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MICROENCRUSTER-MICROBIAL FRAMEWORK AND SYNSEDIMENTARY CEMENTS IN THE ŠTRAMBERK LIMESTONE (CARPATHIANS, CZECH REPUBLIC): INSIGHTS INTO REEF ZONATION

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Abstract: The Štramberk Limestone (Tithonian–lower Berriasian) was developed on a northerly located, isolated intra-Tethyan carbonate platform. It is composed of various facies that can be observed in olistoliths and blocks embedded in the Cretaceous flysch of the Outer Carpathians in Moravia (Czech Republic). Corals, microbialites, microencrusters and synsedimentary cements contributed on various scales to the reef framework. The importance of corals and some microencrusters to the formation of the Štramberk reef complex is well recognized, while other components received less attention in previous studies. Two end members of boundstone types are described from the Kotouč Quarry, near Štramberk. Boundstone type A is dominated by phaceloid (branching-type) corals, encrusted by microbialites and microencrusters, in particular photophile species ("*Lithocodium-Bacinella", Koskinobullina socialis* Cherchi et Schroeder, *Iberopora bodeuri* Granier et Berthou). Boundstone type B is composed of microencrusters, microbialites and synsedimentary isopachous fibrous cements, while corals are absent or subordinate. Microencrusters [*Crescentiella morronensis* (Crescenti)*, Labes atramentosa* Eliášová*, Perturbatacrusta leini* Schlagintweit et Gawlick*, Radiomura cautica* Senowbari-Daryan et Schäfer*,* thin encrusting calcified sponges] are main biotic components of the microencruster-cement boundstone. Some identified microencrusters are known only or mostly from intra-Tethyan carbonate platforms. Except for *C. morronensis,* other common microencrusters in the coral-microbial boundstone (type A) are rare in the microencruster-cement boundstone (type B). The depositional setting of boundstone type A corresponds to a low-energy environment of an inner platform. Boundstone type B, until now not recognized in the Štramberk Limestone, was developed in a high-energy, upper fore-reef slope environment. Other important facies in the Kotouč Quarry are reef-derived breccias: matrix-supported breccia and clast-supported breccia with radiaxial-fibrous cement (showing some similarities to Triassic "evinosponges" cement), interpreted as being dominantly synsedimentary (pre-burial). The preliminary studies by the present authors, supported by observations under cathodoluminescence, highlight the significance of synsedimentary cementation for the formation of a boundstone framework (type B) and the stabilization of fore-reef, slope deposits.

Key words: Coral reefs, carbonate platforms, microframework, sedimentary breccia, Moravia, Jurassic, Cretaceous.

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INTRODUCTION

Most of the information about Upper Jurassic reefs comes from the northern margin of the Tethys and North Atlantic shelf seas in Europe, where reefs (mostly of Oxfordian−Kimmeridgian age), built by sponges, corals and microbialites (as a main component or associated with metazoan reef-builders), are common and diversified (Leinfelder *et al*., 2002; for coral reefs case studies see Geister and Lathuilière, 1991; Leinfelder *et al*., 1994; Insalaco *et al*., 1997; Dupraz and Strasser, 2002; Olivier *et al*., 2004; Lathuilière *et al*., 2005; Helm and Schülke, 2006). Upper Jurassic and lowermost Cretaceous (Berriasian–Valanginian) reefs developed on the intra-Tethyan carbonate platforms have been far less studied in the 20th century (Steiger and Wurm, 1980; Turnšek *et al*., 1981; Eliáš and Eliášová, 1984; Morsilli and Bosellini, 1997). Recently, there has been a significant increase in studies of sedimentary, palaeontological and ecological aspects of carbonate platforms of the Tethyan domain (e.g., Leinfelder *et al*., 2005; Schlagintweit *et al*., 2005; Bucur *et al*., 2005, 2010; Săsăran, 2006; Schlagintweit and Gawlick, 2008; Ivanova *et al*., 2008; Rusciadelli *et al*., 2011; Pleş *et al*., 2013, 2016; Chatalov *et al*., 2015; Kaya and Altıner, 2015; Kołodziej *et al*., 2015).

The Tithonian–lower Berriasian Štramberk Limestone from the Western Carpathians of Moravia (Czech Republic) represents different shallow-water to slope facies, developed on the northerly located intra-Tethyan carbonate platform. It has been extensively studied since the middle of 19th century in terms of palaeontology (for a comprehensive review see Vašíček and Skupien, 2004, 2005). The spatial and temporal relations of particular limestone olistoliths and smaller blocks are unknown, hindering reconstruction of the Štramberk carbonate platform. The only platform zonation model was proposed by Eliáš and Eliášová (1984; see also Eliášová, 1981b), but since that time knowledge and understanding of the Upper Jurassic–Lower Cretaceous reefs have significantly increased. Previous studies of reef facies of the Štramberk Limestone showed the importance of abundant and diversified corals (ca. 120 species; e.g., Ogilvie 1897; Eliášová, 1975, 1978, 2008; for references see also Vašíček and Skupien, 2004), associated with microencrusters (Eliášová, 1981a, b, 1986; Eliáš and Eliášová, 1984). The present studies revealed the importance of microbialites in both of the boundstone types described. The terms "microbialites" and "microbial crusts" are used here in a broad meaning, namely as structures that are the result of microbially induced or microbially influenced mineralization (Dupraz *et al*., 2009). Their detailed analysis and assignment to the types in Schmid's (1996) classification is beyond the scope of this paper. The preliminary studies by the present authors focused on selected components of the reef framework (microframework) and reef-derived breccias, which were poorly studied or not studied at all previously. These data provide some new insights into the zonation of the Štramberk reef complex.

GEOLOGICAL SETTING

The Štramberk Limestone represents sediments formed in different settings of a carbonate platform during the Late Jurassic and earliest Cretaceous along the northern Tethyan margin. Although the best recognized is the reef facies, the commonest types are biodetrital limestones. Limestones occur as olistoliths, blocks in a wide range of sizes, embedded in the Cretaceous flysch deposits of the Silesian Unit of the Outer Carpathians (Eliáš and Eliášová, 1984; Picha *et al*., 2006; Vašíček and Skupien, 2014).

The Outer Western Carpathians represent the most external zone of the Western Carpathian mountain chain. They comprise a structurally complex area, which consists of folded and thrusted strata of latest Jurassic to Late Miocene age. At present, the Outer Western Carpathians consist of two groups of nappes (from the lowest to the highest): (1) the Outer Group of Nappes, divided from lowest to highest into the Subsilesian, Silesian, and Ždánice nappes, and (2) the Magura Group of Nappes, divided into the Rača, Bílé Karpaty, and Bystrica nappes (Fig. 1). The entire nappe allochthon was thrusted more than 60 km over Miocene sediments of the Carpathian Foredeep (Picha *et al*., 2006).

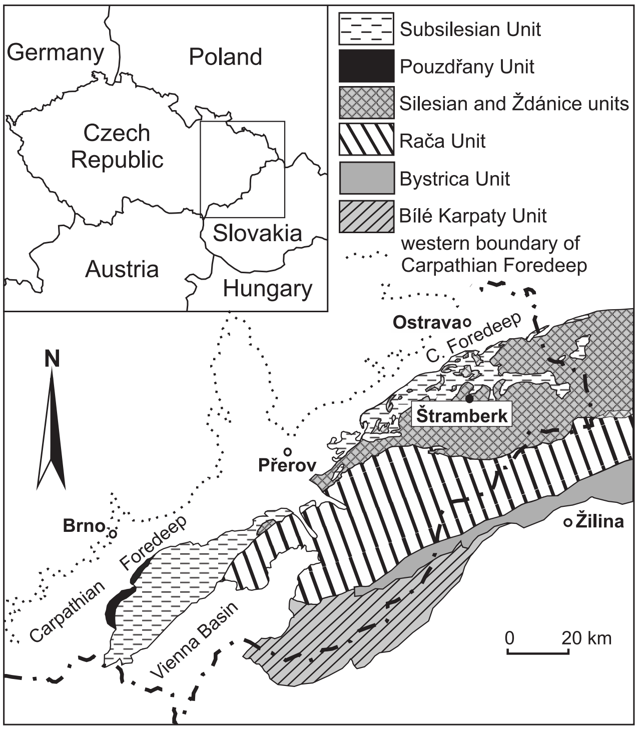

Fig. 1. General geographic position of the study area and the tectonic map of the Outer Carpathian area in the Czech Republic.

The Silesian Nappe consists of Upper Jurassic to Oligocene−Miocene sediments, deposited in the Silesian Basin that developed from Jurassic times under the extension regime along the southern edge of the western part of the Palaeoeuropean Platform. Three fundamentally different facies are preserved in the present-day structure of the Silesian Nappe in the part of Carpathians discussed: (1) the Godula facies (basinal setting), (2) the Baška facies (frontal slope setting), and (3) the Kelč facies (continental slope setting; Picha *et al*., 2006).

The block accumulations of the Štramberk Limestone form part of the continental-rise (bottom of the continental slope) facies of the Baška facies in the Silesian Unit that was deposited in the flysch trough around the Baška ridge, assumed to have been situated between the Silesian and Subsilesian basins (Picha *et al*., 2006). This uppermost Jurassic to Upper Cretaceous sedimentary succession includes slumps, slides, olistoliths and sporadic turbidites, which were fed from the uppermost Jurassic to the Coniacian carbonate platform on the Baška Cordillera and its slopes, including the Tithonian–Berriasian reef complex. The intervals between gravity flows usually are represented by hemipelagic sediments. The gradual, lateral and vertical transition of the block accumulations into facies that are clearly the products of mass movement contradicts the classical interpretation of the tectonic klippes in the Silesian Unit (Vašíček and Skupien, 2013).

The geology of the Štramberk area and the nature of the megablocks are the subject of a long-standing controversy. Houša (1990) interpreted the carbonate blocks as tectonic klippen, which were separated from the carbonate platform during the Silesian Nappe overthrust. In this author's interpretation, the associated Lower Cretaceous deeper-water deposits represent material, which filled fissures or cavities of different origins in the Štramberk Limestone, or covered the original surfaces of the limestone bodies. According to Eliáš and Stráník (1963), Eliáš (1970) and Eliáš and Eliášová (1986), the limestones are embedded in base-of-slope conglomerates and slump bodies within the Cretaceous part of the Hradiště Formation, constituting an extreme development of the Chlebovice Conglomerate. This accumulation was formed between Tithonian and Turonian (see Svobodová *et al*., 2004, 2011; Vašíček and Skupien, 2014). According to Picha *et al*. (2006), the Štramberk carbonate platform was the source of the clastics and large fragments of the carbonate body, later created by a combination of mass movement and tectonic activity. Gravitational slides and turbidity currents transported both small and large blocks and limestone fragments from the edge of the platform to the bottom of the adjacent basin. However, during the Neogene nappe thrusting, large pieces of the carbonate platform were separated from the softer, less resistant sediments of the platform slope. The result is a melange, in which larger blocks from the carbonate platform are reminiscent of the characteristics of klippen. The smaller blocks and debris correspond to clastic sediments at the foot of the platform. These developed during the Early Cretaceous and the earliest part of the Late Cretaceous, in particular.

Traditionally, the Štramberk Limestone was believed to be Tithonian, which may be the correct age for the main stage of reef development. However, Houša (1990) supposed without any precise justification that the Štramberk Limestone had originated already during the latest Kimmeridgian. The identified calpionellid zonation in the limestone bodies, exposed in the Štramberk area, is indicative of the upper part of the lower Tithonian, the entire upper Tithonian and the earliest Berriasian (Houša and Vašíček, 2005). Ammonites from the limestone bodies are indicative of the early Tithonian, the entire late Tithonian and the lowermost Berriasian (Vašíček *et al*., 2013; Vašíček and Skupien, 2013, 2014, 2016).

In terms of age, the facies development and fossil content (especially corals) that are most similar to the Štramberk Limestone are the Štramberk-type limestones in the Polish Outer Carpathians. They occur as clasts (termed *exotics*) of pebble to boulder size, very rarely as small unrooted klippes, in the uppermost Jurassic to Miocene deposits, dominantly in the flysch successions (e.g., Morycowa, 1964, 1974; Książkiewicz, 1971, 1974; Olszewska and Wieczorek, 2001; Hoffmann and Kołodziej, 2008; Kołodziej, 2015a, b; Salamon and Trzęsiok, 2015; Kowal-Kasprzyk, 2018).

MATERIAL AND METHODS

The Štramberk Limestone is exposed in several quarries (Kotouč, Municipal, Horní Skalka and Castle Hill) in the immediate vicinity of the town of Štramberk (Fig. 2A). The material studied comes from the large Kotouč Quarry. More than 110 samples were collected from levels VI and VII (Fig. 2B). The Štramberk Limestone is usually poorly recrystallized (except for originally aragonitic components), which allows facies observations on wet rock surfaces. Particular blocks may be closely adhered to each other and their boundaries are commonly uncertain without detailed observations. Collected samples are representative for blocks representing the main facies described here. There was no distinct pattern in the distribution of the blocks studied, thus the sampling from loose blocks as well as directly from outcrops was random. 62 thin sections of standard size (40 x 27 mm) and 5 larger thin sections (60 x 50 mm) were prepared from 41 samples. Observations also were performed on cut rock surfaces,

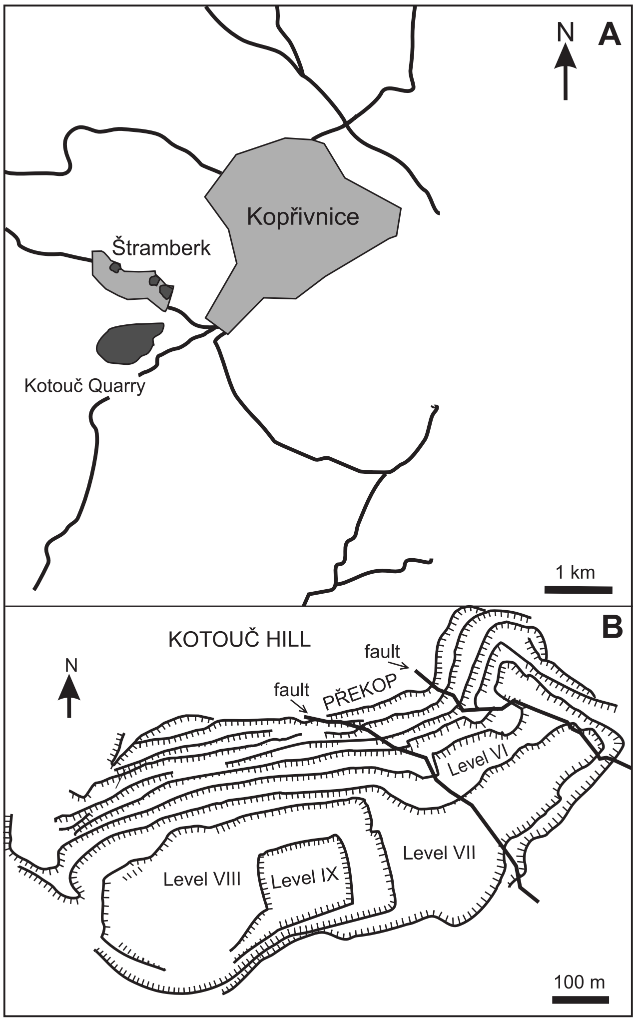

Fig. 2. The Kotouč Quarry. **A.** Topographic situation of the Kotouč Quarry and other main locations of the Štramberk Limestone (indicated in dark grey). **B.** The Kotouč Quarry, based on Svobodová *et al*. (2011), simplified. Only levels from VI to IX are marked. Samples were collected from levels VI and VII.

including 4 polished slabs. Fourteen thin sections of the microencruster-cement boundstone and cement-rich breccias were studied with cathodoluminescence. Observations were carried out at the Institute of Geological Sciences, Jagiellonian University, using a cold-stage cathodoluminescence microscope CLmk3A of Cambridge Image Technology Ltd., coupled to the Nikon Eclipse 50T. The accelerating voltage was 15–16 kV and the electron-beam intensity 450–500 µA. To enhance differences between non-luminescent part of cements and those that show dull luminescence, observations were made also on images with the contrast increased by 75%. However, with the exception of one image (what is clearly marked in the text), other images included in the paper show the original view under cathodoluminescence. The samples and thin sections studied are deposited at the Institute of Geological Sciences, Jagiellonian University, Kraków.

MICROENCRUSTERS FROM UPPER JURASSIC–LOWER CRETACEOUS REEFS: AN OVERVIEW

Encrusting microorganisms significantly contributed to the reef framework of the Štramberk Limestone. The microencruster association, their abundance and environmental demands are essential for the interpretation of the sedimentary environment and reef zonation. Table 1 provides the list of selected microencrusters, recognized in the studies of the present authors and by Eliášová (1981a, b, 1986) and Eliáš and Eliášová (1984). Information about other epibionts, not listed in Table 1, is included in the description of both boundstone types. Microencrusters from samples with uncertain attribution to boundstone type A or B were not taken into account. Certainly, studies of more thin sections will reveal additional species (especially calcified sponges) and will allow their quantitative evaluation in different facies. The systematic and/or biological affiliations of the microencrusters most discussed here have been changed since the 1980s. More detailed reviews of the Upper Jurassic–Lower Cretaceous microencrusters and references to the literature can be found in Schmid (1996), Schlagintweit *et al.* (2005), Pleş *et al.* (2013, 2017) and Kaya and Altıner (2015). Before the description of the two main boundstone facies, the biological affiliation, systematic position and environmental preferences of the microencrusters are summarized. References to the original papers, in which the species discussed were established, can be found in the papers cited above.

Lithocodium aggregatum Elliott, 1956 and *Bacinella irregularis* Radoičić, 1959, commonly referred as to *Lithocodium-Bacinella* association, are perhaps the most commonly reported microencrusters from the Upper Jurassic–Lower Cretaceous carbonate platforms. Research in this decade has revealed that different organisms or organic structures were described under these names. *Lithocodium aggregatum s.s.,* that is a micritic crust with a prostrate and erect system, recently is classified as an ulvophycean green alga (Schlagintweit *et al*., 2010). Cherchi and Schroeder (2010, 2013) and Schlagintweit (2010) showed that many Upper Jurassic structures, described as *L. aggregatum*

Table 1.

List of microencrusters in the Štramberk Limestone, identified in the present study. Microencrusters reported by Eliášová (1981a, b, 1986) and Eliáš and Eliášová (1984) are marked by ●. Relative abundance of microencrusters, recognized in the present study (A − boundstone type A; B − boundstone type B): present: +, common: ++, very common: +++, not recognized: —, ?: uncertain occurrence. For details about abundance of previously reported microencrusters in different carbonate platform zones, see the original papers and Discussion in the present paper.

List of microencrusters	**Previous reports (original taxonomic names)**	**Present studies**	
		A	**B**
Lithocodium aggregatum	• (possibly described as *Bacinella irregularis*)	+	—
Bacinellid microbial structures	• (*Bacinella irregularis*)	++	?
Calcimicrobial crusts with entobian borings (*Lithocodium aggregatum* sensu Schmid and Leinfelder, 1996)	• (*Bacinella crispa*)	++	?
Koskinobullina socialis	•	++	+
Iberopora bodeuri	• (*Archaeolithotamnium* sp.)	++	—
Crescentiella morronensis	• (*Tubiphytes morronensis*)	+++	+++
Thaumatoporella parvovesiculifera	•	+	—
Labes atramentosa	•	+	+++
Radiomura cautica	—	+	+++
Perturbatacrusta leini	—	+	+++
Murania reitneri	—	+	++
Calcistella jachenhausenensis	—	+	++
Neuropora lusitanica	—	++	+++

(interpreted as algae, calcimicrobes or foraminifera), are in fact calcimicrobial crusts with sponge (entobian) borings (*Lithocodium aggregatum* sensu Schmid and Leinfelder, 1996). The empty chambers of entobian borings (chambers of *Lithocodium* in previous interpretations) were commonly inhabited by the cryptoendolithic foraminifera *Troglotella encrustans* Wernli et Fooks, 1992, which frequently bored in encrusted carbonate substrates, such as coral skeletons (e.g., Wernli and Fookes, 1992; Schmid and Leinfelder, 1996; Kołodziej, 1997; Schlagintweit, 2010, 2012; Cherchi and Schroeder, 2013). *Bacinella irregularis s.s.* is interpreted by Schlagintweit and Bover-Arnal (2013) as a boring chlorophycean alga, producing galleries in biogenic, hard substrates (including crusts of *L. aggregatum*). This species was not recognized in the Štramberk Limestone. Vesicular structures commonly described in the literature as *Bacinella irregularis*, are most probably of calcimicrobial origin (Schlagintweit and Bover-Arnal, 2013 and references therein). These structures recently were termed “bacinellid” fabrics (Schlagintweit and Bover-Arnal, 2013), *Bacinella*-type structures (Pleş *et al.*, 2013, 2016; Kaya and Altıner, 2015) and bacinellid structures (Pleş *et al.*, 2017). In this paper, the terms bacinellid microbial structures and bacinellid structures are used.

L. aggregatum is essentially an encrusting epilithic alga with a possible heteromorphic life. In its chasmoendolithic stage (in cryptic microhabitats), *L. aggregatum* shows vesicular bacinellid-like fabric, hence it can be confused with bacinellid microbial structures (Schlagintweit *et al.*, 2010; Schlagintweit and Bover-Arnal, 2012). The euendolithic sporophyte *Gomontia* stage (boring stage of *L. aggregatum*) is represented by differently shaped cells, bored in carbonate substrates (Schlagintweit *et al.*, 2010). Spheroidal to ovoidal structures may be confused with borings produced by *T. incrustans*.

In the past, some authors considered *Lithocodium* and *Bacinella* as one taxon (see references in Schlagintweit *et al.*, 2010), which creates additional difficulties in the evaluation of the literature data, especially when documentation is lacking or insufficient. For example, *Lithocodium aggregatum* from the Štramberk Limestone was previously classified as *Bacinella irregularis* (Eliášová, 1981b, pl. 4, fig. 2), while calcimicrobial crusts with entobian borings (*Lithocodium aggregatum* sensu Schmid and Leinfelder, 1996) were classified as *Bacinella crispa* (Eliášová, 1981a, pl. 2, fig. 3). If the attribution to particular species (*L. aggregatum*) or structures (calcimicrobial crusts with entobian borings, bacinellid microbial structures) is problematic or not possible, they are collectively referred here as *“Lithocodium-Bacinella”*.

Crescentiella morronensis (Crescenti, 1969) is abundant, widespread and eurytopic species. Prior to the work of Senowbari-Daryan *et al.* (2008), this species was reported as *Tubiphytes morronensis* or “*Tubiphytes*” *morronensis*. It is recently interpreted as a symbiotic association or encrustation between cyanobacteria and a nubeculariid foraminifera or an uncertain tube. *Labes atramentosa* Eliášová, 1986, for the first time described from the Štramberk Limestone, is morphologically close to *C. morronensis*, but shows a different cortex microstructure composed of dense micritic laminae, separated by very thin, darker lines (Eliášová, 1986; Senowbari-Daryan *et al.*, 2008). Tubiform microfossils, possibly mutualistic sponges, are embedded in microbial crusts of *C. morronensis* and *L. atramentosa* (Schlagintweit and Gawlick, 2009).

Koskinobullina socialis Cherchi et Schroeder, 1979, classified as an organism incertae sedis, algae or foraminifera, is characterized by hemispherical chambers with perforate walls (see Pleş *et al.*, 2013, 2017; Kaya and Altıner, 2015). Upper Jurassic–lowermost Cretaceous specimens of *K. socialis* are commonly accompanied by crusts of the microproblematicum *Iberopora bodeuri* Granier et Berthou, 2002, consisting of tiny, bubble-like, superimposed cells (Schlagintweit, 2004a). *Thaumatoporella parvovesiculifera* (Raineri, 1922) is a microproblematicum attributed to green algae, red algae or cyanophyceans. Isolated *Thaumatoporella* cell layers may be incorporated into irregular, calcimicrobial crusts, showing a bacinellid fabric (Schlagintweit, 2013). *“Lithocodium-Bacinella”*, *I. bodeuri, K. socialis* and *T. parvovesiculifera* are photophile species and their presence has implications for the interpretation of the environmental settings of the two distinctive boundstone types described here.

Radiomura cautica Senowbari-Daryan et Schäfer, 1979 is composed of several hemispheric or spherical chambers. Morphologically close is *Perturbatacrusta leini* Schlagintweit et Gawlick, 2011 (previously classified as *R. cautica*), showing a labyrinthic structure composed of an irregular, interconnected system of tubes. Both species possibly represent calcified sponges (Schlagintweit and Gawlick, 2011; Pleş and Schlagintweit, 2014).

Thin, encrusting calcified sponges (also called hypercalcified, coralline sponges or sclerosponges), with stromatoporoid, chaetetid and sphinctozoan-like morphology are significant components of a pure microencruster-cement boundstone (Schlagintweit and Gawlick, 2008; Kołodziej *et al.*, 2015) and microencruster frameworks in some coral reefs (Pleş *et al.*, 2013). Species recognized in the Štramberk Limestone that are taxonomically determined, namely *Calcistella jachenhausenensis* Reitner 1992, *Murania reitneri* Schlagintweit, 2004 and *Neuropora lusitanica* Termier, Termier et Ramalho, 1985, are included in Table 1 (for references see Schlagintweit, 2004b; Leinfelder *et al.*, 2005; Schlagintweit and Gawlick, 2008).

The presence, abundance and distribution pattern of microencrusters have palaeoenvironmental implications. For instance, Kaya and Altıner (2015), on the basis of recent progress in the study of this topic, revealed the distribution pattern of Late Jurassic–Early Cretaceous microencrusters from the İnaltı carbonate platform, Turkey. *Lithocodium*, *Bacinella* (bacinellid structures) and *Koskinobuliina* are common in the back-reef facies, but are rare in the shallowest, marginal reefal facies. *Crescentiella* occurred both in shallow (lagoon, coral reefs) as well as in deeper settings (sponge reefs, slope facies). *P. leini* and *R. cautica* occur in the reef and fore-reef facies. This distribution pattern is consistent with those recognized on other rimmed carbonate platforms of the Tethyan domain (see references in Pleş *et al.*, 2013; Kaya and Altıner, 2015).

Quantitative analysis performed by Pleş *et al.* (2013) revealed the abundance and distribution pattern of encrusting microorganisms in coral-microbial boundstones from the Štramberk-type limestones in the Southern Carpathians (Romania). *C. morronensis* was present in most samples from the two sections studied (75% in the Buila-Vânturariţa Massif and 69% in the Piatra Craiului Massif), whereas other species were much rarer. *L. aggregatum* was present in 8% and 9% of studied samples, respectively. Other microencrusters (*Bacinella*-like structures = bacinellid structures, *P. leini, R. cautica, K. socialis, Coscinophragma* sp., *C. jachenhausenensis*) were much rarer. These species commonly co-occur; however *P. leini*, *R. cautica, K. socialis, Coscinophragma* sp. and *C. jachenhausenensis* were more common in samples with *L. aggregatum* and bacinellid-type structures mostly subordinate or absent. In the Piatra Craiului Massif, another distribution pattern was revealed. The increased occurrence of *R. cautica* was positively correlated with an increased number of *C. morronensis.* The opposite trend was revealed between the abundance of *L. aggregatum* and bacinellid-type structures *versus* the abundance of *C. morronensis*.

The "*Lithocodium-Bacinella"* association from shelf seas, located along the northern Tethys and North Atlantic, occurs both in lagoonal facies as well as in coral reefs (Leinfeder *et al*., 1993). *P. leini* and *R. cautica,* relatively common in microencruster-cement boundstones, are absent in reefs developed north of the Tethys (Schlagintweit and Gawlick, 2008, 2011). It is noteworthy that they were not reported from the Upper Jurassic–lowermost Cretaceous reefs from the Torinosu Limestone (Japan), located in the Tethyan gateway (Shiraishi and Kano, 2004; Ohga *et al.,* 2013). Calcified sponges are much more common in the reefs of the Tethyan domain, than in the reefs of marginal seas of the northern Tethys shelf and the North Atlantic (Leinfelder *et al*., 2005).

FACIES DESCRIPTION

Three main facies of the Štramberk Limestone are described in the present paper: (1) boundstone type A; (2) boundstone type B; (3) matrix-supported and clast-supported breccias.

Boundstone type A

The boundstone framework is composed primarily by corals, mostly of a phaceloid or dendro-phaceloid (branching-type) growth form (Fig. 3). Corals are as large as 1.5 m in diameter (even 3 m; Eliášová, 1981b). Macroscopically laminated, poorly structured, thrombolitic microbialites and agglutinated microstromatolites (*sensu* Schmid, 1996) may be equal in importance to corals or developed only as mm-thick crusts (Figs 3, 4A–B). Their abundance and distribution vary on the scale of a hand specimen (Fig. 3B). Microencrusters occur in most studied thin sections, but they are usually subordinate components, especially if compared with those in boundstone type B. Cavities are filled with internal sediment (peloidal wackestone) or laminated, peloidal microbialite (Figs 3, 4). In contrast to boundstone type B, growth cavities filled with cement are rare. Microscopically, microbialites are composed of micropeloids (up to ca. 30 μm in diameter) and clotted micrite. The space between coral branches (and microbial and microencruster crusts, if present) is filled with bioclastic-peloidal packstone to grainstone, rarely wackestone sediment (Figs 3, 4B, F).

The microencruster association includes, in order of abundance, *C. morronensis* (Fig. 4B, F)*,* the "*Lithocdium-Bacinella*" association (Fig. 4C−H; see comments below), *I. bodeuri* (Fig. 4G–H)*, K. socialis* (Fig. 4H)*,* encrusting calcified sponges (*N. lusitanica,* Fig. 4F*, C. jachenhausenensis,* chaetetids), *T. parvovesiculifera,* rare *Labes*

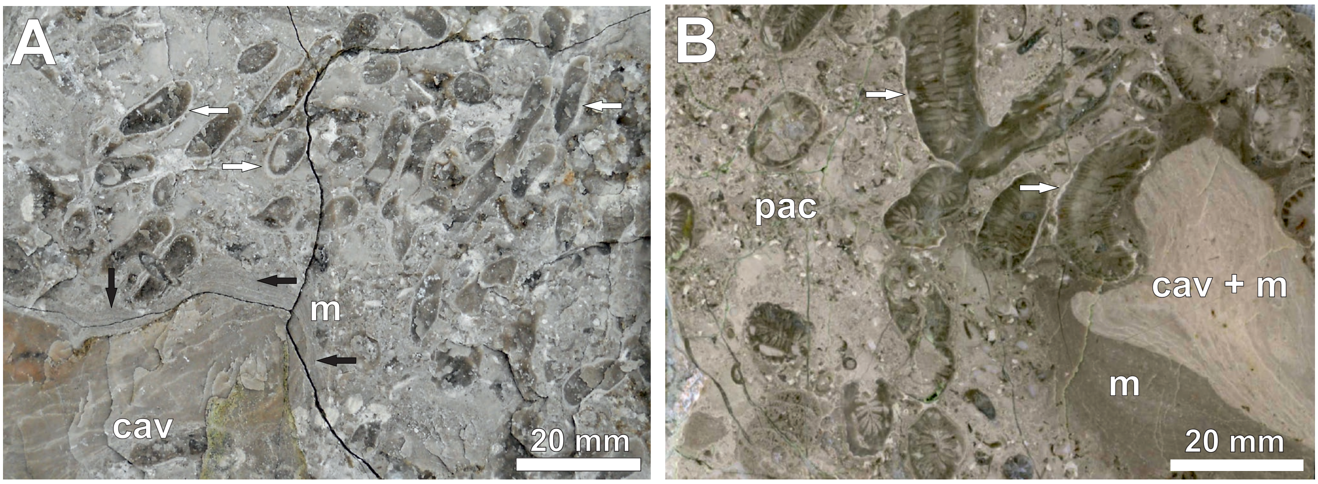

Fig. 3. Boundstone type A. **A.** Field view of the boundstone showing phaceloid corals, thin microencrusters (white arrows), microbialites (m, black arrows) and growth cavity (cav) which is filled with laminated sediment. **B**. Polished slab showing phaceloid-flabelloid rhipodogyrid coral with thin biotic crusts (arrows) and cavity (cav) resulted from coral and microbialite (m) growth. Cavity is largely filled with laminated peloidal microbialites (see close-up in Fig. 4A). Note that microbialites (m) occur only locally, while most of the matrix sediment is a bioclastic packstone (pac).

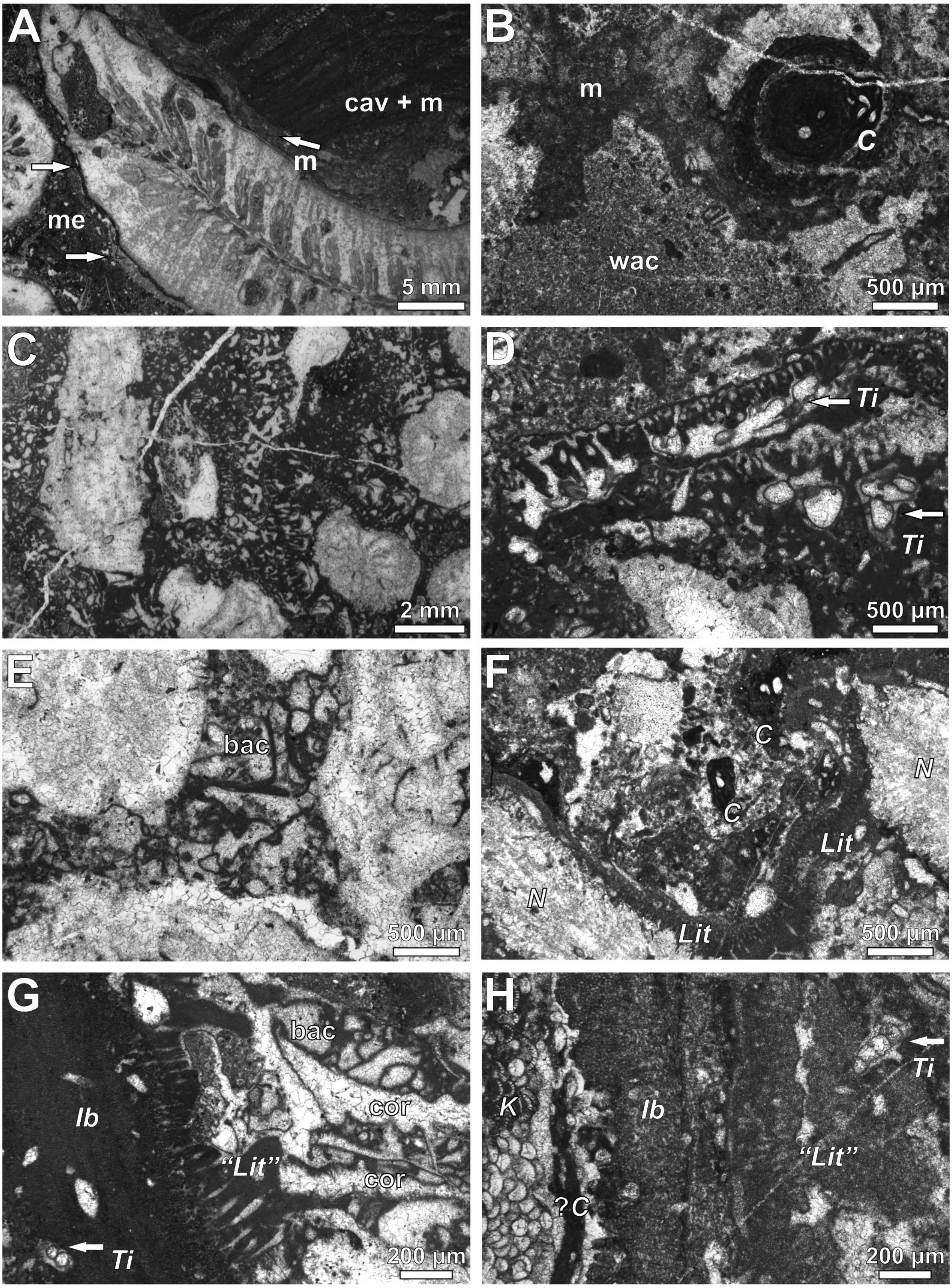

Fig. 4. Boundstone type A. **A.** Phaceloid-flabelloid coral encrusted by thin microbial crust (m) and microencrusters (me). Growth cavity (cav) is filled with laminated peloidal, partly agglutinated, microbialite; St 108. **B.** *Crescentiella morronensis* (*C*), microbialites (m) and internal wackestone sediment (wac) filling a growth cavity; St 93. **C–D.** Dense encrustations of "*Lithocodium-Bacinella*" between branches of phaceloid coral. On D cryptic foraminifera *Troglotella incrustans* (*Ti*) is arrowed; C – St 83, D – St 3. **E.** Bacinellid microbial structures (bac) between coral branches; St 83. **F.** *Lithocodium aggregatum* (*Lit*)*, Crescentiella morronensis* (*C*) and *Neuropora lusitanica* (*N*); St 103. **G.** *Iberopora bodeuri* (*Ib*)*,* calcimicrobial crusts with entobian boring (*"Lithocodium"*-like structure – *"Lit"*)*,* boring foraminifer *Troglotella incrustans* (*Ti*) and bacinellid structures (bac) between coral septa (cor); St 61. **H.** *Koskinobullina socialis* (*K*), ?*Crescentiella morronensis* (?*C*), *Iberopora bodeuri* (*Ib*), calcimicrobial crusts (possibly "*Lithocodium*"-like structure – *"Lit"*) with boring of *Troglotella incrustans* (*Ti*)*;* St 40.

atramentosa, R. cautica and *P. leini.* As mentioned in the previous section, *"Lithocodium-Bacinella"* is a collective term used because of difficulties in the determination of particular species or structures. The preliminary studies of the present authors suggest that calcimicrobial crusts with entobian borings (*"Lithocodium"*-like structures; Fig. 4C, D, G, H) and bacinellid structures (Fig. 4E, G) are more common than *L. aggregatum* (Fig. 4F). Other biotic encrusters include annelids (serpulids, *T. lapilloides*), bryozoans and foraminifera (nubeculariids, *Coscinophragma* sp. = ?*Pseudolithocodium* of Eliáš and Eliášová, 1984, pl.4, fig. 2).

Boundstone type B

The boundstone framework is composed of a complex intergrowth of microencrusters, microbialite and cement crusts (Figs 5–6). Because of the size of the components, microfacies analysis is required. However, in well preserved samples the microencruster-cement framework is recognizable under low magnification on the surfaces of polished slabs (Fig. 5A–B) or even macroscopically (Fig. 5C). The microencruster association of the boundstone framework includes, in order of abundance, *C. morronensis* (including uncertain determinations; Fig. 6A, C, E), *L. atramentosa* (Figs 6A, B, D, 7C), *P. leini* (Fig. 6A, B), *R. cautica* (Fig. 6C), common crusts of calcified sponges (*N. lusitanica, C. jachenhausenensis*, *M. reitneri,* and other undetermined species, especially chaetetids, Figs 5A, B, 6A, B, D, E, G), spicular sponges (Fig. 6D, E), annelids (serpulids, *T. lapilloides*), bryozoans, thecideid brachiopods and foraminifera (nubeculariids, *Coscinophragma* sp.).The microencrusters are of small size; even calcified sponges are usually a millimetre to a few millimetres in thickness. Corals, mostly thin encrusting microsolenids, are subordinate components (Fig. 6F) or were not recognized, neither macroscopically (in decimetre-size slabs) or under the microscope. Bivalve borings were observed in the microsolenid coral specimen (Fig. 6F). Microencrusters that are common in boundstone type A, namely, "*Lithocodium-Bacinella*", *K. socialis* and *I. bodeuri* are very rare, uncertian or absent in the thin sections studied. Laminated and poorly structured thrombolitic microbialites consist of micropeloids and clotted micrite. Some crusts display a microcrystalline, "cloudy" appearance (Fig. 6G, H), with irregular ca. 1-mm-thick laminae with dark dust lines (cf. Săsăran, 2006, fig. 3.8, 3.14; Pleş *et al*., 2013, fig. 8). Altered spicular sponges may be confused with cement (Fig. 6D, E). Irregular growth cavities, a millimetre to several centimetres in size, clearly visible, even on the polished surfaces of hand specimens, are coated with microbialite crusts (Fig. 5A, B) or isopachous fibrous cement (Figs 6A, B, 7A, C) and/or filled with micritic and peloidal-bioclastic wacke- to packstones (Fig. 5A, B) and blocky cement (Figs 6A, B, 7A, C). Some microencrusters are attached to isopachous fibrous cement, indicating synsedimentary nature of the cement (Fig. 7C). The boundaries between some microencrusters, the isopachous fibrous cement and microbialites are commonly blurred. The microencruster-microbial-cement framework contains minor amounts of bound sediment. A large growth cavity, more than 20 cm in diameter, filled with fine-grained sediment, was observed in the field in the block representing boundstone type B (Fig. 5C).

Under the cathodoluminescence microscope, the cement filling cavities shows the following pattern: (1) non-luminescent isopachous fibrous cement and the first generation of blocky cement, and (2) dull or bright orange luminescence (especially at the calcite crystal rims) of the second generation of blocky cement (Fig. 7B, D).

Matrix- and clast-supported breccias

Two types of breccia are recognized in this paper: (1) matrix-supported breccia (Fig. 8A), and (2) clast-supported, cement-rich breccia (Fig. 8B–D). Large clasts are blocks at least some dozen centimetres in diameter, but this preliminary study is concerned with breccias with clasts of a few centimetres in diameter. The wackestone to packstone matrix of the matrix-supported breccia contains common calpionellids and small ammonite remains (Figs 8A, 9A). In this paper, the focus is on the clast-supported breccia, composed of carbonate clasts (commonly boundstones), fragments of corals and other fossils, bound by radiaxial-fibrous cement and locally containing internal sediment. Rarely, the inner part of cavity is filled also with dog-tooth and blocky calcite cement. Most clasts are directly coated with calcite cement, some are first coated with microbial crusts or cement with a microbial-like appearance (Fig. 9E), but never by epibionts. The recrystallized radiaxial-fibrous calcite cement forms crusts up to 3 cm, but mostly a few millimetres thick (Figs 8B–D, 9B–F, 10A, C). The banded cement crusts, especially the thick ones (Figs 8C, 9E), show some similarities to cements called "evinosponges" (or "evinospongiae"), that is radiaxial-fibrous calcite with bright bands, alternating with narrow, micritic laminae (ca. 50 µm–1.5 mm in Frisia-Bruni *et al*., 1989; Russo *et al*., 2000). Such banding may be recognizable even in hand samples (Fig. 8C). Radiaxial-fibrous calcite cement is intercalated with thin micrite laminae ("dust lines" of Flügel, 2010 and Popa *et al*., 2014), in a range of 20–100 µm, in places ca. 1 mm (Figs 9C–F, 10C), and in one case by a 1- to 2-mm-thick, microstromatolite crust (Fig. 10A). Micritic grains or micrite produced *in situ* may be embedded in the cement (Fig. 9F). Cement crusts are broken locally (Fig. 9D, arrowed), but reworked fragments of cements crusts were not observed. In some samples,the remaining void space is filled with internal sediment (commonly as geopetal fillings), mostly represented by laminated, peloidal and peloidal-bioclastic wacke- to grainstones (Figs 8B–D, 9B–C) and blocky or dog-tooth calcite cement (Figs. 8D,10). Some larger voids are filled with greenish calcimudstones (Fig. 8C).

Under the cathodoluminescence microscope, radiaxial-fibrous calcite (Fig. 10A, C) is non-luminescent or dull (Fig. 10B, D, E). Dog-tooth cement and blocky cement (including this one filling diagenetic microfractures) reveal a commonly zoned structure with insignificant to bright orange luminescence, especially at the outer rims (Fig. 10B). Differences between non-luminescent and dull luminescent calcite are slightly more clearly visible when the image contrast is artificially enhanced (compare Fig. 10D, E).

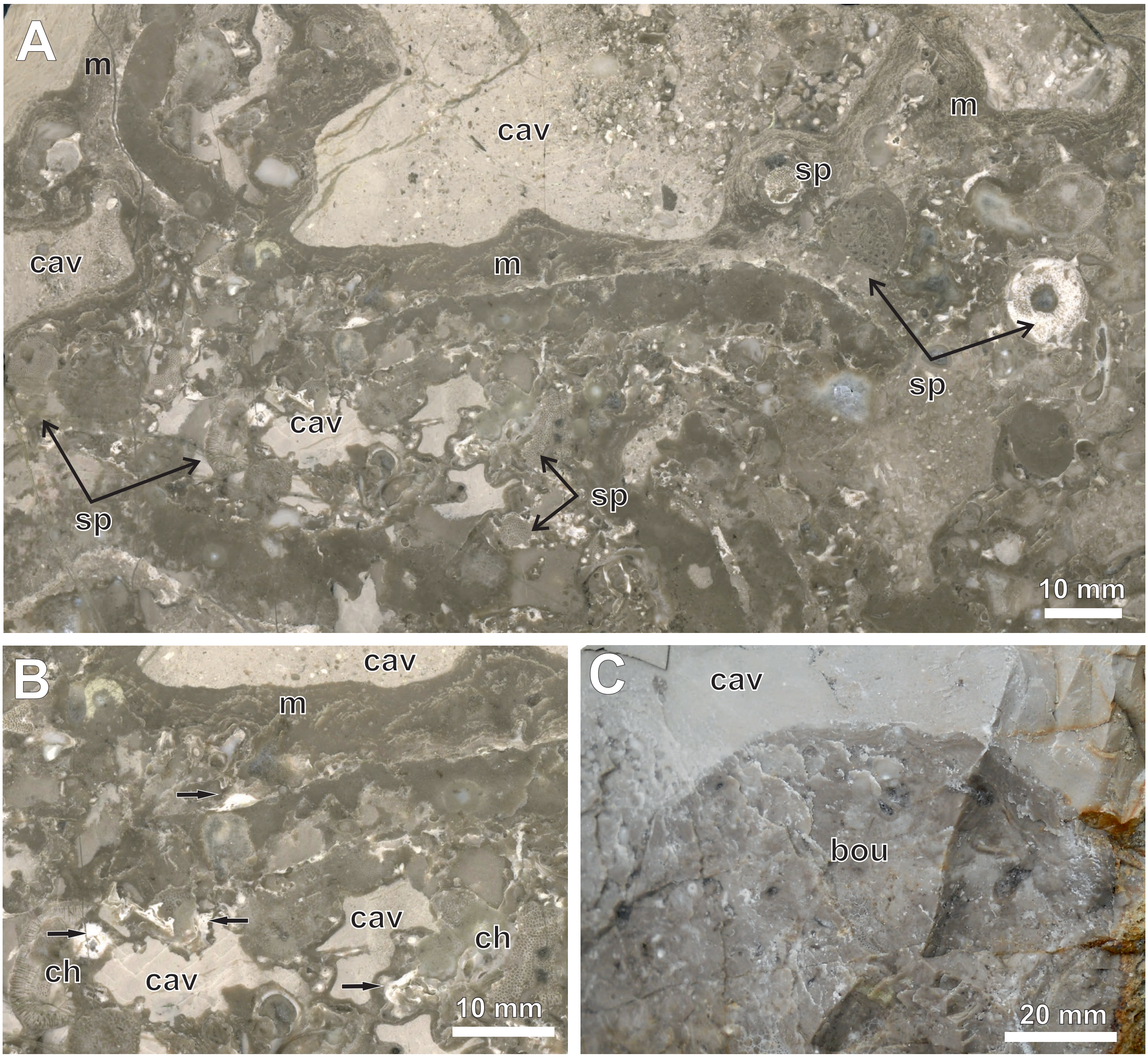

Fig. 5. Boundstone type B. **A.** Polished slab of the boundstone (see close-up in B); cav – growth cavities within the microencruster-cement framework filled with wacke- to grainstone (larger cavities) and calcimudstone internal sediment (small cavities); sp – selected (larger) calcified sponges; m – microbialite crusts coating cavity wall. **B.** Boundstone framework composed of a complex intergrowth of microencrusters, microbialite (m) and cement crusts (close-up from A). Recognizable microencrusters represent mostly *Crescentiella morronensis* and/or *Labes atramentosa* (white spots, arrowed) and calcified sponges, mostly chaetetids (ch). Note growth cavities (cav), filled with internal sediment. **C.** Field view of the microencruster-cement boundstone (bou) and large cavity (cav), filled with fine-grained sediment.

DISCUSSION

The role of microbialites and microencrusters

The preliminary studies revealed the importance of microbialites in both boundstone types, comparable to many Upper Jurassic–Lower Cretaceous reefs (Leinfelder *et al*., 2002). For instance, microbialites are important in coeval Štramberk-type limestones from the Polish Outer Carpathians (Hoffmann, 1992; Bucur *et al*., 2005; Hoffmann and Kołodziej, 2008; Kołodziej, 2015b). Eliáš and Eliášová (1984, p. 131) reported "*bioliths−bindstones [...] bound by algae*" from the Štramberk Limestone representing the inner reef flat with extensive growth of phaceloid corals. But it is unclear, whether these algae correspond to microbial crusts in the recent meaning, or correspond to *Lithocodium aggregatum*, "*Lithocodium*"-like structures and bacinellid microbial structures (in recent terminology), which were reported (as *Bacinella irregularis* and *B. crispa*) from this zone as well.

Microbialites are important for reef growth, synsedimentary lithification, the formation of a rigid framework,

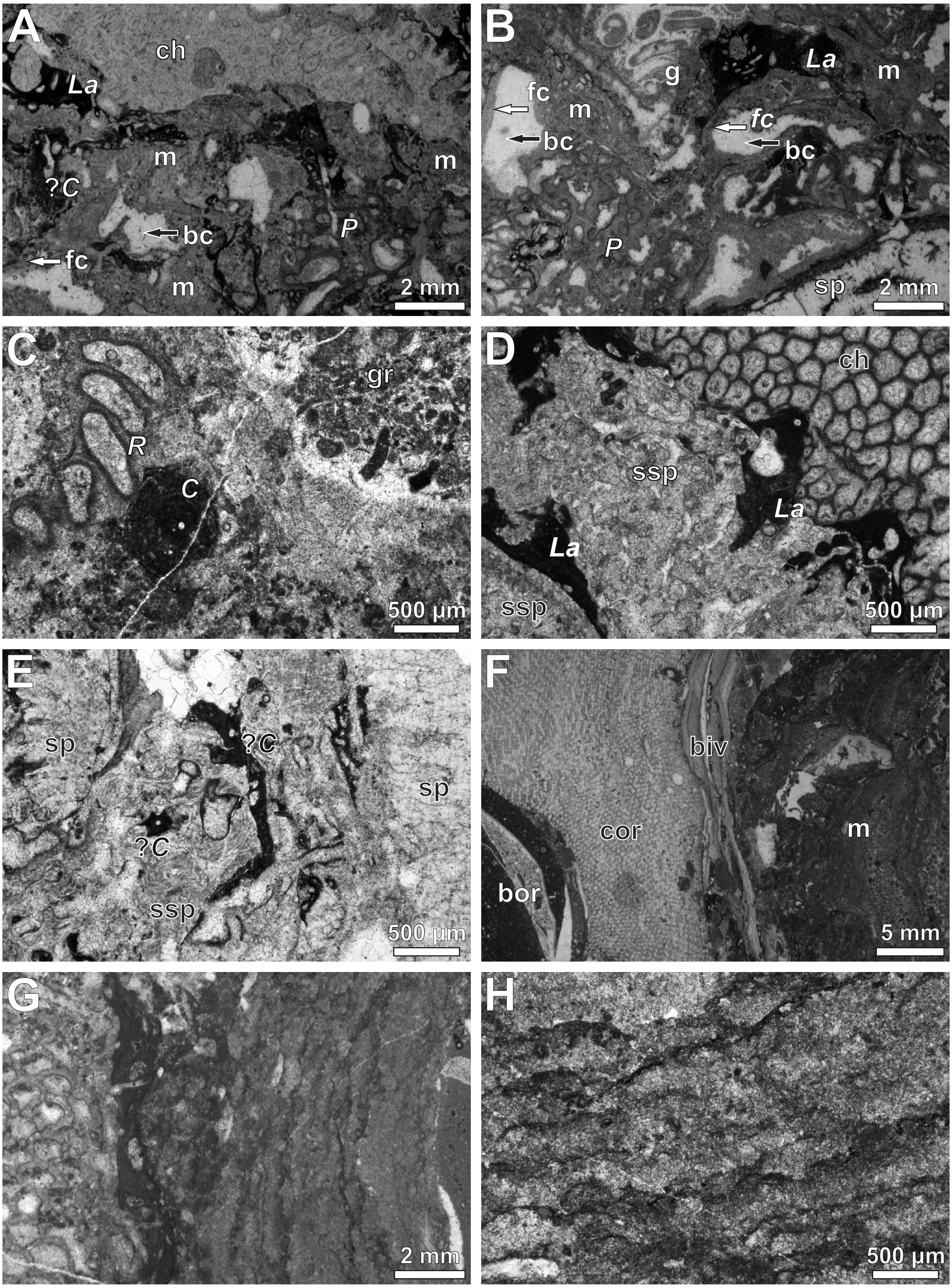

Fig. 6. Boundstone type B. **A–B.** Microscopic images showing a complex intergrowth of microbial crusts (m), microencrusters (ch – chaetetid sponges, sp – other calcified sponges, *La* – *Labes atramentosa, P* – *Perturbatacrusta leini*, ?*C* – *Crescentiella morronensis,* g – gastropods) and synsedimentary cements. Growth cavities are filled with synsedimentary isopachous fibrous cements (fc, white arrows) and late (?) diagenetic blocky calcite cement (bc, black arrows); St 107, St 68. **C**. *Radiomura cautica* (*R*), *Crescentiella morronensis* (*C*), grainstone matrix (gr) and cement; St 93. **D.** Intergrowth of chaeteid (ch), *Labes atramentosa* (*La*) and poorly preserved spicular sponges (ssp); St 79. **E.** Intergrowth of calcified sponges (sp), spicular sponges (ssp) and ?*Crescentiella morronensis* (?*C*); St 107. **F.** Microsolenid coral (cor) encrusted by ostreid bivalve (biv) and microbial crust (m) and bored by the bivalve (bor); St 108. **G.** Calcified sponge encrusted by undetermined microencruster (?*Crescentiella morronensis*) and by microbial laminated crust; St 93. **H**. Microcrystalline, “cloudy” appearance of microbial crust; St 93.

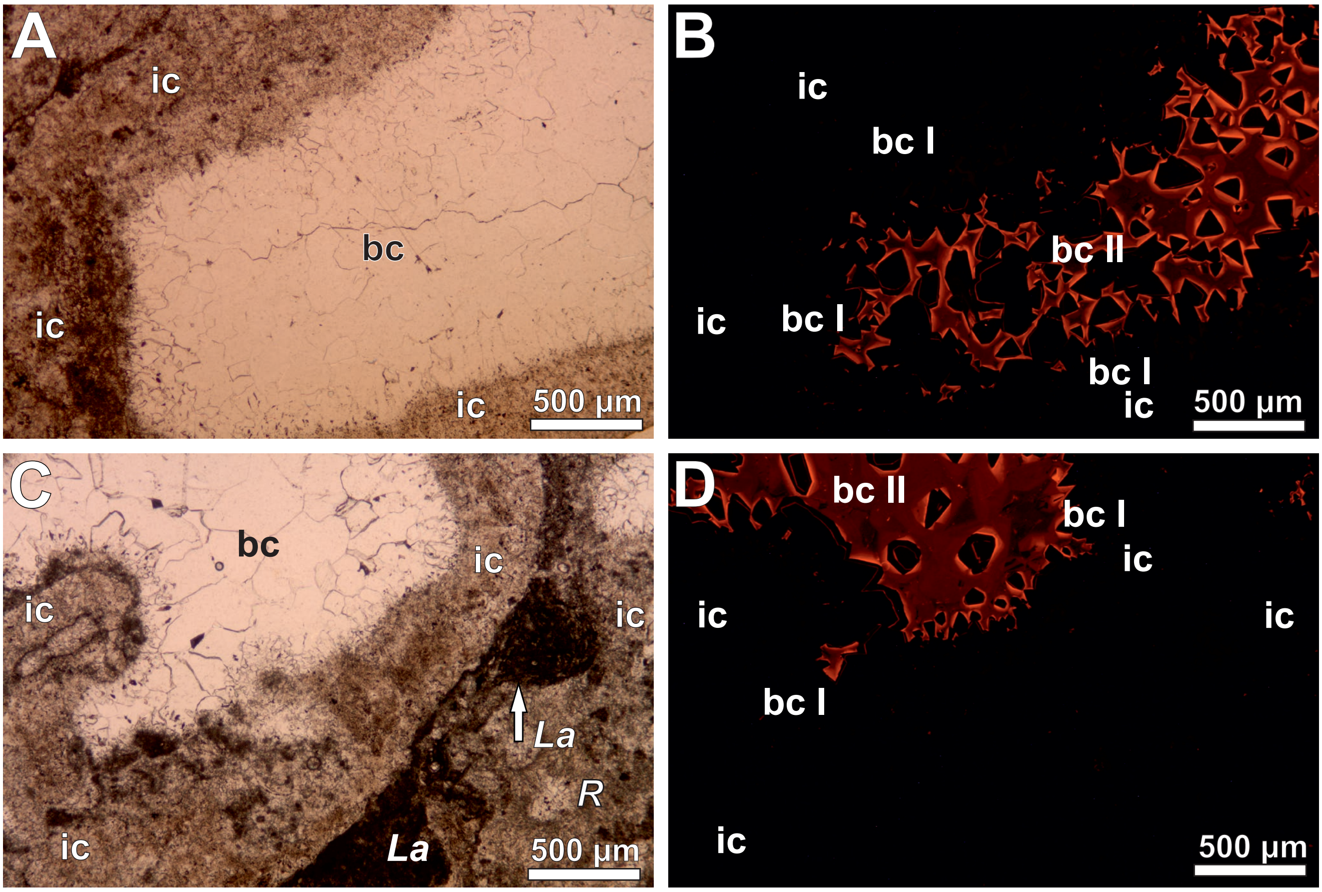

Fig. 7. Photomicrographs of representative cements from microencruster-cement boundstone (type B) under transmitted light (A, C) and under the cathodoluminescence microscope (B, D). Images are an enlargement of Figure 6B; St 68. **A, C** – Cavities within the cement-microencruster framework, lined by isopachous fibrous cement (ic), followed by blocky calcite (bc). *La* – *Labes atramentosa* (arrowed) encrusting isopachous fibrous cement; *R* – *Radiomura cautica.* **B, D.** Images of the same area as on A and C under the cathodoluminescence, showing a distinct cement succession. Isopachous fibrous cement (ic) and the first generation of blocky cement (bc I) is non-luminescent, while the second generation of blocky cement (bc II) shows orange luminescence.

the development of growth cavities inhabited by cryptic biota and the construction of a positive relief. Microbialite growth is usually favoured by a low sedimentation rate. A moderate sedimentation rate can be assumed in the case of agglutinating stromatolites (e.g., Matyszkiewicz *et al*., 2012). Some microbialites can grow as fast as corals, that is, 1–2 mm/year (Schmid *et al*., 2001), and even 7 to 12 mm/year in unstable environments (Seard *et al*., 2011). Generally, however, boundstone with poorly developed microbialites and microencrusters indicate higher sedimentation rates and the lack of distinct relief of bioconstructions (e.g., Leinfelder *et al*., 1994; Leinfelder, 2001). Evaluation of the significance of microbialites in the Štramberk Limestone requires detailed microscopic studies of particular boundstone samples, because the abundance of microbialites varies even on the scale of a hand specimen.

Microencrusters typical for coral-microbial boundstone (boundstone type A), such as "*Lithocodium-Bacinella*", *I. bodeuri, K. socialis,* are frequently reported from the Upper Jurassic–lowermost Cretaceous coral reefs with phototrophic-dominated biota, developed in reefal and internal platform (back-reef) environments (e.g., Leinfelder *et al*., 1993; Dupraz and Strasser, 2002). On intra-Tethyan carbonate platforms, *L. aggregatum* and bacinellid microbial structures were extensively developed in a lagoonal setting (e.g., Kaya and Altıner, 2015). Such a distribution pattern was revealed also in the Štramberk Limestone (Eliáš and Eliášová, 1984) and the Štramberk-type limestones from Poland, where these microencrusters are most common in an algal-foraminiferal facies (Bucur *et al*., 2005). "*Lithocodium-Bacinella*" is not a volumetrically important component in the samples studied. Difficulties in the determination of *L. aggregatum*, bacinellid structures and calcimicrobial crusts with entobian borings do not detract from their environmental importance. These components, associated with *K. socialis* and *I. bodeuri*, are indicative of the moderately oligotrophic to mesotrophic settings of Late Jurassic coral reefs (Leinfelder *et al*., 1994; Dupraz and Strasser, 2002). Conversely, the widespread development of *L. aggregatum* in the Aptian recently was interpreted as controlled among other factors by a significant nutrient supply (Immenhauser *et al*., 2005). Thus, environmental controls of Aptian buildups, dominated by *L. aggregatum* and bacinellid microbial structures, were different than in the case of Upper Jurassic reefs with *L. aggregatum* usually occurring as a moderate component (Schlagintweit *et al*., 2010).

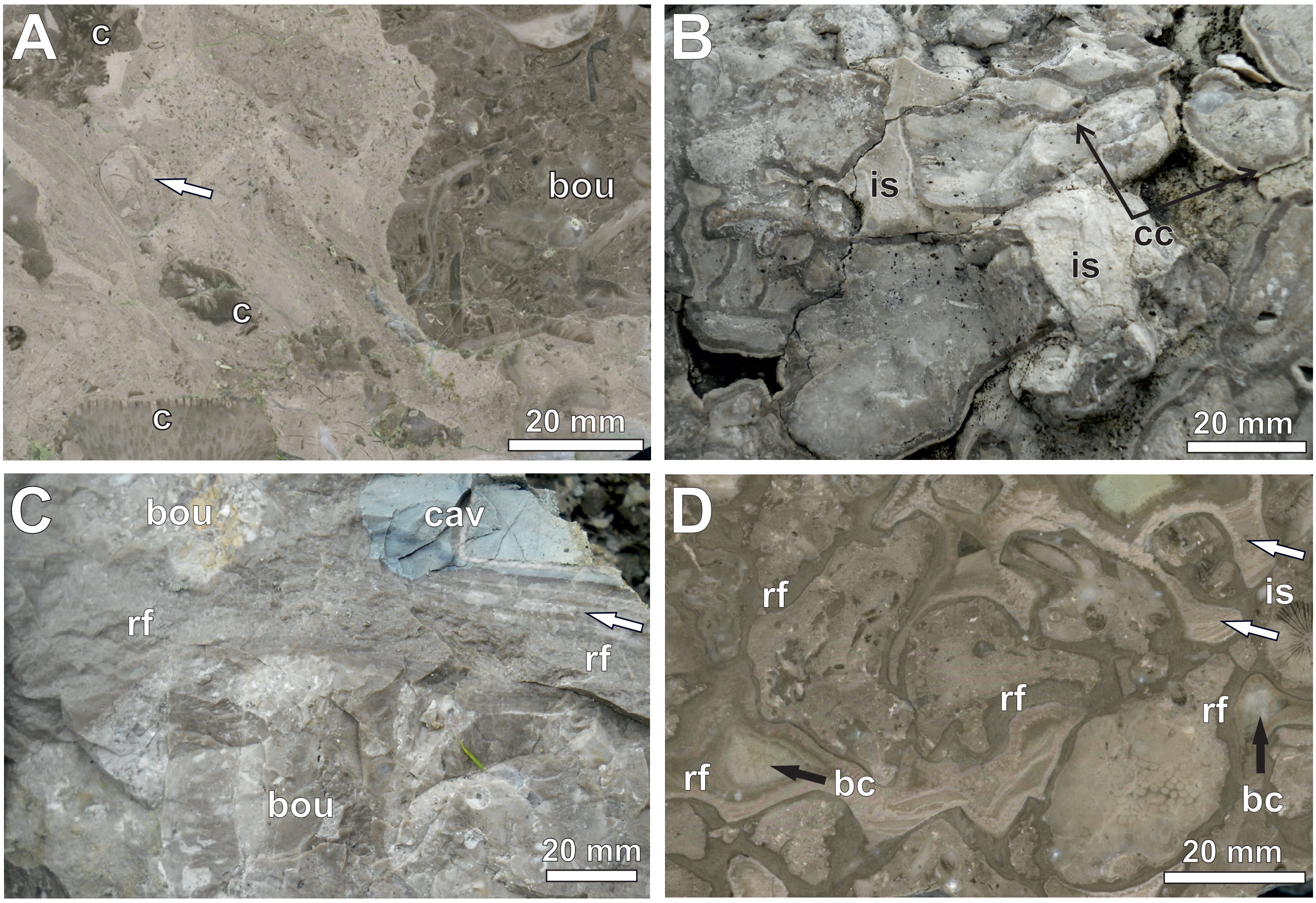

Fig. 8. Matrix-supported and clast-supported breccias. **A.** Polished slab of the matrix-supported breccia with boundstone clasts (bou) and fragments of corals (c). Matrix contains calpionellids (see Figure 9A) and small ammonites (arrowed). **B.** Field view of the clast-supported breccia with clasts bound by cement crusts (cc*,* arrowed), with remaining cavity space filled with internal sediment (is). **C.** Field view of the clast-supported breccia. Radiaxial-fibrous cement (rf) occurs between boundstone clasts (bou). Arrow indicates macroscopically visible banding of the cement. A void between clasts (cav) is filled with greenish mudstone **D.** Polished slab of the breccia composed of clasts encrusted by radiaxial-fibrous cement (rf). Remaining space between clasts is locally filled with internal sediment (is, white arrows) and blocky calcite cement (bc, black arrows).

While the microencrusters mentioned above were commonly reported in previuos studies of the Štramberk Limestone (Eliášová, 1981a, b, 1986; Eliáš and Eliášová, 1984), the presence of the microencruster association and their significant construction role in boundstone type B is recognized here for the first time. Boundstone frameworks composed mostly of microencrusters, microbial crusts and synsedimentary cements are known from ancient reefs, especially those of Permian and Triassic age (e.g., Flügel *et al.*, 1984a, b; Harris, 1993; Emmerich *et al.*, 2005; Weidlich, 2002; Flügel, 2010; Sánchez-Beristain and Reitner, 2012; Popa *et al.*, 2014). Upper Jurassic–Lower Cretaceous reefs dominated by a microencruster-cement framework were recognized for the first time by Schlagintweit and Gawlick (2008) in the Kimmeridgian and Berriasian of the Northern Calcareous Alps, Austria (Plassen Carbonate Platform). In terms of the reef framework and sedimentary setting, boundstone type B bears striking similarities to reefs in the Alps (Schlagintweit and Gawlick, 2008), Upper Kimmeridgian reefs in SW Bulgaria (Ivanova *et al.*, 2008; Kołodziej *et al.*, 2015) and shows some similarities to the Štramberk-type limestones in Romania (see below). In the well described reefs of the Alps, microencruster-cement boundstones with rare corals occur above monotypic, microsolenid floatstones and below coral-stromatoporoid patch-reefs. Schlagintweit and Gawlick (2008) interpreted these reefs as developed in an upper fore-reef slope environment (depth ~10 to 20 m, down to ~50 m). In the Bulgarian example (less documented, compared to the Alpine example), microencruster-cement boundstones with rare corals (mostly microsolenids) occur within a shallowing-upward succession. They occur above bio-lithoclastic, detrital limestones with *Saccocoma* and below a short interval of upper Kimmeridgian peloidal-*Saccocoma* limestones (upper Kimmeridgian), followed by Tithonian–Valanginian shallow-water, bio-lithoclastic and coral-microbial limestones. Paradoxically, the microencruster-cement boundstones in Bulgaria are bioherms, whereas the coral-microbial boundstones are biostromes (Ivanova *et al.*, 2008; Kołodziej *et al.*, 2015). Boundstones composed of a microencruster framework also were recognized in the Štramberk-type limestones in the Polish Outer Carpathians (Hoffmann *et al.*,

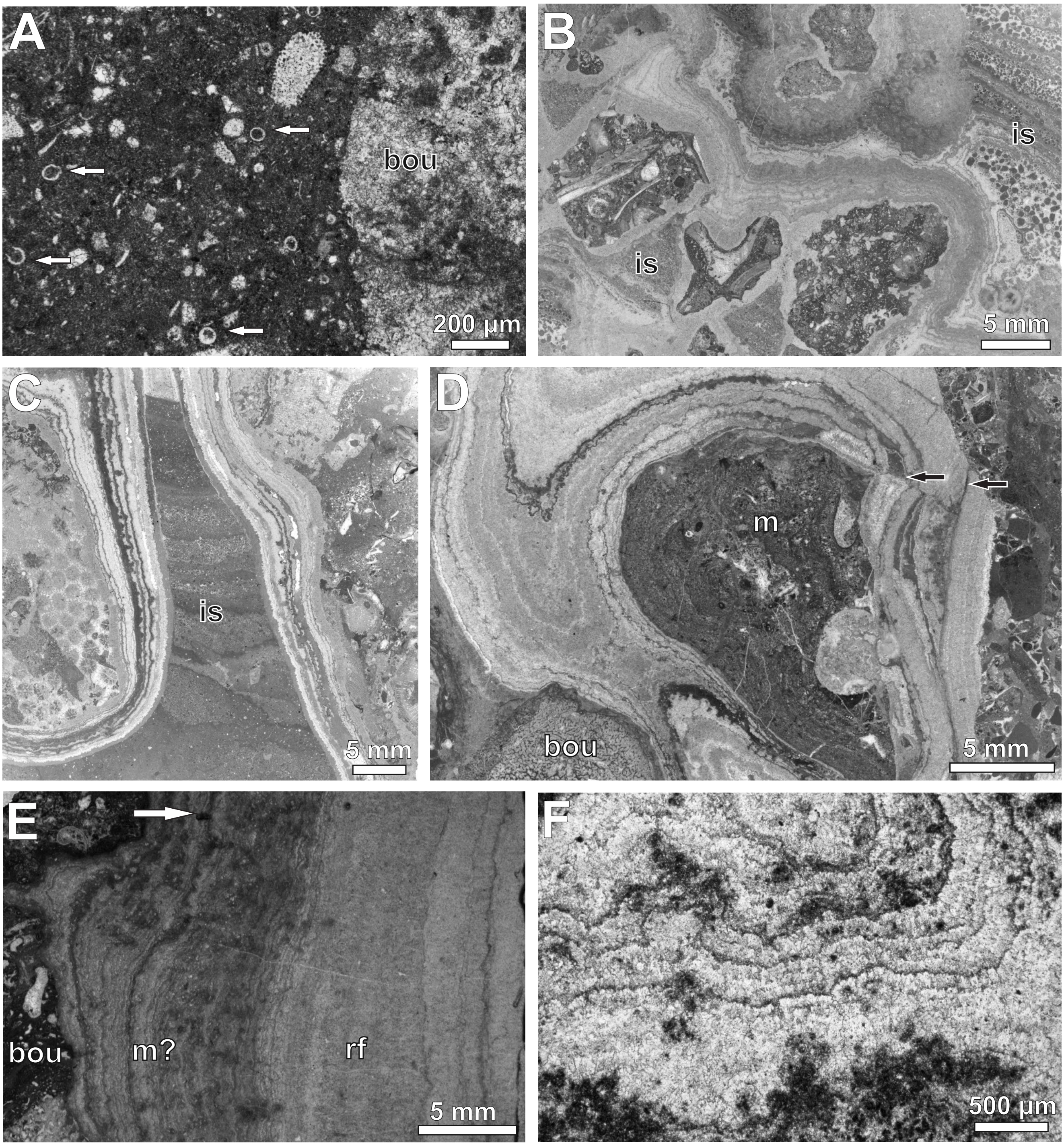

Fig. 9. Scanned thin sections and microphotographs of matrix (A) and clast-supported (B–F) breccias. **A.** Matrix-supported breccia (see Figure 8A) with calpionellids (arrows) in a wackestone matrix. On right side of the image, fragment of boundstone clast (bou) is present; St 3. **B.** Clast-supported, cement-rich breccia, locally with geopetal internal sediment (is); St 2. **C**. Boundstone clasts coated by synsedimentary radiaxial-fibrous cement with dark micrite laminae. Laminated, peloidal sediment (is) fills internal cavity; St 1. **D.** Microbialite (m) and boundstone clasts with calcified sponge (bou), coated by radiaxial-fibrous cement, alternated with micrite laminae. Some cement crusts are broken (arrows); St 78. **E**. Boundstone clast (bou), coated by crust of possible microbial origin (m?), followed by banded synsedimentary radiaxial-fibrous cement (rf; crust up to 3 cm thick). Arrow indicates direction of crust growth; St 75. **F**. Fragment of the radiaxial-fibrous cement crust showing light and dark bands. Note micrite embedded in radiaxial-fibrous calcite. The boundary between cement crust and microbial crust (lower part of the image) is diffuse; St 5.

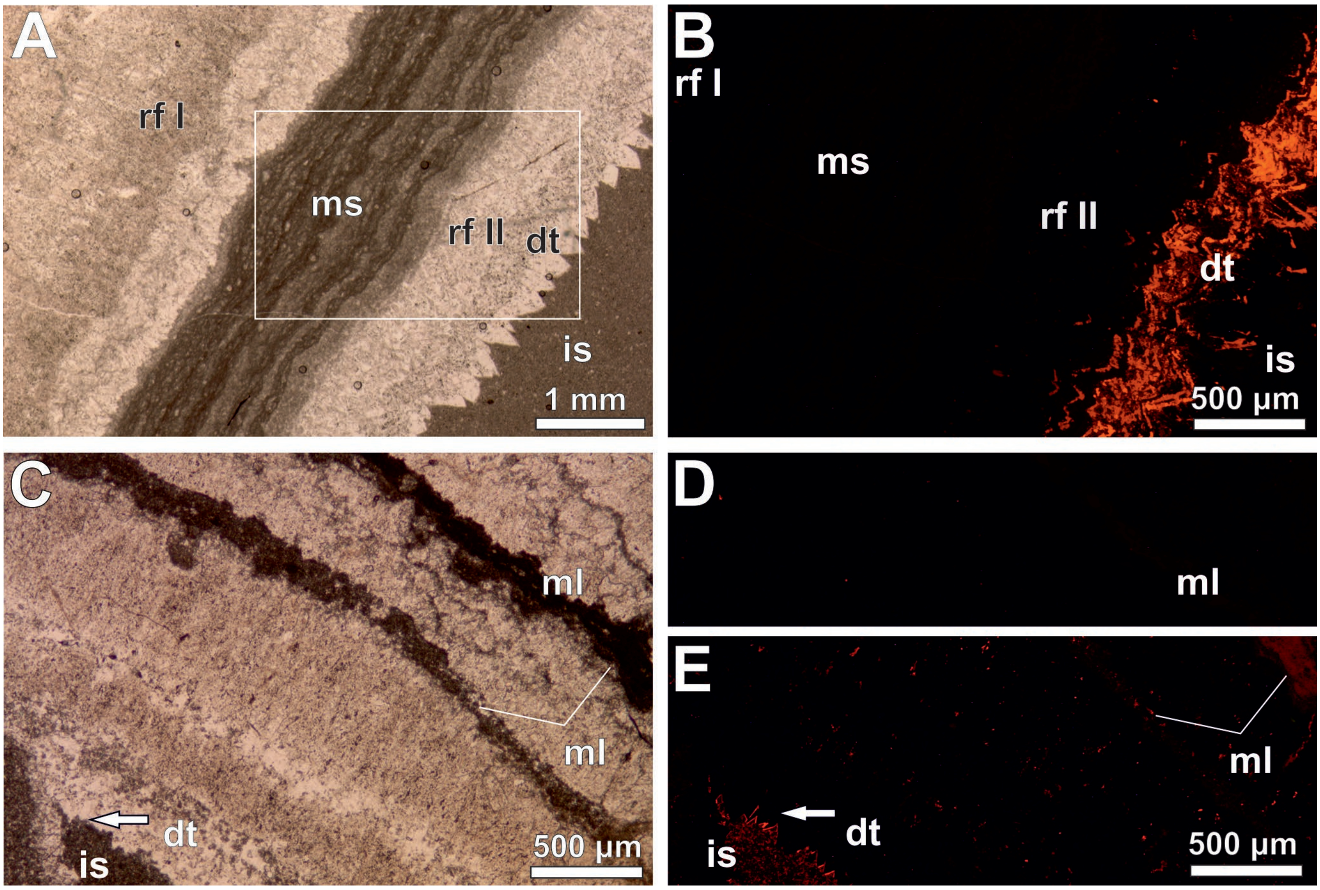

Fig. 10. Photomicrographs of representative cements from clast-supported breccias, under transmitted light (A, C) and under the cathodoluminescence (B, D , E). **A−B**. The cavity wall (on the left, not visible), coated by two generations of non-luminescent radiaxial-fibrous calcite (rf I, rf II), interlayered with dull microstromatolite crust (ms), and followed by zoned dog-tooth cement (dt) showing bright orange luminescence. An inner part of a cavity (is) is filled with mudstone. Image A shows a larger area than image B (see framed area on A); St 92. **C−E**. Radiaxial-fibrous cement, non-luminescent under the cathodoluminescence (with rare bright spots), alternated with dull, micritic laminae (ml); dt − dog-tooth cement shows orange luminescence on the outermost edges (arrowed); is − an internal sediment. Images on C−E are enlargements from Figure 9D. The cathodoluminescence image on D shows upper part of image on C. The image contrast in Figure E (cathodoluminescence view of the lower part of the image on C) is increased by 75% to enhance poor luminescence of micritic laminae, dog-tooth cement and an internal sediment; St 78.

2008; Kołodziej *et al*., 2015). Other Upper Jurassic (mostly) and Lower Cretaceous examples of microencruster-cement boundstones, briefly discussed by Schlagintweit and Gawlick (2008), are poorly documented. Microencruster-dominated frameworks are not common (or not enough recognized) in Upper Jurassic reefs and were mostly restricted to the margins of isolated platforms within the Tethys.

Schlagintweit and Gawlick (2008) noted that photophile microencrusters, such as *L. aggregatum,* are extremely rare in microencruster-cement boundstones; this is confirmed by the studies mentioned above (Hoffmann *et al*., 2008; Ivanova *et al*., 2008; Kołodziej *et al*., 2015) and the present study of the Štramberk Limestone. This is also consistent with a general bathymetric distribution pattern of microencrusters on Upper Jurassic–Lower Cretaceous carbonate platforms (e.g., Kaya and Altıner, 2015). A deeper depositional setting and the presence of poorly lit growth cavities within the microencruster-cement framework facilitated growth of non-photophile species. Large skeletons of metazoans are rare in pure microencruster-cement boundstones. Coral-microbial boundstones with the microencruster-cement framework are recognized in the Štramberk-type limestones of Romania (Săsăran, 2006; Bucur *et al*., 2010; Pleş *et al*., 2013, 2016; Săsăran *et al*., 2014). However, the microencruster association includes also photophile species, indicating a shallow-water environment.

The possible occurrence of pure microencruster-cement frameworks should be kept in mind when Upper Jurassic–lowermost Cretaceous reefs developed in deeper settings are studied. In some samples of the Štramberk Limestone, the microencruster-cement framework can be recognized under a low magnification on the surfaces of polished slabs. Without detailed microscopic analysis, such a framework may be overlooked in recrystallized boundstones (e.g., discussed in the Bulgarian case study mentioned above; Ivanova *et al*., 2008; Kołodziej *et al*., 2015). There is an analogy with Middle Triassic "*Tubiphytes*" boundstones, in which "…*the realtively unspectactural combination of microscopic organisms, biotic crusts and early cementation formed wave-resistant reefs and allowed development of facies zonation, similar to their large framework counterparts*" (Harris, 1993, p. 399).

The role of synsedimentary cements

Early cements, interpreted here to be dominantly synsedimentary, contributed to the framework of boundstone type B and the lithification of clast-supported, cement-rich breccias. The term "synsedimentary cement" is used in qualitative meaning, as an equivalent of pre-burial cement. Quantitative, isotopic studies revealed that recent, synsedimentary aragonite cement in a steep, marginal slope environment grew at an average rate of 8–10 mm/100 yr, with maximum rates of up to 25 mm/100 yr (Grammer *et al*., 1993).

According to Schlagintweit and Gawlick (2008), cement crusts that contribute to the microencruster-cement framework are synsedimentary. The synsedimentary nature of isopachous fibrous cement in boundstone type B is evidenced by the overgrowth of cement crusts by microencrusters (Fig. 7C), which previously was observed in the microencruster-cement framework by Schlagintweit and Gawlick (2008), Kołodziej *et al.* (2015) and Pleş *et al.* (2016). Additionally, such an interpretation is suggested by the study under cathodoluminescence, which revealed similar luminescence of isopachous fibrous cement (boundstone type B), synsedimentary cements in the clast-supported breccias studied here and the "evinosponges" cement of the Triassic carbonate platforms (see discussion below).

There are several lines of evidence, which support the synsedimentary origin of radiaxial-fibrous cement in the clast-supported breccia. In some samples, the internal sediment fills the space between clasts encrusted by radiaxial-fibrous cement (Figs 8B, D, 9B, C). Thus, the cement pre-dates deposition of the internal sediment, which in turn indicates that cementation proceeded when the voids were still open to marine water (see Payne *et al*., 2006; Flügel, 2010; Popa *et al*., 2014). Micritic laminae (in one sample, a 1- to 2-mm-thick microstromatolite crust; Figs 9C, D, 10A, C), of possible microbial origin, alternating with radiaxial-fibrous cement layers, also support synsedimentary origin of the cement (Frisia-Bruni *et al*., 1989; Payne *et al*., 2006; Flügel, 2010, p. 306; Popa *et al*., 2014).

The luminescence of isopachous fibrous cement (boundstone type B) and radiaxial-fibrous cements (clast-supported breccia) is similar to the luminescence of the marine synsedimentary radiaxial-fibrous cement called "evinosponges" (shortly characterized in the section Matrix and clast-supported breccias). Radiaxial-fibrous cements are reported from the Middle–Upper Triassic carbonate platforms of the Southern Alps from boundstones and breccias representing mostly the outer-margin and upper-slope environments with extensive synsedimentary marine cementation (Frisia-Bruni *et al*., 1989; Harris, 1994; Russo *et al*., 2000; Keim and Schlager, 2001; Seeling *et al*., 2005). The cathodoluminescence studies revealed that "evinosponges" are non-luminescent, or more rarely dull (compare with isopachous fibrous cement; Fig. 7B, D, and with radiaxial-fibrous cement; Fig.10B, D, E). The first generation of late diagenetic blocky calcite cement in the "evinosponges"-bearing sediments is composed of dully luminescent calcite, while the second generation is composed of several bright luminescent layers (Frisia-Bruni *et al*., 1998; Seeling *et al*., 2005). Similar luminescence of late diagenetic blocky and dog-tooth cements was recognized in the Štramberk Limestone (Figs 7B, D, 10B).

The causes of the observed luminescence pattern of carbonate minerals may be complex and controlled by a variety of parameters. Commonly, it is interpreted as a complex function of Mn^{2+} (the most important activator) and Fe^{2+} (the most important quencher). In conventional interpretations, non-luminescent calcite cement (isopachous fibrous and radiaxial-fibrous cement described in this paper) points to an oxygenated environment and thus a synsedimentary or early diagenetic origin. Bright luminescent of calcite cement (blocky and dog-tooth cement in this paper) suggests precipitation under reducing conditions, possibly during late diagenesis (e.g., Machel, 2000; Boggs and Krinsley, 2010). On the basis of petrographic and cathodoluminescence observations and comparison with Triassic "evinosponges" cements, the assumed synsedimentary origin of thin, isopachous fibrous cement (boundstone type B) and radiaxial-fibrous cement (breccia) in the Štramberk Limestone appears to be justified. However, it can not be excluded that some of these cements were precipitated not on the sea floor, but in a shallow-burial, well oxygenated environment (cf. Payne *et al*., 2006).

As discussed in following section, the assumed depositional setting of the microencruster-cement boundstones and clast-supported, cement-rich breccia is that of a slope environment. Synsedimentary cementation is known from modern and ancient (especially Carboniferous, Permian and Triassic) carbonate slopes. Pervasive cementation (radiaxial-fibrous and botryoidal cements) in modern and ancient, fore-reef slopes is interpreted as a result of the pumping of seawater at the frontal, seaward margins. This process is facilitated by the occurrence of interconnected vugs (e.g., growth cavities), a prerequisite for cement precipitation in moderate- to high-energy conditions. Apart from effective fluid flow (porosity, elevated energy), other controlling factors of synsedimentary and early marine cementation include a high topographic relief of the reef edge, low carbonate production, water chemistry, and the influence of organic matter and microbial communities (e.g., Flügel *et al*., 1984a, b; Harris, 1993, 1994; Russo *et al*., 2000; Seeling *et al*., 2005; Flügel, 2010; Van der Kooij *et al*., 2010).

Implications for zonation of the Štramberk reef complex

Eliášová (1981b) and Eliáš and Eliášová (1984) subdivided the Štramberk reef complex into the following zones and subzones: (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). The model of the Štramberk reef complex has been interpreted on the basis of a comparison with modern reefs of the Red Sea and the Caribbean region (Eliášová, 1981b; Eliáš and Eliášová, 1984). However, because of the different ecological demands and physiological abilities of pre-Cenozoic corals (e.g., modern branching *Acropora* versus Jurassic branched phaceloid corals), uniformitarian reasoning may be invalid (e.g., Wood, 1999; Leinfelder *et al*., 2002). As Lathuilière *et al.* (2005) noted, the zonation of modern reefs is frequently used in reconstructions of Cenozoic fossil reefs, while zonations of Jurassic reefs based on corals are nearly non-existent. The zonation model proposed by Lathuilière *et al.* (2005) is for Oxfordian reefs of the French Jura, representing reefs of the northern Tethyan shelf that differ significantly from the reefs developed on intra-Tethyan carbonate platforms (see the following section). The different morphologies of epicontinental carbonate platforms and those of the Tethyan realm must be taken into account, when reef zonation is interpreted. Recently, a zonation model for the Upper Jurassic Ellipsactinia Limestones representing the intra-Tethyan reef complex, well exposed in the central Apennines, was proposed by Rusciadelli *et al.* (2011). As discussed below, this model can be only partially extrapolated to the Štramberk reef complex. More qualitative and quantitative data on the Štramberk Limestone are required for any proposal of a comprehensive model that will take into account new data and concepts concerning Upper Jurassic–Lower Cretaceous carbonate platforms and reefs. Nevertheless, the results of the present studies provide some insights into zonation of the Štramberk reef complex. The comparison of the main facies described here with the facies described by Eliáš and Eliášová (1984) and assignment of them to the zones and subzones of their proposed model encounter certain difficulties. Some components essential for environmental interpretation, such as microbialites, microencruster-cement framework and synsedimentary (pre-burial) cements were undetermined before or insufficiently described and illustrated.

Boundstone type A, meaning a coral-microbial boundstone, corresponds to the facies dominated by phaceloid corals placed by Eliášová (1981b) and Eliáš and Eliášová (1984) in two zones: (1) a sheltered, inner-reef flat (phaceloid corals, largely of the suborder Pachythecaliina = = Amphiastraeina), and (2) the sheltered setting of the reef front at medium depths (largely non-pachythecaliine phaceloid corals). According to these authors, the presence of calpionellids is the argument supporting the placement of some phaceloid corals-dominated facies in the second zone. On the other hand, Eliášová (1981a, b) and Eliáš and Eliášová (1984) mentioned that phaceloid corals from the reef front are encrusted by "*Bacinella-Lithocodium*", *I. bodeuri* (recent terminology) and *K. socialis,* thus rather photophile species, indicating an shallow-water setting.

Boundstone type A shows similarities with the coral-microbial boundstones of the Štramberk-type limestones of the Polish Outer Carpathians. These similarities include the following: (1) common and diversified phaceloid corals (especially pachythecaliines), (2) the microencruster association, (3) the contribution of microbialites, and (4) the inferred depositional setting (Bucur *et al*., 2005; Hoffmann and Kołodziej, 2008; Kołodziej, 2015b). Hoffmann and Kołodziej (2008) interpreted coral-microbial boundstones as patch reefs developed in an open inner platform, dominated by the deposition of algal-foraminiferal, bioclastic and peloidal facies. Clasts of boundstones with "*Lithocodium-Bacinella*" are common in the Berriasian Cieszyn Limestone as debris-flow deposits from the Polish Outer Carpathians. These clasts were derived from reefal sequences developed on the Silesian Ridge (Matyszkiewicz and Słomka, 2004).

On the basis of preliminary studies and literature data, the maximum growth of the phaceloid corals of the Štramberk Limestone was located in the inner platform zone. Reefs dominated by phaceloid corals (exemplified by boundstone type A) were common during the Late Jurassic, especially in protected, inner platform settings (Leinfelder *et al*., 1994; but see Lathuilière *et al*., 2005). The inferred sedimentary setting of boundstones dominated by phaceloid corals is consistent with the model proposed by Rusciadelli *et al.* (2011) for the reef complex of the Ellipsactinia Limestones. There, corals occur mostly in the internal zone (a relatively deep back-reef/lagoon) of the reef complex studied and are rare in a more external zone (reef crest), dominated by stromatoporoids.

The microencruster-cement boundstone (type B) has no close counterpart among the facies described by Eliáš and Eliášová (1984). There is some similarity with the facies composed of robust, branched/nodular corals and abundant microencrusters *C. morronensis, L. atramentosa,* chaetetids, bryozoans and containing "*cavities rimmed by microstromatolitic units*". This facies was assigned to the uppermost part of the reef front (Eliáš and Eliášová, 1984, p. 129). The presence of more numerous corals clearly distinguishes this facies from boundstone type B. However, pure microencruster-cement boundstone is assumed to be an end member of the spectrum of boundstone types. Therefore, further studies of the Štramberk Limestone certainly will reveal a similar microencruster framework in boundstones with more abundant corals, comparable to the boundstones of the Štramberk-type limestones in Romania (Pleş *et al*., 2013). As was discussed earlier, a well established sedimentary setting of pure microencruster-cement boundstones in Austria (Schlagintweit and Gawlick, 2008) and Bulgaria (Ivanova *et al*., 2088; Kołodziej *et al*., 2015) indicate the location of the sedimentary environment of boundstone type B in an upper fore-reef slope position.

Sedimentary breccias are an end member of the detritus-dominated facies that are common in the Štramberk Limestone (Eliáš and Eliášová, 1984; Vašíček and Skupien, 2014). The breccias are the result of erosion of boundstones and other facies and subsequent redeposition of clasts, even of boulder-size, on the slope of the carbonate platform. Reef-derived breccias imply steepened slopes of the Štramberk carbonate platform, as previously was assumed by Eliáš and Eliášová (1984). The presence of abundant calpionellids and ammonite fragments supports the placement of the matrix-supported breccia in a fore-reef environment (Eliáš and Eliášová, 1984). The clast-supported, cement-rich breccias most probably correspond to facies described by Eliáš and Eliášová (1984, p. 130, pl. 3) as follows: "*These large ?oncoids (as much as 30 cm in diameter) occur rarely in close contact and without matrix*". "Large ?oncoids" correspond to carbonate clasts coated with radiaxial-fibrous cements, arranged in concentric bands. This facies was attributed by Eliáš and Eliášová (1984) to the high-energy environment in the shallowest part of the reef front, still inhabited by massive corals. Because the clast-supported breccias contain clasts of microencruster-cement boundstones, the present authors place the deposition of the breccias discussed below or at the upper slope setting. The large size of clasts, the absence or rare occurrence of a fine-grained matrix and dominantly synsedimentary cements point to a high-energy sedimentary environment and rapid cementation. The matrix-supported breccias without cement crusts originated in a low-energy, deeper setting.

Steep morphological profiles are inferred also for the outer margins of some other intra-Tethyan carbonate platforms: the Upper Jurassic coral-stromatoporid reefs from Slovenia (Turnšek *et al*., 1981) and the Upper Jurassic–lowermost Cretaceous Plassen Carbonate Platform of the Northern Calcareous Alps, Austria (Steiger and Wurm, 1980; Schlagintweit and Gawlick, 2008). However, there are no data about comparable, contemporaneous breccias showing massive synsedimentary cementation.

Intra-Tethyan character of the Štramberk Limestone

The Štramberk Limestone is rarely referenced in discussions of intra-Tethyan carbonate platforms (Leinfelder *et al*., 2002, 2005; Rusciadelli *et al*., 2011). The Štramberk carbonate platform shares with coeval platforms of the Tethyan domain many biotic and sedimentary features and clearly differs from the carbonate platforms developed on the shelves of the northern Tethys and North Atlantic. Intra-Tethyan reef complexes usually show the following: (1) a strongly zoned character, expressed in sediment characteristics and the distribution of corals, calcified sponges and other biota; (2) high or moderate topographic relief at the reef edge, evidenced by the presence of detritic limestones and reef-derived breccias; (3) the presence of a microencruster-cement framework with some species (*L. atramentosa, P. leini, R. cautica*) known only from the Tethyan realm; (4) the reef-building role of calcified sponges; and (5) the considerable contribution of bio-lithoclastic debris and the subordinate role of micritic matrix and terrigenous material (Leinfelder *et al*., 2002, 2005; Schlagintweit and Gawlick, 2008; Rusciadelli *et al*., 2011).

Despite similarities, there are some differences between the Štramberk Limestone and reefs of the carbonate platforms of the central and southern Tethys (Italy, Slovenia, Austria) with regard to the role of metazoan constructors. Leinfelder *et al*. (2005), in their paper on the significance of stromatoporoids (and other calcified sponges) in Jurassic reefs, suggested that development of the Štramberk Limestone on the northward-lying intra-Tethyan platform was possibly (like other carbonate platforms of the Tethyan domain) influenced by similar environmental factors. According to these authors, the Late Jurassic mixed coral-stromatoporoid reefs of isolated intra-Tethys platforms developed under the influence of oligotrophic waters, while the coral-microbial reefs of epicontinental seas developed in mildly oligotrophic, mesotrophic and even strongly mesotrophic, clay-influenced environments. In the Štramberk reef complex, however, especially in contrast to the reefs of Slovenia and Italy, corals outcompeted stromatoporoids as the main metazoan reef builders. Differences between the Štramberk reefs and reefs of the central Apennines (Ellipsactinia Limestones), recently studied in details by Rusciadelli *et al*. (2011), include: (1) coral-dominated reefs in the Štramberk Limestone *vs.* mixed coral-stromatoporoid reefs in the Ellipsactinia Limestones, (2) the lack of microencruster-cement boundstones in the Ellipsactinia Limestones, except for the discontinuous frameworks in the more external unit, and (3) an inferred high topographic relief at the platform margin of the Štramberk carbonate platform and a rather gentle platform margin in the case of the carbonate platform represented by the Ellipsactinia Limestones.

Phaceloid corals are very well represented in the Štramberk Limestone. Environmental constraints on proliferatation of phaceloid corals of the suborder Pachythecaliina, described already in the 19th century, both in terms of abundance and numbers of species (ca. 35 species, 17 genera; e.g., Ogilvie, 1897; Eliášová, 1975, 1978, 2008), are unknown. These corals are also diversified in the Štramberk-type limestones in Poland (22 species, 14 genera; e.g., Kołodziej, 2003, 2015b), while in other Upper Jurassic–Cretaceous coral communities they are moderately or poorly represented (see Kołodziej, 2015b). The only exception is a unique community in the Barremian of Bulgaria, which is strongly dominated by phaceloid pachythecaliines. Coral assemblages, strongly dominated by phaceloid, possibly non-photosymbiotic corals, imply an increased nutrient level, rather than oligotrophic waters (Kołodziej *et al*., 2012). It is plausible that in terms of coral diversity the Štramberk Limestone is unique among coral communities of the Tethyan domain, although knowledge of the taxonomy of Upper Jurassic–lowermost Cretaceous corals from this palaeogographic domain is far less, compared with Upper Jurassic reef corals from the northern margin of the Tethys. For comparison, the coral communities of the Kimmeridgian–Valanginian reefs of the Moesian Carbonate Platform (intra-Tethys platform) of SW Bulgaria (Ivanova *et al*., 2008) contain 72 species (Roniewicz, 2008), whereas in the Štramberk Limestone about 120 species were determined (see Eliášová, 2008).

In contrast to the reefs of Italy and Slovenia, calcified sponges contributed to the framework of boundstone type B in the Štramberk Limestone, but mostly as millimetre- to centimetre-sized crusts. Bachmayer and Flügel (1961a, b) reported from the Štramberk Limestone 10 species of calcified sponges classified as chaetetids and hydrozoans (mostly stromatoporoids in the recent classification). Eleven species, mostly thin, encrusting forms, were identified in the Štramberk-type limestones of Poland (Podoba, 2009). In the coral-stromatoporoid reef complex of Slovenia, about 35 species (some of them important reef builders) were recognized (Turnšek *et al*., 1981; Leinfelder *et al*., 2005). The Štramberk Limestone certainly contains more species, but detailed microscopic studies are required. It was proposed that the depositional model of Upper Jurassic reefs of the central Apennines can be extrapolated to other intra-Tethyan reef complexes (Rusciadelli *et al*., 2011). However, all of the differences discussed above show that this model can be only partly applied to the Štramberk reef complex.

On the other hand, there are clear differences between deposition on the Štramberk carbonate platform and deposition on the Brno carbonate platform (autochtonous Jurassic of the Bohemian Massive) and the Ernstbrunn-Pavlov platform (Austria, Czech Republic) representing the Peri-Tethys domain. These two last-mentioned carbonate platforms were palaeogeographically close, but located slightly more northerly than the Štramberk platform. Differences in sedimentary conditions according to Eliáš and Eliášová (1986) result from different tectonic regimes. The Štramberk Limestone originated on a tectonically active Baška cordillera. Intensive subsidence was compensated by the development of reefal facies, especially during the late Tithonian (Eliáš and Eliášová, 1986). The Brno and Ernstbrunn-Pavlov carbonate platforms were located in a less mobile area, being part of the epi-Variscan platform (West European Platform). These platforms were characterized by lower subsidence and sedimentation rates. Environmental conditions favoured sedimentation of carbonate sediments with ooids, oncoids, algae, aggregated and micritzed grains. The Ernstbrunn Limestone contains only poorly developed reefal structures with poorly diversified corals (26 species; Eliáš and Eliášová, 1984, 1986; Eliášová, 1990; Schneider *et al*., 2013).

The Štramberk-type limestones of the Polish Outer Carpathians also show differences with the coeval carbonate platform deposits of the subsurface of the Carpathian Foredeep in Poland, a part of the northern Tethys shelf. Reef sequences developed along the North Tethys margin are usually intercalated with marls, evidencing terrigeneously influenced sedimentary settings, presumably linked with an elevated nutrient level (Leinfelder *et al*., 2005). Tithonian coral-bearing limestones contain poorly diversified corals (42 species; Morycowa, 2012) with a poorly developed, microbial and microencruster framework or are dominated by microsolenids typical for deeper settings (Krajewski *et al*., 2011). In other boreholes, Gutowski *et al.* (2007) recognized coral boundstones, but a detailed description was not provided. Matyja (2009) reported from some boreholes a thick succession of the Tithonian Pilzno Coral Limestone Formation that was compared with the Štramberk Limestone. However, there are no data about the taxonomy and diversity of corals and the reef framework that would allow a comparison of these limestones with the Štramberk Limestone.

CONCLUSIONS

1. The framework of the reef facies (boundstones) of the Štramberk Limestone (Kotouč Quarry, near Štramberk) in various proportions is composed of corals, microbialites, microencrusters and synsedimentary cements, reflecting environmental parameters in different reef zones. Two main boundstone types are recognized. Boundstone type A consists primarily of phaceloid (branching-type) corals, associated with more or less developed microbialites and subordinately, microencrusters mostly of uncertain origin: *Crescentiella morronensis,* "*Lithocodium-Bacinella*" (a collective term for bacinellid microbial structures, *Lithocodium aggregatum* and calcimicrobial crusts with entobian borings)*, Koskinobullina socialis, Iberopora bodeuri*. The framework of boundstone type B is composed of the intergrowth of microencrusters with microbial crusts and synsedimentary cements, whereas corals, mostly thin encrusting microsolenids, are rare or absent. The microencruster association includes *Crescentiella morronensis*, *Labes atramentosa, Perturbatacrusta leini, Radiomura cautica,* and thin crusts of calcified sponges, a few millimetres thick (*Calcistella jachenhausenensis*, *Murania reitneri, Neuropora lusitanica*, chaetetids and others). Microencrusters recognized in boundstone type A, which were more photophilic ("*Lithocodium-Bacinella*", *K. socialis, I. bodeuri*), are absent or rare.

2. Microbialites in the Štramberk Limestone, as in many Upper Jurassic–Lower Cretaceous reefs, contributed to the reef framework. Laminated and poorly structured thrombolites are composed mostly of micropeloids and clotted micrite. Reefs dominated by phaceloid corals (boundstone type A) were common during the Late Jurassic–Early Cretaceous. In contrast, pure microencruster-cement reefs (boundstone type B) are much less frequent and occur mostly on the margins of intra-Tethyan isolated platforms. In terms of the reef framework and sedimentary setting, boundstone type B shows a striking similarity to Kimmeridgian and Berriasian microencruster-cement reefs of the Plassen Carbonate Platform (Northern Calcareous Alps, Austria; Schlagintweit and Gawlick, 2008) and Upper Kimmeridgian reefs in Bulgaria that originated in an upper fore-reef slope environment.

3. Matrix-supported and clast-supported, reef-derived breccias are common facies in the Kotouč Quarry. Clasts in the second type of breccia are bound by radiaxial-fibrous calcite cement, interpreted as being dominantly synsedimentary (pre-burial). The thick, banded cement crusts show similarity to radiaxial-fibrous cement ("evinosponges") of the Middle–Upper Triassic boundstones and breccias from the Alps. This study highlights the importance of synsedimentary cementation in the formation of a rigid boundstone framework (type B) and the stabilization of fore-reef slope deposits of the Štramberk Limestone.

4. The preliminary studies of the authors provide some new insights into the zonation model of the Štramberk reef complex, proposed by Eliáš and Eliášová (1984). Coral-microbial boundstone (type A) is attributed to a low-energy setting of the inner platform, but not to the reef front. The sedimentary setting of the microencruster-cement boundstone (type B) corresponds to the high-energy setting of an upper fore-reef slope environment. Reef-derived, matrix-supported breccia is attributed to a low-energy, deeper slope environment, while cement-rich breccia to a high-energy, upper slope setting. The presence of breccias supports the previous interpretation of steepened slopes of the Štramberk carbonate platform.

5. The Štramberk Limestone shares many similarities with some other reefs of intra-Tethyan carbonate platforms: (1) a strongly zoned character of the reef complex, (2) a topographic relief at the reef edge, (3) the presence of the microencruster-cement framework (boundstone type B), (4) a considerable contribution of bio-lithoclastic debris. In contrast to some coeval intra-Tethyan reefs (Slovenia, Italy), corals and not calcified sponges (stromatoporoids, chaetetids) are the main metazoan reef builders (boundstone type A). There are clear differences between the Štramberk Limestone and the coeval carbonate platform deposits developed on the northern Tethyan shelf (Brno and Ernstbrunn-Pavlov carbonate platforms, Czech Republic, Austria).

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