians (after Lexa *et al.*, 2000; Cieszkowski *et al.*, 2009, modified and simplified), and the position of the Polish Carpathians in the Carpathian belt. Numbers of localities – see Table 3. The simplified location of geological and geographical units discussed in the paper located north of the Carpathians is shown. Subsurface geological units are in italics.

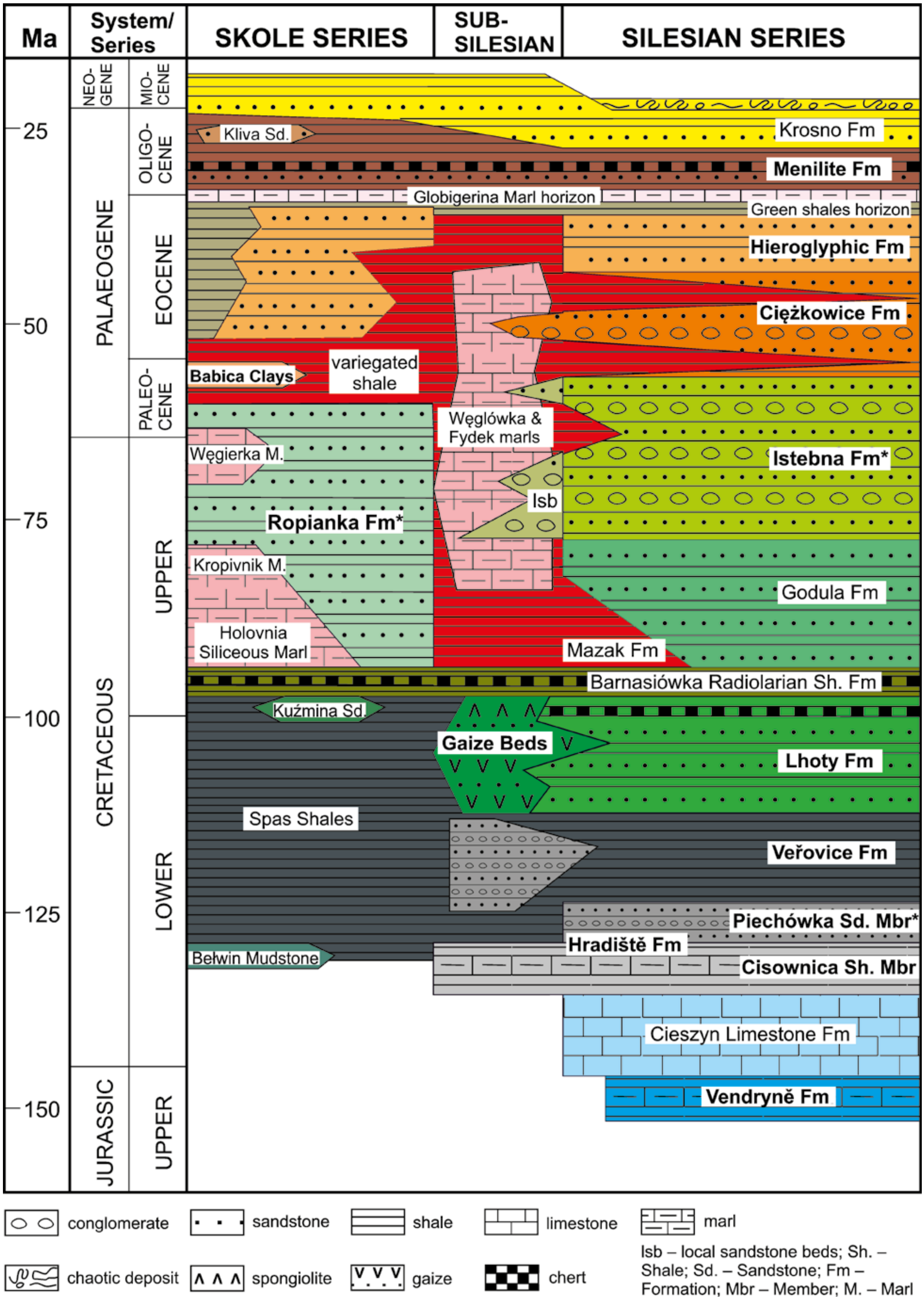

Fig. 2. Lithostratigraphic profiles for sedimentary series of the Silesian, Sub-Silesian and Skole nappes with the sites of the exotics studied. Names of lithostratigraphic units according to Ślączka *et al.* (2006), Cieszkowski *et al.* (2012), and Łapcik *et al.* (2016). Lithostratigraphic units, from which studied exotic clasts were sampled, are labelled in bold letters. Units indicated with the mark * are particularly rich in exotics.

in the areas of the Czech Republic and Ukraine. The sites with the exotics are also located in the lower nappes, i.e., the Sub-Silesian Nappe and the Skole Nappe. The Sub-Silesian Nappe occurs as narrow, discontinuous outcrops to the north of the Silesian Nappe. In the eastern part of the Polish Carpathians, these two nappes are thrust over the Skole Nappe. In the south, the Silesian Nappe borders with the Fore-Magura group of nappes and the Magura Nappe, the largest nappe of the Outer Carpathians. In the north, these nappes are thrust over the Miocene of the Carpathian Foredeep, and partly on the lower tectonic units, the Stebnik and Zgłobice units (the folded Miocene at the front of the Outer Carpathians). Exotics of the Štramberk-type limestones from the Fore-Magura group of nappes, the Magura Nappe and the Stebnik and Zgłobice units were not studied for this paper.

The Silesian, Sub-Silesian and Skole nappes are composed mainly of thick flysch sequences, which are latest Jurassic–Miocene in age, but the oldest (latest Jurassic) deposits are preserved only locally in the Silesian Nappe. Initially, the flysch sequences were deposited in one sedimentary basin, the Proto-Silesian Basin (e.g., Golonka *et al.*, 2006b; Waśkowska *et al.*, 2009), also termed the Severin–Moldavidic realm (Balintoni, 1998; Ślączka *et al.*, 2006), in Romania commonly referred as to the Outer Dacides and the Moldavides (e.g., Săndulescu, 1988). At the end of the Early Cretaceous, the Proto-Silesian Basin was developed again and deposition took place in several sub-basins separated by ridges (e.g., Książkiewicz, 1965; Golonka *et al.*, 2000). The Sub-Silesian Series was deposited in shallower conditions than the Silesian and Skole series, possibly on the slope of the Sub-Silesian Ridge (e.g., Ślączka *et al.*, 2006; Waśkowska *et al.*, 2009), and variegated shales and marls are relatively frequent there.

Provenance area of exotic carbonate clasts

The source areas of the exotic clasts and other detrital material of the flysch deposits of the Polish Outer Carpathians are not preserved. The Outer Carpathian Basin was composed of some isolated subbasins, subdivided by intrabasinal ridges (the cordilleras of Książkiewicz, 1956b, 1965). Together with the margins of the basins, they were source areas that periodically emerged and were eroded (Figs 4, 5), and finally consumed, mostly during the Miocene subduction (e.g., Sikora, 1976; Książkiewicz, 1977). The following

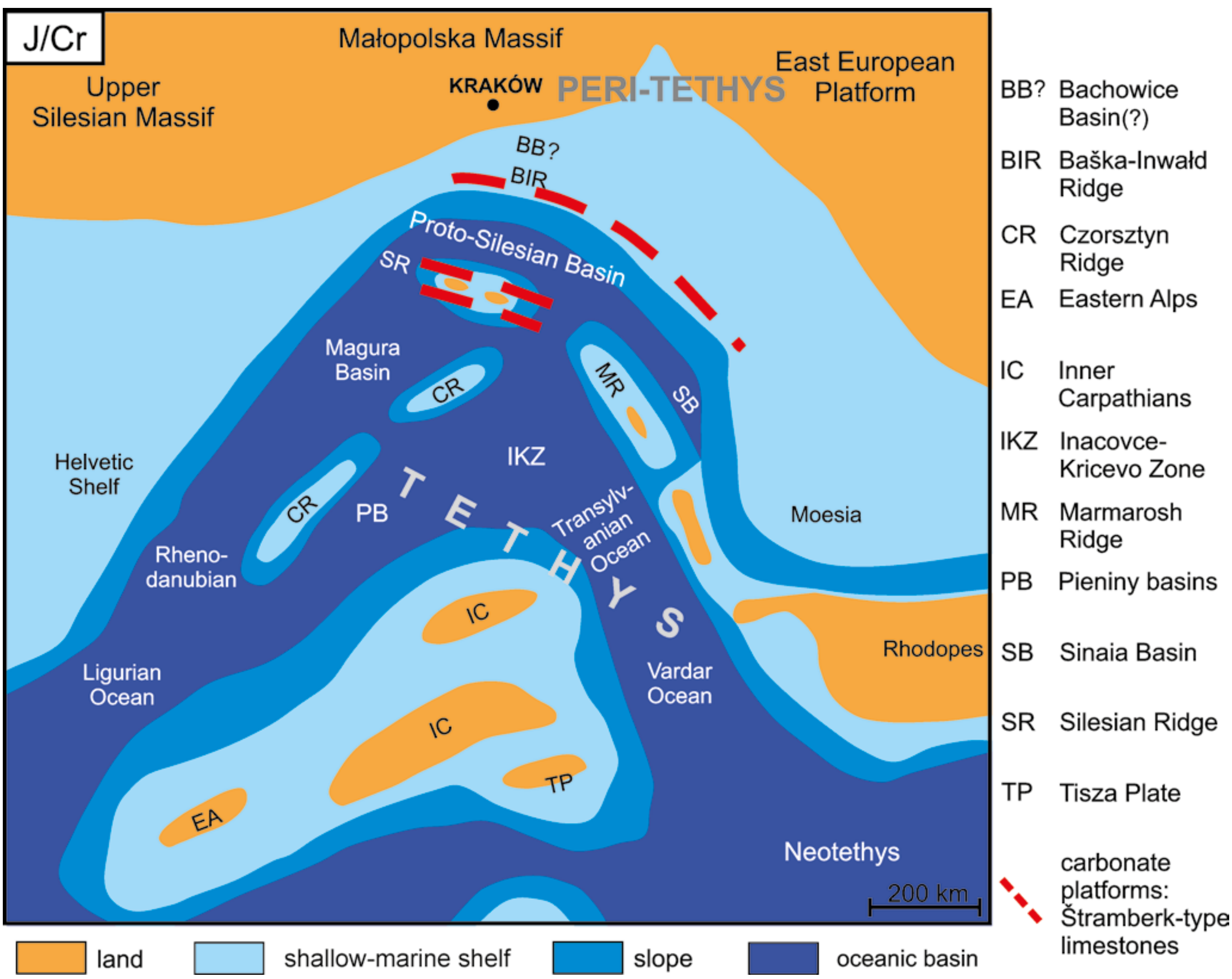

Fig. 3. Palaeogeography and palaeoenvironment of the circum-Carpathian area during the latest Late Jurassic–earliest Early Cretaceous with the location of the carbonate platforms of the Štramberk-type limestones (after Golonka *et al.*, 2006a, simplified and slightly modified).

deposits were eroded on the ridges: (1) previously deposited flysch (so-called "cannibalism" *sensu* Matyszkiewicz and Słomka, 1994), (2) sediments contemporaneous with the flysch, but representing different environments (e.g., shallow-water carbonates), and (3) pre-flysch deposits. In the Carpathians, some ridges were distinguished, from which the Silesian Cordillera (Książkiewicz, 1965; Unrug, 1968), recently referred to as the Silesian Ridge, was the most important. Traditionally, this ridge is described as existing since the Late Jurassic and was the stable provenance area, located between the Silesian (initially: Proto-Silesian) and Magura basins (Fig. 5). According to Unrug (1968), there is no need to postulate a large land as the provenance area, but possibly relatively small ridges were eroded. Hoffmann (2001), on the basis of analysis of exotics from the western part of the Polish Outer Carpathians, found that structures of different ages and different compositions were described under the term "the Silesian Ridge". In the Late Jurassic–Early Cretaceous, the Silesian Ridge possibly emerged as part of the Upper Silesian Massif (Brunovistulicum Terrane). Since the Albian–Turonian, the ridge was possibly a collision orogen, showing a thrust-nappe structure. It involved sediments of different environments, including Precambrian crystalline rocks, limestones of the Štramberk Carbonate Platform and the Cretaceous flysch. The development of the accretionary prism of the Silesian Ridge also was assumed by other authors (Soták, 1990; Poprawa *et al*., 2002, 2006a; Oszczypko, 2004; Poprawa and Malata, 2006; Cieszkowski *et al*., 2009).

The northern provenance area was active mostly in the early stage (till the end of the Early Cretaceous) of development the Proto-Silesian basin. It is thought that this area was the Baška-Inwałd Ridge, separating the Proto-Silesian Basin and the hypothetical Bachowice Basin (Figs 3–5; Książkiewicz, 1956a, 1965; Olszewska and Wieczorek, 2001; Golonka *et al*., 2008). The Bachowice Basin was supposed to be located north of the proto-Silesian Basin and the Baška-Inwałd Ridge (Książkiewicz, 1956a; Kowal-Kasprzyk *et al*., 2020). In the opinion of Hoffmann (2001), there was no broad Bachowice Basin. Hoffmann (2001) noticed the similarity in the lithologies of exotics from Bachowice with the southerly situated Cetechovice–Magura sedimentary unit (see Houša *et al*., 1963; Soták, 1990). He concluded that these sediments were included to the Sub-Silesian Unit during resedimentation and development of the accretionary prism of the orogen of the Silesian Ridge (see also Bucur *et al*., 2005, p. 108). The Baška Ridge (the Baška-Inwałd Ridge in the Polish literature) was the place where the Štramberk Limestone, known from Moravia, originated (Eliáš and Eliášová, 1984; Picha *et al*., 2006). The northern source area, especially since the Late Cretaceous, is commonly referred to as the Sub-Silesian (sometimes called Węglówka) Ridge. In the Sub-Silesian Unit, exotics, known mainly from the Lower Cretaceous deposits, are related to the later mentioned stage of intense activity of the Baška-Inwałd Ridge. Exotics in the younger Sub-Silesian flysch beds – deposited after the reorganisation of the Proto-Silesian Basin into several sedimentary areas – are not very common, because coarse-grained deposits occur only locally in this unit.

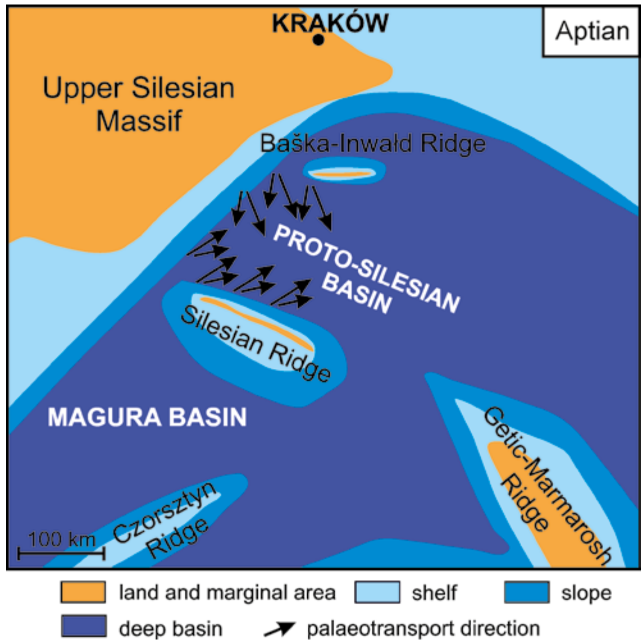

Fig. 4. Palaeotransport directions of detrital material in the western part of the Proto-Silesian Basin in the Aptian during deposition of the Veřovice Formation (after Golonka *et al.,* 2006a; Strzeboński *et al*., 2009).

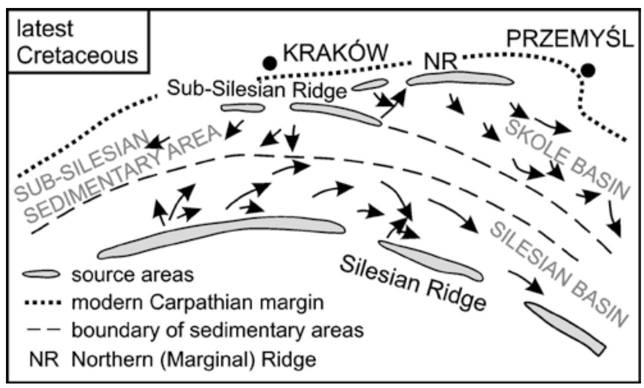

Fig. 5. Palaeotransport directions of detrital material in the northern Carpathian basins in the latest Cretaceous; deposition of the Lower Istebna Formation (directions in conglomerates and thick-bedded sandstones), Ropianka Formation and local sandstones beds in the Sub-Silesian Series (after Książkiewicz, 1962; Unrug, 1963). Note that tectonic rotations in the Outer Carpathians are not included.

Detrital material accumulating in the Skole Basin was derived from the Northern (Marginal) Ridge (Cordillera), meaning the southern part of the Upper Silesian and Małopolska massifs, and from the Sub-Silesian Ridge to the south (e.g., Książkiewicz, 1962; Łapcik *et al*., 2016; Łapcik, 2018 and literature therein).

Figures 4 and 5 present palaeogeographic maps, showing the palaeotransport directions of detrital material in two flysch lithostratigraphic units: transport from the northern and southern areas during the Early Cretaceous, and dominantly from the southern area during the Late Cretaceous (based on Książkiewicz, 1962; Unrug, 1968; Strzeboński *et al*., 2009).

Age of the studied limestones

"Štramberk-type limestones" is a field term. These limestones are traditionally believed to be the age and facies equivalent of the Štramberk Limestone, which is Tithonian–early Berriasian in age (e.g., Houša, 1990; Houša and Vašíček, 2004; Vašíček and Skupien, 2013, 2014, 2016, 2019; Vašíček *et al*., 2013; Vaňková *et al*., 2019), although a latest Kimmeridgian–early Berriasian age was also assumed (Houša, 1990; Houša and Vašíček, 2004). Until the 1980s, the Štramberk Limestone was commonly dated as Tithonian.

Both recent (Kowal-Kasprzyk, 2014, 2016, 2018) and earlier studies (summarized below; see also the review in Kołodziej, 2015a) showed that most exotic carbonate clasts, traditionally designated the Štramberk-type limestones, are of Tithonian–early Berriasian age. During field studies or even in microscopic studies, it is often impossible to determine the age of the Štramberk-type limestones. Recent studies of exotics, which could be in the field classified as the Štramberk-type limestones, revealed that some percentage of the determinable clasts represent the Oxfordian–Kimmeridgian (Kowal-Kasprzyk, 2016; Kowal-Kasprzyk *et al*., 2020).

Calpionellids are the best stratigraphic markers of the uppermost Jurassic and lowermost Cretaceous deposits. They were determined in the Štramberk-type limestones, including the coral-bearing facies, mainly by Morycowa (1964a, 1988), Ciborowski and Kołodziej (2001) and Kowal-Kasprzyk (2014, 2018), but they were noted also in other works (see Table 1). Generally, the late Tithonian Chitinoidella and Crassicollaria zones, as well as the early Berriasian Calpionella zone are well documented. Younger calpionellid zones were observed in the Kruhel Wielki klippe, where Morycowa (1988) described assemblages of latest Tithonian to early Valanginian age (Crassicollaria to Calpionellites zones). Although Morycowa (1988) did not classify the Valanginian–Hauterivian pelitic limestone blocks (with calpionellids and stomiospherids) from the Kruhel klippe as the Štramberk-type limestones, these limestones seem to be analogous to FT 8 of the present authors (see below).

In contrast to the Štramberk Limestone (Vašíček and Skupien, 2013, 2014, 2016; Vašíček *et al*., 2013), well preserved ammonites are very rare in the exotics. Książkiewicz (1974) described *Pseudovirgatites scruposus* (Oppel), implying an early late Tithonian age for the large limestone boulder at Woźniki.

Ivanova and Kołodziej (2010), on the basis of foraminifera determined the ages of 30 exotic clasts of the Štramberk-type limestones. Fifteen of them were not older than Tithonian, 13 not older than Berriasian, and at least two of them were Valanginian in age. However, some foraminiferal species, not known from before the Valanginian, may in fact occur in older strata. Vaňková *et al*. (2019) recognized that assemblages of the Berriasian peri-reefal limestones at Štramberk contain several taxa previously reported from the Valanginian. Some of the important studies on the shallow-water foraminifera, which appear also in the Štramberk-type limestones, were based on Lower Cretaceous profiles that did not include the Jurassic–Cretaceous boundary. New data from Romania indicate that *Meandrospira favrei* (Charollais, Brönnimann et Zaninetti), recognized in the Štramberk-type limestones (Ivanova and Kołodziej, 2010), is not restricted to Valanginian–Hauterivian, but occurs also in Berriasian (Krajewski and Olszewska, 2006; Bucur *et al.,* 2020).

Recently, Kowal-Kasprzyk (2016) provided new data on biostratigraphy, based on foraminifera and calcareous dinoflagellate cysts. Some of the earliest Cretaceous foraminiferal taxa have been observed with the late Tithonian calpionellid assemblages. The majority of the foraminifera occurring in the Štramberk-type limestones have relatively wide stratigraphic ranges; some of them occur both before and after the Tithonian–Berriasian interval. Numerous species first appear in the Tithonian, but are also common in the Lower Cretaceous deposits. An exclusively latest Kimmeridgian–Tithonian species is *Bulbobaculites elongatulus* (Dain). Taxa that first appeared before the Tithonian, but disappeared at the Jurassic–Cretaceous boundary (*Protopeneroplis striata* Weynschenk, *Pseudomarssonella*? *dumortieri* (Schwager), *Paleogaudryina varsoviensis* (Bielecka et Pożaryski)) or in the early Berriasian (*Paleogaudryina magharaensis* Said et Barakat, *Textularia depravatiformis* Bielecka et Kuznetsova) are also useful for stratigraphic purposes. *Pseudotextulariella courtionensis* Brönnimann is a Berriasian taxon. Several taxa (*Haplophragmoides cushmani* Loeblich et Tappan, *Haplophragmoides joukowskyi* Charollais, Brönnimann et Zaninetti, *Patellina subcretacea* Cushman et Alexander, *Hechtina praeantiqua* Bartenstein et Brand, *Nautiloculina cretacea* Peybernès) first appeared in the Berriasian and are also known from younger strata.

Calcareous dinoflagellate zones – often interval zones (e.g., Reháková, 2000) – are usually hard to determine in the exotics, because continuous profiles cannot be observed. Moreover, in the deposits of shallow zones, specimens of dinocysts are not very numerous. The biostratigraphic significance of calcareous dinoflagellate cysts is undoubted. In the Tithonian–Berriasian exotics, the most common are taxa with relatively wide ranges, such as *Crustocadosina semiradiata semiradiata* (Wanner), *Colomisphaera carpathica* (Borza). For this time interval, the most important stratigraphically are *Carpistomiosphaera borzai* (Nagy), *C. tithonica* Nowak, *Committosphaera pulla* (Borza), *Parastomiosphaera malmica* (Borza), *Colomisphaera tenuis* (Nagy), *C. fortis* Řehánek (Kowal-Kasprzyk, 2016). Generally, foraminifera and dinocysts confirm the Tithonian–Berriasian age of the Štramberk-type limestones studied, but the separation of the Tithonian from the Berriasian, based on these fossils, is often problematic.

The possibility cannot be excluded that sedimentation of the Štramberk-type limestones (mostly of lagoonal and algal-foraminiferal facies) persisted locally even to the Valanginian (Ivanova and Kołodziej, 2004, 2010), but all available data indicate that the main development of coral reefs (both in the Štramberk Limestone and the Štramberk-type limestones) occurred in the late Tithonian and less extensively in the early Berriasian. Štramberk-type sediments younger than the early Berriasian are not known from the large Kotouč Quarry near Štramberk, but Valanginian shallow-water limestones have already been recognized as pebbles in the Outer Carpathians in the Czech Republic (Soták and Mišík, 1993). Valanginian shallow-water marine carbonates (algal facies) were also recognized recently in the strata drilled in the Carpathian Foredeep (e.g., Matyja, 2009; Urbaniec *et al*., 2010). Zdanowski *et al.* (2001) described Valanginian crinoid-bryozoan grainstones in the Carpathian Foredeep and interpreted them as documenting the transgression maximum.

MATERIAL AND METHODS

The exotics studied, almost exclusively light- or dark-beige in colour (usually the dark-coloured ones are from deeper facies), are mostly of pebble and cobble sizes (from a few centimetres to ca. 20 cm); more rarely they are blocks, up to 1 m in diameter (Fig. 6). The clasts are largely spherical, mostly well-rounded. There are neither macroborings nor encrusting organisms on the surface; only very rare siliceous crusts occur. The exotics were collected at 36 sites in the area of the Silesian, Sub-Silesian and Skole nappes (Fig. 1, Tabs 2 and 3). Sampling by M. Hoffmann started in the 1980s. The outcrops of exotic-bearing flysch deposits studied are small (Fig. 6A, B). The most effective approach to sampling the exotics, especially the larger clasts, was in streams. Thousands of exotics were examined macroscopically in the field. About 800 thin sections were made from 550 exotics. Most of the thin sections are of standard size (4 × 2.7 cm); about 20 of them are large (6 × 5 cm). The exotics are from the uppermost Jurassic to Oligocene flysch deposits of diverse lithostratigraphic units (Fig. 2; Tabs 2 and 3), but the majority of them are from the Hradiště Formation and the Veřovice Formation (Hauterivian–Aptian), the Istebna Formation (Campanian–Paleocene), and the Ciężkowice Formation and the Hieroglyphic Formation (Eocene) of the Silesian Unit. The exotic-bearing sediments in the study area, more rarely at a particular locality, are described or mentioned in the literature references included in Table 3.

The samples were studied macroscopically (in the field and in the laboratory using cut and polished slabs) and microscopically. Nearly all the microscopic images on figures are from exotic clasts with a location provided. Some pictures are from exotics (collected by the present authors), for which no location is given, but they well document the facies described. The exotics and thin sections are housed in

Fig. 6. Field pictures showing exotic-bearing flysch deposits and exotic clasts of the Štramberk-type limestones. **A.** Clasts in the Piechówka Sandstone Member of the Hradiště Formation, Żegocina (locality 27). **B.** Żywiec olistostrome, clasts in conglomerate (Hradiště Formation; locality 2). **C.** Boulder in the Veřovice Formation (co-called “dark exotic-bearing shales”), Barwałd Górny (locality 6). **D.** Small boulder in a stream, Hradiště Formation, Jastrzębia (locality 10).

Table 2

List of localities with the studied exotic clasts of the Štramberk-type limestones, arranged according to their lithostratigraphic and tectonic positions. The number of each locality is in brackets. For the geographic positions, see Figure 1 and Table 3. The names of lithostratigraphic units are according to Ślączka *et al.* (2006), Cieszkowski *et al.* (2012), and Łapcik *et al.* (2016).

Unit	Formation (age)	Locality
Silesian	Vendryně Formation (former Lower Cieszyn Beds, late Kimmeridgian–middle late Tithonian)	Zamarski (1)
	Hradiště Formation, mainly Piechówka Sandstone Member (Hauterivian–Barremian)	Żywiec (2), Biskupice (16), Dobranowice (18), Sułów (19), Żegocina (27), Milówka (32), Roztoka (33)
	Veřovice Formation (Barremian–Aptian)	Leśnica (9)
	Lhoty Formation (Albian–Cenomanian)	Jastrzębia (11)
	Lower Istebna Formation (Campanian–Maastrichtian)	Zarzyce Wielkie (8), Leńcze (12), Izdebnik (13), Krzyworzeka (20), Dzielec (24), Kobylec (25), Rożnów (31)
	Upper Istebna Formation (Paleocene)	Mały Czaniec (3), Targoszów (4), Mucharz (5), Tarnawa (26)
	Ciężkowice Formation (Eocene)	Podole-Górowa (29), Gródek nad Dunajcem (30)
	Hieroglyphic Formation (Eocene)	Lipie (28)
	Menilite Formation (Oligocene)	Skrzydlna (22)
Sub-Silesian	Hradiště Formation (Barremian–Aptian)	Jastrzębia (10), Sygneczów (15), Wiśniowa (21)
	Veřovice Formation (Hauterivian–Albian) and Gaize Beds (late Aptian–early Cenomanian)	Barwałd Górny (6), Woźniki (7), Lusina (= Krzywica) (14), Trąbki (17)
	Frydek-type marls/Rybie Sandstone (latest Cretaceous–earliest Paleocene)	Nowe Rybie (23)
Skole	Ropianka Formation (Maastrichtian–Paleocene)	Wola Rafałowska (35), Lipnik Hill (Wapielnica) (36), Koniusza (37)
	Babica Clays (late Paleocene)	Lubenia (34)

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RESULTS

Facies and microfacies

General remarks

As noted in the section "Age of the studied limestones", several percent of the exotics, especially if beige in colour, can be confused in the field with the Štramberk-type limestones, but in fact they are of Oxfordian–Kimmeridgian age (Kowal-Kasprzyk *et al.*, 2020). These limestones were not described here but are summarized in the chapter "Discussion".

Facies FT 1–FT 8 (Štramberk-type limestones *sensu stricto*), are considered as being of Tithonian–lowermost Cretaceous age. The age was determined palaeontologically or such age is inferred on the basis of similarities in lithology with the carbonate clasts, for which the age had been determined. The age of the samples, assigned to the main facies, was based on the work of Ciborowski and Kołodziej (2001) and Ivanova and Kołodziej (2004, 2010) and for the most part that of Kowal-Kasprzyk (2016, 2018).

Traditionally, the Štramberk-type limestones are considered to be reefal limestones, but in fact, they represent diverse facies of the carbonate platform and its slope. The names of the facies distinguished here are based on sedimentary characteristics on the scale of clasts (pebbles, cobbles, rarely boulders). For the determination of facies, especially shallow-water facies, it is recommended that clasts at least several centimetres in diameter are studied. Owing to the heterogeneity of shallow-water facies, they show high variability in microfacies (especially coral-microbial boundstones) and are represented by more than one microfacies. Therefore, the study of a single thin-section is not necessarily representative of the facies and will be inadequate for the study of some facies. Figure 7 shows an exotic ca. 20 cm in diameter, possibly representing coral-microbial boundstones (FT 1), although not in a characteristic development. In different parts of it, four microfacies can be distinguished. If only a small fragment of such a clast (one thin-section or a much smaller fragment) were to be studied, the assignment to this facies would be correct only in the case of the part labelled as 1. On the other hand, the microfacies study of the packstone-grainstone matrix of the exotic discussed is necessary, because if this matrix contains numerous foraminifera and dasycladalean green algae, the exotic should be assigned to the foraminiferal-algal limestones (FT 5).

Table 4 contains a list of recognized, encrusting microorganisms (microencrusters), their recent biological affiliation (they are usually of uncertain genesis) and their relative abundance in four facies (F1–F3, F5). These microencrusters (important for reef construction and/or for the interpretation of the sedimentary environment) are reviewed and literature references are provided in Leinfelder *et al*. (1993), Schmid (1996), Schlagintweit *et al.* (2005), Pleş *et al.* (2013, 2017) and Kaya and Altıner (2015). Table 5 contains a list of main foraminiferal genera, recognized in the various facies.

FT 1: Coral-microbial boundstones (Figs 8–10)

This boundstone type is defined here as a boundstone, constructed by corals, usually associated with microbialites and/or microencrusters. Corals are represented mostly by phaceloid forms (the branching growth type; Figs 8A, B, 9A; see e.g., Morycowa, 1974; Kołodziej, 2003a). Microbialites, commonly only thin crusts, are developed as clotted thrombolite, layered thrombolite, poorly structured thrombolite, leiolite, clotted leiolite, micritic stromatolite, and peloidal to agglutinated stromatolite (the frequency of microbialite types was not estimated; Figs 8B, D–F, 9B, D–F, 10E). They are composed mostly of micropeloids and clotted micrite. The matrix sediment is composed of bioclastic-peloidal packstone to grainstone (Figs 8B, 9B), rarely wackestone, thus this sediment is similar to the peloidal-bioclastic limestones (FT 6). Calpionellids and calcareous dinoflagellate cysts are present in the micrite-dominated matrix of some samples.

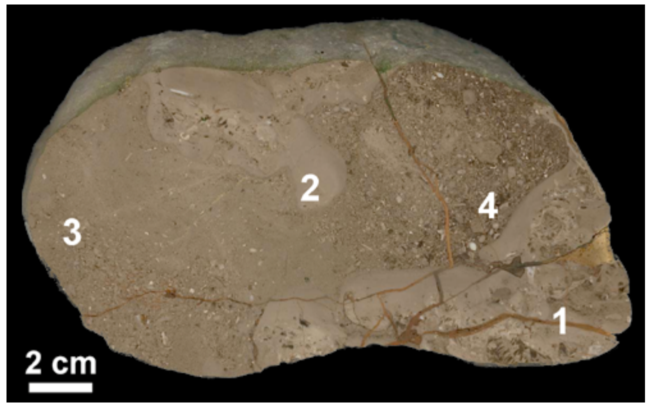

Fig. 7. Microfacies variability within one exotic, presumably the coral-microbial boundstone (FT 1). (1) coral-microbial boundstone, (2) microbial boundstone, (3) bioclastic-peloidal packstone, (4) bioclastic-peloidal grainstone. Gródek nad Dunajcem.

Microencrusters include (in order of abundance): *Crescentiella morronensis* (Figs 10A, E), calcimicrobial crusts with entobian borings (termed here as "*Lithocodium*"–like structures; Figs 9A–D, 10B, C, F), bacinellid microbial structures (Fig. 10D), calcified sponges (Figs 9B, F, 10E), *Iberopora bodeuri* (Fig. 10C), *Koskinobullina socialis* (Figs 9C, 10C), *Labes atramentosa* (Figs 9F, 10A, F), *Thaumatoporella parvovesiculifera*, rare *Lithocodium aggregatum* (Fig. 10B), *Radiomura cautica* (Fig. 10F)

Table 3

Localities (in the order of the numbers marked on Figure 1 and in Table 2) with reference to the literature, in which exotic-bearing sediments in the study area, more rarely a particular locality, are described or mentioned. Most localities have GPS data.

No	Locality	Description	Unit	Formation	Literature
1	Zamarski	6 km N of Cieszyn	Silesian	Vendryně Formation (former Lower Cieszyn Beds)	Król and Decrouez (2002)
2	Żywiec	outcrop in Soła River, western part of Grójec Hill (49°40′18.7″N, 19°11′35.8″E)	Silesian	olistostrome of the Cisownica Shale Member – Hradiště Formation (former Upper Cieszyn Beds)	Cieszkowski *et al.* (2009)
3	Mały Czaniec (Bulowice)	5 km SE of Kęty, clasts from Szybówka stream; area of poor outcrops (around 49°51′38.8″N, 19°15′46.7″E)	Silesian	Upper Istebna Formation (?)	Nowak (1959)
4	Targoszów	10 km W of Sucha Beskidzka, outcrop in Targoszówka stream, close to a road from Kuków to Targoszów (49°45′17.2″N, 19°27′35.3″E)	Silesian	Upper Istebna Formation	Strzeboński *et al.* (2017)
5	Mucharz	8 km S of Wadowice, outcrop in Skawa River (49°49′15.9″N, 19°32′33.1″E)	Silesian	Upper Istebna Formation	Strzeboński *et al.* (2017)
6	Barwałd Górny	5 km W of Kalwaria Zebrzydowska, outcrop in tributary of Zakrzówka stream (49°51′04.6″N, 19°37′15.8″E)	Sub-Silesian	Veřovice Formation	Książkiewicz (1951a, b)

No	Locality	Description	Unit	Formation	Literature
7	Woźniki	6 km N of Wadowice, Rędzina stream in Woźniki village	Sub-Silesian	black shales within the Gaize Beds	Książkiewicz (1974), Morycowa (1974)
8	Zarzyce Wielkie	3 km NE of Kalwaria Zebrzydowska, outcrop in landslide niche in Solca za Lasem hamlet (49°52′49.2″N, 19°43′03.7″E)	Silesian	Lower Istebna Formation	Książkiewicz (1951a, b)
9	Leśnica	2 km S of Kalwaria Zebrzydowska, clasts from tributary of Cedron stream (around 49°50′53.2″N, 19°41′09.9″E)	Silesian	Veřovice Formation	
10	Jastrzębia (= Lanckorona)	1.5 km E of Lanckorona, clasts from Jastrzębia stream in Kopań hamlet (around 49°50′26.3″N, 19°44′23.5″E)	Sub-Silesian	Hradiště Formation	Książkiewicz (1951a, b)
11	Jastrzębia	4 km E of Lanckorona, clasts from tributary of Jastrząbka stream between Jastrzębia and Sułkowice villages, poorly outcropped area (around 49°50′30.0″N, 19°46′15.0″E)	Silesian	Lhoty Formation (?)	Książkiewicz (1951a, b)
12	Leńcze	5 km N of Kalwaria Zebrzydowska, stream in Leńcze village	Silesian	Lower Istebna Formation	Książkiewicz (1951a, b)
13	Izdebnik	6 km E of Kalwaria Zebrzydowska, outcrops in tributary of Jastrząbka stream (around 49°52′29.0″N, 19°45′33.1″E)	Silesian	Lower Istebna Formation	Książkiewicz (1951a, b)
14	Lusina (= Krzywica)	7 km W of Skawina, Krzywa stream in Krzywica village	Sub-Silesian	Veřovice Formation	Michalik (1980)
15	Sygneczów	1) 4 km SW of Wieliczka, old pit (49°58′07.4″N, 20°00′35.2″E); 2) 3 km SW of Wieliczka, tributary of Wilga stream in Łysa Góra hamlet (49°57′55.9″N, 20°01′44.9″E)	Sub-Silesian	Hradiště Formation	Burtan (1956), Książkiewicz (1965)
16	Biskupice	6 km SE of Wieliczka: 1) outcrops in a forest gorge (around 49°57′30.2″N, 20°07′01.5″E); 2), tributary of Bogusława stream, north of a gorge (49°57′32.6″N, 20°06′51.0″E)	Silesian (Sub-Silesian? see Burtan, 1956, 1984)	Piechówka Sandstone Member of the Hradiště Formation	Burtan (1956), Burtan *et al.* (1984)
17	Trąbki	7.5 km SE of Wieliczka, outcrops in small unnamed stream close to Tarnówka hamlet (49°57′33.2″N, 20°08′03.2″E)	Sub-Silesian	Gaize Beds	Burtan (1956)
18	Dobranowice	7 km S of Wieliczka, outcrops in tributary of Sułówka stream between Sułów and Dobranowice villages (around 49°56′51.9″N, 20°07′42.1″E)	Silesian (Sub-Silesian? see Burtan, 1956, 1984)	Piechówka Sandstone Member of the Hradiště Formation	Burtan (1956)
19	Sułów	6 km SE of Wieliczka: 1) Sułówka stream (around 49°57′17.6″N, 20°07′23.8″E); 2) tributary of Zagórzanka stream (around 49°57′10.8″N, 20°06′42.6″E)	Silesian (Sub-Silesian? see Burtan, 1956, 1984)	Piechówka Sandstone Member of the Hradiště Formation	Burtan (1956), Burtan *et al.* (1984)
20	Krzyworzeka	4.5 km SE of Dobczyce, outrcops in two tributaries of Zagórzanka stream, between Krzyworzeka and Kędzierzynka villages (around 49°52′06.4″N, 20°08′37.7″E and around 49°51′47.3″N, 20°09′03.0″E)	Silesian	Lower Istebna Formation	Burtan (1956), Chodyń *et al.* (2005)
21	Wiśniowa	outcrops in tributary of Krzyworzeka stream in Wiśniowa village (around 49°47′13.5″N, 20°06′09.1″E)	Sub-Silesian (Wiśniowa Tectonic Window)	Hradiště Formation	Burtan *et al.* (1984), Burtan (1977)

No	Locality	Description	Unit	Formation	Literature
22	Skrzydlna	11 km NE of Mszana Dolna, quarry in Skrzydlna village (49°44′55.9″N, 20°09′57.9″E)	Silesian	Menilite Formation	Burtan *et al.* (1984), Polak (2000)
23	Nowe Rybie	9 km NW of Limanowa, outcrops in Tarnawka stream (around 49°46′57.7″N, 20°19′49.8″E)	Sub-Silesian	Frydek-type marls ("grey exotic-bearing marls")/Rybie Sandstone	Burtan *et al.* (1984)
24	Dzielec	1.5 km N of Stare Rybie, old small quarry and outcrop in tributary of Przeginia stream below the quarry (49°49′03.2″N, 20°19′08.4″E)	Silesian	Lower Istebna Formation	Burtan *et al.* (1984)
25	Kobylec	2.5 km NW of Łapanów, stream between Syberia and Borówka hamlets (around 49°53′13.8″N, 20°16′57.0″E)	Silesian	Lower Istebna Formation	Burtan *et al.* (1984)
26	Tarnawa	4 km S of Łapanów, outcrops in tributary of Tarnawka stream (around 49°49′47.5″N, 20°17′09.6″E)	Silesian	Upper Istebna Formation	Burtan *et al.* (1984)
27	Żegocina	old quarry in Żegocina village (49°48′33.2″N, 20°25′14.5″E)	Silesian	Piechówka Sandstone Member of the Hradiště Formation	Malik and Olszewska (1984)
28	Lipie	12 km N of Nowy Sącz, outcrop on bank of Rożnów Lake (49°43′33.2″N, 20°42′55.1″E)	Silesian	Hieroglyphic Formation	Cieszkowski (1992)
29	Podole Górowa	16 km NE of Nowy Sącz, outrcops in tributary of Paleśnianka stream (around 49°44′35.7″N, 20°49′29.4″E)	Silesian	Ciężkowice Formation/Hieroglyphic Formation	Cieszkowski *et al.* (1991)
30	Gródek nad Dunajcem	14 km N of Nowy Sącz, outcrop on bank of Rożnów Lake (49°43′56.8″N, 20°43′17.2″E)	Silesian	Ciężkowice Formation	Cieszkowski (1992), Morycowa (1968), Leszczyński (1978)
31	Rożnów	16 km N of Nowy Sącz, outcrop on bank of Rożnów Lake (49°45′53.3″N, 20°40′39.1″E)	Silesian	Lower Istebna Formation	
32	Milówka	14 km SE of Brzesko, stream in Milówka village	Silesian	Piechówka Sandstone Member of the Hradiště Formation	
33	Roztoka	19 km SE of Brzesko, outcrop in Roztoka village	Silesian	Piechówka Sandstone Member of the Hradiště Formation	
34	Lubenia	12 km S of Rzeszów, Lubeńka stream in Lubenia village	Skole	Babica Clays	Kropaczek (1917), Bukowy (1957)
35	Wola Rafałowska	15 km SE of Rzeszów: 1) tributary of the Chmielnik stream (49°59′20.0″N, 22°11′0.9″E); 2) gorge of unnamed stream in Wola Rafałowska village (49°59′11.7″N 22°11′05.4″E)	Skole	Ropianka Formation	Łapcik *et al.* (2016)
36	Lipnik Hill (Wapielnica)	5 km SW of Przemyśl. The locality is in the vicinity of poorly exposed Kruhel klippe	Skole	Ropianka Formation	Bukowy and Geroch (1956), Nowak (1963), Morycowa (1964a)
37	Koniusza	10 km SW of Przemyśl	Skole	Ropianka Formation	Ney (1957), Kotlarczyk (1985), Dżułyński and Kotlarczyk (1988)

Table 4

Biological affiliation of microencrusters and their relative abundance in the coral-microbial boundstones (FT 1), microencruster-microbial-cement boundstones (FT 2), microbial and microbial-sponge boundstones (FT 3), and foraminiferal-algal limestones (FT 5). Microencruster present (•); common (••); very common (•••); not recognized (–); uncertain occurrence (?).

Microencrusters	**Biological affiliation**	**Facies**			
		FT 1	FT 2	FT 3	FT 5
"*Lithocodium-Bacinella*"	umbrella term	•••	?	–	•••
Lithocodium aggregatum Elliott	ulvophycean green algae	•	–	–	?
Bacinellid structures	calcimicrobial origin	••	?	–	•••
"Lithocodium"-like structures	calcimicrobial crusts with entobian borings	•••	?	–	••
Koskinobullina socialis Cherchi et Schroeder	*incertae sedis*: algae? foraminifera?	••	–	–	•
Iberopora bodeuri Granier et Berthou	*incertae sedis*: algae? foraminifera?	••	–	–	•
Thaumatoporella parvovesiculifera (Raineri)	*incertae sedis*: green algae? cyanophyceans?	•	–	–	•••
Crescentiella morronensis (Crescenti)	nubeculariid foraminifera	•••	•••	•••	•
Labes atramentosa Eliášová	*incertae sedis*	•	•••	•	–
Radiomura cautica Senowbari-Daryan et Schäfer	calcified sponge?	•	••	–	–
Perturbatacrusta leini Schlagintweit et Gawlick	calcified sponge?	•	••	–	–
Terebella lapilloides Münster	"worms"	•	•	•••	•
Calcified sponges		••	••	•	•

Table 5

Distribution of foraminifera in facies types.

Facies type	**Typical foraminifers**
FT 1	Benthic calcareous forms (*Bullopora*, *Coscinoconus*, *Dobrogelina*, *Lenticulina*, *Mohlerina*, *Protopeneroplis*, *Spirillina*, *Troglotella*, Trocholinidae, Neotrocholininae, Nodosarioidea, miliolids) and agglutinated forms (*Gaudryina*, *Haghimashella*, *Paleogaudryina*, *Protomarssonella*, *Textularia*, *Uvigerinammina*, *Valvulina*)
FT 2	In obvious examples of this facies, foraminifera are rare, difficult to determine and represent allochthonous elements
FT 3	Benthic calcareous forms (*Bullopora*, *Lenticulina*, *Mohlerina*, *Protopeneroplis*, *Rumanolina*, *Spirillina*, Neotrocholininae, Nodosarioidea, Epistominidae, Nubeculariidea and rare other miliolids) and agglutinated forms (*Glomospira*, *Haghimashella*, *Paleogaudryina*, *Protomarssonella*, *Reophax*, *Textularia*, *Uvigerinammina, Valvulina*)
FT 4	Foraminifers occur mainly in lithoclasts
FT 5	Assemblages rich and diversified; the most typical are larger benthic forms with complex wall structure (*Charentia*, *Everticyclammina*, *Melathrokerion*, *Pseudocyclammina*) and numerous miliolids; other foraminifers: benthic calcareous and calcareous agglutinated forms (*Bullopora*, *Coscinoconus*, *Dobrogelina*, *Lenticulina*, *Mayncina*, *Mohlerina*, *Nautiloculina*, *Pfenderina*, *Protopeneroplis*, *Rumanolina*, *Siphovalvulina*, *Spirillina*, *Troglotella*, Trocholinidae, Neotrocholininae, Nodosarioidea), agglutinated forms (*Ammobaculites*, *Coscinophragma*, *Gaudryina*, *Haghimashella*, *Haplophragmium*, *Paleogaudryina*, *Pseudomarssonella*, *Textularia*, *Uvigerinammina*, *Valvulina, Verneuilina*)
FT 6	Benthic calcareous forms (*Coscinoconus*, *Dobrogelina*, *Everticyclammina*, *Lenticulina*, *Mayncina*, *Mohlerina*, *Patellina*, *Pfenderina*, *Protopeneroplis*, *Rumanolina*, *Siphovalvulina*, *Troglotella*, Trocholinidae, Neotrocholininae, Nubeculariidea, Nodosarioidea, Spirillinidae, numerous miliolids), agglutinated and calcareous-agglutinated forms (*Arenobulimina*, *Charentia*, *Coscinophragma*, *Glomospira*, *Haghimashella*, *Haplophragmium*, *Haplophragmoides*, *Melathrokerion*, *Nautiloculina*, *Paleogaudryina*, *Protomarssonella*, *Pseudocyclammina*, *Reophax*, *Textularia*, *Trochammina*, *Uvigerinammina*, *Valvulina*, *Verneuilina*)
FT 7	Benthic calcareous forms (*Lenticulina*, *Protopeneroplis*, *Spirillina*, miliolids) and agglutinated forms (*Paleogaudryina*, *Protomarssonella*, *Reophax*, *Textularia*, *Verneuilina*)
FT 8	Mainly benthic calcareous forms (*Lenticulina*, *Ophthalmidium*, Spirillinidae, Nodosarioidea, Nubeculariidea), less commonly agglutinated forms (*Protomarssonella*, *Paleogaudryina*)

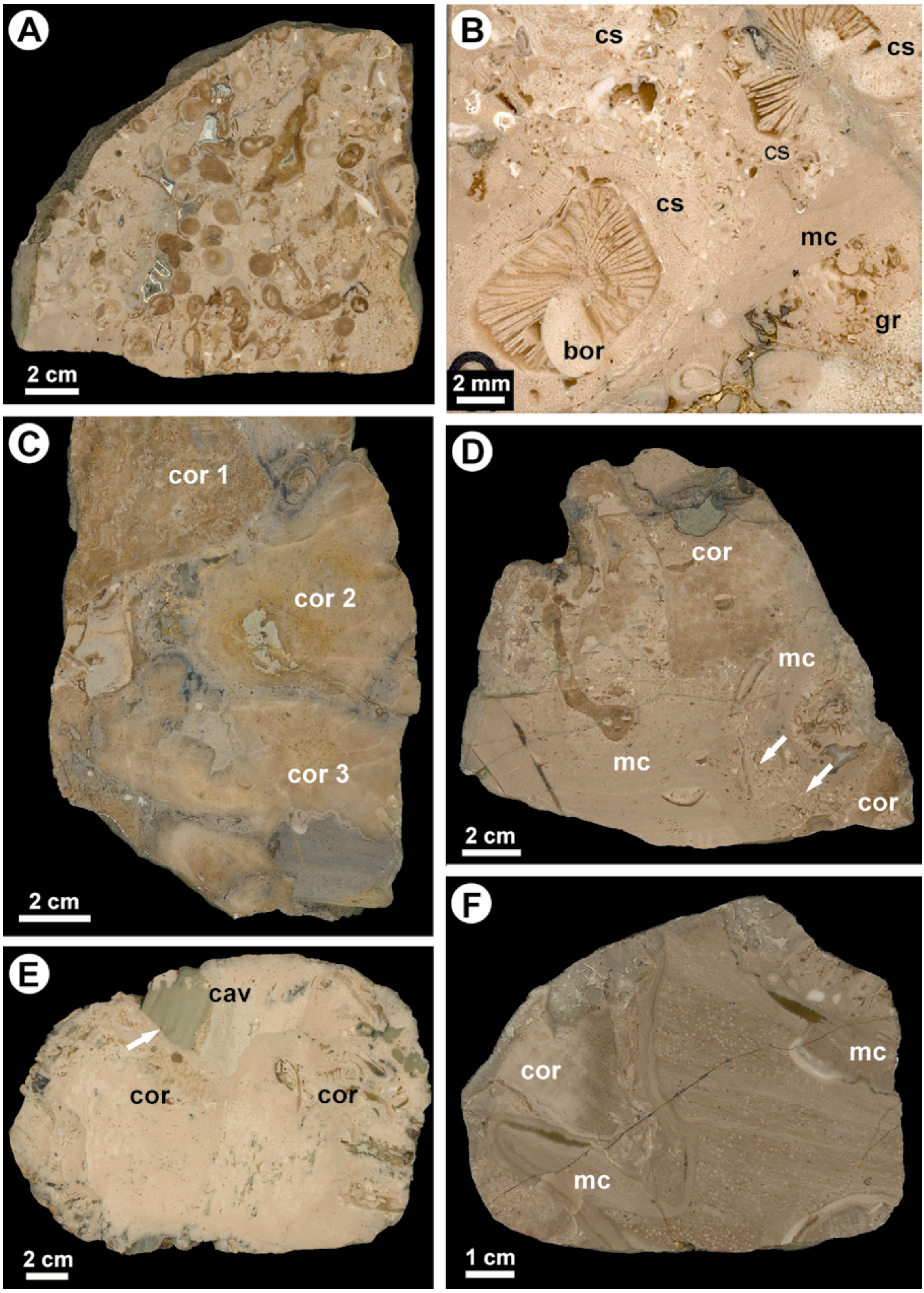

Fig. 8. Exotics representing the coral-microbial boundstones (FT 1). A–C. Coral-dominated boundstones. D–E. Microbialite-dominated boundstones. **A.** Phaceloid (branching) colony of the coral *Placophyllia dianthus*. **B.** Phaceloid coral *Thecosmilia* sp. encrusted by calcified sponges (cs) and bored by bivalves (bor); mc – microbial crust; gr – bioclastic-peloidal grainstone; white spots represent *Crescentiella morronensis* and *Labes atramentosa*. **C.** Dense aggregation of encrusting corals (cor 1, cor 2, cor 3). **D.** Corals (cor), microbialites (mc) and numerous *C. morronensis* and *L. atramentosa* (white spots, some are arrowed). **E.** Microbialite-dominated boundstone with rare corals (cor). Growth cavity (cav) is filled with different generations of the internal sediment, including laminated, dark limestone (arrow). **F.** Cavity formed by the growth of corals (cor) and microbial crusts (mc) and filled with laminated, peloidal sediment (mostly crustacean microcoprolites *Favreina* sp.). A, B – Woźniki, C – Leńcze, D, E – Lusina, F – Jastrzębia.

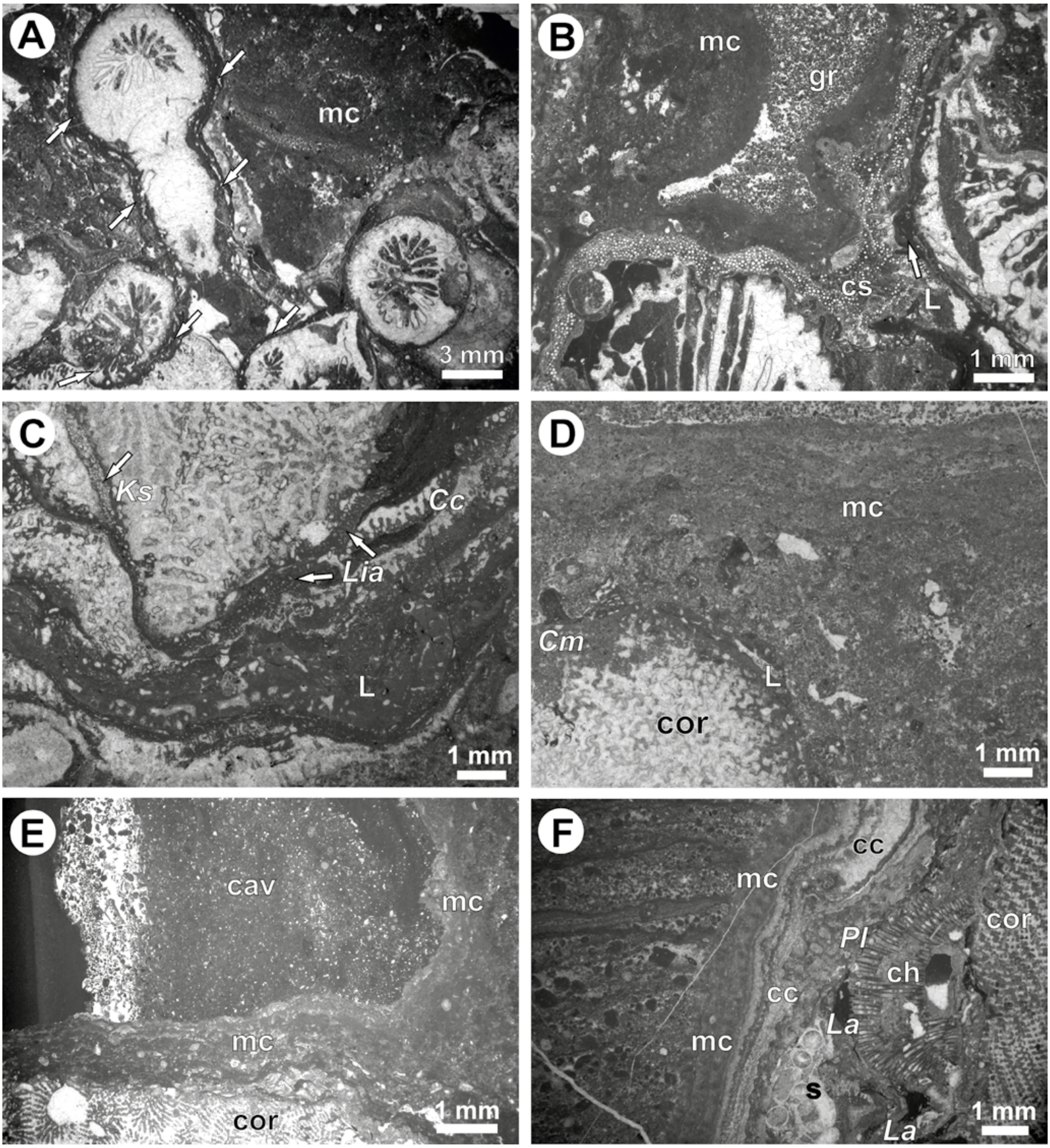

Fig. 9. Microfacies of the coral-microbial boundstones (FT 1). **A.** Corallites of phaceloid pachythecaliine coral *Pleurophyllia* aff. *trichotoma* encrusted mostly by calcimicrobial crusts with entobian borings ("*Lithocodium*"-like structures, arrowed); mc – peloidal-agglutinated microbialite. **B.** Phaceloid coral *Calamophylliopsis* sp. encrusted by "*Lithocodium*"-like structures (L, arrow), calcified sponges (cs) and microbial micropeloidal crust (mc); gr – intra-reef peloidal grainstone. **C.** Coral encrusted by *Koskinobullina socialis* (*Ks*), "*Lithocodium*"-like calcimicrobial crust (L), ?*Lithocodium aggregatum* (*Lia*) and foraminifer *Coscinophragma cribrosum* (*Cc*). **D.** Coral (cor) encrusted by "*Lithocodium*"-like crust (L), *Crescentiella morronensis* (*Cm*) and laminated, micropeloidal, microbial crust (mc). **E.** Cavity (cav) formed by the growth of corals (cor) and microbialite crusts (mc) filled with multigenerational, internal sediment. The youngest sediment generation (on the left) consists of laminated, micritic sediment. For the original sedimentary position, the image should be rotated 90 degrees in a clockwise direction. **F.** Growth cavity formed by the microsolenid coral (cor on the right), lined with non-photophilic microencrusters (ch – chaetetids, *Pl* – *Perturbatacrusta leini*, *La* – *Labes atramentosa*, s – serpulids, cc – cement crusts, mc – microbial crusts). The internal sediment (on the left) consists of peloidal packstone-grainstone, including microcoprolites *Favreina*. A – Zamarski, B – Leńcze, C – Sułów, D – Gródek nad Dunajcem, E – Lusina, F – Jastrzębia.

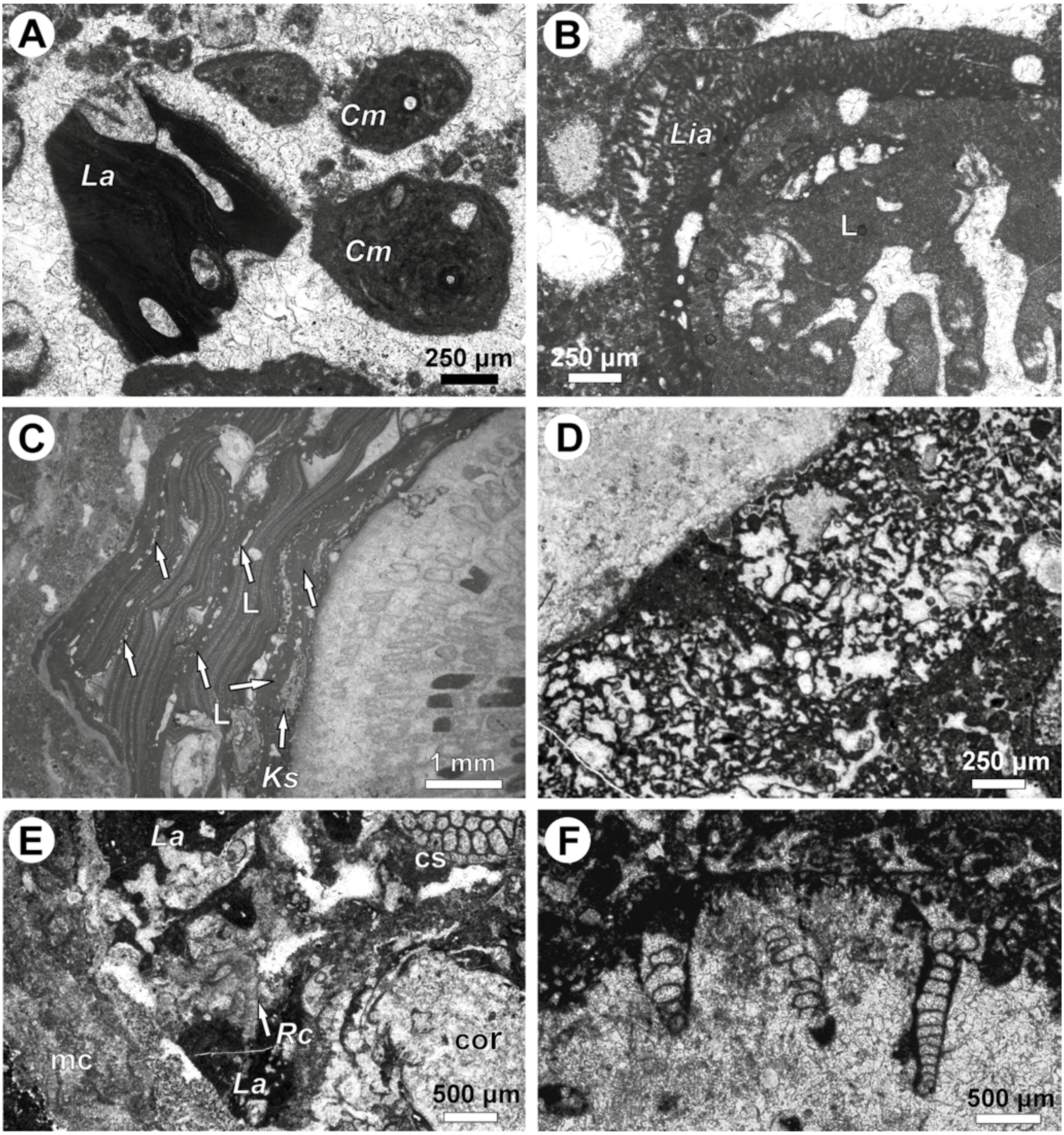

Fig. 10. Microencrusters from the coral-microbial boundstones (FT 1). **A.** *Labes atramentosa* (*La*) and *Crescentiella morronensis* (*Cm*). **B.** Coral fragment encrusted by "*Lithocodium*"-like crust (L) and *Lithocodium aggregatum* (*Lia*). **C.** Thick crust of *Iberopora bodeuri* with thin intergrowths of "*Lithocodium*"-like structures (L, arrowed) and *Koskinobullina socialis* (*Ks*). **D.** Microbial crust showing "bacinellid" vesicular fabric. **E**. *L. atramentosa* (*La*), *Radiomura cautica* (*Rc*), calcified sponges (cs), microbialite crust (mc) and small coral bioclast (cor). Microfabric resembles this one in the microencruster-microbial-cement boundstones (FT 2). **F.** "*Lithocodium*"-like crust with boring and cryptic foraminifer *Troglotella incrustans*. A – Targoszów, B – Podole-Górowa, C – Leńcze, D – Izdebnik, E – Biskupice, F – Zarzyce Wielkie.

and *Perturbatacrusta leini*. "*Lithocodium*"-like structures are commonly associated with the boring and cryptic foraminifer *Troglotella incrustans* Wernli et Fookes (Fig. 10F; for more examples from the Štramberk-type limestones see Kołodziej, 1997a).

An umbrella term, "*Lithocodium-Bacinella*", usually had to be used (like commonly in the literature) in microfacies descriptions, because it was difficult to differentiate between true *L. aggregatum* (an alga with morphologically different euendolithic, chasmoendolithic, epilithic and terminal stages, *sensu* Schlagintweit *et al.*, 2010) and structures of other origins (see the section "Microencrusters" in the chapter "Depositional and environmental settings"). Other algae are not numerous and are represented by green algae (fragments of dasycladales, *Nipponophycus ramosus* Yabe et Toyama), rare red algae ("*Solenopora*"), the problematic *Marinella lugeoni* Pfender and rivulariacean-like cyanobacteria (Bucur *et al*., 2005).

Podoba (2009) described in a Master's thesis common, calcified sponges (= hypercalcified sponges, sclerosponges), mostly millimetres in size (identified in thin sections). It is not clear which facies the species are from. Probably, most of them are from the coral-microbial boundstones, because the microencruster-microbial-cement boundstones are much less common, and in other facies calcified sponges are rare (Table 3). On the other hand, in the coral-microbial boundstones, calcified sponges are not important in the reef framework, although they are more taxonomically diverse. The calcified sponges, described by Podoba (2009), are represented by chaetetids (?*Ptychochaetetes globosus* Koechlin, ?*Chaetetes ehrenbergi* Bachmayer et Flügel and others not determined), *Neuropora lusitanica* Termier, *Burgundia astrotubulata* Turnšek, *Cylicopsis verticalis*? Turnšek, ?*Cladocoropsis mirabilis* Felix, ?*Dehornella crustans* Hudson, ?*Milleporidium remesi* Steinmann, ?*Sobralispongia densespiculata* Schmid et Werner*,* ?*Calciagglutispongia yabei* Reitner*,*and *Calcistella* cf. *jachenhausenensis* Reitner.

Apart of the species mentioned above, corals are encrusted by annelids (serpulids, *Terebella lapilloides*), foraminifera (nubeculariids, *Coscinophragma* sp.), bryozoans (e.g., *Reptomulticava* sp., *Heteropora* sp., ?*Ceriocava* sp.; Hara and Kołodziej, 2001), and more rarely by ostreid-like bivalves and small thecideid brachiopods. Microbialites predominate over corals (on the scale of the clast) in some samples. Nevertheless, these clasts are classified as referable to FT 1 because they are assumed to be parts of the coral-microbial patch-reefs.

The microencruster-microbial-cement microframework of FT 1 can be locally (in the scale of one thin-section) composed as in the microencruster-microbial-cement boundstones (FT 2), of non-photophilic (not light-dependent) microencrusters (Fig. 10F), which makes it resemble the microframework of FT 2. The intergrowth of corals, microencrusters and microbialite crusts has resulted in the origin of growth cavities, up to several centimetres in diameter. The walls of the cavities (cryptic microhabitat) are encrusted by microbialites and non-photophilic microencrusters (Fig. 9E, F). The cavities are mostly filled with peloidal wackestones-packstones, including crustacean microcoprolites *Favreina* (Figs 8F, 9F).

Age: The Tithonian and earliest Cretaceous age of this facies is confirmed by the occurrence of such stratigraphically significant microfossils as the calcareous dinocysts *Carpistomiosphaera tithonica*, *Colomisphaera fortis*; *C. tenuis*, *Committosphaera ornata* (Nowak), *C. pulla*; calpionellids: *Calpionella alpina* Lorenz, *Chitinoidella boneti* Doben, *Ch. elongata* Pop, *Ch. popi* Sallouhi, Boughdiri et Cordey, *Crassicollaria intermedia* (Durand Delga), *C. parvula* Remane, and *Tintinnopsella carpathica* (Murgeanu et Filipescu); and the foraminifers *Coscinoconus alpinus* (Leupold), *Coscinophragma cribrosum* (Reuss), *Massilina mirceai* (Neagu), *Protomarssonella hechti* (Dieni et Massari), *Protopeneroplis ultragranulata* (Gorbatchik), and *Textularia densa* Hoffman.

FT 2: Microencruster-microbial-cement boundstones (Fig. 11)

Macroscopically, FT 2 is hardly recognizable in hand specimens (but see analogous facies in the Štramberk Limestone: Hoffmann *et al*., 2017, fig. 5), but is clearly visible under the microscope. This boundstone type consists of a complex intergrowth of microencrusters, microbialite and cement crusts (Fig. 11). Microencrusters are represented mostly by the following species (in order of abundance): *Labes atramentosa* (Fig. 11A–D), *Crescentiella morronensis* (Fig. 11B–D, F)*, Perturbatacrusta leini* (Fig. 11A, B)*, Radiomura cautica,* calcified sponges (Fig. 11A–E), spicular sponges and *Terebella lapilloides*. Corals are very rare and are mainly opportunistic microsolenids (with a somewhat sponge-like appearance; Fig. 11C). In "typical" examples of FT 2, photophilic (light-dependent) microencrusters (e.g., "*Lithocodium-Bacinella"*), common in FT 1, are not present or are uncertain. Less important for the reef framework are microbialite and cement crusts. Microbialites are represented by laminated and non-laminated, micropeloidal crusts (Fig. 11B, D, E). Growth cavities (up to some millimetres in size) are filled with peloids, pseudo-ooids (Fig. 11F) and cement. Synsedimentary, first cement generation is developed as a thin, brownish cement rim (originally possibly fibrous, isopachous cement; see Schlagintweit and Gawlick, 2008), whereas the second generation is developed as blocky cement (Fig. 11E). Locally, microencrusters are attached to the cement generation 1 (Fig. 11E). Peloidal-bioclastic packstones occur in the matrix.

Age: Lack of stratigraphically significant microfossils. *Perturbatacrusta leini* is a microencruster known from the Kimmeridgian–Berriasian (Pleş and Schlagintweit, 2014; Kaya and Altıner, 2015). Similar boundstones were described from the upper Kimmeridgian–lowermost Berriasian (Schlagintweit and Gawlick, 2008). They occur also in the Štramberk Limestone (Hoffmann *et al*., 2017).

FT 3: Microbial and microbial-sponge boundstones (Figs 12, 13)

FT 3 is built of microbialites (Figs 12A, B, 13B) and remnants of siliceous sponges (usually calcified; Figs 12C, D, 13C, D) associated with *Terebella lapilloides* (Fig. 13B)*, Crescentiella morronensis* (Fig. 13A, E), less often *Labes atramentosa*, and serpulid tubes. The skeletal elements are bound by microbial crusts of diverse microstructures,

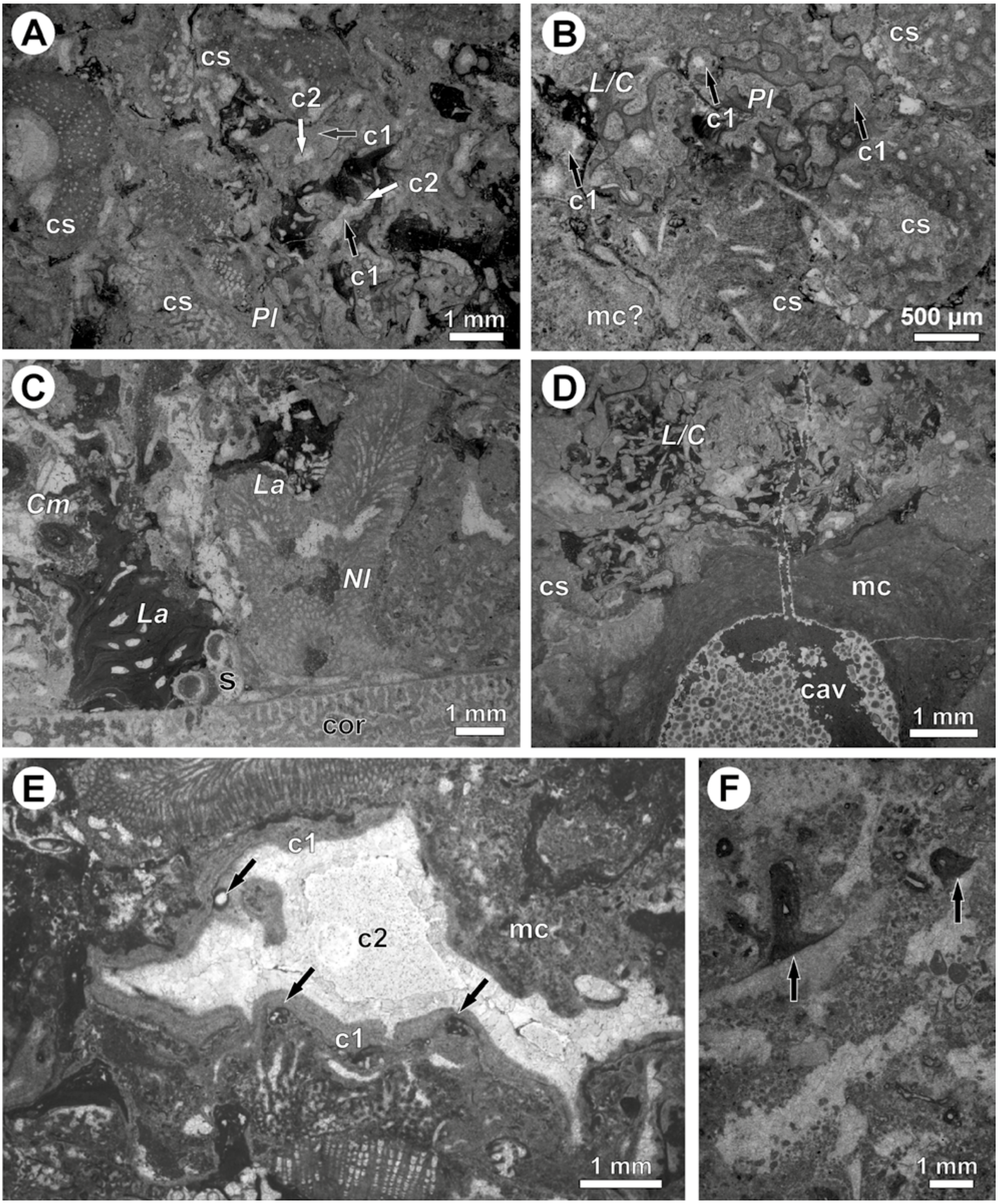

Fig. 11. Microfacies of the microencruster-microbial-cement boundstones (FT 2). **A.** Intergrowth of *Labes atramentosa* and ?*Crescentiella morronensis* (black spots), calcified sponges (cs), *Perturbatacrusta leini* (*Pl*) and supposed thin peloidal microbial crusts. Synsedimentary cement is darker (c1; black arrows); late diagenetic cement (c2; white arrows) is lighter. **B**. Intergrowth of microencrusters (*L/C* – *L. atramentosa* or *C. morronensis, Pl* – *Perturbatacrusta leini,* cs – calcified sponges). Black arrows indicate supposed synsedimentary cements (c1). **C.** Microsolenid coral (cor) encrusted by *L. atramentosa* (*La*), calcified sponge *Neuropora lusitanica* (*Nl*), *C. morronensis* (*Cm*) and serpulids (s). **D.** Intergrowth of microencrusters (mostly *L. atramentosa* and *C. morronensis* – *L/C* and calcified sponges – cs) and microbialites (mc). Growth cavity is filled with peloids and pseudo-ooids (microbial peloids?). **E.** Growth cavity (filled with sparry calcite cement) within the framework formed by microencrusters and presumably microbialite crust with peloidal fabric (mc). The wall of the intra-framework cavity is encrusted by a thin, dark rim of synsedimentary cement (c1) and filled with two generations of light, late-diagenetic cement (c2). Arrows indicate minute microorganisms attached to synsedimentary cement. **F**. *C. morronensis* encrusting synsedimentary cement (arrowed). A, D–F – Woźniki, B – Koniusza, C – Gródek nad Dunajcem.

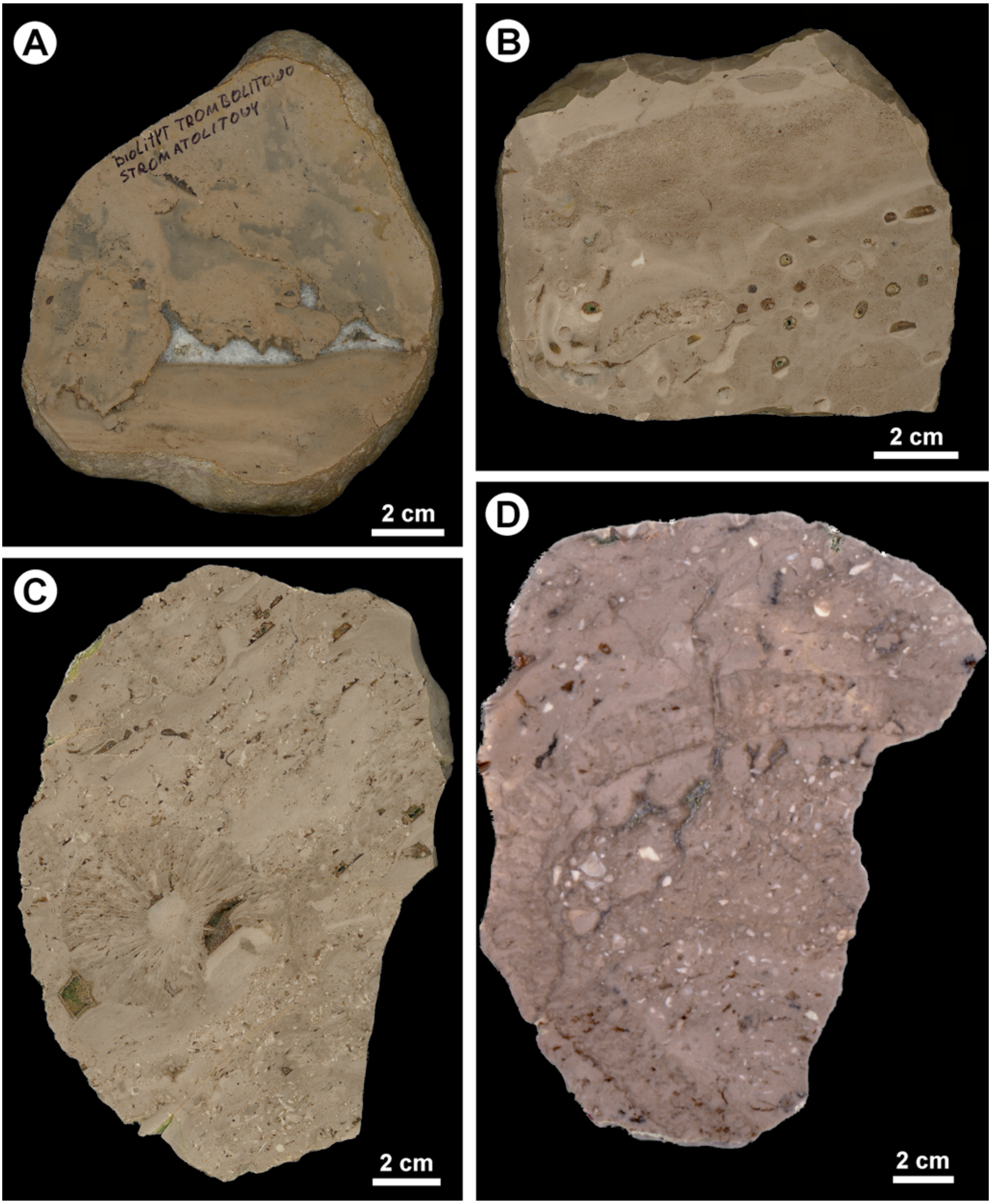

Fig. 12. Exotics representing FT 3. **A**. Microbial thrombolitic-stromatolitic boundstone with a growth cavity filled with blocky calcite. **B.** Large, *Terebella*-like burrows in the microbial-peloidal boundstone. **C.** Siliceous sponge within the microbial-sponge boundstone. White spots are mostly *Crescentiella morronensis.* **D.** Siliceous sponge in bioclatstic packstone. White spots are mostly crinoid fragments. A, C – sites unknown, B – Lusina, D – Gródek nad Dunajcem.

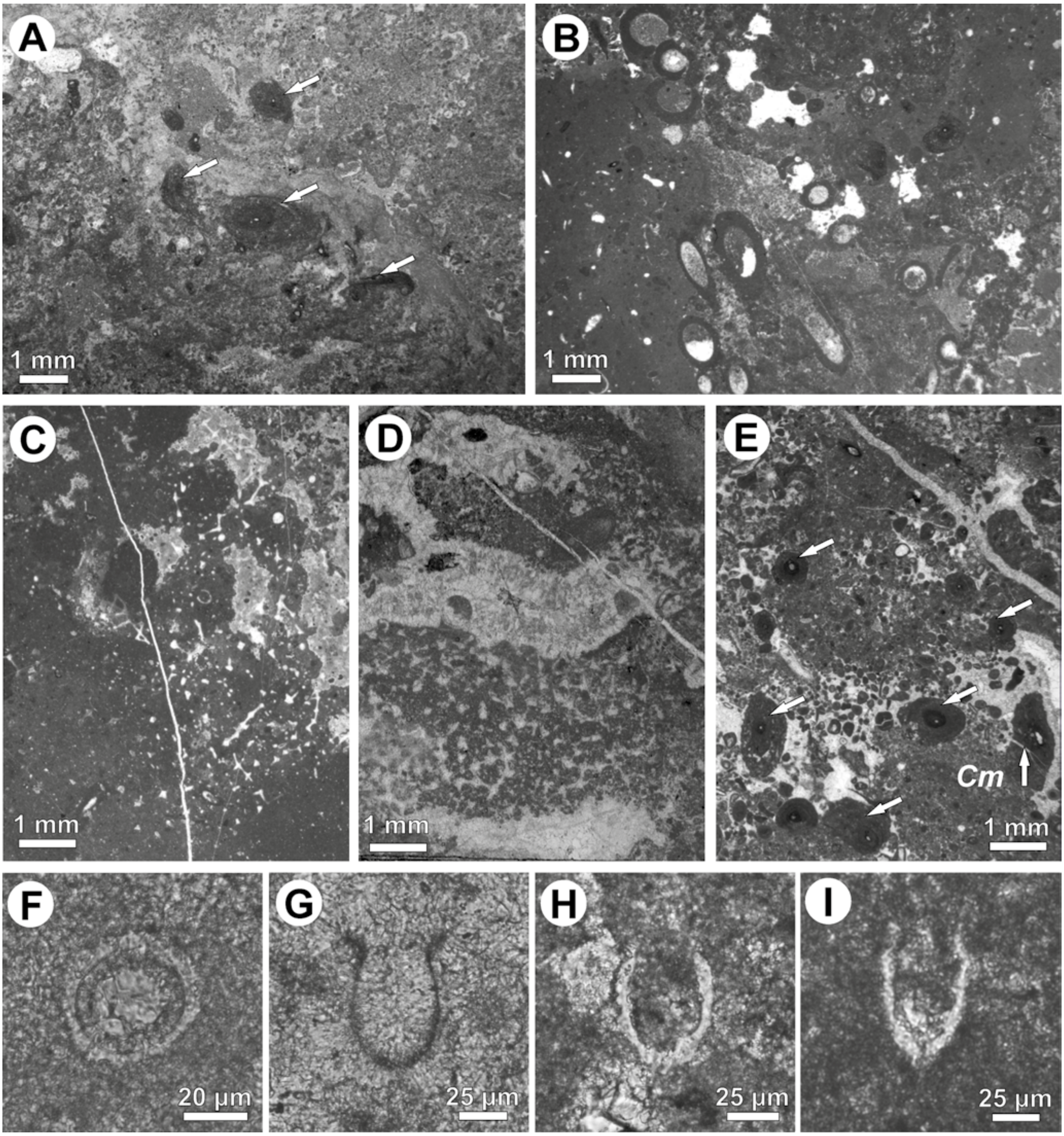

Fig. 13. Microfacies of FT 3: microbial (A–B) and microbial-sponge boundstones (C–E). **A**. Peloidal microbialite with *Crescentiella morronensis* (arrows). **B.** Numerous worm tubes *Terebella lapilloides* within dense to peloidal microbialite. **C, D.** Calcified siliceous sponges from the microbial-sponge boundstones. **E.** Peloidal packstone to grainstone with *C. morronensis* (arrows). **F–I.** Planktonic microfossils evidencing age of FT 3. **F.** Calcareous dinoflagellate cyst *Parastomiosphaera malmica*; Tithonian. **G.** Chitinoidellid *Chitinoidella elongata*; lower upper Tithonian. **G.** Calpionellid *Tintinnopsella remanei*; middle upper Tithonian. **I.** Calpionellid *Crassicollaria parvula*; uppermost Tithonian–lowest Berriasian. A – Sułów, B – Gródek nad Dunajcem, C – Wiśniowa, D – Nowe Rybie, E – Zarzyce Wielkie, F – Rożnów, G – Roztoka, H – Biskupice, I – Zarzyce Wielkie.

similar to FT 1. In addition to the largest sponge remnants, individual sponge spicules are common. Other bioclasts represent crinoid plates, ophiuroid vertebrae, echinoid spines, fragments of bivalve, brachiopod and gastropod shells, ostracod carapaces and bryozoan colonies. Microfossils are represented by foraminifera (Table 3), *Globochaete alpina* Lombard, calcareous dinoflagellate cysts; calpionellids were observed in some samples (Fig. 13F–I). Wackestones, packstones and poorly washed grainstones with bioclasts (sponges and other elements typical for this facies; ocassionally bioclasts typical for FT 1) and coated grains occur as the matrix. Figure 12B shows a polished slab of an exotic clast containing sections through tubular terebellid-like burrows. These traces are much larger than *T. lapilloides* (Fig. 13B) and possibly, like similar burrows recently recognized in the Upper Jurassic–Lower Cretaceous of Romania, belong to a new ichnogenus (Kołodziej *et al*., 2017; compare also burrows from the Oxfordian microbial boundstones: Kędzierski *et al*., 2013, fig. 8c).

Age: The Tithonian (and earliest Cretaceous?) age of this facies is confirmed by the occurrence of such stratigraphically significant microfossils as the calcareous dinocysts *Carpistomiosphaera tithonica*, *Colomisphaera tenuis*, *Committosphaera sublapidosa* (Vogler), *C. pulla*, *C. ornata*, *Crustocadosina semiradiata olzae* (Nowak), and *Parastomiosphaera malmica*; the calpionellids *Calpionella grandalpina* Nagy, *C. alpina*, *C. elliptalpina* Nagy, *Chitinoidella hegarati* Sallouhi, Boughdiri et Cordey, *Ch. boneti*, *Crassicollaria brevis* Remane, *Crassicollaria colomi* Doben, *C. intermedia*, *C. massutiniana* (Colom), *C. parvula*, *Daciella danubica* Pop, *Longicollaria dobeni* (Borza), *Tintinnopsella remanei* Borza, and *T. carpathica*; and the foraminifers *Coscinoconus elongatus* (Leupold), *Mayncina bulgarica* Laug, Peybernès et Rey, *Protomarssonella kummi* (Zedler), *P. hechti,* and *Protopeneroplis ultragranulata*.

FT 4: *Detrital limestones (Figs 14, 15)*

FT 4, the most common facies among the exotics, is represented predominantly by lithoclastic-bioclastic and lithoclastic grainstones and rudstones (Figs 14A, B, 15A–C), occasionally packstones. Rarely among the exotics there are detrital limestones, classified here as the matrix-supported breccias (Figs 14C, D, 15D) and the clast-supported (cement-rich) breccias (Figs 14E, F, 15D). Some of these limestones (especially those containing diverse components, not only reefal components), occur on the scale of the pebble (Fig. 14A). Bioclasts and lithoclasts, diversified in composition, size and roundness, are typical for a shallow-water carbonate platform. In terms of the main components, two types of detrital limestones can be distinguished: (1) with common reefal components (coral fragments, boundstone clasts) and (2) with reefal and non-reefal components. The grainstones include coral fragments, whereas the rudstones and breccias contain boundstone clasts of FT 1. The clasts – mostly below 30 mm in diameter – are usually angular (especially in limestones dominated by reefal components), but in some samples they are rounded.

Age: These limestones include bioclasts and clasts with stratigraphically significant microfossils of Tithonian and earliest Cretaceous ages, such as the calpionellids *Calpionella minuta* Houša, *C. alpina*, *C. grandalpina*, *Chitinoidella carthagensis* Sallouhi, Boughdiri et Cordey, *Ch. boneti*, *Ch. hegarati*, *Ch. popi*, *Crassicollaria brevis*, *C. colomi*, *C. intermedia*, *C. massutiniana*, *C. parvula*, *Dobeniella colomi* (Borza), *Borziella slovenica* (Borza), *Praetintinnopsella andrusovi* Borza, *Tintinnopsella carpathica*, and *T. remanei*; the foraminifers *Anchispirocyclina lusitanica* (Egger), *Coscinoconus cherchiae* (Arnaud-Vanneau, Boisseau et Darsac), *Coscinoconus delphinensis* (Arnaud-Vanneau, Boisseau et Darsac), *Coscinoconus histeri* (Neagu), *Coscinoconus perconigi* (Neagu), *C. alpinus*, *Coscinophragma cribrosum*, *Dobrogelina ovidi* Neagu, *Hechtina praeantiqua*, *Massilina mirceai*, *Mayncina bulgarica*, *Nautiloculina bronnimanni* Arnaud-Vanneau et Peybernès, *N. cretacea*, *Patellina subcretacea*, *Protomarssonella hechti*, *P. kummi*, *Protopeneroplis ultragranulata*, and *Textularia densa*; and the calcareous dinocysts *Cadosina fusca cieszynica* Nowak, *Carpistomiosphaera tithonica*, *Colomisphaera fortis*, *C. tenuis*, *Committosphaera sublapidosa*, *C. ornata*, *C. pulla*, *Crustocadosina semiradiata olzae*, and *Parastomiosphaera malmica.*

FT 5: Foraminiferal–algal limestones (Figs 16, 17)

FT 5 is represented by the following microfacies: foraminiferal-algal grainstone, cortoid-oncoid grainstone to rudstone, bioclastic-oncoid wackestone to floatstone. They include relatively numerous larger foraminifera and miliolids, and much rarer macrofossil bioclasts. Larger benthic foraminifera, dasycladalean green algae, rivulariacean-like cyanobacteria, "*Lithocodium-Bacinella*" (Fig. 17D, E) and *Thaumatoporella parvovesiculifera* (Fig. 17D) are typical for this facies. Bioclasts are commonly micritized and are commonly cortoids. "*Lithocodium-Bacinella*" may be an important component of this facies (at the scale of the clast; decimetre-size, irregular lumps, Fig. 16C), but they are observed only in part of the samples. Usually, they occur as oncoidal envelopes (up to 15 mm) around fragments of corals, calcified sponges, gastropods, bivalves and echinoids. Other macrofossils or their fragments are serpulid tubes, ostracod carapaces, and less frequently brachiopod shells, holothurian sclerites, bryozoan colonies, *Carpathocancer triangulatus* (Mišik, Soták et Ziegler) and *Carpathocancer*? spp. (both reinterpreted as decapod crustacean appendages by Schlagintweit *et al.*, 2007). Bioclasts are commonly the nucleus of oncoids, rarely of ooids, or they are superficially or fully micritized. *T. parvovesiculifera* and the foraminifer *Troglotella incrustans* often co-occur within these structures (cf. Schlagintweit, 2013). *Crescentiella morronensis* and *K. socialis,* common in the coral-microbial boundstones, are rare. Non-skeletal grains are additionally represented by small, rounded intraclasts, diverse peloids, and ooids (usually up to 0.7 mm, often superficial). The assemblages of foraminifera (exclusively benthic) are rich in specimens and in the diversity of forms (Ivanova and Kołodziej, 2010; Kowal-Kasprzyk, 2016). The most common genera are *Bullopora*, *Charentia*, *Coscinoconus* (former *Trocholina* or *Andersenolina*), *Melathrokerion*, *Mohlerina*, *Nautiloculina*, and *Pseudocyclammina*, and miliolids – usually hard to determine in detail – are numerous (Table 5; Fig. 17A–C). Dasycladales are represented by 19 species of the genera

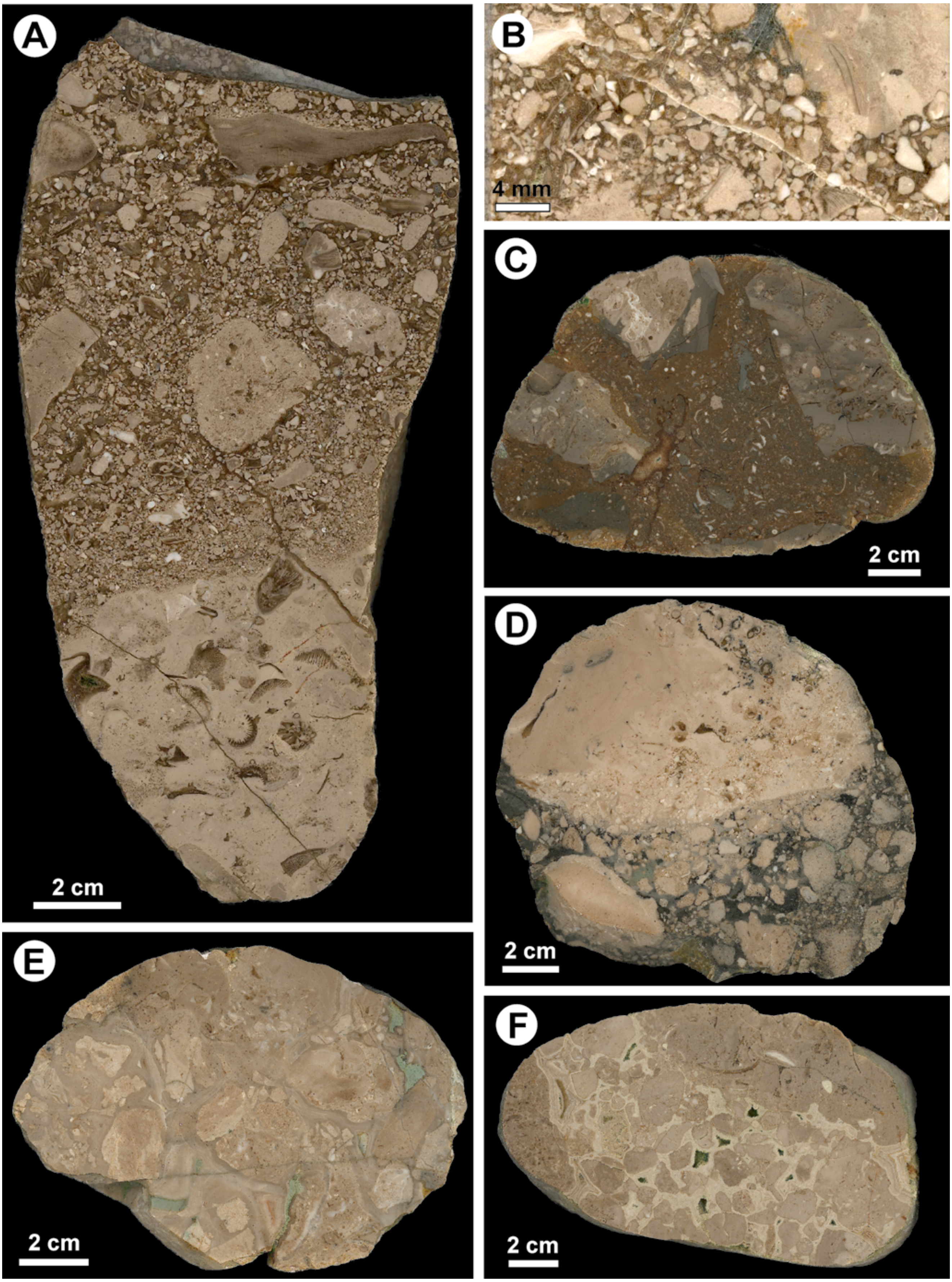

Fig. 14. Exotics representing the detrital limestones (FT 4). **A.** Bioclastic floatstone (lower part) and bio-intraclastic grainstones to rudstones. **B.** Bio-lithoclastic rudstones. **C, D.** Matrix-supported breccia with clasts of shallow-water limestones. **E, F.** Cement-rich, clast-supported breccia with clasts of boundstones. A – Gródek nad Dunajcem, B – site unknown C – Jastrzębia, D – Lusina, E – Leńcze, F – Woźniki.

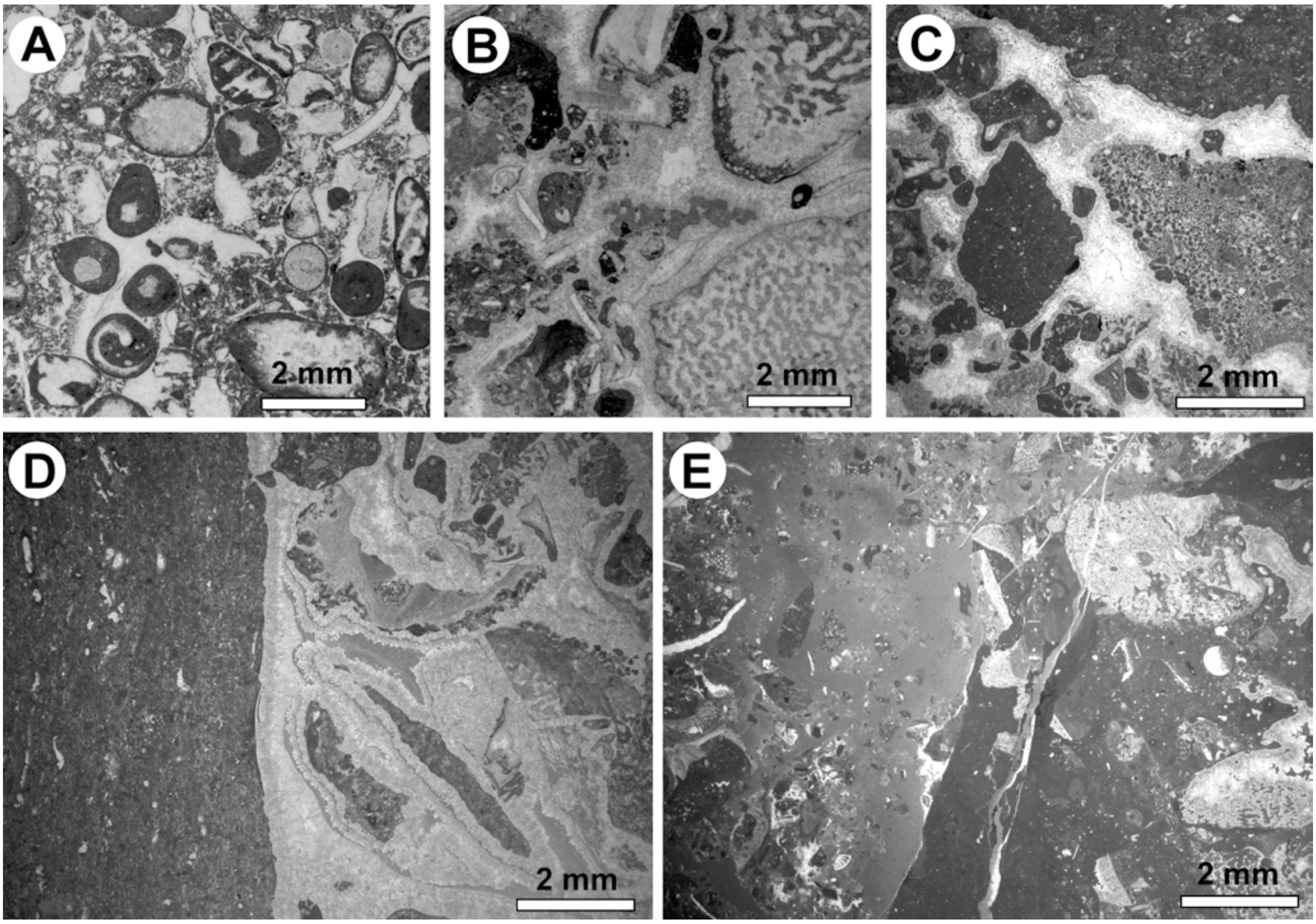

Fig. 15. Microfacies of the detrital limestones (FT 4). **A, B.** Bioclastic grainstones. **C.** Lithoclastic rudstone. **D.** Matrix-supported breccia with large boundstone clast (on the right side). **E.** Cement-rich, clast-supported breccia with the microbialite clast (on the left side). A, B – Izdebnik, C – site unknown, D – Woźniki, E – Jastrzębia.

Salpingoporella, *Griphoporella*, *Petrascula*, *Linoporella*, *Campbeliella*, *Otternstella*, *Montenegrella*, and the relatively rare *Aloisalthella sulcata* (Alth) (Bucur *et al*., 2005).

Age: The Tithonian–earliest Cretaceous age of this facies is confirmed by the occurrence of such stratigraphically significant microfossils as the foraminifers *Coscinoconus campanellus* (Arnaud-Vanneau, Boisseau et Darsac), *C. alpinus*, *C. cherchiae*, *C. delphinensis*, *C. histeri*, *C. perconigi*, *Coscinophragma cribrosum*, *Hechtina praeantiqua*, *Mayncina bulgarica*, *Nautiloculina bronnimanni*, *N. cretacea*, and *Protopeneroplis ultragranulata*; the calcareous dinocysts *Cadosina fusca cieszynica*, *Carpistomiosphaera tithonica*, *Committosphaera pulla*, *C. sublapidosa*, *Colomisphaera tenuis*, and *Crustocadosina semiradiata olzae*; and rare calpionellids: *Calpionella alpina*, *Crassicollaria* sp.

FT 6: Peloidal-bioclastic limestones (Fig. 18)

FT 6 is represented by peloidal-bioclastic and bioclastic-peloidal grainstones, less often by wackestones and packstones. Usually, the shape and size of the peloids are diversified; some of them are poorly rounded. These features indicate that they are micritized grains, small micritic clasts, resulting from the re-working of partly lithified sediment, and possibly also pellets. Additionally, cortoids, small intraclasts, and occasionally small (up to 0.5 mm) ooids are present. Fossil assemblages are composed of dasycladalean green algae, elements of crinoids, echinoids and ophiuroids, serpulid tubes, fragments of bivalve, gastropod and brachiopod shells, fragments of bryozoans, ostracod carapaces, calcified sponges, unidentified calcimicrobes, and occasionally corals and the calcified spicules of siliceous sponges. The foraminiferal assemblages are rich and diversified (Table 5); additionally, calcareous dinoflagellate cysts, the zoospores *Globochaete alpina* Lombard*,* and – in some samples – calpionellids occur. *Crescentiella morronensis, Koskinobullina socialis* and *Thaumatoporella parvovesiculifera* are common, occasionally *Carpathocancer triangulatus, "Lithocodium-Bacinella", Mercierella*? *dacica* Dragastan and *Terebella lapilloides* occur. Similar deposits fill voids in the framework of the coral-microbial boundstones. In some cases, the transition of peloidal-bioclastic grainstones to peloidal or micropeloidal microbial crusts was observed.

Age: The Tithonian and earliest Cretaceous age of this facies is confirmed by the occurrence of such stratigraphically significant microfossils as the foraminifers *Coscinoconus alpinus*, *C. cherchiae*, *C. histeri*, *Coscinophragma cribrosum*, *Dobrogelina ovidi*, *Haplophragmoides cushmani*, *H. joukowskyi*, *Hechtina praeantiqua*, *M. mirceai*, *M. bulgarica*, *Protomarssonella hechti*, *P. kummi*, *Protopeneroplis ultragranulata*, and *Textularia densa*; the calpionellids: *C. alpina*, *C. grandalpina*, *C. elliptalpina*, *Chitinoidella*

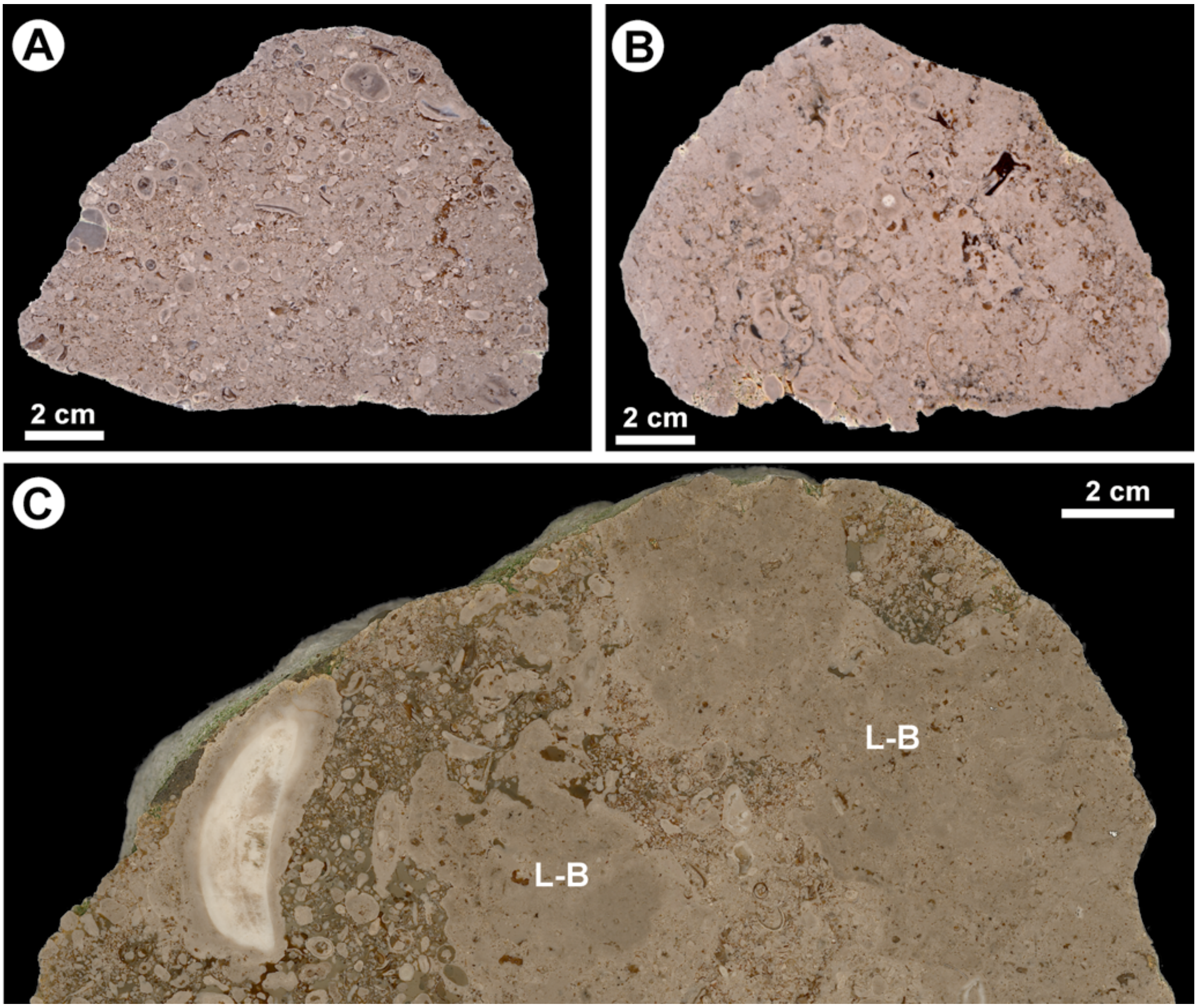

Fig. 16. Exotics representing the foraminiferal-algal limestones (FT 5). **A, B.** Foraminiferal-algal grainstones. **C.** Clast dominated by "*Lithocodium-Bacinella*" (L-B). There is a large bivalve bioclast within a foraminiferal-algal grainstone. A – Lipie, B – Sułów, C – Gródek nad Dunajcem.

elongata Pop, *Ch. boneti*, *Ch. carthagensis*, *Ch. hegarati*, *Ch. popi*, *Crassicollaria intermedia*, *C. massutiniana*, *C. parvula*, *Dobeniella tithonica* (Borza), and *Tintinnopsella remanei*; and the calcareous dinocysts *Cadosina fusca cieszynica*, *Colomisphaera tenuis*, *Committosphaera sublapidosa*, and *Parastomiosphaera malmica*.

FT 7: Ooid grainstones (Fig. 19)

Ooid grainstones, ooid-peloidal, and peloidal-ooid grainstone microfacies can be recognized in this rare facies type. Ooids, less than 1 mm in size, are recrystallized in the majority of samples. Two types of ooids were recognized among those that are better preserved: (1) spherical or ellipsoidal, micritized ooids, less than 1 mm in size; with nuclei of small bioclasts or peloids; some of them are less micritized and the concentric structure of the cortex can be recognized; and (2) more diversified in shape and size, sometimes larger than 1 mm, radial and concentric,-radial ooids; compound ooids and superficial ooids also appear; peloids and bioclasts (fragments of shells, echinoderms, foraminifers) are their nuclei. This facies is poor in fossils. Rare *Crescentiella morronensis,* echinoiderm elements, fragments of bivalve shells, calcareous and agglutinated benthic foraminifers, and even calpionellids and calcareous dinoflagellate cysts were observed.

Age: The Tithonian–earliest Cretaceous age of this facies is confirmed by the occurrence of *Calpionella alpina* and *Colomisphaera tenuis*, as well as several other microfossils with wider stratigraphic ranges, but typical of Tithonian–Berriasian assemblages.

FT 8: Mudstones-wackestones with calpionellids (Fig. 20)

Mudstones and bioclastic wackestones with calpionellids (e.g., Fig. 20E, F) and calcareous dinocysts are included in FT 8. Other bioclasts are less common and are represented by foraminifera, *Globochaete alpina* and calcified sponge spicules, rarely, ostracod carapaces, small fragments of bivalves, holothurian sclerites, echinoid and crinoid fragments, and calcified radiolarians as well as ammonites (Fig. 20D). The foraminiferal assemblages are not

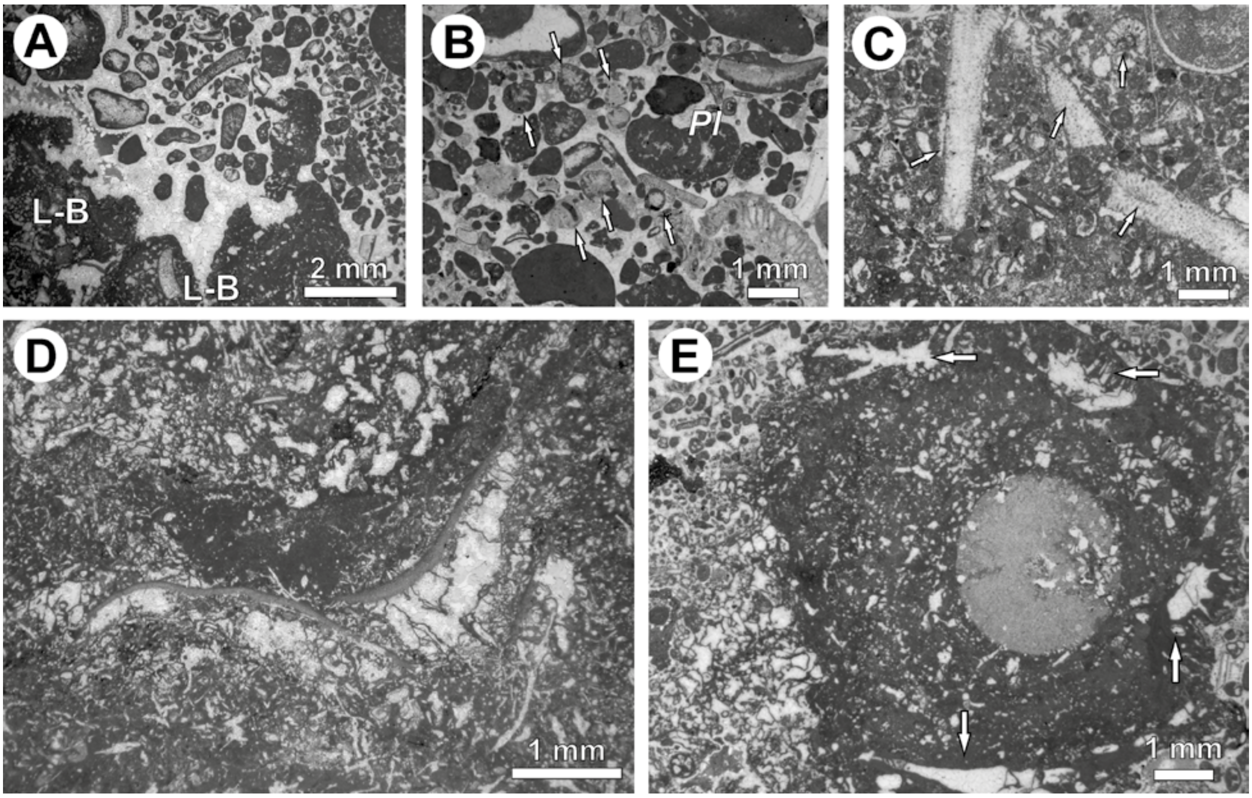

Fig. 17. Microfacies of foraminiferal-algal limestones (FT 5). **A, B.** Foraminiferal-algal grainstone with patches of "*Lithocodium-Bacinella*" (L-B in the image A) and foraminifera: *Pseudocyclammina lituus (Pl)*, and numerous *Coscinoconus* spp. (arrows in B). **C.** Packstone with calcified sponges and dasycladalean green algae (arrows). **D.** *Thaumatoporella parvovesiculifera* in the centre, and "*Lithocodium-Bacinella*" meshwork. **E.** Bioclast encrusted by "*Lithocodium-Bacinella*", including "*Lithocodium*"-like crust with entobian borings (arrowed). A, D, E – Gródek nad Dunajcem, B – Milówka, C – Zarzyce Wielkie.

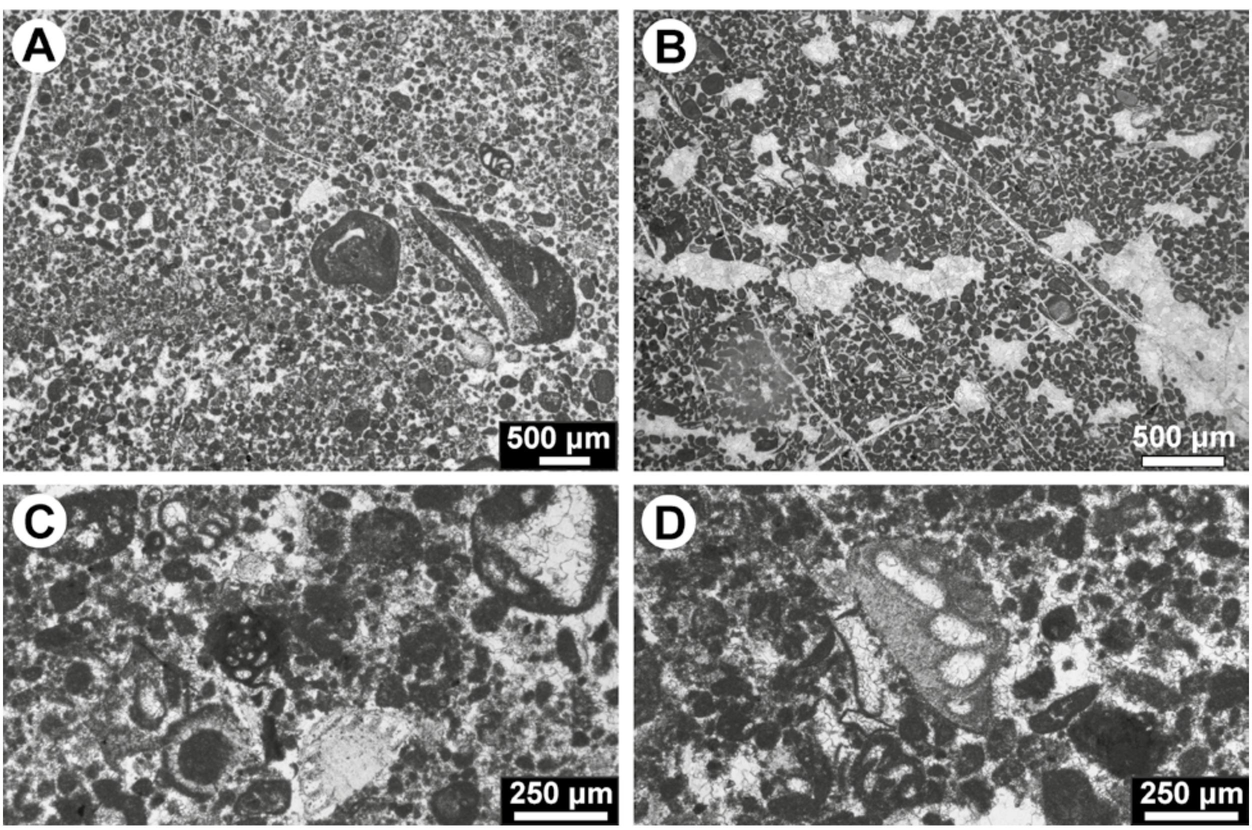

Fig. 18. Microfacies of the peloidal-bioclastic limestones (FT 6). **A.** Peloidal-bioclastic grainstone. **B.** Peloidal grainstone with fenestral structures. **C, D.** Peloidal-bioclastic grainstone with foraminifera *Dobrogelina ovidi* (upper specimen), miliolid (middle specimen) and *Ichnusella* sp. (lower specimen) (C) and *Mohlerina basiliensis* (D). A – Tarnawa, B – Woźniki, C, D – Żegocina.

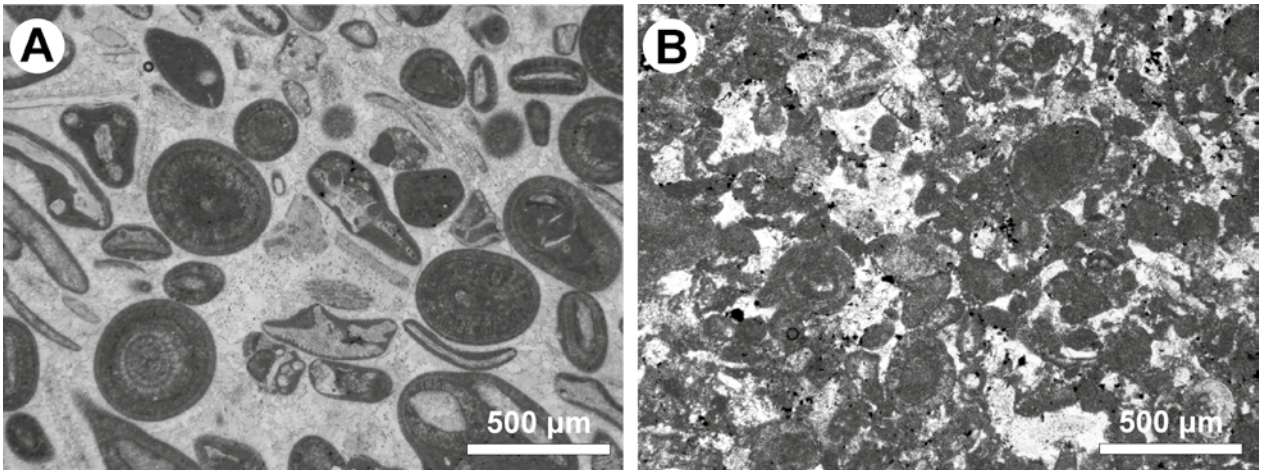

Fig. 19. Microfacies of the ooid grainstones (FT 7). **A**. Ooid grainstone. **B.** Ooid grainstone with micritised ooids. A – Woźniki, B – Zarzyce Wielkie.

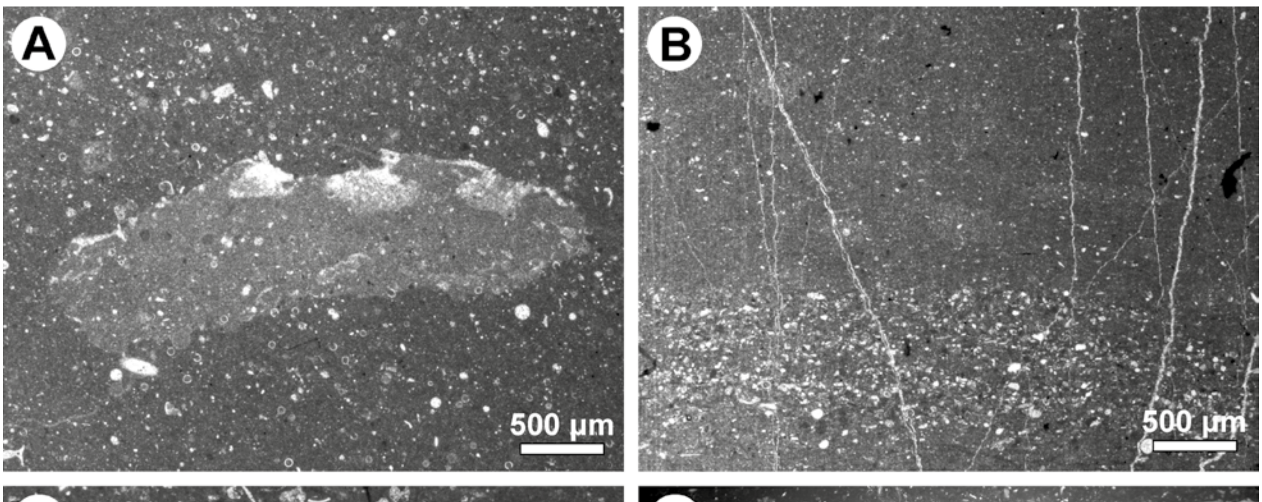

Fig. 20. Microfacies of the mudstones-wackestones with calpionellids (FT 8). **A.** Calpionellid mudstone with burrows. **B.** Wackestone (lower part) and mudstone with calpionellids. **C.** Bioclastic wackestone with calpionellids. **D.** Wackestone with calpionellids and ammonites. **E.** Tithonian calpionellid assemblage (*Calpionella alpina*, *Calpionella grandalpina*, *Crassicollaria* sp.). **F.** Berriasian calpionellid assemblage (small, spherical *Calpionella alpina*). A, B, E, F – Żywiec, C – Sułów, D – unknown site between Woźniki and Lanckorona.

rich and represented mainly by small, benthic, calcareous forms. Fine, siliciclastic grains, mainly of quartz, appear in some samples. Additionally, wackestones with pelagic microfossils and an admixture of bioclasts of shallow-water organisms can be included in the facies type. Small, calcareous, benthic foraminifers dominate in this facies (Table 5); additionally forms of shallower zones (especially miliolids) appear. Other fossils occurring as bioclasts are crinoids (e.g., *Saccocoma*), echinoids, bivalves (including filamentous bivalves), brachiopods, gastropods, bryozoans, siliceous sponges, and ostracods. Fossils typical of shallow zones (e.g., dasycladalean algae, *Crescentiella morronensis, Koskinobullina socialis*) occasionally occur, as well as small lithoclasts and peloids.

Age: The Tithonian and earliest Cretaceous age of this facies is confirmed by the occurrence of microfossils: mainly the calpionellids *Calpionella elliptica* Cadisch, *C. alpina*, *C. grandalpina*, *C. elliptalpina*, *Crassicollaria brevis*, *C. colomi*, *C. intermedia*, *C. massutiniana*, *C. parvula*, *Praetintinnopsella andrusovi*, and *Tintinnopsella carpathica*; and the calcareous dinocysts *Colomisphaera radiata* (Vogler), *C. fortis*, *C. tenuis*, *Committosphaera ornata*, *C. pulla*, *C. sublapidosa*, *Crustocadosina semiradiata olzae*, and *Parastomiosphaera malmica*.

Microfacies not assigned to main facies (Fig. 21)

The microfacies of some exotics cannot be without doubt assigned to the main facies described above, even though

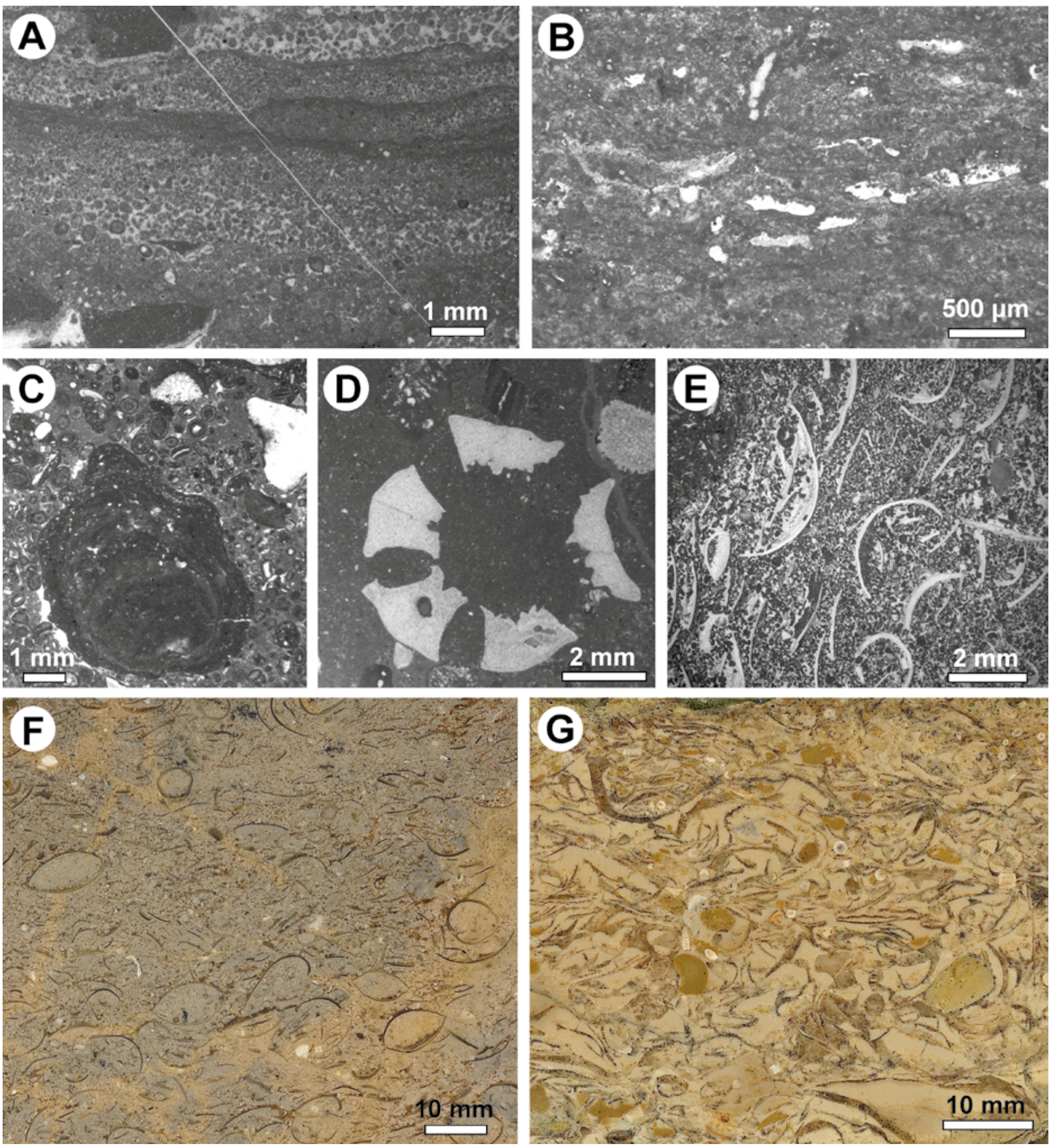

Fig. 21. Limestone clasts not attributed to main facies (FT 1–FT 8). **A.** Peloidal, agglutinated stromatolite (M 1). **B.** Poorly laminated, micropeloidal stromatolite (M 1). Elongated sparitic vugs are fenestral structures or related to encrusting microorganisms without skeletal walls. **C.** Oncoid-ooid packstone (M 2). **D.** Echinoderm wackestone (M 4). **E.** Grainstone with numerous bivalve shells (M 3). **F–G.** Polished slabs of limestones with numerous bivalves (M 3). A – Kobylec, B – Żegocina, C, D – Krzyworzeka, E – Żywiec, F – Żegocina.

they consist of more than one microfacies. They may represent microfacies from the facies described, or they belong to independent, but rare facies. Worth mentioning are clasts developed as agglutinated, laminated and micropeloidal stromatolites in M 1 (Fig. 21A, B), oncoid-ooid packstones in M 2 (Fig. 21C), limestones dominated by bivalves or other shells in M 3 (Fig. 21E–G), and echinoderm wackestones in M 4 (Fig. 21D). The Tithonian and earliest Cretaceous age of all these facies is confirmed by the occurrence of stratigraphically significant microfossils, such as the calpionellids *Calpionella alpina*, *C. elliptica*, *C. minuta*, *Chitinoidella boneti*, *Ch. carthagensis*, *Ch. hegarati*, *Ch. popi*, *Crassicollaria colomi*, *C. massutiniana*, *C. parvula*, *Remaniella duranddelgai* Pop, *Tintinnopsella carpathica*; calcareous dinoflagellate cysts: *Colomisphaera fortis*, *C. tenuis*, *Committosphaera sublapidosa*, and *Crustocadosina semiradiata olzae*; and the foraminifers *Patellina subcretacea*, *Protomarssonella hechti*, *P. kummi*, and *Protopeneroplis ultragranulata*.

Exotics with neptunian dykes (Fig. 22)

Three limestone clasts, developed as shallow-water bioclastic packstones-grainstones, contain thin fissures (up to 35 mm in width). These fissures are filled with dark calcimudstones-wackestones with ostracods and small burrows (*Chondrites*?).

Frequency of facies

The analysis of the frequency of facies is based on 312 exotic clasts of Tithonian–lowermost Cretaceous age from 31 localities (Fig. 23; Kowal-Kasprzyk, 2016). The most common among clasts are limestones that resulted from reef destruction, or, more generally, from the destruction of the carbonate platform. Detrital limestones (FT 4) were observed in ca. 30 % of samples. Coral-microbial boundstones (FT 1) and microbial and microbial-sponge boundstones (FT 3) were observed (each facies) in ca. 15% of samples. FT 7 and FT 8, and especially M 1–M 4 are the least common. These proportions are approximate.

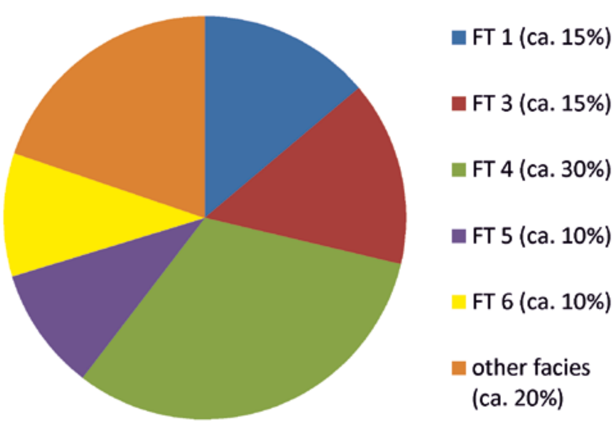

Fig. 23. Frequency of main facies of the Tithonian–lowermost Cretaceous exotic clasts of the Štramberk-type limestones. Based on 312 samples from the Silesian and Sub-Silesian units of the western part (between the Soła and Dunajec rivers) of the Polish Outer Carpathians.

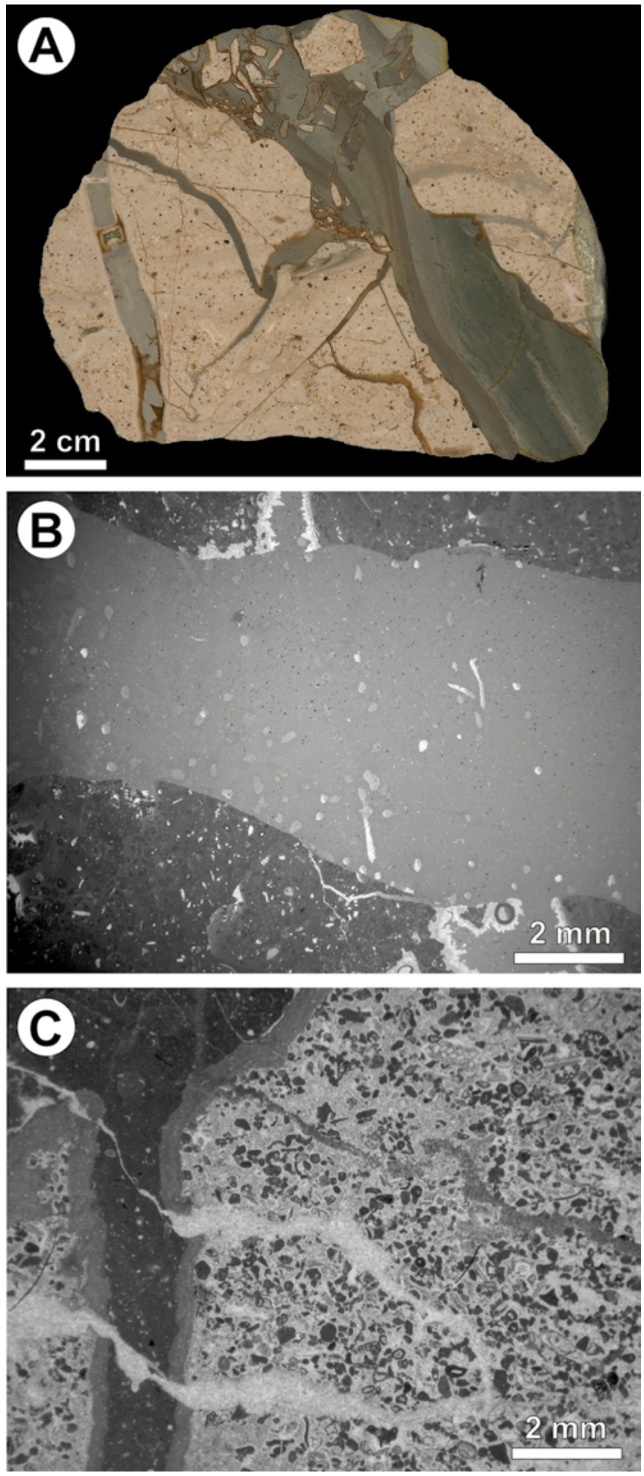

Fig. 22. Thin neptunian dykes (filled with dark Lower Cretaceous limestone) within the exotic clasts of the Štramberk-type limestones documenting the destruction and drowning of the carbonate platform. **A.** Polished slab of the exotic clast showing thin, dark neptunian dykes. **B, C.** Microscopic images of neptunian dykes cutting shallow-water limestones: bioclastic wackestones (B) and grainstone (C). There are numerous, small burrows (*Chondrites* isp.) in the calcimudstone filling of the dyke. The wall of the dyke in C is possibly coated by a thin, microbial crust. A, B – Jastrzębia, C – site unknown.

For example, some samples classified as the bioclastic-lithoclastic grainstones (FT 4) and the peloidal-bioclastic limestones (FT 6), can be in fact intra-reef sediment of the coral-microbial boundstones (FT 1). Owing to the small size of some clasts, the assignment of some microfacies to the main facies is uncertain. This quantitative analysis corresponds in general to the qualitative microscopic analyses of other samples and to observations in the field.

DISCUSSION

Distribution of the Štramberk-type limestones in the Polish Outer Carpathians

The exotics studied here are mostly from the Silesian and Sub-Silesian units. In the Silesian Unit, the Hauterivian–Barremian Hradiště Formation and the Campanian–Paleocene Istebna Formation are the main exotic-bearing beds. In the Sub-Silesian Unit, exotic clasts occur mainly in the Hradiště Formation and less commonly in the Veřovice Formation. Before the reorganization of the Late Cretaceous basin, the Sub-Silesian and Silesian sedimentary series were similar, because sedimentation in the western part of the Proto-Silesian Basin took place in similar basinal conditions (Golonka *et al.*, 2006b; Waśkowska *et al.*, 2009). The exotics from the Skole Unit, much rarer than the exotics in earlier units, are almost exclusively from the Maastrichtian–Paleocene Ropianka Formation.

Currently poorly exposed, but well known from the literature, the Kruhel klippe (near Przemyśl) occurs in the Ropianka Formation. The largest occurrence of different sizes of blocks – traditionally known as the Andrychów Klippen or Klippes (Inwałd, Targanice, Roczyny) – of the Štramberk-type limestones as well as the Middle Jurassic, Oxfordian and Palaeogene limestones occur in front of the Silesian Unit. Originally, they were regarded as tectonic klippen, but recently as olistoliths, which slid down into the Silesian Basin during the late Oligocene or early Miocene, and now occur as olistostromes within the Miocene molasse deposits (see Waśkowska-Oliwa *et al*., 2008; Cieszkowski *et al*., 2009).

Generally, it is hard to recognize any significant trends in facies distribution in particular geographical areas, tectonic units or lithostratigraphic units (see also Burtan *et al.*, 1984). The most common facies types are observed almost everywhere, and the majority of less common facies are observed at various localities. However, it is noteworthy that calpionellid mudstones/wackestones (FT 8) occur at only two localities, Żywiec (locality 2) and Żegocina (locality 27). These localities are geographically distant, but at both sites, clasts occur in the Lower Cretaceous Hradiště Formation (Silesian Unit) and the palaeotransport directions indicate input from the south.

There is no trend in the relationship between the age of exotics and the age of the flysch deposits. In general, the frequency of the Oxfordian–Kimmeridgian carbonate clasts (Kowal-Kasprzyk *et al*., 2020) and the Štramberk-type limestones described here (Tithonian–lowermost Cretaceous) is similar in the older (Lower Cretaceous) and younger (Paleocene–Eocene) flysch deposits. The studies of the present authors and the data in the literature indicate that exotics of the Štramberk-type limestones are rare in the Oligocene deposits (Menilite Formation). The literature indicates that they are absent (rare?) in the Oligocene Krosno Formation, in contrast to exotics of crystalline rocks (Ślączka and Wieser, 1962; Mochnacka and Tokarski, 1972; Bąk *et al*., 2001).

Štramberk-type limestones in other tectonic units, as shown by data in the literature, are much rarer and were not studied here. The Jurassic–Cretaceous exotics are poorly known from the Fore-Magura group of nappes and the Dukla Nappe, but Burtan and Sokołowski (1956) and Burtan *et al.* (1984) described Štramberk-type limestones from a locality near Żywiec (Fore-Magura Unit), which probably were derived from the Silesian Ridge. In the Magura Nappe, Štramberk-type exotics were observed only occasionally in the northern part, whereas in the rest of the unit only carbonate clasts similar to limestones from the Inner Carpathians (Tatra Mts.) and Pieniny Mts. were found (Oszczypko, 1975; Burtan *et al.*, 1984; Krobicki and Olszewska, 2005; Olszewska and Oszczypko, 2010; Oszczypko *et al*., 2020). Tithonian–Berriasian exotic limestones from the Krynica Subunit (close to the Pieniny Klippen Belt) of the Magura Nappe are represented by limestones with calpionellids (possibly analogous to FT 8 of the present study, Hoffmann in Oszczypko *et al*., 1992; Oszczypko *et al*., 2006). On the other hand, the Middle Jurassic and Lower Cretaceous (Urgonian) limestones are much more common there than in the northerly located units. Urgonian limestones in the Polish Outer Carpathians were reported almost exclusively from the Magura Nappe (Hoffmann in Oszczypko *et al*., 1992, Krobicki *et al*., 2005; Krobicki and Olszewska, 2005; Oszczypko *et al*., 2006, 2020). Štramberk-type limestones were also noted in the northerly located, folded Miocene of the Stebnik and Zgłobice units (Ney, 1957).

The lack of any clear distribution pattern of exotics in terms of the ages of exotic clasts and the ages of flysch deposits may be related to (1) the complex geological structure of the source areas, (2) the composition of exotics at a given locality reflecting a very local source area, and (3) possible erosion of exotics out of terrigenous conglomerates, composed both of older and younger carbonate clasts. Besides, the sampling at different locations was extensive to different degrees and therefore a strictly quantitative analysis of the frequency in different facies and the comparison of exotics from different localities would not be reliable.

Depositional and environmental settings

The challenge is to decipher the depositional and environmental characteristics as well as the facies distribution pattern and to propose a depositional model (platform zonation), based on exotics, mostly of pebble and cobble size, or even based on the analysis of olistoliths and large blocks, as in the case of the Štramberk Limestone. The following aspects should be considered in making such interpretations: the small size of the exotics, random source area, the problem with the age determination of particular clasts, their uncertain spatio-temporal relationships, and the rarity or lack of some facies (e.g., marls) due to their low preservation potential. In this chapter, the focus is on biotic components (corals, microencrusters, microbialites), and some facies (detrital facies and the role of synsedimentary cements in boundstones and in clast-supported breccias), which are important for the interpretation of the carbonate platform.

Corals

The Štramberk Limestone contains the most diversified Tithonian–Berriasian corals in the world (about 120 species, e.g., Ogilvie, 1897; Geyer, 1955; Eliášová, 1975, 1978, 1981a, 2008 and references therein) with a unique proliferation of the suborder Pachythecaliina (= Amphiastreina; about 40 species; e.g., Eliášová, 1975, 1978), representing possibly not Scleractinia-like modern reef corals, but an extinct order, Hexanthiniaria. Corals are also diversified in the Štramberk-type limestones (about 80 species, including 20 species of Pachythecaliina; see Kołodziej, 2015b and references in Table 1). It should be kept in mind that much more numerous and diversified coral assemblages of the Štramberk Limestone were described from samples, collected in the large, active Kotouč Quarry, that provided many more specimens than the exotics in the Polish Carpathians. The Tithonian coral faunas are much rarer than those in the Kimmeridgian, while Berriasian to Valanginian corals on a global scale are almost unknown (Löser *et al.*, 2021). For comparison, relatively rich coral assemblages from the upper Kimmeridgian–Valanginian of Bulgaria (Roniewicz, 2008) and from the upper Berriasian of Austria and Switzerland (Baron-Szabo, 2018) include 72 and 61 species respectively. The proliferation of the pachythecaliines in the Štramberk Limestone and the Štramberk-type limestones (only in Poland) is in sharp contrast with other Late Jurassic coral assemblages, including those from Poland (Roniewicz, 1966; Morycowa, 2012), although other coral groups may be comparatively diversified. In the present account, the suborder Pachythecallina is distinguished instead of Amphiastraeina and also corals from the Heterocoeniina were included. These suborders are still accepted by some authors (see the discussion in Kołodziej *et al.*, 2012; Kołodziej and Marian, 2021). The superfamily Amphiastraeoidea disappeared completely at the end of the Albian, while the Heterocoenioidea persisted until the end of the Cretaceous (Löser *et al.*, 2013; Löser, 2016). These corals are the most controversial Mesozoic corals, with contrasting opinions regarding skeleton structure, microstructure and high-rank taxonomy (see the review in Kołodziej and Marian, 2021). Further studies on the sedimentary environment may be helpful in deciphering the palaeoecological constraints on the development of the corals of the Štramberk Carbonate Platform, particularly on the unique diversification of pachythecaliines.

Corals have a largely phaceloid (branching) growth form, as in most Late Jurassic reefs. Corals of the suborder Microsolenina, a coral group with an opportunistic life strategy, occur both in the Štramberk-type limestones and in the Štramberk Limestone, but there is no evidence that they formed microsolenid-dominated boundstones. Microsolenid reefs, usually constratal reefs (biostromes), were typical of deeper, mesophotic settings and now occur usually at the base of the Upper Jurassic reef sequences on the northern Tethyan shelf (Insalaco, 1996), for example, in the Holy Cross Mts., Poland (Roniewicz and Roniewicz, 1971), but are very rare on the intra-Tethyan carbonate platforms.

Corals from the Lower Cretaceous (Barremian–lower Aptian) of the Polish Outer Carpathians, exclusively from the Hradiště Formation, differ both with regard to taxonomy and state of preservation and in that they are not embedded in a carbonate matrix (Morycowa, 1964b; Kołodziej and Gedl, 2000).

Microencrusters

Studies during the last decades reinterpreted the biological and taxonomic affiliation and environmental demands of the Jurassic–Cretaceous microencrusters and showed that an understanding of their associations and abundance is crucial to the interpretation of the sedimentary environments and zonation of carbonate platforms (for review, see Leinfelder *et al.*, 1993; Schlagintweit *et al.*, 2005; Schlagintweit and Gawlick, 2008; Pleş *et al.*, 2013; Kaya and Altıner, 2015).

Microencrusters in the Štramberk Limestone have been studied by Eliáš and Eliášová (1984) and Eliášová (1981c, 1986). Some of them have been reported only recently and allowed the recognition in the Štramberk Limestone of two contrasting boundstone types (Hoffmann *et al.*, 2017). Bacinellid and "*Lithocodium*"-like structures (commonly termed the "*Lithocodium-Bacinella*" association), *Lithocodium aggregatum, Koskinobullina socialis, Iberopora bodeuri* and *Thaumatoporella parvovesiculifera* are light-dependent taxa/biogenic structures, implying shallow-water reef, back-reef or lagoonal settings. Other species, listed in Table 1, have much broader environmental demands, but especially if photophilic microencrusters are absent, they imply fore-reef and slope settings (Leinfelder *et al.*, 1993; Schlagintweit and Gawlick, 2008, 2011; Pleş *et al.*, 2013, 2021; Kaya and Altıner, 2015; Kołodziej and Ivanova, 2021).

"*Lithocodium-Bacinella*", the most common in shallow-water facies (FT 1, FT 5), is of particular significance. Microscopic studies of the Štramberk-type limestones and the Štramberk Limestone indicate that *Lithocodium aggregatum sensu stricto* (green alga; Schlagintweit *et al.*, 2010) is rare. This microencruster also appears to be rare in other Upper Jurassic–lowermost Cretaceous shallow-water limestones, in contrast to the younger (Barremian–Albian) carbonate platform deposits (known worldwide). Instead, "*Lithocodium*"-like structures, that is, calcimicrobial crusts with entobian borings (Cherchi and Schroeder, 2010; Schlagintweit, 2010), associated with the cryptic and boring foraminifer *Troglotella incrustans* (e.g., Schmid and Leinfelder, 1996; Kołodziej, 1997a; Schlagintweit, 2012), are very common in the material studied. This also seems to be the case for other Late Jurassic–earliest Cretaceous carbonate platforms. Structures that are commonly reported from the Upper Jurassic–Lower Cretaceous shallow-water limestones and termed *Bacinella irregularis* in fact represent calcimicrobial crusts (bacinellid or bacinelloid structures/fabrics; Schlagintweit and Bover-Arnal, 2013; Granier, 2021). *Bacinella irregularis sensu stricto* – filamentous structures, not a vesicular meshwork – are microborings of green algae (Schlagintweit and Bover-Arnal, 2013) and as such were very rarely reported in the literature.

Labes atramentosa, Perturbatacrusta leini and *Radiomura cautica,* had broad environmental preferences and are common in boundstones FT 1 and FT 2, but are especially characteristic for the microencruster-microbial-cement reefs (FT 2). This type of boundstone is represented in the samples studied but is subordinate to FT 1. Microencruster-microbial-cement boundstones are unique to the intra-Tethyan carbonate platforms (Schlagintweit and Gawlick, 2008; Ivanova *et al*., 2008; Hoffmann *et al*., 2008; Pleş *et al*., 2013, 2016, 2019, 2021; Hoffmann *et al*., 2017; Krajewski and Schlagintweit, 2018; Kołodziej and Ivanova, 2021). Schlagintweit and Gawlick (2008) were the first to notice in the Kimmeridgian and Berriasian of the Northern Calcareous Alps (Plassen Carbonate Platform) the crucial role of non-photophilic microencrusters and synsedimentary cements for the reef framework. Microencruster-cement boundstones contain only rare corals, mostly microsolenids. Previously, such reefs were not distinguished among the Late Jurassic reefs (Leinfelder, 1993; Insalaco *et al*., 1997). This reef type is characteristic of, although possibly not limited to the isolated platforms of the Neo-Tethys (Schlagintweit and Gawlick, 2008; Pleş *et al*., 2021; Kołodziej and Ivanova, 2021). To recognize the microencruster-microbial-cement boundstones, it is necessary to study them in more than in a single thin-section. A similar microframework on the scale of one thin-section can occur in coral-dominated reefs (FT 1), especially on the walls of growth cavities (cryptic habitat), but in these shallow-water boundstones there are also photophilic microencrusters. An intermediate reef type, showing a framework composed predominantly of the microencruster-microbial-framework, with more (but still subordinate) corals and rare photophilic microencrusters certainly occurred, but such a type is difficult to recognize in pebbles. Riding and Virgone (2020) attributed the microencruster-microbial-cement boundstones described by Hoffmann *et al.* (2017) from the Štramberk Limestone to a type of carbonates with complex genesis and termed Hybrid Carbonates. This type and other hybrid carbonates are result of in situ abiotic, microbial and skeletal co-precipitates.

Reefs described from the Alps were interpreted to be formed in a high-energy setting, at a depth of 10–20 m up to 50 m (upper part of the platform slope), below the coral-stromatoporoid reefal zone (Schlagintweit and Gawlick, 2008). This palaeobathymetric interpretation is supported by the lack or scarcity of corals and photophilic microencrusters, which are common in coral-dominated reefs. Synsedimentary cements support an assumption of a steep platform margin and high energy at the upper platform slope. The upper platform slope was also inferred for boundstone type B (microencruster-cement boundstones) in the Štramberk Limestone (Hoffmann *et al*., 2017) and similar reefs in the Kimmeridgian of Bulgaria (Moesian Carbonate Platform; Kołodziej and Ivanova, 2021). The presence of the microencruster-cement boundstones on the Štramberk Carbonate Platform and their absence from platforms located on the Tethyan margin (see the last section) confirm the conclusion of Schlagintweit and Gawlick (2008) and Kołodziej and Ivanova (2021) that this peculiar facies can be useful in palaeogeographic reconstructions, for deciphering the puzzle of microplates in the Western Neotethyan realm.

Other microencrusters – the worm tube *Terebella lapilloides* – are common in the microbial and microbial-sponge boundstones (FT 3) and are typical for limestones, deposited in low-energy and dysoxic environments, for example, the microbial-sponge reefs (Kaya and Altıner, 2014).

Microbialites

Carbonates produced by microbial growth and metabolism, as well as the passive mineralization of organic matter (microbially-induced and microbially-influenced carbonate precipitation) are important component of most coral-dominated and other types of Late Jurassic reef (e.g., Schmid, 1996; Helm and Schülke, 1998; Leinfelder and Schmid, 2000; Leinfelder, 2001; Dupraz and Strasser, 2002; Olivier *et al*., 2004; Matyszkiewicz *et al*., 2012). Leinfelder and Schmid (2000) summarized types and environmental significance of the Jurassic microbialites. Late Jurassic microbialites were typically restricted to environments with low hydraulic energy. Microbialites are largely lacking in high-energy reefs, but if steep reef margins allowed the export of most of the debris, microbialites were able to stabilize the remaining reef debris. Well-developed coral-microbial (especially thrombolite) reefs were largely restricted to settings close to siliciclastic source areas. Even if during reef growth direct siliciclastic influx was minimal, it may be concluded that nutrient availability was elevated, typical for mesotrophic rather than oligotrophic environments. Late Jurassic reef corals, though having developed symbiosis with photosymbionts analogous to modern zooxanthellae, benefited from slightly elevated nutrient levels (Nose and Leinfelder, 1997).

The contribution of microbialites to the reef facies of the Štramberk-type limestones was not appreciated before the work of Hoffmann (1992; see also Hoffmann and Kołodziej, 1997, 2008; Bucur *et al*., 2005), but they are poorly described and documented. Microbialites are also important in the Štramberk Limestone, as was initially described by Hoffmann *et al*. (2017), but previous studies did not examine their composition and significance. Eliáš and Eliášová (1984, p. 131) only briefly mentioned "*bioliths−bindstones [...] bound by algae*" occurring in the inner reef flat with the extensive growth of corals. It is unclear whether these algae correspond to microbial crusts in the recent meaning or correspond to "*Lithocodium-Bacinella*". It is unclear whether agglutinated, laminated and micropeloidal stromatolites, distinguished in this paper as microfacies and not assigned to the main facies (M 1), should be included in the boundstones facies (rather to FT 1 than to FT 3) or they developed in a restricted lagoonal environment (without corals). The reason is the lack of fossils or structures within these stromatolites of pebble size implying a sedimentary setting. Stromatolites interpreted as lagoonal were reported from the Štramberk Limestone, but were poorly discussed (Eliáš and Eliášová, 1984, pl. 9, fig. 1). Microbialites within exotic clasts, which were recently assigned (based on microfossils) to the Oxfordian−Kimmeridgian, differ in microscopic appearance (Kowal-Kasprzyk *et al*., 2020). Different varieties of microbialites in the Štramberk-type limestones and the

Štramberk Limestone certainly require insightful studies, including geochemical investigations that could provide insight into nutrient availability, redox conditions and changes in the input of terrigenous siliciclastics (e.g., Olivier and Boyet, 2006; Matyszkiewicz *et al*., 2012).

Synsedimentary cements

Hoffmann *et al.* (2017) recognized the important role of synsedimentary cements in two facies of the Štramberk Limestone: in the clast-supported breccias and in the microencruster-microbial-cement boundstones. Microencrusters are attached to the first generation of cement, which implies a synsedimentary origin for this cement, an important component of the framework reef of FT 2 (see also the previous section "Microencrusters"). The reef-derived, clast-supported breccia is one of the characteristic facies of the Štramberk Limestone. Clasts are bound by radiaxial-fibrous calcite cement, interpreted to be dominantly synsedimentary, as implies examination under cathodoluminescence (Hoffmann *et al*., 2017). The thick, banded cement crusts show similarity to the "evinospongiae" cements in the Middle–Upper Triassic boundstones and breccias of the Alps (e.g., Harris, 1993; Russo *et al*., 2000). The presence of similar breccias in the Štramberk Limestone implies steepened slopes of the carbonate platform, as was previously suggested by Eliáš and Eliášová (1984), although they did not describe breccias (but see the discussion in Hoffmann *et al*., 2017, p. 340 on "*large ?oncoids*", described by Eliáš and Eliášová, 1984). A similar assumption can be made for the morphology of platforms in the "Polish part" of the Štramberk Carbonate Platform, although this facies is rarely represented in the exotic clasts studied, possibly because of less available material for study. To the knowledge of the present authors, there are no comparable breccias, showing massive synsedimentary cementation ("evinospongiae" cement), in other Upper Jurassic–lowermost Cretaceous platform deposits.

Detrital facies

Diverse detrital limestones are very common, both in the Štramberk Limestone (Eliáš and Eliášová, 1984; Vašíček and Skupien, 2014; Vaňková *et al*., 2019) and in the Štramberk-type limestones. Except for the preliminary studies of the clast-supported, reef-derived breccias in the Štramberk Limestone (Hoffmann *et al*., 2017), discussed above in the section "Synsedimentary cement", detrital limestones were not studied in terms of volume, components and processes, responsible for the breakdown of biota and lithified sediments as well as their redistribution. Coarse-grained facies, i.e., matrix-supported and clast-supported breccias, are of particular importance for the interpretation of platform morphology and zonation. Bioclastic debris, apart of reef building macroorganisms (corals, calcified sponges), microbialites and microencrusters, are components of coral reefs. High debris production and small content of micrite are typical for the Late Jurassic reefs of the Tethyan domain, and some of them even have been called *coral debris reefs* (Leinfelder, 1992; Leinfelder *et al*., 2005; Rusciadelli *et al*., 2011; Rusciadelli and Ricci, 2013; Ricci *et al*., 2018b). The composition and genesis of detrital limestones have implications for the interpretation of the hydrodynamics in different parts of the carbonate platform, the mechanisms of redeposition of detrital material and platform morphology (gentle *vs* steepened slope profile) and improvement of the understanding of the dynamics and development of carbonate platform systems (e.g., Rusciadelli and Ricci, 2013; Harchegani and Morsilli, 2019). If steep reef margins existed, a large volume of the debris could be exported, allowing the export of most of the reef debris, hence microbialites were able to develop and stabilize the remaining reef debris forming coral-microbial-debris reefs (Leinfelder, 1992, 2001). However, studies of exotics do not allow to determine whether this reef type (reef debris bound by microbialites) was formed on a larger scale.

Oxfordian–Kimmeridgian in exotic pebbles

During field observations, some exotics could be termed Štramberk-type limestones, but in fact they are Oxfordian–Kimmeridgian limestones and differ from most facies described here. These exotics were not described in the present paper, but below the authors briefly characterize them. Oxfordian–Kimmeridgian limestones are represented by three main facies types: (1) light-beige, porous, sponge-microbial limestones, (2) beige, non-porous, oncoid-intraclastic-*Crescentiella* limestones, and (3) dark-grey, fine-grained biodetrital limestones with *Saccocoma* (Kowal-Kasprzyk *et al*., 2020). The first facies is composed mainly of two microfacies: sponge-microbial framestones-floatstones and fine-grained, bioclastic wackestones-packstones. The second facies is represented by oncoid-intraclastic floatstones-wackestones and *Crescentiella*-peloidal wackestones and bindstones. In the third facies, three microfacies types can be distinguished: filamentous-*Saccocoma* wackestones, spicule-*Saccocoma* wackestones and crinoid-*Saccocoma* packstones-wackestones (Kowal-Kasprzyk *et al*., 2020).

These limestones are similar to Oxfordian (mostly) facies types from the northern shelf of the Western Tethys (e.g., extra-Carpathian southern Poland, including the Carpathian Foredeep basement) and are interpreted as being deposited in similar conditions (e.g., Matyszkiewicz, 1997; Krajewski *et al*., 2011, 2016; Matyszkiewicz *et al*., 2012). The sponge-microbial limestones are facies of a distal ramp and mid-ramp; they were deposited mostly in a low-energy, nutrient-rich environment, between the fair-weather and the storm wave bases. The oncoid-intraclastic-*Crescentiella* limestones are related to a mid-inner ramp with moderate water energy. The fine-grained biodetrital limestones with *Saccocoma* were deposited in an outer-ramp setting. On the basis of foraminifers, calcareous and organic-walled dinoflagellate cysts, the age of the samples studied can be determined generally as Oxfordian and Kimmeridgian, but a precise age determination is usually impossible (Kowal-Kasprzyk *et al*., 2020).

In summary, these limestones originated in a deeper depositional setting than most facies of the Tithonian–earliest Cretaceous Štramberk-type limestones. Oxfordian–Kimmeridgian sponge-microbial and oncoid-intraclastic-*Crescentiella* facies are very similar to the Tithonian–?earliest Cretaceous microbial and microbial-sponge boundstones (FT 3), described in this paper, and sometimes are distinguishable only micropalaeontologically. It is noteworthy that the sponge-microbial limestones (sponge megafacies) in the Carpathian Foredeep basement (southeastern segment of the Mid-Polish Trough) ranges in age up into the lowermost Tithonian (Matyja, 2009).

Oxfordian–Kimmeridgian clasts in the flysch can be beige in colour, but they can be also dark in colour, more commonly than the colour of the Štramberk-type limestones. FT 8 (deeper facies) is much more commonly dark than are the other facies. However, colour is not a sound criterion for distinguishing the Oxfordian–Kimmeridgian clasts or exotics representing the deeper facies. Exotics of Štramberk-type limestones from the uppermost Jurassic Vendryně Formation and from the Hauterivian–Barremian Hradiště Formation (locality Żywiec) are more commonly dark, possibly because of a shorter period of weathering in a subaerial environment.

Cieszyn Limestone – a deep-water equivalent of the Štramberk-type limestones

The deep-water Cieszyn Limestone (Cieszyn Limestone Formation, part of the Cieszyn Beds) from the western part of the Polish Outer Carpathians are well described in terms of palaeontology and in particular their stratigraphy (Szydło and Jugowiec, 1999; Olszewska, 2005; Olszewska *et al.*, 2008) and especially sedimentologically (e.g., Nowak, 1967; Peszat, 1967; Malik, 1986; Słomka, 1986; Matyszkiewicz and Słomka, 1994, 2004). The uppermost Kimmeridgian Vendryně Formation (formerly the Lower Cieszyn Beds) – the oldest sediments ("pre-flysch") of the Polish Outer Carpathians – and the Tithonian–lowermost Valanginian Cieszyn Limestone Formation, were deposited in the deeper zones of the Proto-Silesian Basin, now forming mostly the Silesian Unit and locally the Sub-Silesian Unit (Olszewska, 2005; Olszewska *et al.*, 2008). Thus they are deep-water equivalents of the Štramberk Limestone and Štramberk-type limestones. The Vendryně Formation – mainly Tithonian in age – is dominated by dark, marly shales, while the younger Cieszyn Limestone includes detrital, organodetrital and pelitic limestones, with intercalations of marly shales. The Upper Cieszyn Limestone Formation (debris-flow sediments) contains clasts representing shallow-water reefs (analogous to FT 1 of the present account) and deep-water boundstones (FT 2 and/or Oxfordian–Kimmeridgian microbial-sponge boundstones; cf. Matyszkiewicz and Słomka, 2004). Coarse-grained debris-flow deposits are more common in the upper part of the Cieszyn Limestone Formation (Berriasian), reflecting the Neo-Cimmerian movements of the Silesian and Sub-Silesian ridges, probably linked to the initial rifting of the Silesian (Proto-Silesian) Basin (Krobicki and Słomka, 1999; Krobicki *et al.*, 2010). In the initial stage, clastic material was delivered mainly from the northern source area, but since the late Tithonian, the southern source area also was active (e.g., Matyszkiewicz and Słomka, 1994). The tectonic activity resulted in the emergence of the Silesian Ridge from west to east (Unrug, 1968; Matyszkiewicz and Słomka, 1994).

Detrital limestone is dominant lithotype of the Cieszyn Limestone Formation and occurs as thin layers in the Vendryně Formation. These originated from the destruction of the carbonate platform that had developed along the margins of the basin. They include shallow-water bioclasts and intraclasts, but also clasts of pelitic calpionellid limestones (Peszat, 1967; Książkiewicz, 1971a; Matyszkiewicz and Słomka, 1994, 2004). These intraclasts are analogues to the exotics studied, and they also include similar microfossils (e.g., Nowak, 1967; Olszewska, 2005; Olszewska *et al.*, 2008). The pelitic calpionellid limestones – the other main lithotype of the Cieszyn Limestone – are analogues to the FT 8 facies, described here.

It is noteworthy that the name "Štramberk-type limestones" is used here in a broad sense and not exclusively for the shallow-water platform deposits. Therefore, it is hard to put a boundary between the "Štramberk facies" (their deeper facies types) and the "Cieszyn facies". Clasts of some detrital or calpionellid limestones can be indistinguishable from the limestones, observed in profiles of the lowest part of the Silesian Unit. In such a situation, they do not meet the strict definition of "exotic" clasts, because their source rocks are exposed.

Zonation of the carbonate platform studied and other intra-Tethyan platforms

Štramberk Limestone

Because of similarities in the age, facies, and coral assemblages as well as palaeogeographic proximity, it is tempting to apply the zonation of the sedimentary system of the Štramberk-type limestones (Poland) to the proposed platform zonation that is based on studies of the Štramberk Limestone (Czech Republic). As was already highlighted, the limestones of both countries are interpreted here as deposited on carbonate platforms, attached to intra-Carpathian ridges, which are collectively termed the Štramberk Carbonate Platform. This platform is not considered to have been one huge intra-Carpathian carbonate platform, but rather a number of small, narrow platforms, attached to intrabasinal ridges (the largest are the Silesian Ridge and the Baška-Inwałd Ridge) as well as platforms attached to the margins of the Outer Carpathian Basin. At the end of this chapter, the authors present the zonation of the carbonate platform based on their studies of exotics and data from recent literature on the zonation of other intra-Tethyan carbonate platforms with reefs. Earlier, the authors present zonations, proposed for the Štramberk reef complex (Štramberk Limestone) and other European Late Jurassic, reef-bearing carbonate platforms. In accordance with a broad definition of a fossil reef (e.g., Wood, 1999; Riding, 2002; Kiessling, 2009), patch-reefs – the inferred dominant type of reef studied here – safely can be classified as a reef.

The model presented by Eliášová (1981b) and Eliáš and Eliášová (1984) was based on studies of olistoliths and large blocks. However, it should be verified because since the 1980s, knowledge of the Late Jurassic–Early Cretaceous platforms and reefs has increased significantly. A revised interpretation of the sedimentary environments and reef zonation of the Štramberk Limestone requires more qualitative and quantitative data concerning the facies, microfacies and composition of the biota within individual olistoliths and blocks. A preliminary study by Hoffmann *et al*. (2017) has provided a new insight into the zonation of the Štramberk reef complex and is applied in the interpretation, proposed in the present work.

The Štramberk Limestone rarely features in discussions on the intra-Tethyan carbonate platforms (Leinfelder *et al*., 2002, 2005; Rusciadelli *et al*., 2011). Recently, in a paper on the Upper Jurassic reefs of Sardinia (passive margin of the Alpine Tethys) the Štramberk Limestone were not included among examples of Upper Jurassic reefs, even though there were references to ten papers on other Tethyan platforms (Nembrini *et al*., 2021). Hoffmann *et al.* (2017) discussed the biotic and sedimentary characteristics that the Štramberk Limestone shares with the Late Jurassic platforms of the Tethyan realm. These similarities include: (1) the strongly zoned character of the reef complexes, (2) high or moderate, topographic relief at the reef edge, (3) the presence of the microencruster-microbial-cement reefs with some microencruster species, known exclusively from the Tethyan realm, (iv) the reef-building role of calcified sponges, (v) high debris production, and (vi) the subordinate role of micrite and terrigenous material (Leinfelder *et al*., 2002, 2005; Schlagintweit and Gawlick, 2008; Rusciadelli *et al*., 2011; Ricci *et al*., 2018a, b). The small sizes of exotic clasts and much reduced availability of samples is why seeing these features in the Štramberk-type limestones is much more difficult. Nevertheless, the common, detritic limestones and reef-derived breccias and the proximity to deep-water basins (pre-flysch of the Cieszyn Beds) support high or moderate, topographic relief at the reef edge of the carbonate platforms, part of the Štramberk Carbonate Platform, remnants of which are preserved as the Štramberk-type limestones. The low number of exotic clasts, representing matrix- and clast-supported breccias, is considered to be a result of the much reduced amount of material available (the large, active Kotouč Quarry, near Štramberk, in the Czech Republic *vs* the exotic clasts studied here). The microencruster-microbial-cement boundstones (FT 2; typical of the intra-Tethyan carbonate platforms), previously only reported to a minor extent (Hoffmann *et al*., 2008; Kołodziej *et al*., 2015), are well represented in the exotics studied, but as in the Štramberk Limestone (Hoffmann *et al*., 2017), they are subordinate to the coral-microbial boundstones (FT 1).

Eliášová (1981b) and Eliáš and Eliášová (1984) subdivided the Štramberk reef complex into (1) a fore-reef; (2) a reef core, with (a) a reef front, (b) a reef edge, and (c) an inner reef flat; and (3) a back reef (lagoon). This model was proposed on the basis of a comparison with modern reefs in the Red Sea and the Caribbean region. However, because of the different ecological demands and physiological capabilities of the pre-Cenozoic corals (e.g., modern, multiserial, branching *Acropora vs* Jurassic branching, phaceloid corals), an actualistic approach to ancient reefs should be critical (e.g., Wood, 1999; Leinfelder *et al*., 2002). The zonation of modern reefs is used in reconstructions of the Cenozoic fossil reefs, but zonations of the Jurassic reefs based on corals are almost non-existent (Lathuilière *et al.*, 2005, 2021).

Phaceloid corals are common both in the Štramberk Limestone and in the Štramberk-type limestones. The distribution pattern of phaceloid corals in the Štramberk reef, inferred by Eliášová (1981b) and Eliáš and Eliášová (1984), requires modification. It was assumed by these authors that such corals grew in two zones: (1) on a low-energy inner platform, and (2) in deeper parts of the reef front. The second zone was inferred on the basis of the co-occurrence with planktonic organisms, which were, however, not well documented enough in terms of their frequency. Calpionellids are typical of limestones deposited in deeper settings (FT 8, FT 3), but in the Štramberk-type limestones studied, they were recognized also in some samples from the shallow-water facies (FT 1, FT 6, FT 7, and even FT 5). Deeper parts of the reef front were assumed by Eliáš and Eliášová (1984) to be the locations of branching corals. However, this is not in agreement with the present interpretation of the distribution pattern of the Jurassic phaceloid corals (very rare in modern reefs), which are currently assigned to the inner platform (e.g., Leinfelder *et al*., 1996, 2002; Rusciadelli *et al*., 2011; Ricci *et al*., 2018a). Except for the Štramberk Limestone and the limestones studied here, the only proliferation of phaceloid pachythecaliines was observed in the upper Barremian of Bulgaria. The growth of these corals was considered referable to distal settings of the rudist-dominated, inner carbonate platform (Fenerci-Masse *et al*., 2011) and to the inner carbonate platform (Kołodziej *et al*., 2012). In the opinion of the present authors, most of blocks and clasts with phaceloid corals, both in the Štramberk Limestone and in the Štramberk-type limestones, represent the inner platform.

Zonation of other European reef-bearing carbonate platforms

The zonation models proposed by Lathuilière *et al.* (2005, 2021) concerns the Oxfordian reefs representing reefs of the northern Tethyan shelf that differ significantly from the reefs developed on the intra-Tethyan carbonate platforms. The only recent, detailed model (with biotic zonation) of the Tethyan carbonate platform is based on the study of the Upper Jurassic mixed stromatoporoid-coral reef complex (Ellipsactinia Limestones) of the Central Apennines (Rusciadelli *et al*., 2011; Ricci *et al*., 2018a). According to Rusciadelli *et al.* (2011), the proposed sedimentary model can be applied to other Tethyan reef complexes. However, the reefs of the central and southern Tethys are stromatoporoid-coral reefs (Turnšek *et al*., 1981; Leinfelder *et al*., 2005; Rusciadelli *et al.*, 2011; Ricci *et al*., 2018a). The present authors assume that this model can rather be a reference model for the Late Jurassic reef complexes of central and southern Tethys, than for those of its northern part (Štramberk Carbonate Platform).

Calcified sponges (stromatoporoids and chaetetids) occur in the Štramberk Limestone (Bachmayer and Flügel, 1961a, b) and in the Štramberk-type limestones (Podoba, 2009), but their quantitative significance has not yet been evaluated. Thin, millimetres-sized, calcified sponges are important in the framework of the microencruster-microbial-cement boundstones (FT 2), but they are volumetrically subordinate in the coral-microbial boundstones (FT 1). Both previous and recent studies showed that corals out-competed calcified sponges. Nevertheless, calcified sponges are much more common and diversified, in contrast to the situation on the northern Tethyan shelf. For example, on the upper Kimmeridgian carbonate platform of the Holy Cross Mts. in Poland, only chaetetids (locally common) occur in some beds (Kołodziej, 2003b). An analysis of the stromatoporoid and chaetetid sponges of the Štramberk Limestone, even though their significance is lower than in the reefs of the central and southern Tethys, would be crucial for the interpretation of the original position of particular olistoliths and blocks within the reef complex (upper slope, outer and inner platform; Leinfelder *et al.*, 2005; Schlagintweit and Gawlick, 2008; Rusciadelli *et al.*, 2011). Leinfelder *et al.* (2005) hypothesised that Jurassic reefs with the predominance of calcified sponges developed under oligotrophic conditions, controlled by oceanic circulation. The Štramberk Carbonate Platform – located in the northern Tethys – in terms of trophic conditions appears to have been intermediate in character between the central and southern, intra-Tethyan platforms and those in the epicontinental seas of the northern Tethyan shelf.

Štramberk-type limestones

On the basis of an analysis of exotic clasts, previous studies of the Štramberk Limestone and the zonation of other intra-Tethyan carbonate platforms with reefs, the following zonation of the Tithonian–earliest Cretaceous carbonate platform studied is proposed (Fig. 24). Coral-microbial patch-reefs (FT 1) grew in the inner carbonate platform, while the upper slope of the platform was the sedimentary setting for the microencruster-microbial-cement boundstones (FT 2). In the inner, open part of the platform, with diverse hydrodynamics, foraminiferal-algal (FT 5) and peloidal-bioclastic limestones (FT 6) were deposited. "*Lithocodium-Bacinella*" possibly formed lone boundstone patches within the foraminiferal-algal facies (cf., Hofmann, 1991). Reef-derived detrital limestones (FT 4; the commonest facies) and ooid grainstones (FT 7; a rare facies) were formed in a peri-reefal (only FT 4) and on a high-energy margin of the carbonate platform. Detrital limestones with rare or common reef components may indicate habitat and microhabitat heterogenity, but presumably reflect mainly distance to the reef, with more reef components occurring in the peri-reefal environment. Clast-supported (cement-rich) and matrix-supported breccias (classified as FT 4) were deposited on the margin of the platform or on the high-energy, upper slope and low energy, upper slope of the carbonate platform, respectively. Calpionellids were not found in the matrix of the second breccia type, but they were recognized in similar matrix-supported breccias in the Štramberk Limestone (Eliáš and Eliášová, 1984; Hoffmann *et al.*, 2017). The origin of both breccia types was facilitated by the distinct topography of the platform margin, by the high energy (in the case of the clast-supported breccias), and by synsedimentary tectonics. Microbial and sponge-microbial boundstones (FT 3) and mudstones-wackestones with calpionellids (FT 8) were developed in a deeper setting: in a deeper part of the platform slope and/or in a basinal setting. Eliáš and Eliášová (1984) described in the Štramberk Limestone slope deposits with reef-derived clasts and with abundant planktonic organisms in a micrite-dominated

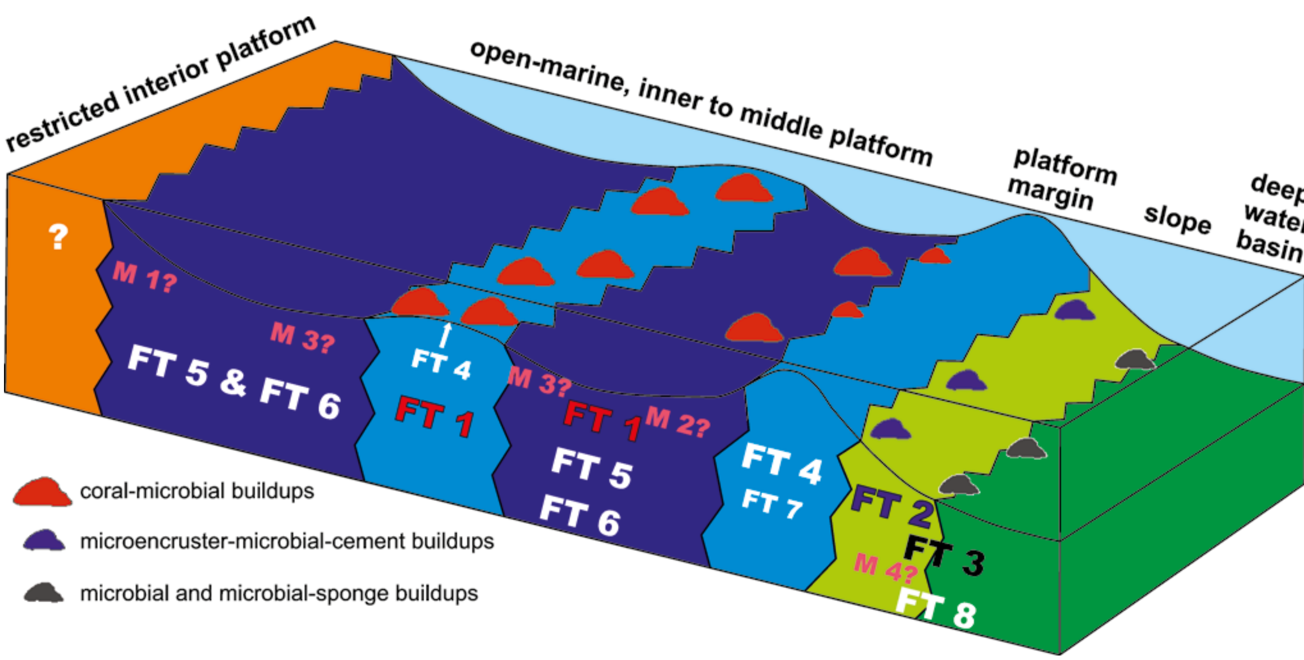

Fig. 24. Schematic facies distribution on a lost carbonate platform, based on the study of the Štramberk-type limestones, Polish Outer Carpathians (Hoffmann and Kołodziej, 2008, modified). Main facies types: FT 1: coral-microbial boundstones, FT 2: microencruster-microbial-cement boundstones, FT 3: microbial and microbial-sponge boundstones, FT 4: detrital limestones, FT 5: foraminiferal-algal limestones, FT 6: peloidal-bioclastic limestones, FT 7: ooid grainstones, FT 8: mudstones-wackestones with calpionellids (and allodapic pre-flysch Cieszyn Beds, not studied in this paper), ?: supposed sediments of hypersaline and intertidal environments (not present in exotics). Microfacies not attributed to the main facies. M 1: stromatolites; M 2: oncoid-ooid packstones; M 3: limestones dominated by bivalves or other shells; M 4: echinoderm wackestones.

matrix. The clasts of FT 8 may have been derived in part from similar deposits. Between carbonate platforms, in tectonic grabens, sedimentation of pelagic (equivalent of FT 8) and the dominantly allodapic Cieszyn Limestone Formation took place. Restricted (hypersaline and intertidal) facies of the carbonate platform are not known from exotic clasts, possibly in part owing to their scarcity and lower preservation potential.

The platforms, on which sedimentation of the Štramberk-type limestones took place, are part of the Štramberk Carbonate Platform, or more precisely, narrow platforms attached to intrabasinal ridges, with morphology determined by Late Jurassic synsedimentary tectonics. Eliáš and Eliášová (1984) estimated that the reef complexes extended for 400 km "from Bečva valley (close to Štramberk – a comment by the present authors) into the eastern Flysch Carpathians". Štramberk-type limestones in Romania (e.g., Getic Carbonate Platform, Southern Carpathians; Apuseni Mts, Western Carpathians) show a clear similarity to the limestones studied here (Săsăran, 2006; Bucur *et al*., 2010; Pleş *et al*., 2013, 2016, 2019; Mircescu *et al*., 2019). Corals in these limestones were not studied, but preliminary observations of thin sections from the material mentioned above as well as field observations in the Sănduleşti Quarry in the Trascău Mountains (Săsăran, 2006; Bucur *et al*., 2010) by one of the authors (B.K.), have not revealed numerous pachythecaliine corals, which are so abundant in Czech Republic and Poland.

Thin fissures, interpreted as neptunian dykes, in three exotic clasts filled with dark limestones, document the destruction and drowning of the Štramberk Carbonate Platform. In the Štramberk Limestone (Kotouč Quarry), there are numerous cavities, including fissures, several decimetres to more than 1 m across. Cavities, mainly filled with laminated micritic limestone, are contemporaneous with the sedimentation of the Štramberk Limestone and younger limestones (Berriasian–Valanginian). They are mostly related to the tectonic activity of the Baška-Inwałd Ridge. The stress-induced environment of these cavities was colonized almost exclusively by the *Chondrites* trace maker (Uchman *et al*., 2003). Similar traces were recognized in the micritic limestones in fissures, transecting the shallow-water limestones in exotics of the Štramberk-type limestones mentioned above.

Comparison to palaeogeographically close platforms of the Tethyan shelf

The limestones of the Štramberk Carbonate Platform show clear differences with coeval limestones of the palaeogeographically close carbonate platforms on the northern Tethyan shelf (Peri-Tethys). During the Late Jurassic (predominantly in the Oxfordian–early Kimmeridgian), carbonate sedimentation in the Polish part of the epicontinental Central European Basin took place on a shelf with a ramp configuration. Since the early Kimmeridgian, in some areas this basin was transformed into a well-developed carbonate platform (Kutek, 1969). The Meta-Carpathian Arch separated structurally and at times palaeogeographically the Central European Basin from basins of the Carpathian (Tethyan) domain in Permian to Cenozoic time (Kutek, 1994).

Tithonian coral-bearing facies, in original depositional position, are known from borehole data in the central and southern parts of the Carpathian Foredeep, Poland (Morycowa and Moryc, 1976, 2011; Gutowski *et al*., 2007; Matyja, 2009; Urbaniec *et al*., 2010; Krajewski *et al*., 2011; Morycowa, 2012). The Pilzno Coral Limestone Formation was compared by Matyja (2009) with the Štramberk Limestone, but without data on the reef framework and the abundance and diversity of corals. In the only taxonomic paper on corals from the Carpathian Foredeep (Dąbrowa Tarnowska–Szczucin area), Morycowa (2012) described 42 species (only one species from the suborder Pachythecaliina, which is highly diversified in the Štramberk-type limestones). Makowiec (2017) and Faka (2017) in their Master's theses observed only poorly developed microbial and microencruster framework fabrics (well developed in the FT 1 facies of the Štramberk-type limestones) in the Tithonian coral-bearing limestones (partly classified as boundstones) from boreholes at Swarzów, near Dąbrowa Tarnowska (southern part of the Carpathian Foredeep). These observations are confirmed by the examination by the present authors of thin sections described by the authors mentioned above as well as those described by Morycowa and Moryc (1976) and Morycowa (2012). Similarly, Krajewski *et al*. (2011), who studied drill-cores from the Kraków-Rzeszów area, stated that there were no large ooid or reef barriers, but rather numerous open-platform shoals. Microencruster-microbial-cement boundstones (= FT 2) are not known in the Carpathian Foredeep. Microbial-sponge facies, known from the Oxfordian of the Kraków Upland (e.g., Matyszkiewicz, 1997; Matyszkiewicz *et al*., 2012; Krajewski *et al*., 2016) and up to the lower Tithonian in the Carpathian Foredeep (Matyja, 2009), occur quite commonly in exotics in the Carpathians. They are of Oxfordian–Kimmeridgian age (Kowal-Kasprzyk *et al*., 2020). Similar facies are represented among the Štramberk-type limestones and classified as FT 3. Dinoflagellate cysts and calpionellids evidently indicate on the Tithonian–Berriasian age of FT 3. Siliceous sponge reefs were restricted in Europe mostly to homoclinal ramp settings along the northern Tethys (Leinfelder *et al*., 2002).

Like many carbonate platforms (including coral reefs) on the northern Tethys shelf, platforms recognized in the Carpathian Foredeep were developed within terrigenously influenced settings, evidenced by the presence of marly limestones and marls. Such terrigenous input was commonly paralleled by an increase in nutrient level and as a consequence, an enhancement in the growth of microbialites (Dupraz and Strasser, 2002 and literature therein). Poorly developed microbial crusts in the limestones of the Carpathian Foredeep may be explained by a high sediment supply. The north-eastward continuation of this platform was recognized in boreholes in the Lublin Upland, which is located on the East European Craton (Platform). In the Lublin Upland, Tithonian deposits are developed among others as the sediments of marginal environments (hypersaline and intertidal) of the carbonate platform (Niemczycka, 1976; Gutowski *et al*., 2005a). These facies were not recognized in the Štramberk-type limestones. The Babczyn Formation of the SE Lublin Upland is an equivalent of the upper Tithonian–lower Berriasian Niżniów (Nyzhniv) Formation, outcropping along the Dniester River, Western Ukraine (Gutowski *et al*., 2005b). Izotova and Popadyuk (1996) regarded limestones at the contact between the Niżniów and the Opary Formations as reefal, but Gutowski *et al*. (2005b) regarded them as bioconstructed. The Niżniów Formation in the area studied by Gutowski *et al*. (2005b) is developed mainly as biomicrites, oncomicrites, and pelmicrites with an abundant fauna, dominated by gastropods, hence cannot be classified as reefal facies.

Eliáš and Eliášová (1986) compared the carbonate sequences of the Štramberk carbonate platform with the Brno carbonate platform (autochthonous Jurassic of the Bohemian Massif) and the Pavlov carbonate platform. The Ernstbrunn Limestone (Austria and Czech Republic), less known than the Štramberk Limestone, was deposited on the Pavlov (Ernstbrunn-Pavlov) carbonate platform (epicontinental shelf of the Tethys). Traditionally, the Ernstbrunn Limestone has been interpreted as a tectonically detached part of a carbonate succession, which evolved on the rifted, passive, Tethyan margins in the Oxfordian–Tithonian. Alternatively, it is interpreted as a pile of carbonate debris, derived from a pre-existing, hypothetical, Tithonian platform and redeposited in the Ždánice Basin (the north-eastward extension of the Sub-Silesian Basin) at a time of eustatic drop in sea level (Eliáš and Eliášová, 1984, 1986; Schneider *et al*., 2013). Poorly developed, reefal structures, with poorly diversified corals (26 species, only one from the Pachythecaliina), occur in the Ernstbrunn Limestone in the Czech Republic (Eliášová, 1990). The "classical" Ernstbrunn Limestone in Austria is represented by lagoonal facies, patch-reef facies, and facies of fringing ooid-oncoid bars. About 30 species of corals were determined (but not illustrated) from the Ernstbrunn Limestone in Austria (see Schneider *et al*., 2013). Generally, the Ernstbrunn Limestone consists predominantly of variable lagoonal facies, whereas the Štramberk Limestone is mainly composed of reef and fore-reef facies. This is evidenced by the fossil content, for example, the rare occurrence of giant gastropods at Štramberk (Harzhauser and Schneider, 2014).

According to Eliáš and Eliášová (1986), different sedimentary conditions on the platforms discussed were heavily constrained by sedimentation in various tectonic settings. The Štramberk Limestone was deposited on the mobile Baška Ridge (= Baška-Inwałd Ridge). The Brno and Pavlov carbonate platforms were located in a tectonically less active area (part of the epi-Variscan European Platform). The tectonic setting determined the sedimentary and palaeoecological conditions. There was compensation for the subsidence of the Baška Ridge by the intensive development of reefal facies. Environmental conditions on the Pavlov carbonate platform favoured the sedimentation of lagoonal facies. These conditions controlled the origin of magnesium brines that resulted in dolomitization. Dolomitization is present in coeval limestones of the Carpathian Foredeep (e.g., Morycowa and Moryc, 1976; Krajewski *et al*., 2011) and occurs in exotics of the Oxfordian–Kimmeridgian limestones (Kowal-Kasprzyk *et al*., 2020). Dolomitization is absent from the Štramberk Limestone (Eliáš and Eliášová, 1986) and very rare in the Štramberk-type limestones.

More detailed, comparative studies of limestones deposited on platforms, collectively termed the Štramberk Carbonate Platform, and palaeogeographically close, northerly located platforms, are needed to reveal local *versus* supra-regional controls (tectonic, oceanographic, palaeobiological) on sedimentation. Differences in sedimentation on the Brno and Pavlov carbonate platforms on the one hand and the Štramberk Carbonate Platform on the other were heavily constrained by various tectonic regimes (Eliáš and Eliášová, 1986), and this is also applicable to the limestones in Poland.

CONCLUSIONS

1. The Upper Jurassic–lowermost Cretaceous limestones, named Štramberk-type limestones, are the most common among the exotic clasts (exotics), embedded in the uppermost Jurassic–Oligocene flysch deposits of the Silesian, Sub-Silesian and Skole units (nappes) in the Polish Outer Carpathians. About 90 % of determinable carbonate clasts (classified in the field as Štramberk-type limestones) are of Tithonian–Berriasian age and can be compared to the Štramberk Limestone in Moravia (Czech Republic), representing limestones of the carbonate platform and its slope.
2. Exotic clasts of the Štramberk-type limestones, predominantly of pebble and cobble sizes, from the Polish Outer Carpathians, as well as the Štramberk Limestone (large blocks, olistoliths) bore witness to a lost carbonate factory. Narrow carbonate platforms were attached to the intra-basinal ridges (the largest are referred to the Silesian Ridge and to the Baška-Inwałd Ridge), with their distribution and morphology determined by Late Jurassic synsedimentary tectonics. In the interpretation of sedimentary environments and platform zonation, these platforms have been considered collectively as the Štramberk Carbonate Platform. The unique taxonomic composition of coral assemblages from the Štramberk Limestone and the Štramberk-type limestones support linking these platforms in a single palaeogeographic unit.
3. Tithonian (mostly)–Berriasian and sporadically possibly also Valanginian, Štramberk-type limestones are represented by eight main facies, which were attributed to different sedimentary environments. Coral-microbial boundstones (FT 1) were formed as patch reefs in the inner platform. The upper slope of the platform was the depositional setting for microencruster-cement boundstones (FT 2). Microbial and microbial-sponge boundstones (FT 3) were developed in a deeper setting (the lower part of the slope?). Detrital limestones (bioclastic-lithoclastic grainstones to rudstones, matrix- and clast-supported breccias, FT 4) developed in a peri-reefal environment and in a high-energy setting of the platform margin. Foraminiferal-algal limestones (FT 5) and peloidal-bioclastic limestones (FT 6) were developed in the inner platform. Ooid grainstones (FT 7) were developed on the platform margin. Mudstones-wackestones with calpionellids (FT 8) represent a deeper part of the platform slope and/or a basinal setting and can be compared

with coeval pelagic lithofacies of the Cieszyn Limestone Formation ("pre-flysch"), deposited in tectonic grabens, between ridges with attached platforms. FT 4 is the most common facies among the exotics. Peloidal stromatolites (M 1), oncoid-ooid packstones (M 2), limestones dominated by bivalves or other shells (M 3) and echinoderm wackestones (M 4) are subordinate, but noteworthy microfacies. They cannot be assigned to the main facies distinguished, even though some facies show high microfacies diversity. Most facies of the Štramberk-type limestones differ from the Oxfordian–Kimmeridgian limestones (not studied here). The latter are much less common among the exotics; in the field, they also would be termed Štramberk-type limestones. They may be compared with limestones of the so-called sponge megafacies, deposited on a homoclinal ramp of the northern margin of the Tethys.

4. The destruction and drowning of carbonate platforms (Štramberk Carbonate Platform) in the earliest Cretaceous is recorded in a few exotics by neptunian dykes (very thin in the exotics studied and thick in the Štramberk Limestone), filled with dark, deep-water limestones
5. Reefal facies in the exotics studied and the Štramberk Limestone exhibit similarities in several respects (e.g., the occurrence of the microencruster-cement boundstones) with the reefs of other intra-Tethyan carbonate platforms, but clearly differ from palaeogeographically close reefs and the coral-bearing facies of the Tethyan shelf (e.g., the coeval limestones occurring in the subsurface of the Carpathian Foredeep and the Lublin Upland in Poland; the Ernstbrunn Limestone in Austria and the Czech Republic).
6. The most important provenance area for the exotic clasts and other detrital material in the Proto-Silesian and Silesian basins was the intra-basinal Silesian Ridge, traditionally called the Silesian Cordillera. It evolved through time from the emerged part of the Upper Silesian Massif (part of the Brunovistulicum Terrane) to an accretionary prism since the Late Cretaceous. Exotic clasts from the Sub-Silesian Unit were derived mostly from the Baška-Inwałd Ridge (till the end of the Early Cretaceous), while the material that accumulated in the Skole Basin mostly came from the Northern (Marginal) Ridge. Most of the exotics studied were collected in the Silesian Unit, where exotics are particularly common in the Lower Cretaceous Hradiště Formation and the Upper Cretaceous–Paleocene Istebna Formation. In the Sub-Silesian Unit, most exotics are from the Hradiště Formation and less commonly from the Barremian–Aptian Veřovice Formation. In the Skole Unit, they are largely in the Maastrichtian–Paleocene Ropianka Formation. The Štramberk-type limestones are much rarer in the Magura and Dukla units as well as in the Stebnik and Zgłobice units (the folded Miocene at the front of the Outer Carpathians) and were not studied here.

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