



The role of the microencruster-microbial reef-building consortium in organic reefs evolution (Late Jurassic, northern Tethys shelf, southern Poland)

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Abstract

The carbonate sediments of the Polish part of Tethys shelf contain *Crescentiella*-microbial-cement facies. The facies is associated with Middle Oxfordian-Lower Kimmeridgian microbial-grain dominated reefs, microbial-sponge dual hybrid reefs, and less frequently sponge/coral-microbial-abiotic triple hybrid reefs. The *Crescentiella (incertae sedis)* and microbialites form numerous cluster bioconstructions with stromatolite-like cavities in which rapid lithification was supported by early marine cementation. However, the factors controlling the development of such bioconstructions and the role of *Crescentiella* in the development of reef frameworks remain enigmatic. The sediments from five localities were investigated using thin-sections analyses supported by cathodoluminescence observations, stable oxygen and carbon isotope analyses and dispersive X-ray spectrometry. The development of *Crescentiella*-microbial-cement facies took place in three intervals spanning the Transversarium, Upper Bifurcatus, and Planula zones and coinciding with the period of maximum development of the Late Jurassic reefs in Poland. The reefs contain microencruster *Crescentiella* which was an important rigid framework constructor among the microbialites while the skeletal metazoans were rare. The inferred palaeosetting of the facies ranges from the seaward steep-fronted outer margin to the upper slope broad reef complex/microplatform where the development of skeletal metazoans was limited and mainly formed stratiform microbialites binding coated grain-biogenic dominated sediments. The occurrence of *Crescentiella*-microbial-cement boundstone facies is useful for palaeogeographic, palaeobathymetric, and palaeotectonic investigations.

Keywords Microencrusters · Microbialites · Hybrid carbonates · Jurassic reef · Northern Tethys

Introduction

The Upper Jurassic sedimentary succession in Poland (central Europe) was developed on the northern Tethys shelf in the palaeogeographic German-Polish subprovince (Submediterranean Province; e.g., Ziegler 1990). In this subprovince, the most frequently described Upper Jurassic bioconstructions include coral-, siliceous sponge-, and microbial-dominated reefs and a combination of these (e.g., Leinfelder et al.

1996, 2002; Matyszkiewicz 1997; Schmid et al. 2001; Helm and Schülke 2006; Matyszkiewicz et al. 2012; Krajewski et al. 2016).

One of the key research issues concerning the Late Jurassic Tethyan realm is the influence of microencrusters such as *Crescentiella*, *Bacinella*, serpulids, *Thaumatoporella*, *Radiomura*, *Lithocodium*, *Iberopora*, *Labes* and *Terebella* in bioconstruction frameworks formation (e.g., Crescenti 1969; Leinfelder et al. 1996; Dupraz and Strasser 1999; Fürsich et al. 2003; Uta and Bucur 2003; Shiraiishi and Kano 2004; Reolid et al. 2005; Schlagintweit and Gawlick 2008; Senowbari-Daryan et al. 2008; Rusciadelli et al. 2011; Pleg et al. 2013, 2017; Kaya and Altiner 2015; Hoffmann et al. 2017, 2021; Krajewski and Schlagintweit 2018; Mircescu et al. 2019; Granier 2021; Kołodziej and Ivanova 2021; Słowiński et al. 2022 and references therein).

The *Crescentiella morronensis* (former *Tubiphytes morronensis*; Crescenti 1969; Senowbari-Daryan et al. 2008;

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Fig. 2) ranges from the Oxfordian to the Aptian with an acme in the Kimmeridgian-Tithonian (e.g., Senowbari-Daryan et al. 2008; Pleş et al. 2013). The significant contribution of *Crescentiella* in the reef facies was also noted from the northern Tethys shelf in southern Germany and southern Poland (e.g., Pomoni-Papaioannou et al. 1989; Schmid 1995; Leinfelder et al. 1996; Matyszkiewicz 1997; Senowbari-Daryan et al. 2008; Krajewski et al. 2016, 2018). However, these works did not include detailed research on the spreading, palaeosetting and the role of the microencruster *Crescentiella* in developing the reef framework. In southern Germany, Pomoni-Papaioannou et al. (1989) noted that *Crescentiella* formed an organic framework that developed within a shallow subtidal environment. Also, Matyszkiewicz and Felisiak (1992) and Matyszkiewicz (1997, 37 p) emphasized the significant role of *Crescentiella* in the development of a rigid framework in large carbonate build-ups on the Polish Jura.

This study aims to present factors controlling the development of bioconstructions formed by the microencruster-microbial-cement reef-building consortium dominated by the *Crescentiella morronensis* microencruster from the Polish Jura (PJ abbreviation; Figs. 1, 2). The timing, regional distribution and the palaeosetting of the *Crescentiella*-microbial-cement boundstone facies (Cmc abbreviation) within the PJ, and its position among the Phanerozoic organic reef types are also discussed.

Geological background

The investigated area includes the SE parts of Wieluń and Kraków-Częstochowa Uplands located in central and southern Poland (Fig. 1). During the Late Jurassic, the investigated area formed the eastern part of an epicontinental ramp-type carbonate platform (sensu Burchette and Wright 1992) on northern Tethys shelf (e.g., Gutowski et al. 2005; Krajewski et al. 2017; Olchowy et al. 2019; Olchowy and Krajewski 2020). In this area, the microbial-sponge-reef limestone facies were composed of different types of microbialites, calcified siliceous sponges and carbonate sand-dominated sediments stabilized by microbialites (e.g., Trammer 1989; Matyszkiewicz et al. 2006, 2012; Krajewski et al. 2018).

One of the most important factors affecting sedimentation on PJ was the synsedimentary tectonics and reactivation of the transcontinental Kraków-Lubliniec Fault Zone. The fault separated Upper Silesian and the Małopolska terranes (Fig. 1) periodically modified the sea-bottom morphology (e.g., Matyszkiewicz et al. 2012, 2016; Brachaniec et al. 2016; Krajewski et al. 2016, 2017; Kowal-Kasprzyk et al. 2020). As a consequence, numerous intra-platform ridges (up to tens of kilometres long) formed along the boundary of these terranes. In particular, intensive development of the reef complexes took place on tectonic ridges that constituted

shelf palaeohighs (e.g., Matyszkiewicz et al. 2006, 2012; Krajewski et al. 2018).

Materials, methods, terminology

In this study, new data along with previously published data from outcrops from the PJ (Fig. 1) and field observations are analyzed (Table 1). The facies and microfacies observations were carried out on 260 thin sections and polished slabs from the studied sample exposures. The microfacies observations were carried out using an optical microscope and supported by cold-stage cathodoluminescence microscope observations with an accelerating voltage of 13–17 kV and electron-beam intensity of 400–500 mA. Such a combination of analytical methods allowed the observations of microstructure of microencrusters and enabled the identification of the various generations of the carbonate cements. Additionally, the sedimentological studies were supplemented with geochemical analyses of stable carbon and oxygen isotopes. The samples were analyzed at GeoZentrum Nordbayern in Nürnberg, Germany. The Wavelength Dispersive X-ray spectrometry (WDS) was used for quantitative analysis. The samples were investigated in terms of the content of major elements (wt.%) from the Rębielska Mt., Wielkanoc and Zabierzów quarries (Table 2). The WDS was applied using the JXA-8230 electron microprobe.

In the case of Jurassic microbialites, classifications of Leinfelder et al. (1996) were used. The organic reef types are based on the classification of Riding (2002). In this paper, the authors apply the term stromatactis-like cavities (sensu Matyszkiewicz 1997). The systematic position and interpretation of *Crescentiella morronensis* (Crescenti 1969) is after Senowbari-Daryan et al. (2008; Fig. 2). The *Crescentiella* is interpreted as an encrustation or symbiosis between nubecularid foraminifera or as tube-like structures (see Schlagintweit and Gawlick 2009) and cyanobacteria (see Fig. 2 for the internal structure of *Crescentiella*).

Results

Examples of the exposures with *Crescentiella*-microbial-cement boundstone facies

Crescentiella, microbialites, and early marine cements dominate locally within the sedimentary succession of the PJ, and also form the main reef constituents. In such sedimentary intervals, the skeletal metazoans are either rare or completely lacking (e.g., Matyszkiewicz and Felisiak 1992; Matyszkiewicz 1997; Krajewski et al. 2018). Thus, in some reef limestones, the term *Crescentiella*-microbial-cement boundstone facies (Cmc facies) or more general

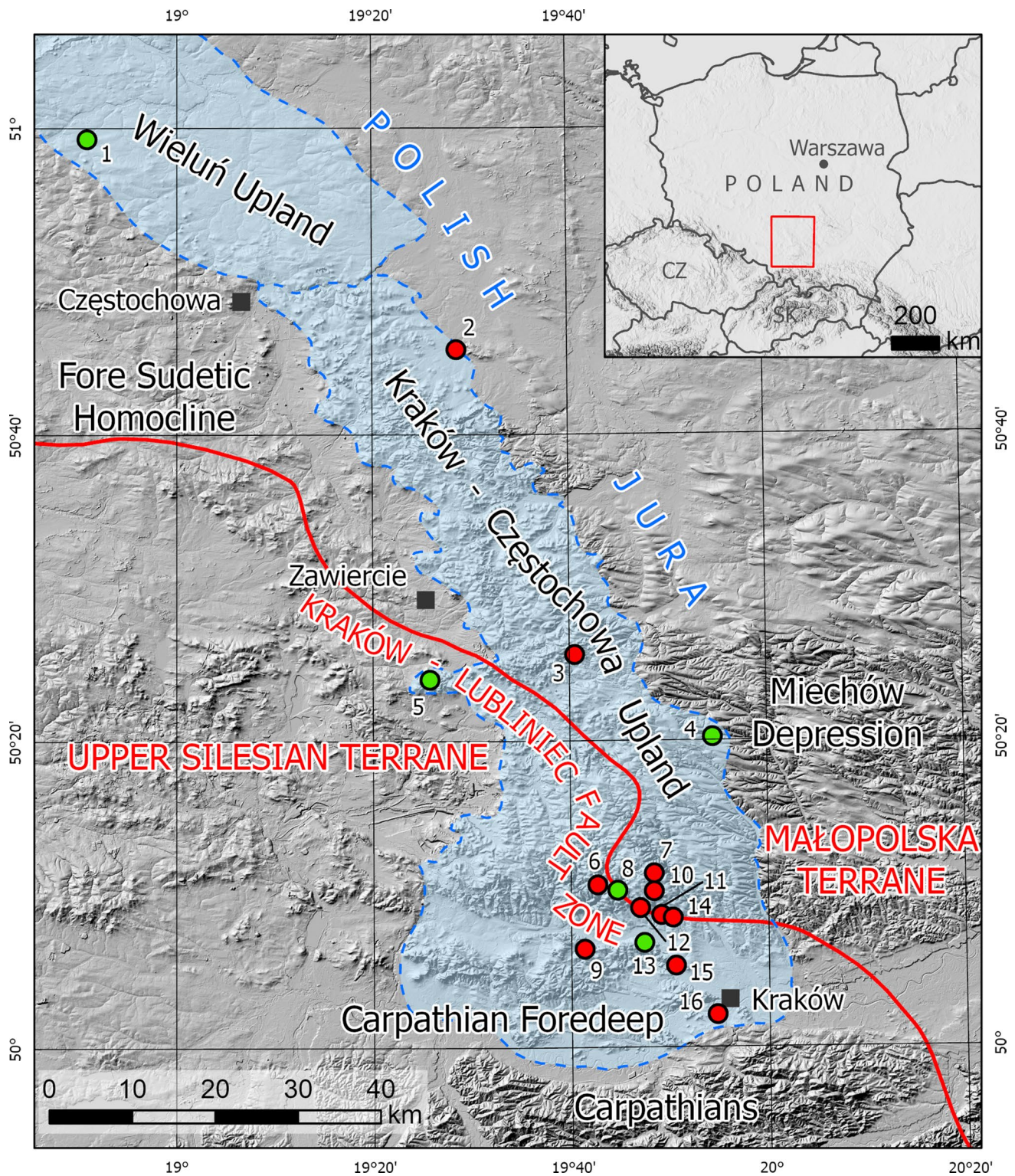


Fig. 1 Geographical and geological location of the study area and exposures with *Crescentiella*-microbial sediments. Green dots show presented examples of exposures; the red dots show other examined examples of exposures; for details see Table 1

microencruster-microbial boundstone facies is preferred rather than the microbial-sponge or microbial facies, that were commonly used for reef limestones descriptions.

Therefore, the Cmc facies is separated from the microbial-sponge or microbial facies types as a distinct facies type and is the subject of this paper.

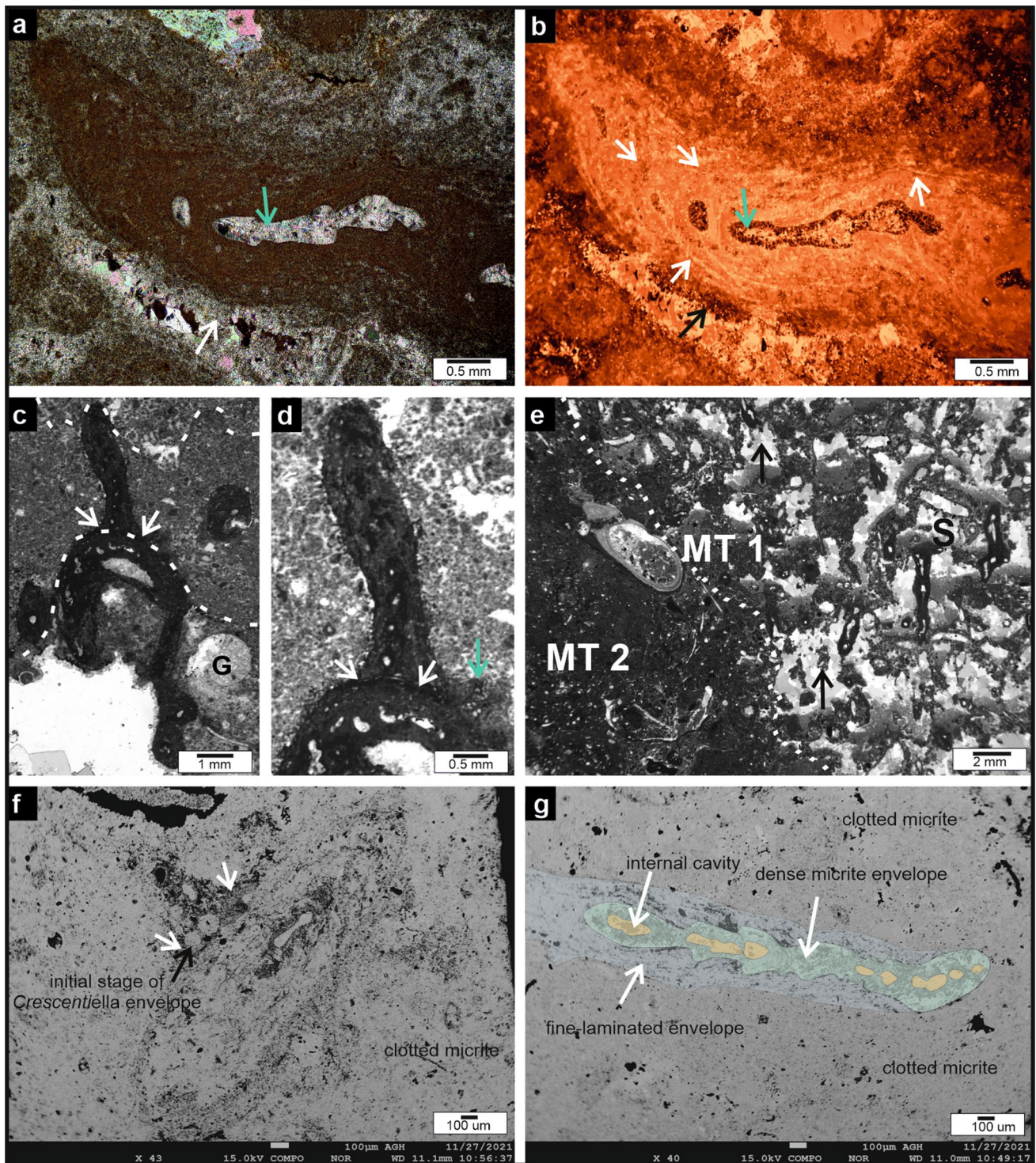


Fig. 2 The internal structure of Upper Jurassic *Crescentiella morronensis* from central and southern Poland. **a, b** Microscopic and CL photographs of *Crescentiella* with growth stages and microbial lamination (white arrows). The central part of *Crescentiella* are foraminifera chambers with radial-fibrous and blocky cements (green arrows) filling the internal cavities. Black arrow shows radial-fibrous cement developed on the external part of *Crescentiella*. **c, d** Succession of *Crescentiella* forming microframework in *Crescentiella*-microbial-

cement boundstone. The white arrows show the distinct boundary between *Crescentiella* specimens. The green arrow shows the initial stage of the *Crescentiella* accretion. **e** Fragment of dm-scale *Crescentiella*-microbial boundstone (MT1) with encrustation of serpulids (S) and cavities with geopetal infillings. The black arrows indicate the internal sediments within the cavities showing the orientation of the sample. **f, g** Scanning electron microscope photograph showing details of the *Crescentiella* internal structure

Table 1 The most important published localities with *Crescentiella*-microbial-rich facies on SE part of the Wieluń and Kraków-Częstochowa uplands

Literature	Locality	Age	Facies/microfacies
(1) Krajewski and Olchowy this paper	N50°59'19", E18°50'43" Klobuck area, Rebińska Mt. Quarry	Middle Oxfordian, Transversarium Zone	Bedded facies, <i>Crescentiella</i> -microbial-cement boundstone with SLC
(2) Matyja and Wierzbowski (2006)	N50°45'52", E19°28'40", Częstochowa area, Juliana Quarry	Lower Kimmeridgian, Planula Zone	Bedded facies, coral and sponge boundstone and bioclastic-packstone with <i>Crescentiella</i>
(3) Matyszkiewicz et al. (2006)	N50°25'41", E19°40'29" Smoleń area, Zegadowe Rocks	Lower Kimmeridgian, Bifurcatus-Planula Zone	Massive facies, microbial-sponge boundstone, bioclastic packstone-grainstone with SLC and <i>Crescentiella</i>
(4) Olchowy (2011); Krajewski and Olchowy this paper	N50°20'15", E19°54'29" Wolbrom area, Wielkanoc Quarry	Lower Kimmeridgian Planula Zone	Massive facies, microbial-sponge boundstone with numerous <i>Crescentiella</i> , corals, numerous SLC
(5) Irmiński (1995); Krajewski and Olchowy this paper	N50°23'56", E19°26'10" Niegowonice, Kromolowiec Hill	Upper Oxfordian Bifurcatus Zone	Massive facies, microbial- <i>Crescentiella</i> -ooid boundstone-grainstone-rudstone
(6) Kochman and Matyszkiewicz (2013)	N50°10'27", E19°41'45" Krzeszowice area, Żary Quarry	Middle-Upper Oxfordian Transversarium Zone	Bedded and massive facies, bioclastic packstone-wackestone and microbial-sponge boundstone with <i>Crescentiella</i>
(7) Matyszkiewicz et al. (2012)	N50°11'22", E19°48'22" Ojców Plateau area, Czajowice Quarry	Upper Oxfordian Bifurcatus Zone	Massive and thick bedded limestone, microbial-sponge boundstone with <i>Crescentiella</i> and SLC
(8) Krajewski et al. (2018); Krajewski and Olchowy this paper	N50°10'20", E19°44'30" Kraków area, Sokolica Reef Complex	Upper Oxfordian Bifurcatus Zone	Massive facies, microbial- <i>Crescentiella</i> -ooid boundstone-packstone-grainstone with SLC
(9) Matyszkiewicz (1997); Matyszkiewicz et al. (2016)	N50°06'28", E19°41'19" Krzeszowice area, Młynka Quarry	Middle Oxfordian Transversarium Zone	Massive and bedded facies, microbial- <i>Crescentiella</i> boundstone with SLC
(10) Matyszkiewicz et al. (2016)	N50°09'48", E19°49'09" Kraków area, Klucz-woda Valley	Upper Oxfordian, Bifurcatus Zone	Massive and bedded limestone facies, microbial- <i>Crescentiella</i> and microbial-sponge
(11) Matyszkiewicz (1997)	N50°08'40", E19°49'00" Kraków area, Klucz-woda Valley	Lower Kimmeridgian, Planula Zone	Massive and bedded limestone facies, microbial- <i>Crescentiella</i> and microbial-sponge
(12) Matyszkiewicz and Krajewski (1996)	N50°09'09", E19°47'05" Kraków area, Bolechowice Gate	Upper Oxfordian Bifurcatus Zone	Massive facies, microbial-sponge boundstone and bioclastic packstone with <i>Crescentiella</i>
(13) Matyszkiewicz (1997); Matyszkiewicz et al. (2012); Krajewski and Olchowy this paper	N50°10'20", E19°47'12" Kraków area, Zabierzów Quarry	Lower Kimmeridgian Planula Zone	Massive facies, <i>Crescentiella</i> -microbial boundstone with SLC
(14) Woźniak et al. (2018)	N50°08'29", E19°09'44" Kraków area, Tomaszowice Quarry	Lower Kimmeridgian Planula Zone	Bedded facies, bioclastic packstone-wackestone, microbial- <i>Crescentiella</i> boundstone
(15) Matyszkiewicz and Felisiak (1992)	N50°05'23", E19°50'32" Kraków area, Mydlniki Quarry	Lower Kimmeridgian Planula Zone	Massive facies, <i>Crescentiella</i> -microbial boundstone, bioclastic- <i>Crescentiella</i> wackestone
(16) Krajewski and Olchowy (2021)	N50°02'23", E19°54'34" Kraków, Zakrzówek Horst	Lower Kimmeridgian Planula Zone	Thick-bedded facies, detrital-bioclastic packstone-grainstone with numerous <i>Crescentiella</i>

SLC" means stromatolite-like cavities

Table 2 Geochemical composition with major elements of Cmc boundstone facies from Rębielska Mt., Zabierzów and Wielkanoc quarries

Major oxides (wt%)												
SiO ₂	ZnO	BaO	SO ₃	K ₂ O	P ₂ O ₅	SrO	CaO	FeO	MnO	Na ₂ O	MgO	Al ₂ O ₃
Rębielska Mt. Quarry												
bdl	0	bdl	bdl	bdl	bdl	bdl	55.51	bdl	bdl	bdl	0.199	bdl
bdl	bdl	bdl	0.076	bdl	0.045	bdl	54.331	bdl	bdl	bdl	0.187	bdl
bdl	0	0.078	bdl	bdl	bdl	bdl	54.82	bdl	bdl	bdl	0.226	bdl
bdl	0	bdl	0.037	bdl	bdl	bdl	55.325	bdl	bdl	bdl	0.245	bdl
bdl	0	bdl	0.06	bdl	0.043	bdl	53.37	bdl	bdl	bdl	0.177	bdl
bdl	bdl	bdl	0.053	bdl	bdl	bdl	55.686	bdl	bdl	bdl	0.188	bdl
bdl	bdl	bdl	0.032	bdl	0.049	bdl	55.763	bdl	0.053	bdl	0.102	bdl
bdl	0.111	bdl	0.04	bdl	0.061	0.05	55.225	bdl	bdl	bdl	0.221	bdl
bdl	bdl	bdl	0.081	bdl	0.046	bdl	55.543	bdl	bdl	bdl	0.248	bdl
bdl	bdl	0.095	0.069	bdl	0.035	bdl	54.971	bdl	bdl	bdl	0.234	bdl
bdl	bdl	bdl	0.085	bdl	0.052	bdl	54.238	bdl	0.132	bdl	0.238	bdl
bdl	bdl	0.075	bdl	bdl	bdl	bdl	54.75	bdl	0.081	0.044	0.146	0.059
bdl	bdl	bdl	bdl	bdl	bdl	bdl	55.41	bdl	0.096	bdl	0.083	bdl
bdl	0.118	bdl	bdl	0.011	bdl	bdl	56.432	bdl	bdl	0.041	0.16	0.049
Wielkanoc Quarry												
bdl	bdl	bdl	bdl	0.093	bdl	bdl	55.61	0.047	bdl	0.058	0.403	bdl
bdl	bdl	bdl	0.095	bdl	0.049	bdl	54.887	bdl	bdl	bdl	0.273	bdl
bdl	bdl	bdl	bdl	bdl	0.041	bdl	55.044	bdl	bdl	bdl	0.5	bdl
bdl	bdl	bdl	0.073	0.01	0.03	bdl	55.261	bdl	bdl	bdl	0.268	0.047
bdl	bdl	bdl	0.078	bdl	0.063	bdl	55.286	0.06	bdl	bdl	0.283	bdl
bdl	bdl	bdl	0.037	bdl	0.059	bdl	55.318	bdl	bdl	bdl	0.285	bdl
Zabierzów Quarry												
bdl	bdl	bdl	0.082	bdl	bdl	bdl	55.066	bdl	0.05	bdl	0.252	bdl
bdl	bdl	bdl	0.044	bdl	bdl	0.076	54.826	bdl	bdl	bdl	0.305	0.084
bdl	bdl	bdl	0.086	bdl	bdl	bdl	55.086	bdl	bdl	bdl	0.242	0.045
bdl	bdl	bdl	0.072	bdl	bdl	bdl	55.019	bdl	bdl	bdl	0.223	bdl
bdl	bdl	bdl	0.071	bdl	0.048	bdl	54.606	bdl	bdl	0.034	0.317	bdl
bdl	bdl	bdl	0.043	bdl	0.054	bdl	55.825	bdl	bdl	bdl	0.084	bdl

bdl means below detection level

Below, we present five examples of the Cmc facies from the PJ, along with its geological setting and position within the sedimentary succession. For other examples of *Crescentiella*-microbial rich facies, see Table 1. A detailed description of the facies is presented in the “Description of the *Crescentiella*-microbial-cement boundstone facies” chapter.

Example I—Rębielska Mt. Quarry

Location: (N50°59'19", E18°50'43").

Cmc facies age: Middle Oxfordian, Transversarium Zone.

This quarry is situated in the SE part of the Wieluń Upland within the western part of Rębielska Mt. Horst (Figs. 1,

4a, b). The Upper Jurassic succession represents medium and thick-bedded limestone facies so-called Zawodziankie Beds (Plicatilis-Transversarium Zone; Kutek et al. 1977; Głowniak 2006; Fig. 3).

The sedimentary succession at the quarry with the Cmc boundstone facies begins with sponge-pelitic facies that grades into coral-fine-grained facies (Fig. 5). Above the coral-fine-grained facies, a 2 m thick bed of Cmc boundstone facies with numerous stromatactis-like cavities occurs (Figs. 4a, b, 5a, b). The boundary between these facies is sharp (Fig. 5a). The dominant components of the Cmc facies include *Crescentiella*, microbialites, non-skeletal grains, and numerous bryozoans, serpulids, crabs (Dromioidea), echinoids, and brachiopods. *Crescentiella* is very abundant both as individual specimens and in colonial forms (Fig. 5b, d).

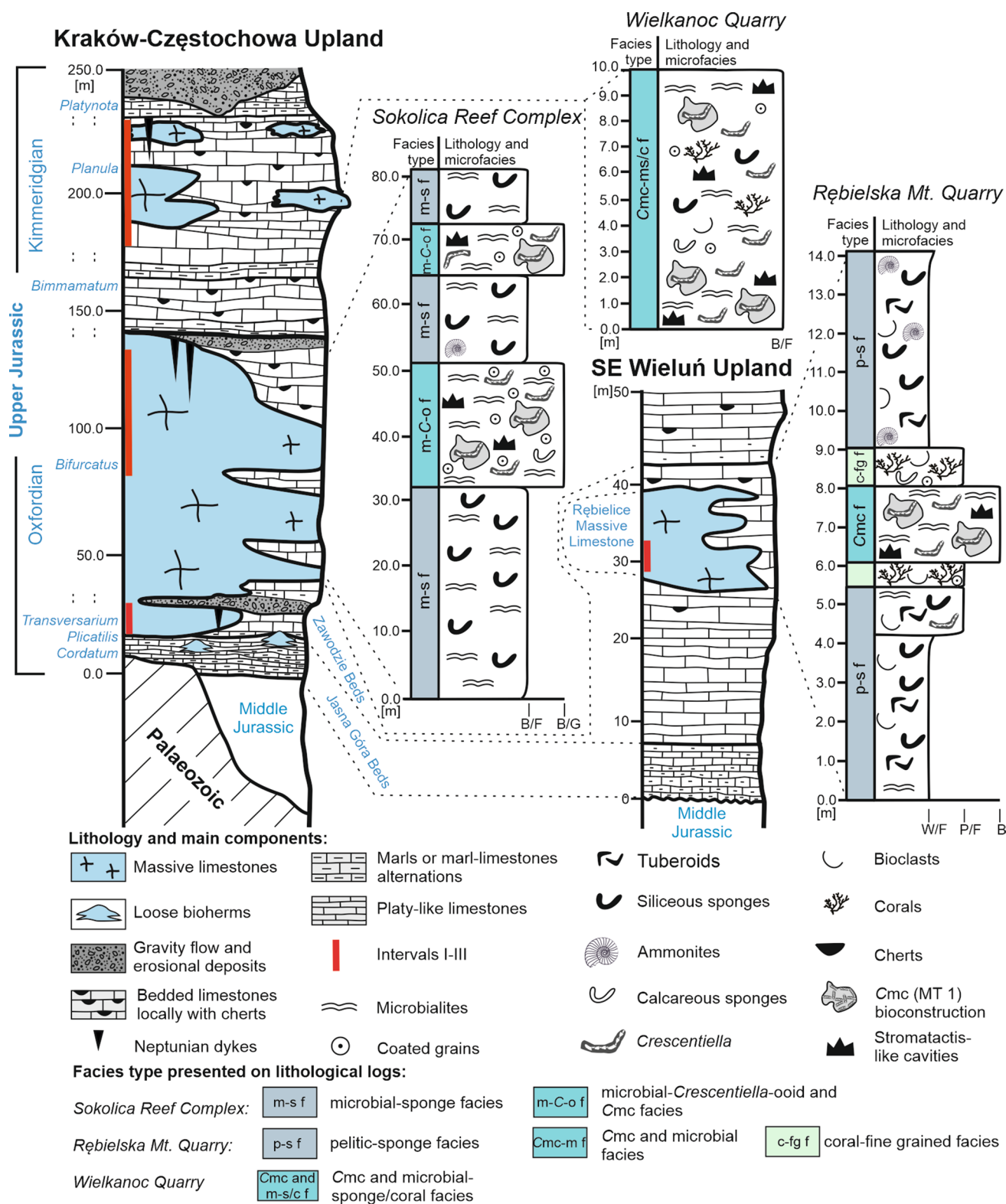


Fig. 3 Lithostratigraphic profiles from the southern Kraków-Częstochowa Upland (after Matyszkiewicz et al. 2016; modified and supplemented) and SE part of Wieluń Upland with the position of presented outcrops and facies/microfacies logs representing Middle-, Upper Oxfordian and Lower Kimmeridgian examples with Cmc

boundstone facies. The stratigraphic position and lithology for other examples (Kromolowiec Mt. and Zabierzów quarries) are presented in Irmiński (1995) and Matyszkiewicz et al. (2012). Microfacies: W-wackestone, F-floatstone, B-boundstone, G-grainstone, P-packstone

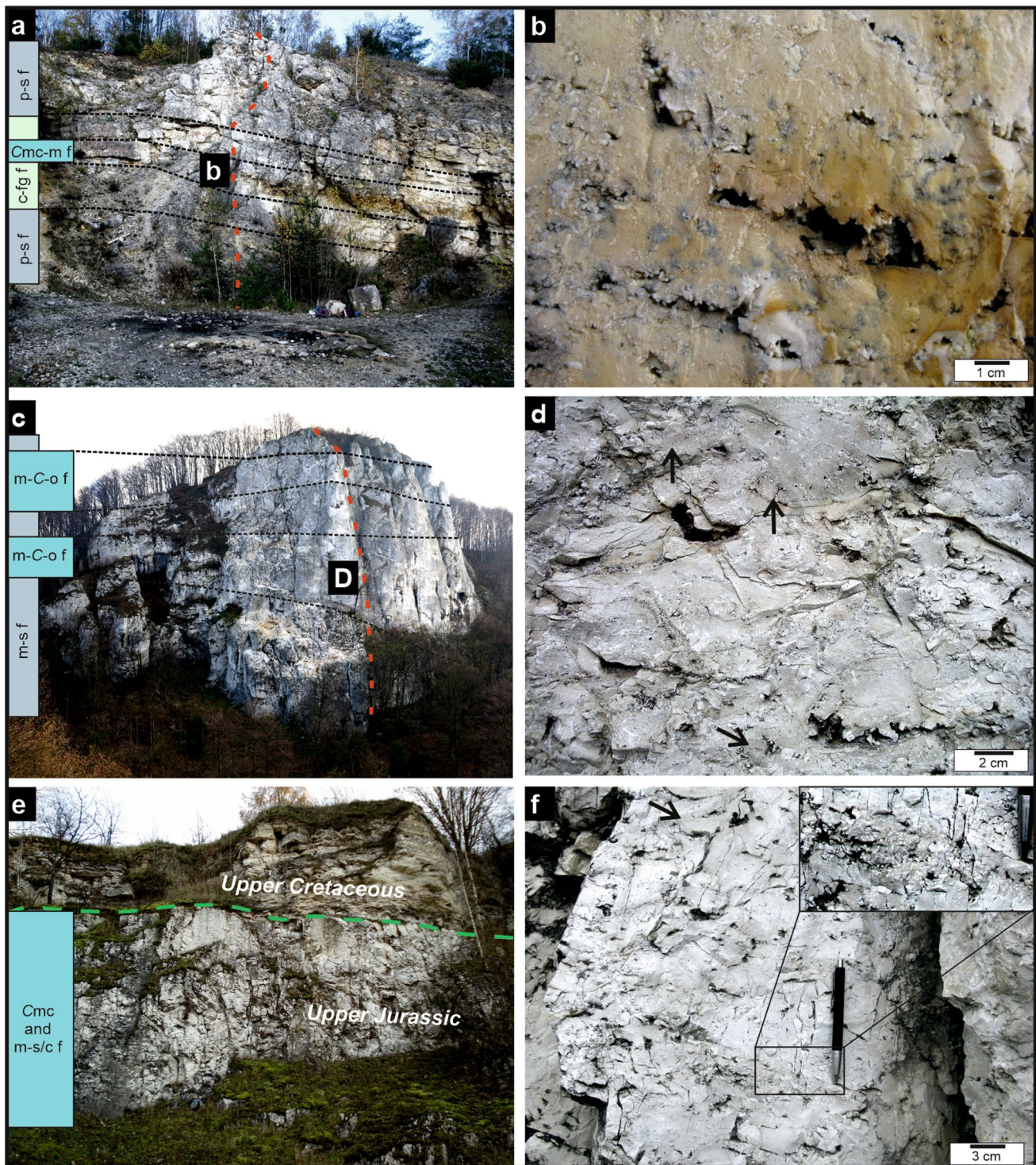


Fig. 4 Examples of the Upper Jurassic Cmc boundstone facies from central and southern Poland. **a** Middle Oxfordian ~14 m sedimentary succession from Rebielska Mt. Quarry. The red line indicates the facies/microfacies section presented in Fig. 3. **b** Middle Oxfordian Cmc facies with numerous stromatactis-like cavities from Rebielska Mt. Quarry. **c** Upper Oxfordian ~80 m sedimentary succession from Sokolica Reef Complex. The Red line indicates the facies/microfacies section presented in Fig. 3. **d** Upper Oxfordian Cmc facies with

stromatactis-like cavities from Sokolica Reef Complex. Black arrows show rare sponges. **e** Lower Kimmeridgian ~10 m succession of microbial-sponge/coral and Cmc facies (presented in Fig. 3) from Wielkanoc Quarry. **f** Lower Kimmeridgian example of Cmc facies from Wielkanoc Quarry with numerous stromatactis-like cavities. The enlargement part of the rock shows numerous *Crescentiella* (see also Fig. 5f)

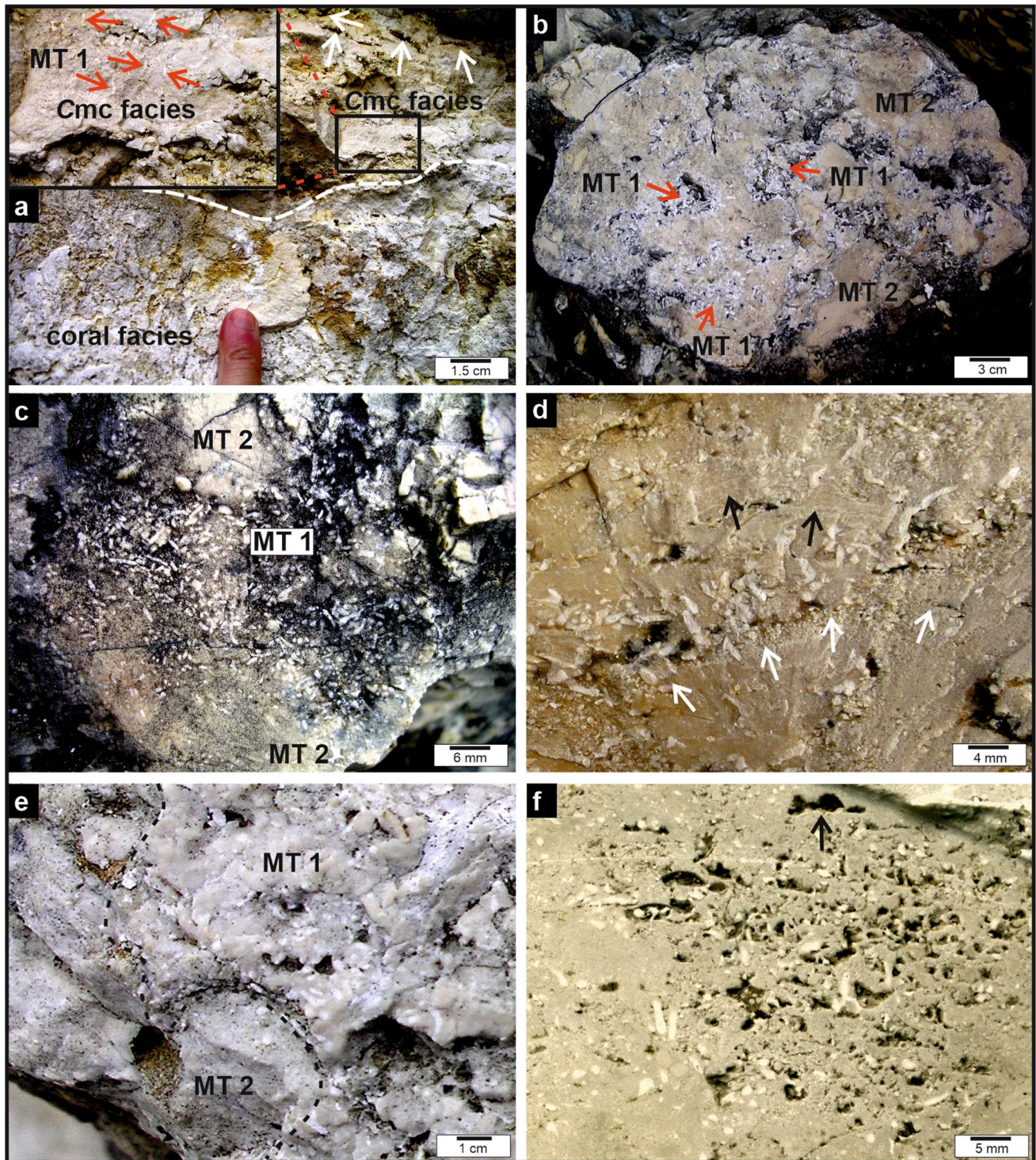


Fig. 5 Presented examples of the Upper Jurassic Cmc facies from central and southern Poland. **a** Sharp contact (dashed line) of coral-fine-grained facies and Cmc facies (MT1) with numerous stromatolite-like cavities (white arrows). The red arrows on the enlargement rock fragment indicate numerous *Crescentiella* in vertical-growth position. **b**, **c** Connected Cmc (MT1) clusters forming dm-scale cluster-like bioconstructions (red arrows) together with microbial-cemented grain-dominated sediments (MT2). **d** Cmc microframe-

work. The white arrows show prevail directions of the *Crescentiella* specimen's growth. Black arrows indicate agglutinating stromatolite between successive *Crescentiella* generations. **e** Sharp boundary (dashed line) between *Crescentiella*-microbial boundstone (MT1) and microbial cemented grain-dominated sediments (MT2). **f** Cmc porous microframe-structure with geopetal infilled cavities (black arrow) indicating the orientation of the sample

In the Cmc facies, the skeletal-metazoans such as sponges or corals are not observed. The Cmc facies grade upwards into the coral-fine-grained facies and the mud-dominated sponge-pelitic facies (Figs. 3, 4a).

Example II – Będkowska Valley; Sokolica Reef Complex

Location: N50°10'20", E19°44'30".

Cmc facies age: Upper Oxfordian, Upper Bifurcatus Zone.

The Będkowska Valley is located in the southern part of the Kraków-Częstochowa Upland (Fig. 1). In this region in Poland the largest Oxfordian reef complex (Sokolica Reef Complex) is available for direct observation (Fig. 3). This reef complex is developed on the horst of an intra-platform palaeohigh that was tectonically active during the Late Jurassic (Matyszkiewicz et al. 2012). The Cmc facies from the reef complex represents the ammonite Bifurcatus Zone (Krajewski et al. 2018; Fig. 4c).

The Cmc facies together with the microbial-*Crescentiella*-oid facies are observed between the microbial-sponge facies and the microbial-cemented ooid-intraclast-bioclastic facies (Fig. 4c). The Cmc facies consists of *Crescentiella*, stromatactis-like cavities and various types of microbialites (mainly agglutinating or peloidal stromatolites and layered thrombolites) that bound coated grains and bioclasts (Fig. 4d). The *Crescentiella* and microbialites form clusters up to several tens of centimetres in diameter within the grain-dominated sediments (Fig. 6e). The skeletal metazoans in Cmc facies are rare and represented by calcareous sponges and calcified siliceous sponges.

Example III – Kromołowiec Hill

Location: N50°23'56", E19°26'10".

Cmc facies age: Upper Oxfordian, Upper Bifurcatus Zone.

The Kromołowiec Hill is situated in the central part of the Kraków-Częstochowa Upland (Fig. 1) and represents active in the Late Jurassic western part of the Smoleń-Niegowonice Range (Matyszkiewicz et al. 2006). The sedimentary succession represents medium-bedded pelitic-bioclastic limestones with sponges and Upper Oxfordian massive reef limestone facies (Upper Bifurcatus Zone; Matyja and Wierzbowski 1992). The Kromołowiec Hill represents a transitional zone extending between an elevated reef complex and a deeper basin situated further to the north (Fig. 11a). The upper part of a sedimentary succession of the reef complex contains microbial-sponge facies and occurs as the marginal part of the reef complex, while the Cmc and the microbial-*Crescentiella*-oid facies, form its internal part (Figs. 6a, 11g).

The Cmc facies consists of coated grains, peloids, coprolites and bioclasts, commonly bound by various types of microbialites mainly agglutinating or peloidal stromatolites (Figs. 6a, 11d–e). The *Crescentiella* and microbialites form clusters up to several tens of centimetres across embedded within the grain-dominated sediments (Fig. 11d). The skeletal metazoans in the Cmc facies are rare. These are calcified siliceous sponges and calcareous sclerosponges.

Example IV – Zabierzów Quarry

Location: N50°10'20", E19°47'12".

Cmc facies age: Lower Kimmeridgian, Planula Zone.

The Zabierzów Quarry is situated in the southern part of the Kraków-Częstochowa Upland (Fig. 1), on the escarpment of the Tęczynek Horst that was tectonically active during the Late Jurassic (Matyszkiewicz et al. 2012; Woźniak et al. 2018). The Lower Kimmeridgian bioconstructions in the nearby area represents an open-frame microbial-sponge reef and thick biostromal bedded facies of the ammonite Planula Zone (Fig. 3).

The Cmc facies is observed in the upper SW part of the Zabierzów Quarry, where *Crescentiella* is very abundant and together with microbialites dominate and form a rigid framework of carbonate reef with growth cavities and stromatactis-like cavities (Matyszkiewicz et al. 2012, p. 124). The microbialites are developed as agglutinating stromatolites, micropeloidal stromatolites, or pure and layered leiolites. They form massive, irregular clusters of tens of centimetres across that bind the abundant benthic fauna of the reef framework. The reef framework fauna includes *Crescentiella* and serpulids, brachiopods, bryozoans, bivalves, and relatively rare siliceous and calcareous sponges. The sediments from the Zabierzów Quarry grade toward the tectonic graben located north of the quarry into gravity flow deposits, tectonic breccia and thick-bedded pelitic-bioclastic and sponge-microbial limestones (Matyszkiewicz et al. 2012).

Example V – Wielkanoc Quarry

Location: (N50°20'15", E19°54'29").

Cmc facies age: Lower Kimmeridgian, Planula Zone.

The Wielkanoc Quarry is located in the eastern part of the Kraków-Częstochowa Upland (Fig. 1). The quarry is located in the marginal zone of the Wielkanoc tectonic horst that is situated on the marginal part of the fault zone active in the Mesozoic. The lithology of the ~ 10 m Upper Jurassic sequence is dominated by the reef and thick-bedded

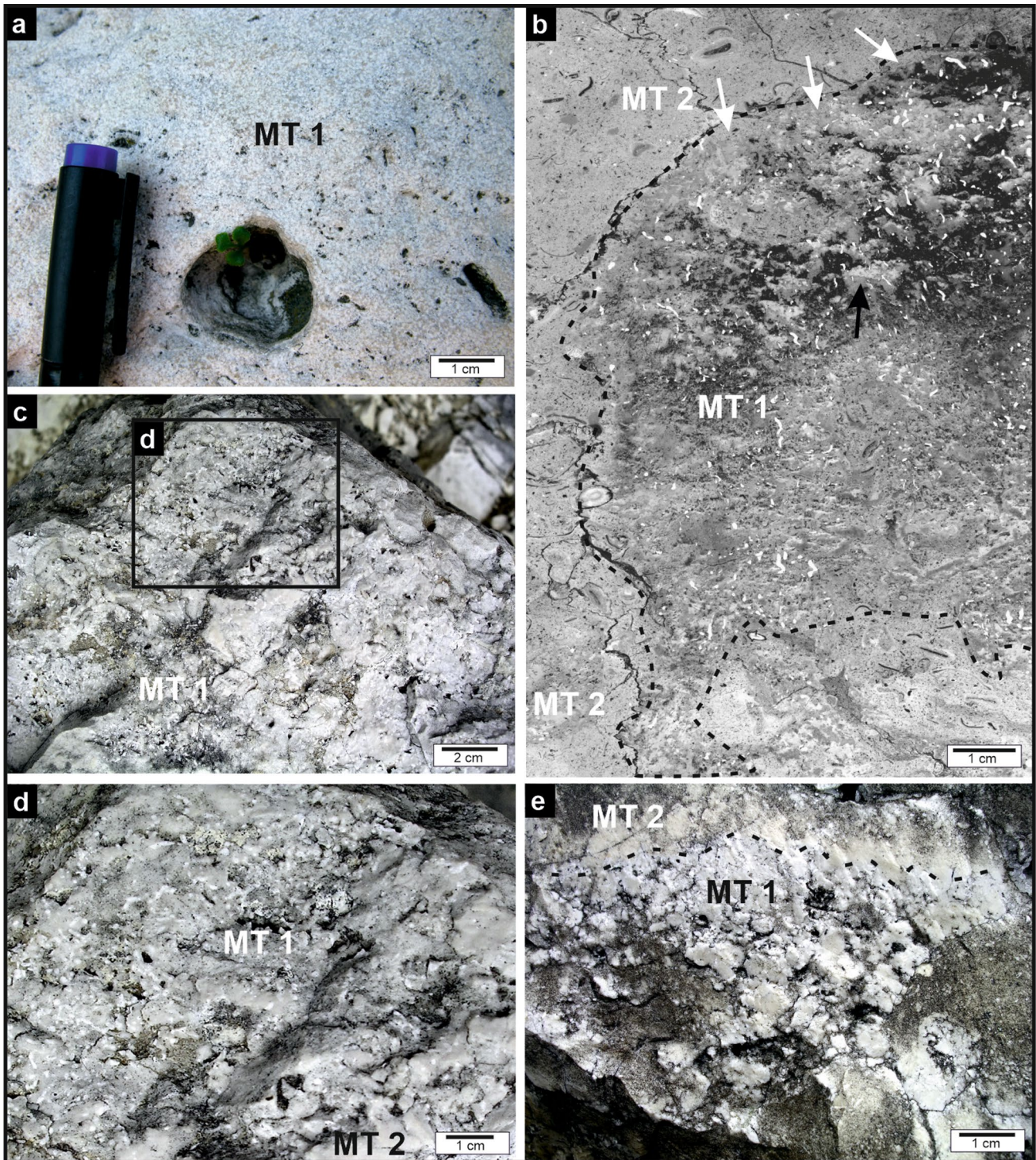


Fig. 6 Examples of the Upper Jurassic Cmc facies from central and southern Poland. **a** *Crescentiella*-microbial-oid facies from Kromolowiec Hill. Moldic porosity in the lower part of the photograph is probably after dissolved corals. For microfacies details see Fig. 10e. **b** Cmc bioconstruction (MT1) and surrounding sediments with bioclasts and coated grains (MT2). In the lower part, the initial finger-like stage of the cluster is visible. In the upper part, biocon-

struction is formed mainly by microbialites where *Crescentiella* disappears (white arrows). The black arrow indicates internal sediment showing the orientation of the sample. **c, d** Dm-scale cluster-like bioconstruction formed by Cmc facies of MT1 above MT2 facies. **e** Cmc facies from Sokolica Reef Complex with a sharp boundary (dashed line) between MT1 and MT2 highlighted by color change

biostromal microbial-sponge facies of the Lower Kimmeridgian age (ammonite Planula Zone; Olchowy 2011; Fig. 4e).

In the Wielkanoc quarry, the Cmc facies contains numerous stromatactis-like cavities (Fig. 4f). The dominant components include *Crescentiella* and microbialites (mainly laminated thrombolites and stromatolites; Fig. 5f). The rock contain also fragments of siliceous sponges, echinoderms, bivalves and serpulids. Locally, hermatypic corals (Cladophyllidae, *Microsolena*) and elongated and oval biomolds after cladophyllid corals are present (e.g., Fig. 4 in Olchowy 2011).

Description of the *Crescentiella*-microbial-cement boundstone facies

The most important macroscopic features of the Cmc boundstone facies that distinguish it from other Oxfordian-Kimmeridgian reefs/biostrome facies types from PJ, are: (i) very strong lithification, (ii) microencruster *Crescentiella* commonly forming cluster-like structures together with microbialites, (iii) the lack or minor occurrence of skeletal metazoans, and (iv) numerous stromatactis-like cavities. The thicknesses of individual Cmc facies vary from ~1 m up to several metres (Figs. 3, 4a, c, e). In vertical succession, the boundary between the Cmc facies and the coral-fine-grained limestone facies is either sharp and irregular (Fig. 5a; cf. Krajewski and Schlagintweit 2018, p. 8) or diffused and gradual in a distance of several to tens of centimetres (Fig. 4d). Observations made at exposures suggests that the lateral extent of the Cmc facies is wider than horizontal dimensions of exposures which attains hundreds of metres.

In the Cmc boundstone facies, two microfacies types are distinguished: (i) *Crescentiella*-microbial-cement bindstone/bafflestone (MT1), and (ii) bioclastic-peloid-coated grain-microbial grainstone/bindstone, more rarely packstone/wackestone (MT2; Figs. 5b, c, e, 6b, d, e, 7). The boundary between both microfacies types is sharp and irregular (Figs. 2e, 5b, c, e, 6b, e, 7). The *Crescentiella*-microbial-cement bindstone/bafflestone (MT1) is formed by numerous *Crescentiella*-microbial clusters of irregular shapes and diameters up to several ten of centimetres (Figs. 2e, 5b, c, 6b). In the MT1, growth and stromatactis-like cavities are commonly observed (Figs. 4b, d, e, 5f). The most important component of the MT1 is the ubiquitous presence of *Crescentiella*, microbialites, peloids and bioclasts (Figs. 7, 8). The specimens of *Crescentiella* are 6 mm long, although they generally do not exceed 4 mm, with diameters up to 1.5 mm (Figs. 2, 5d, 7, 8). Often *Crescentiella* is bridged by microbial crusts (Figs. 6b, 7, 8e, f). The microbialites are generally made of peloidal microstructure and represent irregular layered thrombolite and micropeloidal stromatolites (Figs. 2e, 5d, 6b, 7, 8). The *Crescentiella* specimens are covered by several generations of carbonate cements

between individual *Crescentiella* specimens or growth cavities (Figs. 2a, b, 8e, f, 9). The infillings of growth cavities are represented by massive, radiaxial fibrous (up to 0.05 mm thick) and dog tooth cements with crystals up to 1.2 mm across (Fig. 9). The isopachous rims of the radiaxial fibrous marine cements represent the earliest generation of cements that developed on the walls of cavities and *Crescentiella*. Sometimes, the isopachous radiaxial fibrous cement contains dark and light-coloured zones indicating several episodes of cement precipitation (Fig. 9d). In case of lack of carbonate cements, spaces between *Crescentiella* specimens are filled with internal sediments composed of peloids, small intraclasts, coated grains, and bioclasts, among which juvenile brachiopods, bryozoans, gastropods, crabs, ostracods, polychaetes, thin-shelled bivalves, echinoid plates and spines dominate (Figs. 7, 8).

In the largest *Crescentiella*-microbial clusters of the MT1, three stages of development are noted: (i) initial, (ii) aggradational, and progradational with massive *Crescentiella* development, and (iii) final microbial-dominated (Fig. 7). The initial stage of development of clusters are characterized by the presence of single specimen of *Crescentiella*, enveloped by micropeloidal-micrite crusts (Fig. 7aI, bI), embedded within primary soft grain-dominated sediments (MT2). These single pioneering specimens formed the basis for the development of clusters, which in this stage, form finger-like forms up to 2.5 cm high and 1 cm wide (Figs. 6b, 7aI, bI). At the aggradational stage, numerous specimens of *Crescentiella* are often in life position (for *Crescentiella* strategy of growing see Schmid 1995; Senowbari-Daryan et al. 2008; Figs. 2, 5d, e, 6b, 7aII, bII, 8c–f). *Crescentiella* is elongated in different directions and can be observed in longitudinal, transverse, and oblique sections along their longer axes (Figs. 7, 8). Often, successive generations of *Crescentiella* are built one after another to form a microreticulate framework (Figs. 4e, 5d, 6b, 7aII, bII). In the final stage of the cluster development, the amount of *Crescentiella* decreases, and the sediment is formed by agglutinating or peloidal flat or domal stromatolites (Figs. 6b, 7aIII, bIII). The few *Crescentiella* specimens developed on the upper surface of the cluster formed by stromatolite, are often erosive cut (Fig. 8a). The individual neighboring clusters are often joined together to form the larger *Crescentiella*-microbial clusters up to several ten of centimetres in size (Figs. 5b, c, 6c).

The bioclastic-peloid-coated grain-microbial grainstone/bindstone, more rarely packstone/wackestone microfacies (MT2), in contrast to MT1, is monotonously developed (Figs. 7, 8a, b). The main components include numerous peloids, *Crescentiella*, coated grains, coprolites, and intraclasts of MT1, stabilized by thin microbial crusts and peloidal stromatolites and leiolites forming macroscopic

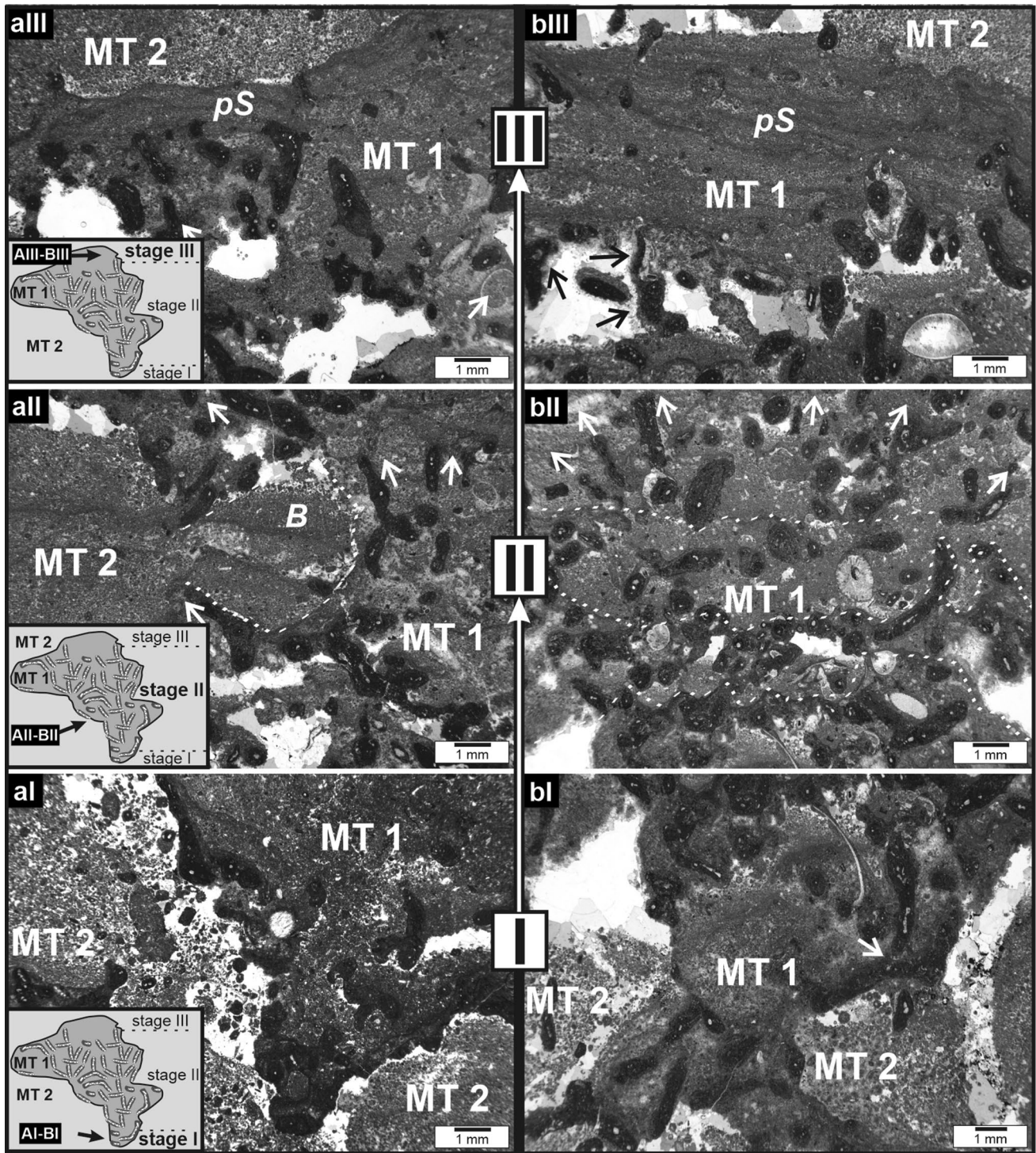


Fig. 7 Accretion (I-III stages) of Cmc clusters (MT1) of two (aI-aIII and bI-bIII) examples from the study area; see also Fig. 6b. aI, bI show initial stages I. aII, bII show the main stage of cluster accretion; the white arrows show the growth direction of the cluster; B – boring.

aIII, bIII show the final stage of cluster accretion. In the upper part, peloidal stromatolite is visible (pS); the black arrows show fibrous cements on cavity walls

laminites. Among the bioclasts, thin-shelled brachiopods and echinoderm plates dominate.

One of the characteristic features of the Cmc facies is the stromatactis-like cavities (Fig. 4b, d, f). These isolated cavities are up to 4 cm wide and 2 cm high. The side walls

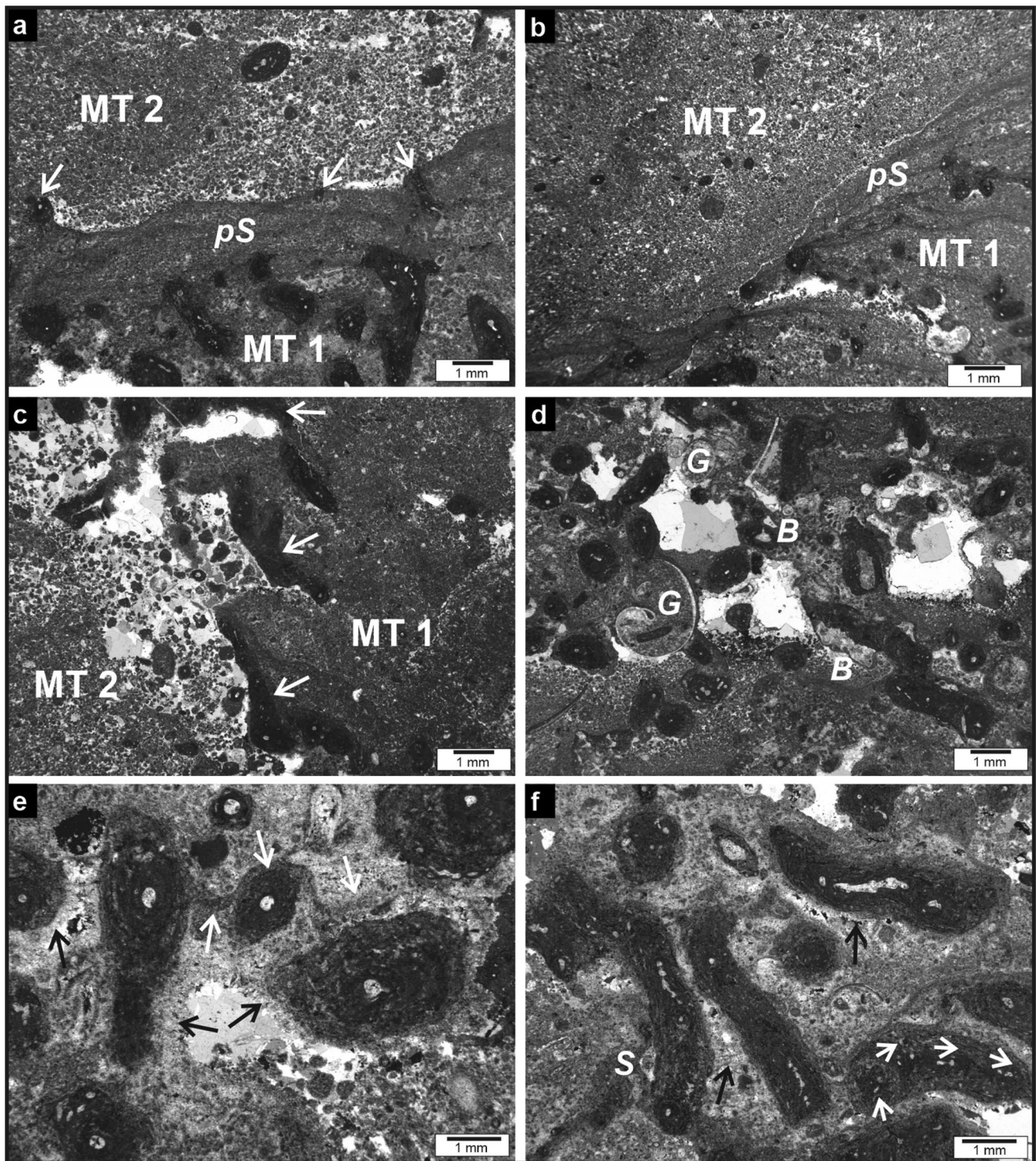


Fig. 8 Details of the Cmc facies from central and southern Poland. **a**, **b** Upper parts of MT1 with peloidal stromatolite (*pS*); white arrows show *Crescentiella* which is erosionally cut on the upper part of the cluster in contact with MT2. **c** The sharp boundary between MT1 and MT2. The arrows indicate the side, marginal part of the *Crescentiella*. **d** The internal part of the cluster with micropeloidal fabric, *Crescentiella*, and numerous bioclasts e.g., bryozoans (*B*) and gastropods (*G*)

and thin shells. **e** Spaces between *Crescentiella* specimens are occupied by early diagenetic cements (back arrows) and microbial laminae (white arrows). **f** Clotted micropeloidal fabric, microbial laminae, and early diagenetic cements (black arrows) between *Crescentiella* specimens. Serpulids encrustation (*S*) is developed on *Crescentiella*. The white arrows show a direction change in *Crescentiella* accretion

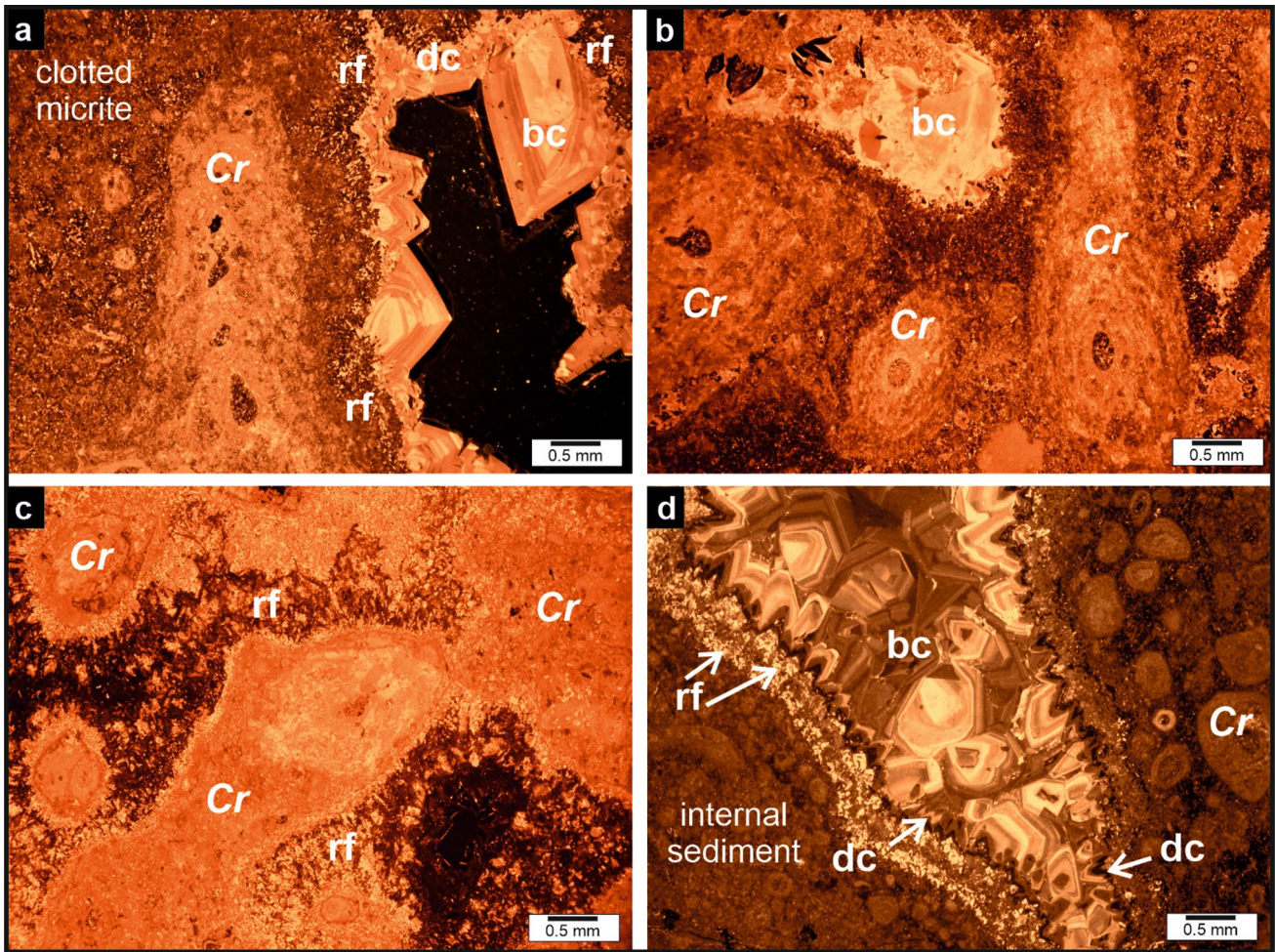


Fig. 9 a–d CL images of the *Crescentiella* (Cr) and void filled with different generations of cements in the microframework and chronological order of cementation are highlighted by cathodoluminescence; radiaxial-fibrous cement (rf) is covered with non-luminescent,

marine, phreatic dog-tooth cement (dc), which shows red luminescence only in the outer crystals zones (D); blocky cement (bc) in the central part of the void

of the cavities are covered by the isopachous cement, that passes towards the central parts of the cavities into radiaxial and blocky cements.

Geochemical results

The investigated sediments are characterized by the values of $\delta^{13}\text{C}$ varying from 0.15‰ to 3.17‰ and $\delta^{18}\text{O}$ varying from -3.81‰ to -2.26‰. In the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ plot, three sets of points are distinguished (Fig. 10), showing the differentiation between investigated Middle Oxfordian and Lower Kimmeridgian examples. In the first set, representing the Wielkanoc Quarry, the values of $\delta^{13}\text{C}$ range from 2.85‰ to 3.17‰ (average 3.02‰), and $\delta^{18}\text{O}$ values range from -2.85‰ to -2.26‰ (average -2.56‰). The second, characterizing the sediments from the Rębielska Mt. Quarry, covers the values of $\delta^{13}\text{C}$ in the range from 1.63

‰ to 2.28 ‰ (average 2.05‰), and $\delta^{18}\text{O}$ from -3.81‰ to -3.29 ‰ (average -3.62‰). The third set of results from the Zabierzów Quarry includes the values of $\delta^{13}\text{C}$ from 0.15

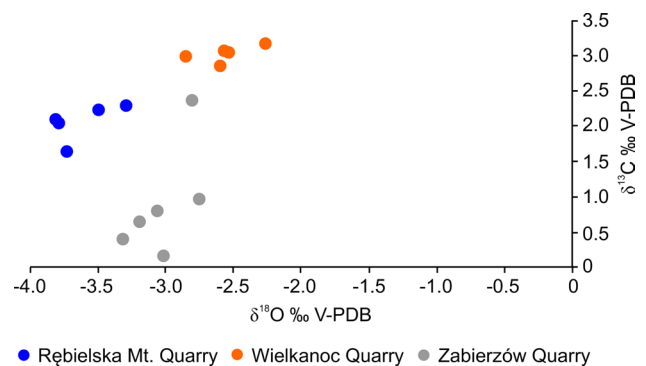
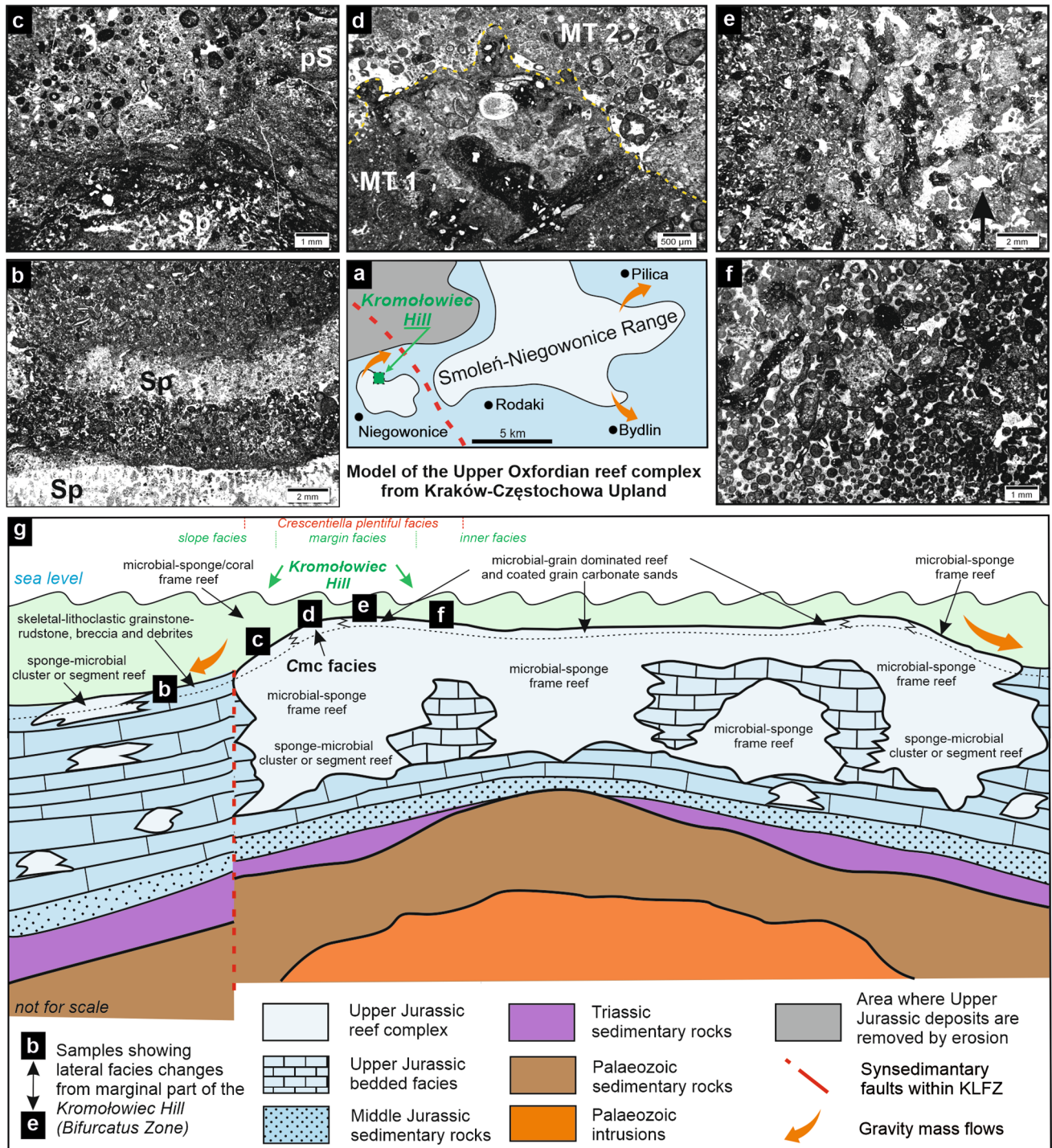


Fig. 10 Distribution of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of calcite matrix from Rębielska Mt., Wielkanoc and Zabierzów quarries



‰ to 2.36 ‰ (average 0.88‰) and of $\delta^{18}\text{O}$ from -2.74 ‰ to -3.31‰ (average -3.02‰). The correlation of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values do not show differences; all are significant and positive (Wielkanoc Quarry: $r=0.63$, Rębielska Mt. Quarry: $r=0.59$, Zabierzów Quarry: $r=0.61$).

The investigated Cmc facies do not show significant differences in the content of major elements between Wielkanoc, Rębielska Mt. and Zabierzów quarries (Table 2) and

are comparable with the data from similar facies types from other PJ outcrops (e.g., Kochman and Matyszkiewicz 2012; Matyszkiewicz et al. 2012; Krajewski and Olchowy 2021). There are slight differences in the content of MgO. The MgO content is highest in the Cmc facies from the Wielkanoc Quarry (average 0.335 wt.%) and the lowest in samples from the Rębielska Mt. Quarry (average 0.189 wt.%).

Fig. 11 Palaeosetting of Cmc boundstone facies from Polish Jura based on examples from Smoleń-Niegowonice Range (see Matyszkiewicz et al. 2006) and Kromołowiec Hill area; not for scale. **a** Sketch with facies distribution. The central part of the isolated Upper Jurassic reef complex was developed on tectonically active elevation. The Kromołowiec Hill was situated on the marginal part of the reef complex. Mostly pelitic (dark blue) and gravity flow sediments were deposited toward the north direction from the Kromołowiec Hill (arrows). **b–f** Lateral facies changes in the vicinity of Kromołowiec Hill representing Bifurcatus Zone. **b** Sponge floatstone/packstone; siliceous sponges (Sp) within bioclastic-coated grains redeposited from the reef complex slope. **c** Microbial-sponge facies; sponge (Sp) in the lower part of the photograph is covered with peloidal stromatolite and coated grain-bioclastic sediments. **d** Cmc facies with MT1 and MT2. **e** *Crescentiella*-oid-microbial grainstone. The black arrow indicates the orientation of the sample. **f** Coated grain facies with numerous ooids, oncoids, bioclasts, and *Crescentiella*. **g** Palaeosetting model of Cmc facies and facies changes in the marginal part of the reef complex. The reef complex was situated on elevation in the shallow basement formed by the coincidence of lower subsidence of sediments above the palaeozoic intrusion and synsedimentary tectonic on the marginal part of the Małopolska and Upper Silesian terranes

Interpretation and discussion

Interpretation of Cmc boundstone facies

Cmc boundstone facies from the PJ is formed by a large number of decimetre-scale clusters (MT1) forming low-relief cluster bioconstructions on the sea bottom. The Cmc facies developed in an environment with grain-dominated sediments (MT2) bound by microbial crusts. In the environment where the Cmc boundstone facies developed, skeletal metazoans did not constitute important reef-building organisms. *Crescentiella*-microbial clusters can be classified as microencruster-microbial-cement reef builder consortiums that caught and bound peloids, bioclasts, and other grains, which was an important process of cluster accretion (Suarez-Gonzalez et al. 2019).

Rapid lithification is supported by the early marine cementation leading to the formation of different types of carbonate cements between *Crescentiella* specimens. The fibrous cement developed on the microencrusters indicates the synsedimentary origin of the cement (Kendall and Tucker 1973; Koch and Schorr 1986; Flügel 2004; Richter et al. 2011; Krajewski and Schlagintweit 2018). Moreover, the succession of microbial laminae alternated with radial-fibrous cement (Fig. 8e, f), also supports a synsedimentary origin of the cement (e.g., Flügel 2004, p. 306; Popa et al. 2014; Krajewski and Schlagintweit 2018).

The development of *Crescentiella* clusters with microbialites played an important role in stabilizing the soft grain-dominated sediments. The *Crescentiella*-microbial clusters probably also took an important role as a habitat for microbial mats feeding fauna e.g., echinoderms and gastropods, settling the clusters and the surrounding seafloor.

The presence of rather fine-grained sediments and allochthonous internal sediments within the cluster indicates moderate water energy. However, the water energy had to be high enough to enable early cementation.

Timing of *Crescentiella*-microbial-cement facies in the upper jurassic sedimentary succession of the Polish Jura

In the Oxfordian-Lower Kimmeridgian sedimentary succession from the PJ (Fig. 3), three intervals are distinguished during which Cmc boundstone facies developed. These are Interval I (Middle Oxfordian, Transversarium Zone), Interval II (Upper Oxfordian, Upper Bifurcatus Zone), and Interval III (Lower Kimmeridgian, Planula Zone) (Fig. 3; Table 1). The above sedimentary intervals are separated by pelitic-bioclastic bedded limestone facies and marly limestone and marl facies (Fig. 3). In addition the intervals I–III are emphasized by the horizons in which gravity flow deposits (e.g., olistolites, debris-flow deposits) originated from the erosion of microbial-sponge, Cmc, and microbial-grain-dominated reef facies were deposited. Their genesis, like the development of the neptunian dykes, in the study area, is associated with periodic synsedimentary tectonic activity along the marginal parts of the Małopolska and Upper Silesian terranes (Fig. 1; e.g., Matyszkiewicz et al. 2012, 2016; Woźniak et al. 2018). The mentioned facies changes and intervals in the sedimentary succession can be correlated with the Late Jurassic sequences and variations in the sea level (e.g., JOx5, JOx6; Haq 2018).

Regional distribution and palaeosetting of the *Crescentiella*-microbial-cement boundstone facies

The wide regional distribution of *Crescentiella*-microbial-cement boundstone facies within the PJ (Fig. 1; Table 1) suggests that during some periods (Intervals I–III; Fig. 3) of the main reef complex development, these facies were relatively common. Data from the Mid Oxfordian-Lower Kimmeridgian PJ reefs allows for the distinction of two basic types of depositional systems. The first type represents a low-relief depositional system where sponge-microbial cluster or segment reefs or siliceous sponge-microbialite mud mounds or sponge biostromes developed (Leinfelder et al. 1996; Matyszkiewicz 1997; Schmid et al. 2001). No Cmc boundstone facies were found in these sediments. The second, depositional system type is related to the development of large reef complexes/microplatforms on sea bottom palaeohighs (Fig. 11; Matyszkiewicz et al. 2006, 2012; Krajewski et al. 2018). During the aggradational phase of the reef complex development, the microbial-sponge frame reefs prevailed. During the progradation stage, in the conditions of shallow

water (close to wave base) sedimentation on the marginal and inner flat part of the reef complexes, microbial and grain-dominated deposition with Cmc boundstone facies, dominated (Fig. 11). In such paleosettings on the PJ, the microbialites intensively developed, especially stratiform, agglutinating, peloidal stromatolites and layered thrombolites, along with the development of facies with grain-dominated coated grains, intraclasts, bioclasts including coprolites, calcareous green algae (Matyszkiewicz et al. 2006, 2012; Kochman and Matyszkiewicz 2012; Krajewski et al. 2018). The microbial-dominated reef facies from the PJ including the Cmc boundstone facies were studied in detail by Matyszkiewicz et al. (2012) who concentrated particularly on the microbialite structures related to the environmental setting. According to Matyszkiewicz et al. (2012), the diversification of microbialites is an effect of local sedimentary conditions. The changes in the seawater chemistry changes did not play a role in microbial diversification. Such statements are confirmed by the geochemical data from major and minor elements (Matyszkiewicz et al. 2012; Table 2).

In the Polish Jura (PJ), it can be observed that microbial-sponge facies overlap with Cmc facies and microbial-grain dominated facies (Fig. 11; Matyszkiewicz et al. 2006, 2012; Kochman and Matyszkiewicz 2012; Krajewski et al. 2018). The microbial mats provided effective traps and bounded grain-dominated sediments that were quickly cemented. The microbial-grain-dominated facies, in which coated grains and bioclasts predominate, are typical of the internal parts of flat-topped microplatforms during their progradational phase (Fig. 11). In marginal and upper slope parts of the reef complexes, where grain-dominated sediments prevailed, and intensive synsedimentary cementation took place, the Cmc boundstone facies, occurred. On the reef complex slope grain-flow, detrital facies with numerous bioclasts and *Crescentiella* dominate while in more distal parts of the slope, microbial-sponge facies predominate. The more distal and deeper parts of slopes and areas between the reef complexes are filled with mud-dominated pelitic-bioclastic facies. In these areas, among bioconstruction, small sponge cluster reefs or biostromes forming bedded limestones, dominate (Fig. 11).

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values indicate that calcite precipitation in the investigated localities took place in marine waters for which $\delta^{13}\text{C}$ values vary from 0‰ to ± 4 ‰ and $\delta^{18}\text{O}$ from -4 ‰ to 0‰ (Hudson 1977; Tucker and Wright 1990; Hoefs 2004). The oxygen isotope values for primary carbonates in normal marine conditions are approximately close to 0‰ PDB (Milliman 1974; Faure 1998; Moore 2001). The rock samples from the studied localities do not differ significantly geochemically in terms of major elements, indicating that carbonate sedimentation occurred under similar geochemical conditions. However, variations of $\delta^{18}\text{O}$ values between the

limestones from localities suggest slight changes in water composition within the sedimentary environment from normal seawater to slightly diluted seawater. The calcite precipitation in limestones from the Rębielska Mt. Quarry took place in slightly different environmental conditions compared to the limestones from the Wielkanoc and Zabierzów quarries. Calcite precipitation took place generally in marine waters with a small share of meteoric waters, as evidenced by the values of $\delta^{18}\text{O}$ up to -3.81 ‰ (Matthews and Allan 1978; Allan and Matthews 1982; Hoefs 2004).

In the case of the Polish-German part of the northern Tethys shelf, so far, similar analogues regarding facies relationship with microencruster-microbial boundstones have not been described in detail. In the area of the PJ, the examples from the Sokolica Reef Complex, Wielkanoc and Czajowice quarries, and Zegarowe Rocks (Table 1) are similar to those observed in the presented model (Fig. 11). Similar Upper Jurassic example is the microbial cemented grain-dominated facies described from the reef complex as platform sands from the Franconian Jura (Germany; e.g., Koch et al. 1994). Another similar examples to the Upper Jurassic facies from the Tethys shelf are the Lower Jurassic examples of palaeohigh from Morocco, where an isolated carbonate platform developed on the Palaeozoic elevation (Della Porta et al. 2013). After Della Porta et al. (2013, p. 249), the microbial microencruster boundstone probably expanded to the outer platform facies belt when environmental conditions excluded most of the metazoans (e.g., corals) and microbial precipitation was favoured. The composition of the biota is similar to the Upper Jurassic deposits from the PJ. Therefore, it can be assumed that in both cases, microencruster-microbial boundstone palaeosetting can be classified as steep-fronted, moderate energy, outer margin to upper slope settings, that were tectonically active in Late Jurassic, as structural palaeohighs. The examples discussed in this paper, similarly to the Lower Jurassic example, indicate that the occurrence of microencruster-microbial-cement bioconstructions may be useful for palaeogeographic, palaeobathymetric, and palaeotectonic investigations (see also Hoffmann et al. 2021; Kołodziej and Ivanova 2021).

Position of the *Crescentiella*-microbial-cement boundstone facies among organic reef types

In the Phanerozoic, various types of bioconstruction are formed by corals, sponges, stromatoporoids, microbialites, microencrusters, and synsedimentary cements that were classified by Riding and Virgone (2020) as the so-called hybrid carbonates forming various types of organic reefs (e.g., Wood 1999; Kiessling 2002; Leinfelder et al. 2002; Flügel 2004; Riding and Virgone 2020). Hybrid carbonates are understood as in situ associations of two (dual hybrid) or three (triple hybrid) of abiotic (or quasi-abiotic),

bioinduced (mainly microbialites) and biocontrolled (skeletal e.g., corals or sponges) carbonates. Examples from the northern Tethys shelf were most often formed by dual hybrids of microbial-sponge open frame reefs or microbial agglutinated reefs (pure microbial reefs (> 10% metazoans) or microbial dominated metazoan reefs (sensu Leinfelder et al. 1996). In the Late Jurassic sediments of the northern Tethys shelf, the triple hybrids are rare. The *Crescentiella* included in the microencruster-microbial-cement consortium is an important reef-builder in the dual hybrid microbial-grain dominated reefs, and the microbial-sponge reefs and occur less frequently in the triple hybrid carbonate skeleton–microbial–abiotic components on the Late Jurassic northern Tethys shelf. In the case of the PJ, some fragments of the presented Sokolica Reef Complex and Wielkanoc Quarry examples (Table 1) can be included in the microencruster-sponge-cement triple hybrids. A similar Upper Jurassic example of triple hybrid carbonates has been reported from the Oxfordian and Tithonian Crimea reef (Krajewski and Olszewska 2006; Krajewski and Schlagintweit 2018). In the case of the PJ, abiotic carbonates are often associated with microbial carbonates which indicates that conditions that were favourable for abiotic carbonate precipitation also favoured microbialites development. The Cmc boundstone facies most closely resembles agglutinated microbial reefs or the sponge and coral microbial-dominated open frame reefs. Some studies (e.g., Schlagintweit and Gawlick 2008; Krajewski and Schlagintweit 2018) emphasize that the Late Jurassic bioconstructions formed by microencruster-microbial-cement microframework with numerous *Crescentiella* resembles the Permian reefs (e.g., Flügel 1994; Wood 1999; Weidlich 2002; Kershaw et al. 2007; Peryt et al. 2016) and the Triassic *Tubiphytes* and cement crust-dominated reefs (e.g., Senowbari-Daryan et al. 1993; Flügel 2002; Marangon et al. 2011; Popa et al. 2014). As in the examples studied, radial-fibrous cements reported in boundstones from the Middle-Upper Triassic carbonate platforms represent mainly the margin and upper slope settings with syndimentary marine cementation (e.g., Keim and Schlager 2001; Seeling et al. 2005).

Conclusions

The Upper Jurassic succession from the Polish Jura displays a distinct variability of reef facies with the locally dominant *Crescentiella*-microbial-cement boundstone facies. These facies are dominated by *Crescentiella*-microbial-cement consortium forming decimetre-scale bioconstructions with stromatolite-like cavities.

The intensive development of *Crescentiella*-microbial-cement boundstone facies took place during three sedimentary intervals, encompassing the ammonite *Transversarium*

Zone of the Middle Oxfordian, Upper *Bifurcatus* Zone of the Upper Oxfordian, and the *Planula* Zone of the Lower Kimmeridgian.

The sedimentary environment of *Crescentiella*-microbial-cement boundstone facies is characterized by a relatively small amount of metazoans, together with the intensive development of microbialites and the intensive deposition of non-skeletal grains that were stabilized by microbial mats. The trapping and bounding of such grains were an important process of bioconstruction accretion.

The *Crescentiella*-microbial-cement boundstone with stromatolite-like cavities is best explained by their development in the marginal and upper parts of the slope of broad reef complexes/microplatforms developed on structural palaeohighs. The palaeosetting of such facies can be associated with the transition zone between deeper microbial-sponge and generally shallow water microbial-bioclastic-coated grain dominated and/or coral-fine-grained facies representing the internal part of the reef complexes/microplatforms.

Microencruster-microbial-cement boundstones can be classified as microbial-sponge or microbial-grain dominated dual hybrids, less often microencruster / microbial-skeletal metazoan-cement triple hybrids. Described microencruster-microbial-cement boundstone resembles and coexists with agglutinated microbial reefs formed by microbial trapping and binding of grains and microbial-sponge skeleton-supported open frame reefs with significant contribution from microencrusters and early cements.

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Data availability The materials and data are housed at the Faculty of Geology, Geophysics and Environmental Protection (AGH University of Science and Technology).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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References

- Allan JR, Matthews RK (1982) Isotope signatures associated with early meteoric diagenesis. *Sedimentology* 29:797–817
- Brachanec T, Salamon MA, Szopa K, Gedl P, Brom KR, Leško K (2016) Origin of jurassic-cretaceous neptunian dikes from the Cracow-Częstochowa Upland in southern Poland. *Geobios* 49:155–165. <https://doi.org/10.1016/j.geobios.2016.01.021>
- Burchette TP, Wright VP (1992) Carbonate ramp depositional systems. *Sediment Geol* 79:3–57
- Crescenti U (1969) Biostratigrafia delle facies Mesozoiche dell'Appennino Centrale: correlazioni. *Geol Romana* 8:15–40
- Della Porta G, Merino-Tomé O, Kenter JAM, Verwer K (2013) Lower Jurassic microbial and skeletal carbonate factories and platform geometry (Djebel Bou Dahar, High Atlas, Morocco). In: Verwer K, Playton TE, Harris PM (eds) *Deposits, architecture, and controls of carbonate margin, slope, and basinal settings*. SEPM Special Publication, Tulsa
- Dupraz C, Strasser A (1999) Microbialites and micro-encrusters in shallow coral bioherms (Middle to Late Oxfordian, Swiss Jura mountains). *Facies* 40:101–129
- Faure G (1998) *Principles and applications of geochemistry* (2nd Edition). Prentice Hall, Upper Saddle River, New Jersey, p 600
- Flügel E (1994) Pangean shelf carbonates: controls and paleoclimatic significance of permian and triassic reefs. *Geol Soc Am Special Papers* 288:247–266
- Flügel E (2002) Triassic reef patterns. In: Kiessling W, Flügel E, Golonka J (eds) *Phanerozoic Reef Patterns*. SEPM Special Publication, Tulsa
- Flügel E (2004) *Microfacies of carbonate rocks: analysis interpretation and application*. Springer, Berlin, p 984
- Fürsich FT, Wilmsen M, Seyed-Emami K, Schairer G, Majidifard MR (2003) Platform-basin transport of a middle to late jurassic large-scale carbonate platform system (Shotori Mountains, Tabas Area, East-central Iran). *Facies* 48:171–198
- Głowniak E (2006) Correlation of the zonal schemes at the middle-upper Oxfordian (Jurassic) boundary in the Submediterranean Province: Poland and Switzerland. *Acta Geol Polon* 56:33–50
- Granier BRC (2021) *Bacinella*, a discrete type of mesozoic calcimicrobial structure. *Carnets De Geol* 21:1–25. <https://doi.org/10.2110/carnets.2021.2101>
- Gutowski J, Popadyuk I, Olszewska B (2005) Late Jurassic–earliest cretaceous evolution of the epicontinental sedimentary basin of southeastern Poland and Western Ukraine. *Geol Quart* 49:31–44
- Haq BU (2018) Jurassic sea-level variations: a reappraisal. *GSA Today* 28:4–10
- Helm C, Schülke I (2006) Patch reef development in the florigemma-bank member (Oxfordian) from the deister Mts (NW Germany): a type example for Late Jurassic coral thrombolite thickets. *Facies* 52:441–467
- Hoefs J (2004) *Stable isotope geochemistry*, 5th edn. Springer-Verlag, Berlin, p 244
- Hoffmann M, Kołodziej B, Skupien P (2017) Microencruster-microbial framework and syndimentary cements in the Štramberk Limestone (Carpathians, Czech Republic): insights into reef zonation. *Ann Soc Geol Pol* 87:325–347. <https://doi.org/10.1441/asgp.2017.018>
- Hoffmann M, Kołodziej B, Kowal-Kasprzyk J (2021) A lost carbonate platform deciphered from clasts embedded in flysch: Štramberk-type limestones, polish outer carpathians. *Ann Soc Geol Pol* 91:203–251. <https://doi.org/10.14241/asgp.2021.15>
- Hudson JD (1977) Stable isotopes and limestone lithification. *J Geol Soc Lond* 133:637–660
- Irmiński W (1995) Górnojurajski kompleks biohermalny w okolicach Niegowonic i Grabowej k. Zawiercia. *Prz Geol* 43:853–858 (in Polish)
- Kaya MY, Altiner D (2015) Microencrusters from the upper jurassic-lower cretaceous inalti formation (Central Pontides, Turkey): remarks on the development of reefal/peri-reefal facies. *Facies* 61:18. <https://doi.org/10.1007/s10347-015-0445-5>
- Keim L, Schlager W (2001) Quantitative compositional analysis of a Triassic carbonate platform (Southern Alps, Italy). *Sediment Geol* 139:261–284
- Kendall AC, Tucker ME (1973) Radial-fibrous calcite: a replacement after acicular carbonate. *Sedimentology* 20:365–389
- Kershaw SLY, Crasquin-Soleau S, Feng Q, Mu X, Collin PY, Reynolds A, Guo L (2007) Earliest Triassic microbialites in the South China block and other areas: controls on their growth and distribution. *Facies* 53:409–425
- Kiessling W (2002) Secular variations in the Phanerozoic reef ecosystem. In: Kiessling W, Flügel E, Golonka J (eds) *Phanerozoic Reef Patterns*. SEPM Special Publication, Tulsa
- Koch R, Schorr M (1986) Diagenesis of Upper Jurassic sponge-algal reefs in SW Germany. In: Schröder JH, Purser B (eds) *Reef diagenesis*. Springer, Berlin, pp 224–244
- Koch R, Senowbari-Daryan B, Strauss H (1994) The Late Jurassic 'Massenkalk Fazies' of Southern Germany; calcareous sand piles rather than organic reefs. *Facies* 31:179–208
- Kochman A, Matyszkiewicz J (2012) Microbial laminites with coprolites from upper jurassic carbonate buildups (Kraków-Częstochowa Upland, Poland). *Ann Soc Geol Pol* 82:331–347
- Kochman A, Matyszkiewicz J (2013) Experimental method for estimation of compaction in the Oxfordian bedded limestones of the southern krakow-czestochowa upland, Southern Poland. *Acta Geol Polon* 63:681–696
- Kołodziej B, Ivanova D (2021) Microencruster-microbial-cement framework of the upper jurassic reef developed on the slope of the intra-Tethyan carbonate platform (Bulgaria). *Proc Geol Assoc* 132:158–169. <https://doi.org/10.1016/j.pgeola.2020.10.007>
- Kowal-Kasprzyk J, Krajewski M, Gedl P (2020) The oldest stage of the outer carpathian evolution in the light of Oxfordian-Kimmeridgian exotic clast studies (southern Poland). *Facies* 66:11. <https://doi.org/10.1007/s10347-020-0595-y>
- Krajewski M, Olchow P (2021) Upper Jurassic bedded limestones and early diagenetic dolomitized limestones in the light of mineralogical, geochemical and sedimentological studies; Kraków area, Poland. *Minerals* 11:1–15. <https://doi.org/10.3390/min11050462>
- Krajewski M, Olszewska B (2006) New data about microfacies and stratigraphy of the late jurassic ay-petri carbonate buildup (southwestern Crimea Mountains, South Ukraine). *N Jb Geol Paläont Mh* 5:298–312. <https://doi.org/10.1127/njgpm/2006/2006/298>
- Krajewski M, Schlagintweit F (2018) Crescentiella-microbial-cement microframeworks in the Upper Jurassic reefs of the Crimean Peninsula. *Facies* 64:21. <https://doi.org/10.1007/s10347-018-0534-3>
- Krajewski M, Olchow P, Felisiak I (2016) Late Jurassic facies architecture of the Złoczew Graben: implications for evolution of the tectonic-controlled northern peri-Tethyan shelf (Upper Oxfordian-Lower Kimmeridgian, Poland). *Facies* 62:4. <https://doi.org/10.1007/s10347-015-0455-3>
- Krajewski M, Olchow P, Zatoń M, Bajda T (2017) Kimmeridgian hardground-sequence boundary from the mesozoic margin of the holy cross mountains (Central Poland): implications for the evolution of the northern tethyan carbonate shelf. *Facies* 63:15. <https://doi.org/10.1007/s10347-017-0496-x>
- Krajewski M, Olchow P, Rudziński D (2018) Sedimentary successions in the Middle-Upper Oxfordian reef deposits from the southern part of the Kraków-Częstochowa Upland (Southern Poland). *Geol Quart* 62:653–668. <https://doi.org/10.7306/gq.1429>

- Kutek J, Wierzbowski A, Bednarek J, Matyja BA, Zapašnik A (1977) Notes on the Upper Jurassic stratigraphy in the Polish Jura Chain. *Prz Geol* 25:438–445
- Leinfelder RR, Werner W, Nose M, Schmid DU, Krautter M, Laternser R, Takacs M, Hartmann D (1996) Paleocology, growth parameters and dynamics of coral, sponge and microbialite reefs from the Late Jurassic. *Göttinger Arb Geol Paläont Sb* 2:227–248
- Leinfelder RR, Schmid DU, Nose M, Werner W (2002) Jurassic reef patterns - the expression of a changing globe. In: Kiessling W, Flügel E, Golonka J (eds) *Phanerozoic Reef Patterns*. SEPM Special Publication, Tulsa
- Marangon A, Gattolin G, Della Porta G, Preto N (2011) The Latemar: a flat-topped, steep fronted platform dominated by microbialites and syndimentary cements. *Sediment Geol* 240:97–114. <https://doi.org/10.1016/j.sedgeo.2011.09.001>
- Matthews RK, Allan JR (1978) Carbon and oxygen isotopes as diagenetic tools: surface and subsurface data, Barbados, West Indies. *Geology* 5:16–20
- Matyja BA, Wierzbowski A (1992) Kromołowice Hill, the biohermal complex to basin transitional zone topography; Oxfordian, Bifurcatus and Bimammatum Zones. In: Matyja BA, Wierzbowski A, Radwański A (eds) *Oxfordian & Kimmeridgian joint working groups meeting, Guidebook and Abstracts*. International Subcommittee on Jurassic Stratigraphy, Warszawa
- Matyja BA, Wierzbowski A (2006) Julianka, coral colonization of the cyanobacteria-sponge bioherms at the turn of the Oxfordian and Kimmeridgian. In: Wierzbowski A, Aubrecht R, Golonka J, Gutowski J, Krobicki M, Matyja BA, Pieńkowski G, Uchman A (eds) *Field trip guidebook 7th International Congress on the Jurassic System, Kraków Poland*. Polish Geological Institute, Warszawa
- Matyszkiewicz J (1997) Microfacies, sedimentation and some aspects of diagenesis of Upper Jurassic sediments from the elevated part of the Northern peri-Tethyan Shelf: a comparative study on the Lochen area (Schwäbische Alb) and the Cracow area (Cracow–Wielun Upland, Poland). *Berliner Geo Abh E* 21:1–111
- Matyszkiewicz J, Felisiak I (1992) Microfacies and diagenesis of an Upper Oxfordian carbonate buildup in Mydlniki (Cracow area, Southern Poland). *Facies* 27:179–190
- Matyszkiewicz J, Krajewski M (1996) Lithology and sedimentation of upper jurassic massive limestones near Bolechowice, Kraków–Wieluń Upland, south Poland. *Ann Soc Geol Polon* 66:285–301
- Matyszkiewicz J, Krajewski M, Kędzierski J (2006) Origin and evolution of an upper jurassic complex of carbonate buildups from Zegarowe Rocks (Kraków–Wieluń Upland, Poland). *Facies* 52:249–263. <https://doi.org/10.1007/s10347-005-0038-9>
- Matyszkiewicz J, Kochman A, Duś A (2012) Influence of local sedimentary conditions on development of microbialites in the Oxfordian carbonate buildups from the southern part of the Kraków–Częstochowa Upland (south Poland). *Sediment Geol* 263–264:109–132. <https://doi.org/10.1016/j.sedgeo.2011.08.005>
- Matyszkiewicz J, Krajewski M, Kochman A, Kozłowski A, Duliński M (2016) Oxfordian neptunian dykes with brachiopods from the southern part of the Kraków–Częstochowa Upland (southern Poland) and their links to hydrothermal vents. *Facies* 62:1–28. <https://doi.org/10.1007/s10347-016-0464-x>
- Milliman JD (1974) Marine carbonates. recent sedimentary carbonates, part I. Springer, Berlin, p 375
- Mircescu CV, Bucur II, Săsăran E, Pleş G, Ungureanu R, Oprişa A (2019) Facies evolution of the Jurassic-Cretaceous transition in the eastern getic carbonate platform, romania: integration of sequence stratigraphy, biostratigraphy and isotope stratigraphy. *Cretac Res* 99:71–95. <https://doi.org/10.1016/j.cretres.2019.01.015>
- Moore CH (2001) Carbonate reservoirs: porosity evolution and diagenesis in a sequence stratigraphic framework. *developments in sedimentology*, 55. Elsevier, Amsterdam, p 444
- Olchoway P (2011) Possible origin of stromatactis-like cavities in Upper Jurassic sediments from the Wielkanoc quarry near Golcza (Kraków–Częstochowa Upland, southern Poland) –experimental studies. *Facies* 57:613–625. <https://doi.org/10.1007/s10347-010-0262-9>
- Olchoway P, Krajewski M (2020) Lower Kimmeridgian facies and sedimentary succession of a shallow-water coated-grain-dominated carbonate ramp of the northern peri-Tethyan shelf: an example from the Radomsko Folds (central Poland). *Geol Quart* 64:969–987. <https://doi.org/10.7306/gq.1563>
- Olchoway P, Krajewski M, Felisiak I (2019) Late Jurassic facies succession of the Kleszczów Graben area (southern border of the Łódź Depression, peri-Tethyan shelf, central Poland). *Geol Quart* 63:657–681. <https://doi.org/10.7306/gq.1496>
- Peryt TM, Raczynski P, Peryt D, Chłódek K, Mikołajewski Z (2016) Sedimentary history and biota of the Zechstein Limestone (Permian, Wuchiapingian) of the Jabłonna Reef in Western Poland. *Ann Soc Geol Pol* 86:379–413. <https://doi.org/10.14241/asgp.2016.011>
- Pleş G, Mircescu CV, Bucur II, Săsăran E (2013) Encrusting microorganisms and microbial structures in upper jurassic limestones from the Southern Carpathians (Romania). *Facies* 59:19–48. <https://doi.org/10.1007/s10347-012-0325-1>
- Pleş G, Bărtas T, Chelaru R, Bucur II (2017) *Crescentiella morronensis* (Crescenti) (*incertae sedis*) dominated microencruster association in lower cretaceous (lower Aptian) limestones from the Rarău Massif (Eastern Carpathians, Romania). *Cret Res* 79:91–108. <https://doi.org/10.1016/j.cretres.2017.07.015>
- Pomoni-Papaioannou PF, Flügel E, Koch R (1989) Depositional environments and diagenesis of Upper Jurassic subsurface sponge- and Tubiphytes reef limestones: Altensteig 1 well, western Mollase Basin, southern Germany. *Facies* 21:263–284
- Popa L, Panaiotu CE, Grădinaru E (2014) An early Middle asianian (Middle Triassic) Tubiphytes and cement crusts-dominated reef from North Dobrogea (Romania): facies, depositional environment and diagenesis. *Acta Geol Polon* 64:189–206
- Reolid M, Gaillard C, Olóriz F, Rodríguez-Tovar FJ (2005) Microbial encrustations from the middle Oxfordian–earliest Kimmeridgian lithofacies in the prebetic zone (Betic Cordillera, southern Spain): characterization, distribution and controlling factors. *Facies* 50:529–543. <https://doi.org/10.1007/s10347-004-0030-9>
- Richter DK, Neuser RD, Schreuer J, Gies H, Immenhauser A (2011) Radial-fibrous calcites: a new look at an old problem. *Sediment Geol* 239:23–36
- Riding R (2002) Structure and composition of organic reefs and carbonate mud mounds: concepts and categories. *Earth Sci Rev* 58:163–231. [https://doi.org/10.1016/S0012-8252\(01\)00089-7](https://doi.org/10.1016/S0012-8252(01)00089-7)
- Riding R, Virgone A (2020) Hybrid carbonates: *in situ* abiotic, microbial and skeletal co-precipitates. *Earth Sci Rev* 208:103300. <https://doi.org/10.1016/j.earscirev.2020.103300>
- Rusciadelli G, Ricci C, Lathuilière B (2011) The ellipsactinia limestones of the Marsica area (Central Apennines): a reference zonation model for upper jurassic intra-tethys reef complexes. *Sediment Geol* 233:69–87
- Schlagintweit F, Gawlick HJ (2008) The occurrence and role of microencruster frameworks in Late Jurassic to early cretaceous platform margin deposits of the Northern Calcareous Alps (Austria). *Facies* 54:207–231. <https://doi.org/10.1007/s10347-007-0131-3>
- Schlagintweit F, Gawlick HJ (2009) Enigmatic tubes associated with microbial crusts from the late Jurassic of the Northern Calcareous Alps (Austria): a mutualistic sponge-epibiont consortium? *Lethaia* 42:452–461. <https://doi.org/10.1111/j.1502-3931.2008.00143.x>

- Schmid DU (1995) “*Tubiphytes*” *morronensis*—eine fakultativ inkrustierende Foraminifere mit endosymbiontischen Algen. *Profil* 8:305–317
- Schmid DU, Leinfelder RR, Nose M (2001) Growth dynamics and ecology of upper jurassic mounds, with comparisons to Mid-Palaeozoic mounds. *Sediment Geol* 145:343–376. [https://doi.org/10.1016/S0037-0738\(01\)00157-9](https://doi.org/10.1016/S0037-0738(01)00157-9)
- Seeling M, Emmerich A, Bechstädt T, Zühlke R (2005) Accommodation/sedimentation development and massive early marine cementation: latemar vs. Concarena (Middle/Upper Triassic, Southern Alps). *Sediment Geol* 175:439–457
- Senowbari-Daryan B, Zühlke R, Bechstädt T, Flügel E (1993) Anisian (Middle Triassic) buildups of the northern Dolomites (Italy): the recovery of the reef communities after the Permian/Triassic crisis. *Facies* 28:181–256
- Senowbari-Daryan B, Bucur II, Schlagintweit F, Säsarän E, Maty-skiewicz J (2008) *Crescentiella*, a new name for “*Tubiphytes*” *morronensis* Crescenti 1969: an enigmatic Jurassic-Cretaceous microfossil. *Geol Croatica* 61:185–214
- Shiraishi F, Kano A (2004) Composition and spatial distribution of microencrusts and microbial crusts in upper Jurassic–lowermost Cretaceous reef limestone (Torinosu Limestone, southwest Japan). *Facies* 50:217–227
- Słowiński J, Vinn O, Jäger M, Zatoń M (2022) Middle and Late Jurassic tube-dwelling polychaetes from the polish basin: diversity, palaeoecology and comparisons with other assemblages. *Acta Palaeontol Pol* 67:827–864. <https://doi.org/10.4202/app.01006.2022>
- Suarez-Gonzalez P, Benito MI, Quijada IE, Mas R, Campos-Soto S (2019) ‘Trapping and binding’: A review of the factors controlling the development of fossil agglutinated microbialites and their distribution in space and time. *Earth Sci Rev* 194:182–215. <https://doi.org/10.1016/j.earscirev.2019.05.007>
- Trammer J (1989) Middle to Upper oxfordian sponges of the Polish Jura. *Acta Geol Polon* 39:49–91
- Tucker ME, Wright VP (1990) *Carbonate sedimentology*. Blackwell Scientific, Oxford, p 482
- Uta A, Bucur II (2003) Microbial structures and microencrusts in the Upper Jurassic – Lower Cretaceous deposits from Buila-Vanturita Massif (South Carpathians). *Stud Univ Babeş-Bolyai Geol* 48:3–14
- Weidlich O (2002) Middle and Late Permian reefs – distributional patterns and reservoir potential. In: Kiessling W, Flügel E, Golonka J (eds) *Phanerozoic Reef Patterns*. SEPM Special Publication, Tulsa
- Wood R (1999) *Reef evolution*. Oxford University Press, Oxford, p 414
- Woźniak T, Bania G, Mościcki WJ, Ćwiklik M (2018) Electrical resistivity tomography (ERT) and sedimentological analysis applied to investigation of upper jurassic limestones from the Krzeszowice Graben (Kraków Upland, southern Poland). *Geol Quart* 62:287–302. <https://doi.org/10.7306/gq.v62i2.25763>
- Ziegler PA (1990) *Geological Atlas of Western and Central Europe*. Shell Internationale Petroleum Maatschappij, The Hague, 239. enclosures