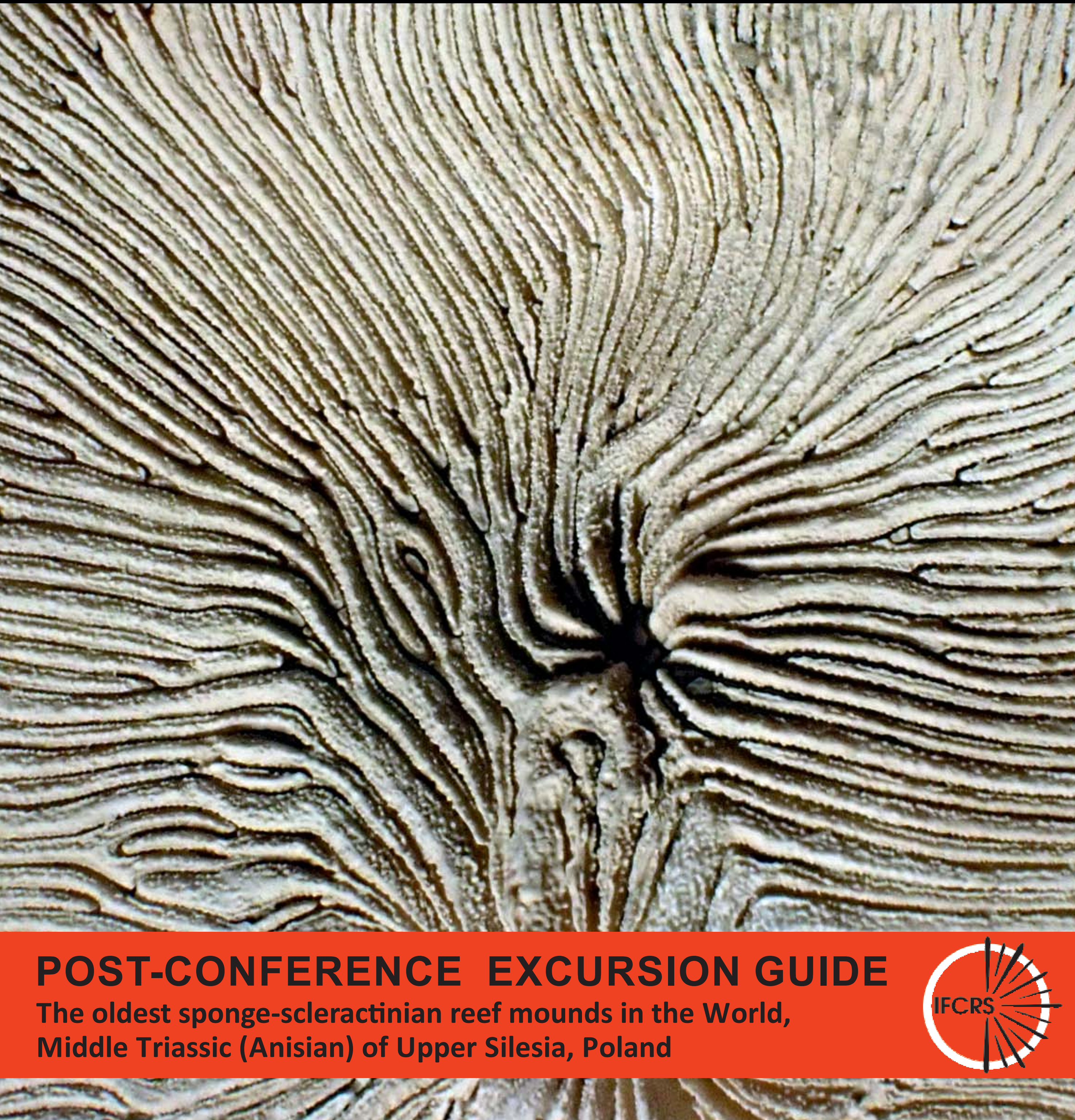
14th Symposium of the International Fossil Coral and Reef Society Poland 2023



POST-CONFERENCE EXCURSION GUIDE

The oldest sponge-scleractinian reef mounds in the World,
Middle Triassic (Anisian) of Upper Silesia, Poland

14th Symposium of the International Fossil Coral and Reef Society (IFCRS)
Poland, 10–16 September 2023

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THE OLDEST SPONGE-SCLERACTINIAN REEF MOUNDS IN THE WORLD, MIDDLE TRIASSIC (ANISIAN) OF UPPER SILESIA, POLAND

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GENERAL CONTEXT

Paleogeographic and tectonic setting of the Germanic Basin

During the Triassic, much of Europe formed a large depression (Germanic Basin) extending for over 1500 km from the British Isles to eastern Poland. The basin was enclosed from the east by the Precambrian East-European Platform (Baltika), from the north and west by the Caledonian Mountains, and from the south by the Variscan Orogen. The area was located at subtropical latitudes, which resulted in an overall hot and arid climate (Fig. 1A; Szulc 2000).

The basin topography and subsidence pattern were strongly controlled by reactivated older tectonic structures (Szulc 2000). The Mid Polish Trough that played the role of the main depocenter was controlled by the Teisseyre-Tornquist Fault Zone (TTFZ). Other important faults in the Polish part of the basin included the Silesian-Moravian Fault (SMF) and the Kraków-Lubliniec-(Odra-Hamburg) Fault Zone (KLFZ), both forming local subsidence centers (Fig. 1A). In the western part of the basin the Elbe Fault and the Saxothuringian Lineament were important, while towards the north-west the basin was influenced by the North Sea rifting zone. All those fault zones were active throughout most of the Triassic, but at slightly different times. They produced several regional to basinwide unconformities and numerous synsedimentary tectonic deformations.

General evolution of the Germanic Basin

In the early Triassic the Germanic Basin was dominated by continental environments: fluvial plains, playas and deserts (Feist-Burkhardt et al. 2008). They are represented by conglomerates, sandstones and claystones. Thin intercalations of limestones represent short-lived marine ingressions from the North Sea rifting zone, as the basin was still connected with the Barents Sea shelf area and followed the disposition of the Permian evaporitic Zechstein Basin. All those rocks are collectively termed as the Buntsandstein (ger. 'reddish sandstone'). The thickness of the complete Buntsandstein succession ranges between 500 and 1200 m, but can reach up to 4000 m in local grabens (Feist-Burkhardt et al. 2008).

The situation changed towards the end of the Early Triassic when the north connection was closed for good and three southern connections with the Tethys Ocean were opened (from the east to west): the East-Carpathian Gate developed along the Teisseyre-Tornquist Line (TTL), the Silesian-Moravian Gate developed upon the Silesian-Moravian Fault, and the Western (Burgundy) Gate (Fig. 1A). The gate opening coincided with a global sea-level rise that brought warm tropical water from the Tethys into the Germanic Basin. The transgression resulted in the deposition of a 150- to 300-m-thick succession of carbonates and evaporites, with siliciclastics being present only along the basin shore (Szulc 2000). Those strata define the Röt and the Muschelkalk (ger. 'shelly limestone').

The three gates developed at the tips of the Tethyan rift system and were opening and closing diachronously from the east to west, following the westward relocation of the Tethyan spreading center (Szulc 2000). The East-Carpathian and Silesian-Moravian Gates were already open by the Olenekian and were the only connections with the Tethys until the middle Anisian (Pelsonian) when the Western (Burgundy) Gate also became active. This was the time when the Muschelkalk Sea reached its maximum spatial extent and maximum depth. Subsequent crustal uplift in the Polish province resulted in the gradual closing of the two eastern gates, whereas the Western (Burgundy) Gate persisted until the latest Ladinian (Longobardian). This diachronism and semi-closed configuration of the basin produced a characteristic facies pattern in which normal-marine

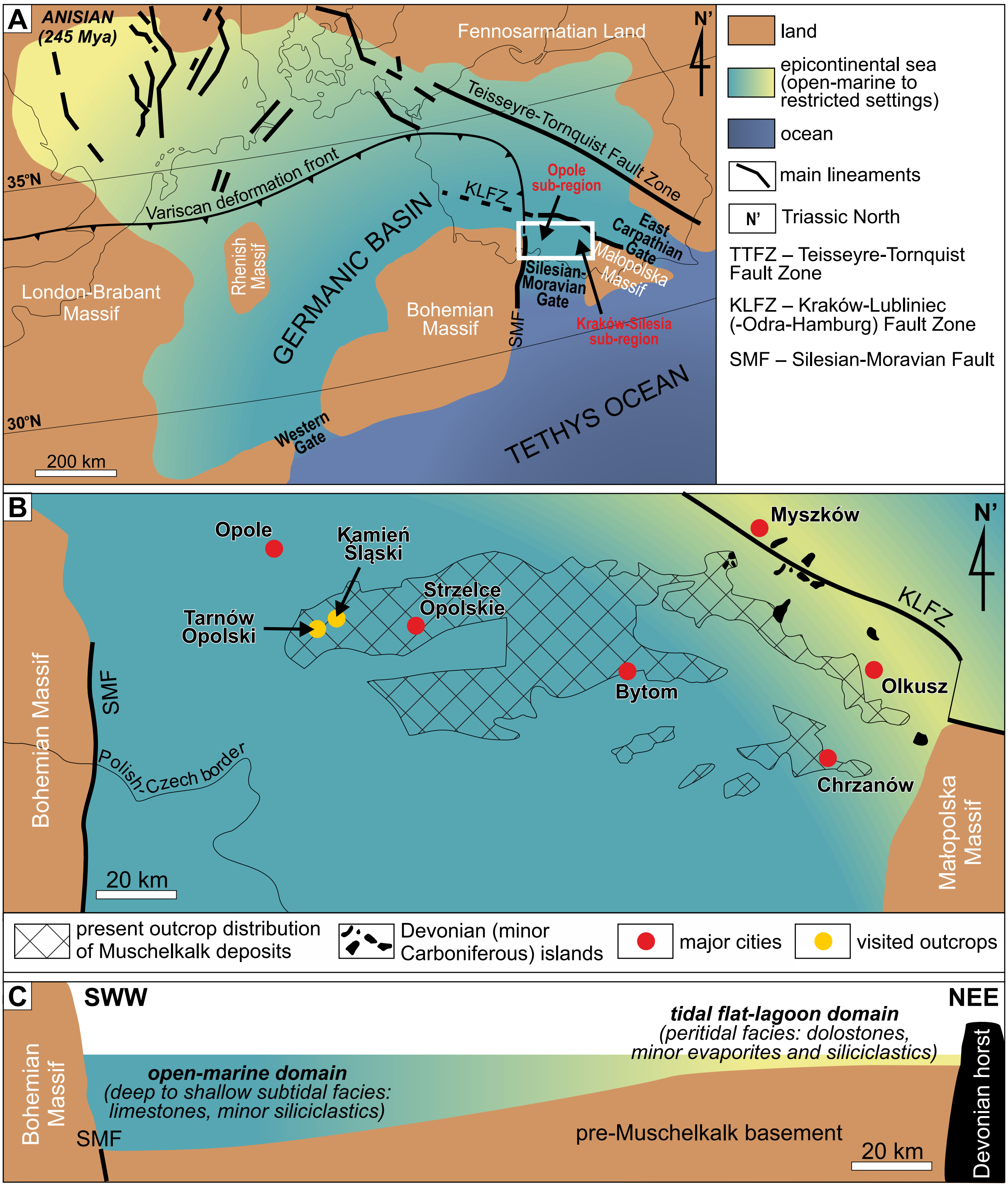

Fig. 1. Paleogeographic setting of the Upper Silesia region in the Middle Triassic. **A**. Position of the Upper Silesia region (white rectangle) within the northern mouth of the Silesian-Moravian Gate. **B**. Paleogeographic reconstruction of the northern outlet of the Silesian-Moravian Gate, framed to the west by the Bohemian Massif and to the east by the Małopolska Massif and an archipelago of Paleozoic islands. **C**. Regional schematic cross-section of the Upper Silesian carbonate platform, showing the transition from the restricted-marine to the open-marine domain. Figure taken from Matysik (2016).

settings dominating near the active gates were gradually replaced by more restricted environments towards the basin margins and inactive gates (Szulc 2000).

The marine sedimentation in the basin was strongly influenced by third-order relative sea-level fluctuations recorded as several transgressive-regressive depositional sequences correlatable across the entire basin. Superimposed on these were high-frequency relative sea-level oscillations producing meter-scale cyclicity. The cycles are ascribed to Milankovitch-driven climatic changes by some authors (e.g., Bachmann and Kozur 2004), but were proven to have only a local to subregional distribution and thereby are inappropriate for astrochronological inferences (Matysik 2019). The cycles were probably formed by an interplay of eustasy, regional subsidence, synsedimentary tectonic-block movements, and mosaic infilling of accommodation space, with the contribution of these factors changing with time and regionally or even locally.

Following the final gate closure with the beginning of the Late Triassic, the Germanic Basin became a vast playa-gilgai-fluvial area represented mainly by mudstones, with thinner soils, sandstones, and conglomerates (Feist-Burkhard et al. 2008; Jewuła et al. 2019). These strata are called the Keuper and reach the thickness of several hundred meters (Feist-Burkhard et al. 2008).

The three major lithostratigraphic subdivisions (Buntsandstein, Muschelkalk, Keuper) are highly diachronous across the Germanic Basin, reflecting the progressing transgression from the Tethys and final regression of the sea. For example, the Muschelkalk facies appeared in southern Poland three depositional sequences earlier than in Western Europe where the Bundsandstein sedimentation still took place . Conversely, the Muschelkalk deposition persisted in Western Europe three conodont and six ceratite zones longer than in southern Poland where the Keuper facies were already developing.

Triassic recovery of marine communities after the end-Permian mass extinction

The Paleozoic ended with the most severe biotic crisis in Earth's history. This mass extinction wiped out 80–90% of marine species (Stanley 2016). Moreover, many groups dominating in the Paleozoic went completely extinct (trilobites, rugose and tabulate corals) or were significantly reduced in diversity (brachiopods, crinoids, bryozoans). Their places were taken by completely new forms (scleractinian corals) or previously subordinate organisms (bivalves, gastropods, echinoids), leading to the emergence of 'modern fauna' and the ecosystem structure we know today (Chen and Benton 2012).

The Triassic recovery of marine communities was generally stepwise from low to high trophic levels, but its rate was different for different biota. Ammonoids and conodonts bounced back rapidly within 1–3 Myr (early Olenekian); foraminifera and brachiopods achieved pre-extinction diversity in 5–7 Myr (late Olenekian to early Anisian); corals and metazoan reefs only re-emerged in the mid-Anisian (Pelsonian/Illyrian) 8–9 Myr after the crisis, marking the final phase of the recovery (Chen and Benton 2012). These oldest scleractinian-rich reefs formed small mounds and are known from the Dolomites in northern Italy (Fois and Gaetani 1984; Senowbari-Daryan et al. 1993), southern China (Qi 1984; Deng and Kong 1984; Qi and Stanley 1989; Deng 2006; Bo et al. 2017) and the Upper Silesian region in southern Poland, the latter being the main goal of this fieldtrip. Corals gradually replaced calcifying sponges and microbes as the main reef constructors. Ladinian reefs are slightly more common than the Anisian ones (see Flügel, 2002). However, the coral reef explosion took place in the Late Triassic (Norian), which is interpreted to have resulted from the spread of photosynthesis, although could also be the consequence of climatic changes (see Stanley 2003 and Raja et al. 2023).

A similar gradual recovery pattern is seen for burrowing organisms that reached Permian ichnodiversity, burrow sizes and complexity, and tiering and bioturbation levels in the Anisian, several million years after the extinction (Luo et al. 2016; Feng et al. 2017, 2018; Stachacz and Matysik 2020). It is also widely accepted that the return of large and complex *Rhizocorallium* and *Thalassinoides* burrows indicates the full recovery of trace-making communities (Luo et al. 2016; Feng et al. 2017, 2018; Stachacz and Matysik 2020).

The recovery was also globally asynchronous, which is evident for both skeletal and burrowing biotas. Regional comparisons of species and ichnospecies diversity show that the Germanic Basin recovered more quickly than any other area in the World, reaching the diversity levels observed elsewhere yet in the earliest Anisian (Aeganian–Bithynian) and reaching the highest diversity out of all Triassic successions worldwide (Assmann 1944; Hagdorn 2007; Knaust 2007; Stachacz and Matysik 2020). The latter took place in the mid-Anisian (Pelsonian) and coincided with the reappearance of sponge-coral reefs in southern Poland, which are the main goal of this fieldtrip. The region with reefs is called Upper Silesia and it was located in the northern outlet of the Silesian-Moravian Gate that was the main communication pathway with the southerly Tethys Ocean in the Anisian (Szulc 2000). Some authors regard this reef complex as a fragment of the circum-Tethyan reef belt that fortuitously avoided later subduction (Szulc 2000). Nonetheless, one has to remember that the Upper Silesia region was an integral part of the Germanic Basin, not the Tethys Ocean, as evidenced by typical Germanic Basin facies.

GEOLOGICAL SETTING FOR THE MIDDLE TRIASSIC CARBONATES (MUSCHELKALK) IN UPPER SILESIA, POLAND

Paleogeography of Upper Silesia

Being located at the northern mouth of the Silesian-Moravian Gate (Fig. 1B), the Upper Silesia region formed an elevated, tectonically mobile threshold block separating the Bohemian Massif on the west and the Małopolska Massif with an archipelago of Devonian islands on the east. The morphology of the Upper Silesia threshold was differentiated both on the regional and local scales, and it reflected the Variscan structural framework (Wyczółkowski 1982), syndepositional tectonic block movements (Szulc 1993, 2000; Matysik and Szulc 2019), and perhaps the asymmetric opening of the adjacent gate. The area generally dipped to the SW at an angle of about 0.5º, which resulted in a lateral gradient of depositional environments. As a consequence, its SW part (the Opole sub-region) was dominated by subtidal facies even during highstands which allowed for the development of the discussed sponge-coral reefs (Szulc 2000), whereas its eastern part (the Kraków-Silesia sub-region) temporarily entered into the inter- and supratidal zone (Figs. 1B, C, 2; Pawłowska and Szuwarzyński 1979; Pawłowska 1982, 1985; Myszkowska 1992; Matysik, 2014). Local highs and lows modified this simple facies pattern, producing a complex facies mosaic over the entire region (Wyczółkowski 1982; Myszkowska 1992; Matysik 2014, 2016).

Stratigraphy

The 150-m-thick, flat-lying Muschelkalk succession of Upper Silesia is subdivided into nine formations (informally called “Beds” after Assmann 1944 and Śliwiński 1961). They roughly correspond to the systems tracts of four 3rd-order depositional sequences (Szulc 2000; Matysik 2014, 2016). The sequences are bounded by unconformities (locally angular) that are traceable over the entire region and correlatable within the Germanic Basin. A combination of sequence boundaries, systems tracts, and several marker lithostratigraphic horizons allows reliable correlation within the succession, albeit there is no geochronological or biostratigraphic control for the sedimentary units and accordingly some facies diachronism is expected. The lithostratigraphic and sequence stratigraphic framework is well correlated with the Alpine successions using magnetostratigraphy (Nawrocki and Szulc 2000) and conodont, ammonoid, crinoid, and green alga biostratigraphy (Assmann 1944; Zawidzka 1975; Hagdorn and Głuchowski 1993; Kotański 1994; Kaim and Niedźwiedzki 1999; Narkiewicz and Szulc 2004; Bucur and Matysik 2020). The key elements of the Upper Silesian Muschelkalk succession are shown in Fig. 2 and basic description of the four depositional sequences is given below.

Sequence 1 equates with the lower Gogolin Beds and represents the Aegean. It is 15 m thick and is characterized by a minor lateral variability and predominance of normal-marine carbonates displaying an overall transgressive trend, from mid-ramp shoal sands to outer-ramp bioclastic tempestites and lime muds. The latter are directly capped (without evident highstand deposits) by lagoonal to supratidal facies (Zellenkalk 2; ger. ‘cellular limestone’) regarded as the sequence boundary (Szulc 2000).

Sequence 2 is 40 m thick and commences with a very similar transgressive and laterally unified mid- to outer-ramp succession (upper Gogolin Beds and lower Olkusz Beds of the Bithynian age) as observed in Sequence 1. However, this transgressive systems tract is succeeded by a 25-m-thick shoaling-upward suite of outer-ramp lime muds, bioclast-lithoclast tempestites, and final oncoid-ooid-peloid shoal sands (Górażdże and upper Olkusz Beds of the early Pelsonian age). The latter most likely formed on an extensive shallow bank (Matysik 2016). Assmann (1944: 44–45) reported

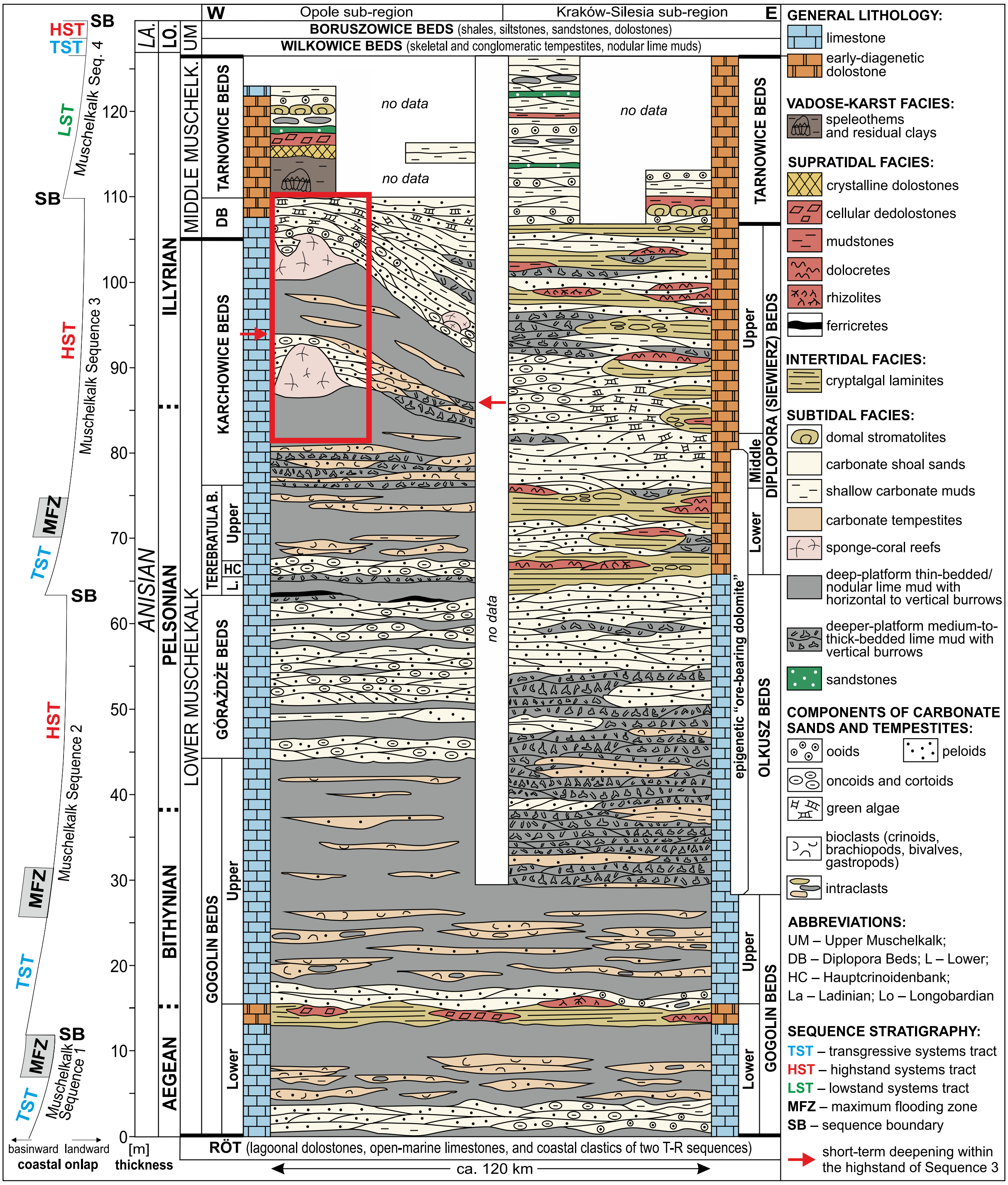

Fig. 2. Generalized stratigraphic section for the Upper Silesian Muschelkalk, showing thickness, overall lithological character, provisional formation names, 3rd-order transgressive-regressive sequences and chronostratigraphy. The transition between the eastern Kraków-Silesia sub-region and western Opole sub-region is not recognized because of the lack of outcrops. Red rectangular indicates the succession visited during this fieldtrip. Scheme taken from Matysik et al. (2022).

corals *Thamnastraea silesiaca* and *Montlivaltia chonocalyx* as well as undetermined sponges with 'destroyed skeletons' in these shoal sand facies, and more recently Hagdorn (2007) mentions rare occurrence of corals *Pamiroseris* and *Montlivaltia* and hexactinellid sponges. But in both cases it is not mentioned if they formed isolated specimens or small buildups. The shoal system was subaerially exposed due to the relative sea-level drop, leading to formation of ferricretes and erosional relief defining the sequence boundary (Szulc 2000; Matysik 2014).

Sequence 3 (late Pelsonian to Illyrian) represents the maximum transgression into the Germanic Basin and maximum opening of the Silesian-Moravian Gate at the same time, which is manifested by its greatest thickness of 50 m, the richest fauna assemblage, and the appearance of the discussed sponge-coral reefs. This is also the time when the Upper Silesia region evolved into a rimmed platform and consequently displayed the greatest regional differentiation in depositional environments and facies. The eastern shallower part (Kraków-Silesia sub-region) was typified by peritidal facies deposited in a back-barrier area with a restricted circulation and pervasive early-diagenetic dolomitization which eliminated development of sponge-coral reefs, although isolated colonies were found in some lagoonal facies (Morycowa 1988; Matysik 2012). These strata are collectively called the Diplopora Beds because of the massive occurrence of calcareous green algae in some levels, with *Diplopora* sp. being most common. The strata are tripartite, with the lower and upper parts being organized into typical peritidal cycles, while the middle part lacks intertidal and supratidal facies and thus is regarded as a maximum flooding zone of Sequence 3 in this area. In contrast to the eastern part, the western deeper area (Opole sub-region) was dominated by open-marine facies formed in front of the barrier. This open-marine succession begins with the Terebratula Beds rich in terebratulide brachiopod *Coenothyris vulgaris*. The lower half of this formation shows a transgressive trend from oncoid-cortoid-peloid shoal sands (so-called Hauptcrinoidenbank; ger. 'main crinoid bank'), through wavy-nodular lime muds and interbedded bioclastic tempestites, to monotonous wavy-nodular lime muds, the latter interpreted as maximum flooding deposits in this area (Szulc 2000). Higher up, tempestite intercalations re-appear within the Terebratula Beds, which is considered as the onset of a regressive trend (Szulc 2000). This trend continues in the overlying Karchowice Beds which shallow from firmgrounds and interbedded bioclastic tempestites to sponge-coral patch reefs and surrounding peloidal-bioclastic limestones and firmgrounds (Matysik 2010). The further shoaling buried the reef complex under ooid-peloid-green algal sands of the Diplopora Beds (Matysik 2010). This highstand systems tract – as the main target of this fieldtrip – is described in more detail in the following sections. It is important to emphasize that the barrier separating the peritidal domain (Kraków-Silesia sub-region) from the open-marine domain (Opole sub-region) is unknown due to the lack of outcrops, but certainly it could not be the patch reefs of the Karchowice Beds, as they only developed in the middle part of this highstand and disappear eastwards, i.e. towards the potential barrier (Fig. 2). They most likely formed an independent complex.

The last Sequence 4 is poorly documented because of the lack of representative sections. It starts with cellular and crystalline dolostones, lagoonal dolomitic muds, sandstones and local stromatolite heads of the Tarnowice Beds (Szulc 2000; Matysik 2012, 2016) interpreted as a lowstand systems tract (Szulc 2000). They are succeeded by the transgressive Wilkowice Beds consisting of nodular lime muds with bioclast-intraclast tempestites (Assmann 1944; Szulc 2000). The following regressive state is recorded as claystones with sandstone and dolosiltite intercalations which form the Boruszowice Beds (Assmann 1944; Szulc 2000). All these strata are c. 30 m thick and late Illyrian to Fassanian in age.

Biota

The Muschelkalk of Upper Silesia is widely known for its rich fossil and ichnofossil content. The most comprehensive studies of skeletal fossils from the Upper Silesian Muschelkalk belong to Assmann (1944) and Hagdorn (2007), while trace fossils have been investigated in detail by Szulc (2000) and Stachacz and Matysik (2020). Both groups show temporal changes in the taxa and diversity, which reflect both (1) the recovery after the P/Tr mass extinction and (2) changes in environmental conditions between and within consecutive transgressive-regressive pulses (see discussion in Stachacz and Matysik 2020).

For skeletal fossils, three main regularities can be observed: (1) the number of identified invertebrate species increases from Sequence 1 to Sequence 3 after which the species diversity drops by ~75% in Sequence 4 (Table 1); (2) the vast number of species occur only in one sequence; and (3) each sequence shows a various proportion of Alpine forms, Germanic forms and endemic Silesian forms. Sequence 3 – which is the main goal of this fieldtrip – is characterized by the highest

Table 1. Secular changes in the diversity of invertebrate taxa in the Muschelkalk formations of the Opole sub-region. 'Other' includes crustaceans, scaphopods, ophiuroids, and worms. Green calcaerous algae and small benthic foraminifers are not listed. Data compiled from Assmann (1944) and Hagdorn (2007).

Sequence stratigraphy (TST – transgressive systems tract; HST – highstand systems tract; LST – lowstand systems tract)		Lithostratigraphy		The number of identified invertebrate taxa								
				Bivalves	Brachiopods	Crinoids	Echinoids	Gastropods	Cephalopods	Corals	Sponges	Other
Sequence 4	HST	Upper Muschelkalk	Boruszowice Beds	5	0	0	0	0	2	0	0	1
	TST		Wilkowice Beds	12	3	0	0	1	8	0	0	0
	LST	Middle Muschelkalk	Tarnowice Beds	9	1	0	0	0	0	0	0	0
Sequence 3	HST		Diplopora Beds	36	10	4	2	61	0	2	1	0
		Lower Muschelkalk	Karchowice Beds	44	15	10	7	33	7	18	4	7
	TST		Terebratula Beds	12	10	6	4	0	7	0	0	0
Sequence 2	HST		Górażdże Beds	25	8	7	3	21	11	3	1	4
	TST		Upper Gogolin Beds	34	12	5	5	16	10	0	0	6
Sequence 1	TST		Lower Gogolin Beds	37	0	3	0	13	1	0	0	4

Table 2. Secular changes in the dominant ichnoassemblages in the Muschelkalk formations of the Opole sub-region. Data from Stachacz and Matysik (2020) and unpublished.

Sequence stratigraphy (TST – transgressive systems tract; HST – highstand systems tract; LST – lowstand systems tract)		Lithostratigraphy		Dominant ichnotaxon
Sequence 4	HST	Upper Muschelkalk	Boruszowice Beds	unknown
	TST		Wilkowice Beds	*Rhizocorallium*
	LST	Middle Muschelkalk	Tarnowice Beds	rare ichnofossils due to elevated salinity
Sequence 3	HST		Diplopora Beds	rare ichnofossils due to the dominance of grainy facies
		Lower Muschelkalk	Karchowice Beds	*Balanoglossites*
	TST		Terebratula Beds	*Thalassinoides*
Sequence 2	HST		Górażdże Beds	*Oravaichnium*
	TST		Upper Gogolin Beds	
Sequence 1	TST		Lower Gogolin Beds	*Rhizocorallium*

species diversity out of all sequences (Table 1), which resulted from the maximum opening of the adjacent gate (= most oceanic influences onto the region) and the development of sponge-coral reefs (= habitats for non-reefal biota). The most diverse are bivalves and gastropods; the second diverse are corals and brachiopods; other groups are much less diversified (Table 1). For the Karchowice Beds alone, Assmann (1944) counted that among 44 bivalve species, 15 are endemic in Upper Silesia, 12 are exclusively Germanic, 4 are Alpine and 13 occur both in the Alpine and the Germanic provinces. Among 33 gastropod species, two thirds were described as endemic Silesian, 5 species as Alpine and 2 as Germanic.

When it comes to ichnofossils, the Upper Silesian Muschelkalk shows a very high ichnotaxonomical diversity, with 20 softground ichnotaxa, 2 firmground ichnotaxa, 3 hardground ichnotaxa, and undetermined mottles and spots in a soupground suite being identified so far (Stachacz and Matysik 2020). Most ichnospecies are found in all depositional sequences. Nonetheless, monoichnospecific and almost monoichnospecific assemblages of *Rhizocorallium*, *Oravaichnium*, *Thalassinoides*, and *Balanoglossites* dominate and they change stratigraphically (Table 2). This temporal change – along with the increase in the size of key trace fossils – was interpreted to reflect the recovery of tracer-maker communities after the P/Tr biota crisis (Stachacz and Matysik 2020). The bioturbation degree is overall much higher in low-energy open-marine strata than in grainy or dolomitic ones.

DESCRIPTION OF THE VISITED REEF COMPLEX

The environmental context for the sponge-coral reefs

The discussed sponge-coral reefs appear exclusively in the Opole sub-region (Fig. 3) and are a hallmark of the Karchowice Beds which developed during the middle part of the highstand of Sequence 3 (Fig. 2). The highstand shows a clear regressive trend which is nicely expressed in several aspects: (1) facies change (from deep platform to nearshore); (2) sediment brightening (from dark grey to yellow and cream) due to the increase in oxygen contents; (3) overall increase in bed thickness and the contribution of high-energy sedimentary structures; and (4) increase in biota diversity and the number of shallow-water forms. Based on these parameters, the highstand can be subdivided into several major intervals described below.

The highstand begins with a 5-m-thick suite of dark grey nodular lime mudstones (fair-weather deposits) interbedded with grey-beige skeletal wackestones-packstones (tempestites), which build the uppermost Terebratula Beds (Figs. 2, 4A). The strata are heavily burrowed by *Thalassinoides*-forming organisms (Table 2; Fig. 4B) and contain a little diversified assemblage of skeletal fossils (Table 1) dominated by brachiopod *Coenothyris vulgaris* (Fig. 4C). The numerous mm-thick black shale partings indicate a high influx of clay minerals that were most likely washed from land by transgressing water. Collectively, this interval is interpreted to represent an early highstand phase and to have been formed in a deeper platform setting located above the storm wave base and

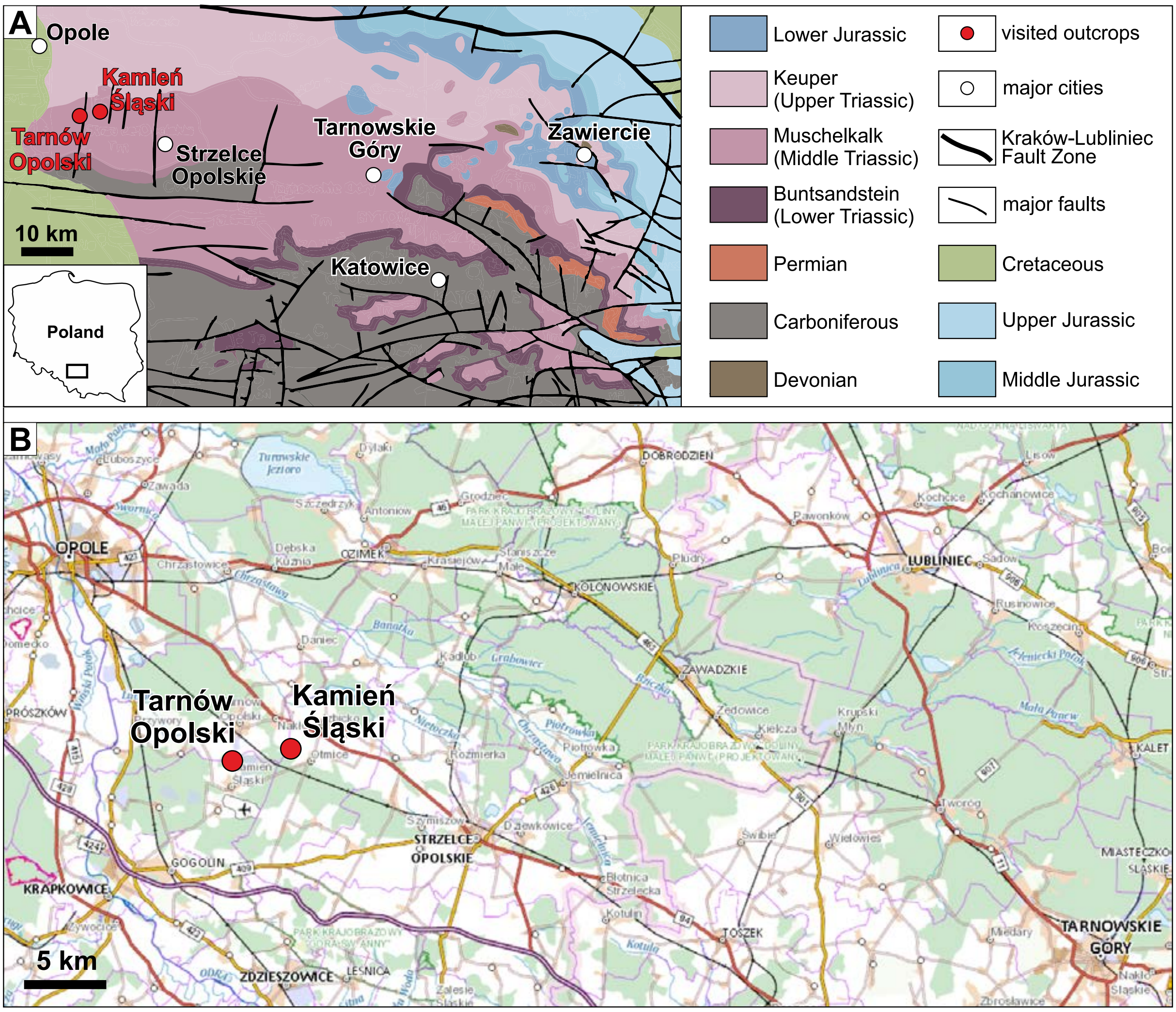

Fig. 3. Location of two main outcrops (Tarnów Opolski and Kamień Śląski) with sponge-coral reefs. **A**. Simplified geological map of the Upper Silesian region. **B**. Road map of the Opole sub-region.

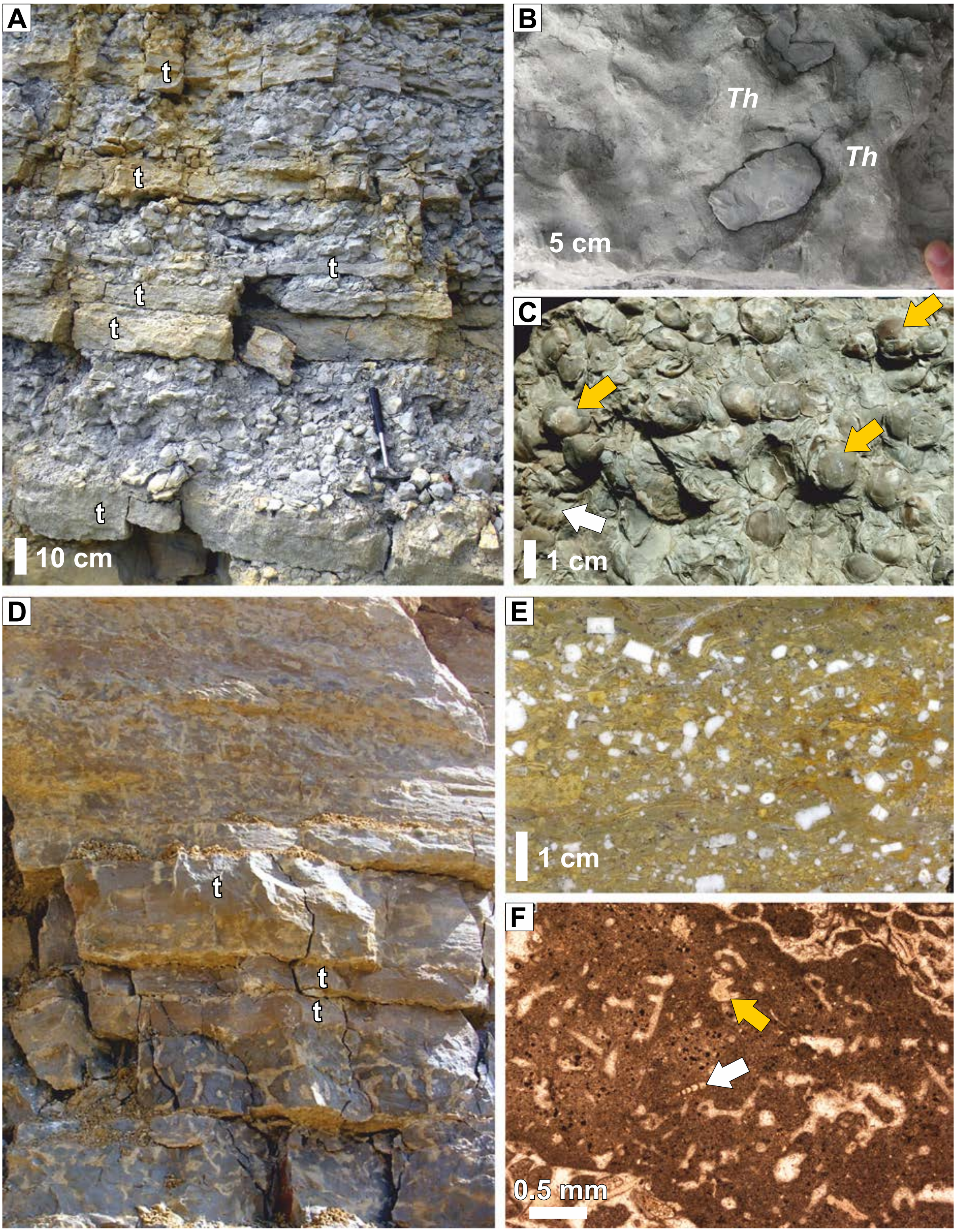

Fig. 4. Selected features of the early highstand systems tract of Sequence 3 in the Upper Silesian Muschelkalk (A–C – uppermost Terebratula Beds; D–F – lowermost Karchowice Beds). **A**. Storm-deposited bioclastic beds (t) within dark grey nodular lime mudstones rich in *Thalassinoides*. Górażdże. **B**. Bedding plane view of lime mudstone with a network *Thalassinoides* burrows. Górażdże. **C**. Bedding plane view of tempestite layer dominated by brachiopod *Coenothyris vulgaris* (yellow arrows), with minor oyster *Umbrostra difformis* (white arrow). Strzelce Opolskie. **D**. Succession of several *Balanoglossites* micritic firmgrounds with yellow dolomitized infill, alternated with bioclast-cortoid-peloid tempestites (t). Strzelce Opolskie. **E**. Example of bioclast-cortoid-peloid tempestite. Strzelce Opolskie. **F**. Mm-sized clump of sponge automicrite with calcite-cemented molds after siliceous spicules. Yellow arrow points at crinoid and white arrow indicates small benthic foraminifer, both stacked within the automicrite. Tarnów Opolski

characterized by some oxygen deficiency and clay input (Bodzioch 1985; Szulc 2000; Matysik 2016). These monotonous rocks are the same over the entire Opole sub-region, indicating uniform conditions within this part of the platform (Fig. 2). The conodont biostratigraphy shows a Pelsonian age for the Terebratula Beds (Zawidzka 1975).

The Terebratula Beds are overlain by the Karchowice Beds having a completely different character, as they are brighter in color, more grainy, thicker bedded, lacking shale partings, and with rich biota including sponge-coral reefs (Assmann 1944; Bodzioch 1989, 1997a, b; Szulc 2000; Matysik 2010). Also, the depositional system becomes to be bathymetrically differentiated into the NW proximal part and SE distal part (Fig. 2), which could have been initiated by some block tectonics and enhanced with time by the discussed sponge-coral reefs which developed in the NW shallower part. Furthermore, the strata underwent advanced diagenesis that obliterated to various degrees some of the primary features, which sometimes makes observations and interpretations uncertain. The Karchowice Beds start with a 5-m-thick interval of medium-grey medium-bedded lime mudstones (fair-weather deposits) interbedded with beige skeletal-peloidal-cortoidal wackestones-to-grainstones (tempestites; Fig. 4D, E). All mudstone beds and some tempestitic beds are heavily penetrated by *Balanoglossites* burrows which belong to the *Glossifungites* ichnofacies diagnostic of firmground omission surfaces and thus point to highly punctuated sedimentation, with rapid depositional events followed by longer pauses, the latter allowing semi-lithification of the substrate and its colonization by *Balanoglossites* producers (Matysik 2010). The burrows are frequently enclosed by a mm-thick dark diagenetic halo that gradually grades into the surrounding host sediment. The haloes have lower $\delta^{13}C$ and $\delta^{18}O$ ratios and increased concentration of redox-sensitive elements (U, As, Mo, Cu, Zn, Pb, Ni) compared to the host micrite, which were interpreted – along with their darker color – to indicate a significant enrichment in organic matter, which most likely resulted from impregnation of the burrow walls with organic mucus by the burrowing organism to prevent a burrow collapse (Matysik et al. 2022). The burrow walls were apparently also in contact with stagnant, saline water filling the burrows, as implied by elevated $^{87}Sr/^{86}Sr$ values relative to the host micrite (Matysik et al., 2022). The strata are Pelsonian in age based on conodont biostratigraphy (Zawidzka 1975). There is no reefs in the area at that time, but isolated mm-sized clumps of sponge automicrite were found in cortoidal-peloidal tempestites (Fig. 4F), which opens a possibility that such buildups might have already existed somewhere north-westwards, or these are just fragments of isolated sponges (Matysik 2010).

This basal 5-m-thick package ends with a <1-m-thick level with first evident sponges, which are highly broken in its lower half (Fig. 5A, B) and intact in the upper half (Fig. 5C, D). The sponges occur as (1) cup-shaped forms up to a few across (Fig. 5D) or (2) highly sinusoidal to almost flat forms up to several decimeters long (Fig. 5C). Most sponges are preserved as automicrite, but some still show a net-like to cubic organization of siliceous megascleres and hence were classified as hexactellids (*Hexactinoderma trammeri* and *Silesiaspongia rimosa*) by Pisera and Bodzioch (1991). The enclosing sediment is mudstone to bioclastic wackestone. The entire buildup can be regarded as a biostrome. This level is seen in the two most distant outcrops (Strzelce Opolskie on the east and Tarnów Opolski on the west) and thus one can assume it occured over the entire Opole sub-region.

Higher up within the Karchowice Beds, a monotonous <7-m-thick section of highly cavernous, recrystallized and patchily dolomitized thin-bedded limestones occurs (Fig. 5E, F). For many years, they were interpreted as diagenetically obliterated sponge biostromes, with caverns regarded as sponge paragasters and intersponge cavities (Szulc 2000; Matysik 2010). This interpretation was based on the close similarity to the fabric of the overlying sponge bioherms. However, the recent ichnological study of Matysik et al. (2022) and Master Thesis of Ryczkowska (2023) showed that the cavities formed by selective karst-related dissolution of the infill and walls of *Balanoglossites* and other undetermined burrows. The burrows cut through several successive 3 to 10 cm thick amalgamated layers of yellow-beige-grey lime mudstones (fair-weather deposits) and peloid wackestones-to-grainstones (tempestites; Fig. 5G, H). It is not clear why these strata were so heavily diagenetically altered compared to the underlying firmgrounds since the only major difference is

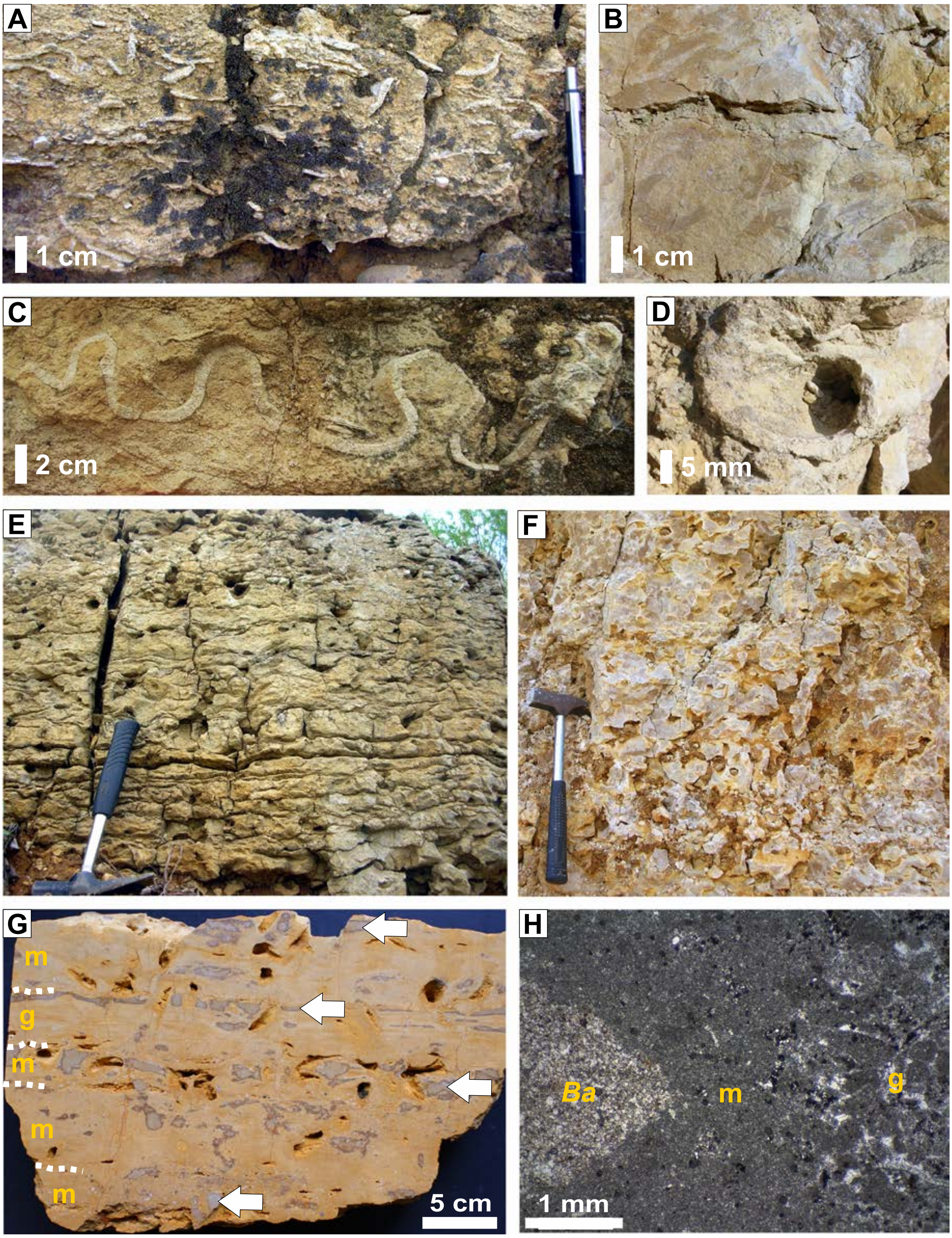

Fig. 5. Selected features of the lower Karchowice Beds. All photos are from Strzelce Opolskie, except for D which is from Tarnów Opolski. **A**, **B**. Broken siliceous sponges in the distal (A) and proximal (B) part of the Opole sub-region. Photos from Matysik (2010). **C**, **D**. Whole siliceous sponges in the distal (A) and proximal (B) part of the Opole sub-region. **E**. Thin-bedded cavernous limestone, formerly interpreted as sponge biostromes and recently recognized as micrite layers cut by vertical burrows. **F**. Cavernous limestone resembling a sponge bioherm fabric, but in fact representing a karst-enhanced burrow system. **G**. Thin amalgamated layers of dolomitized yellow micrite (m) and quasi-planar-laminated peloid grainstone (g), penetrated by burrows some of which have a dissolved infill. Note remnants of early-lithified grey micrite layers (arrows). Photo from Matysik et al. (2022). **H**. Plane-polarized view of micrite (m) and peloid grainstone (g), penetrated by *Balanoglossites* burrow (Ba) with dolomitized infill. Photo from Matysik et al. (2022).

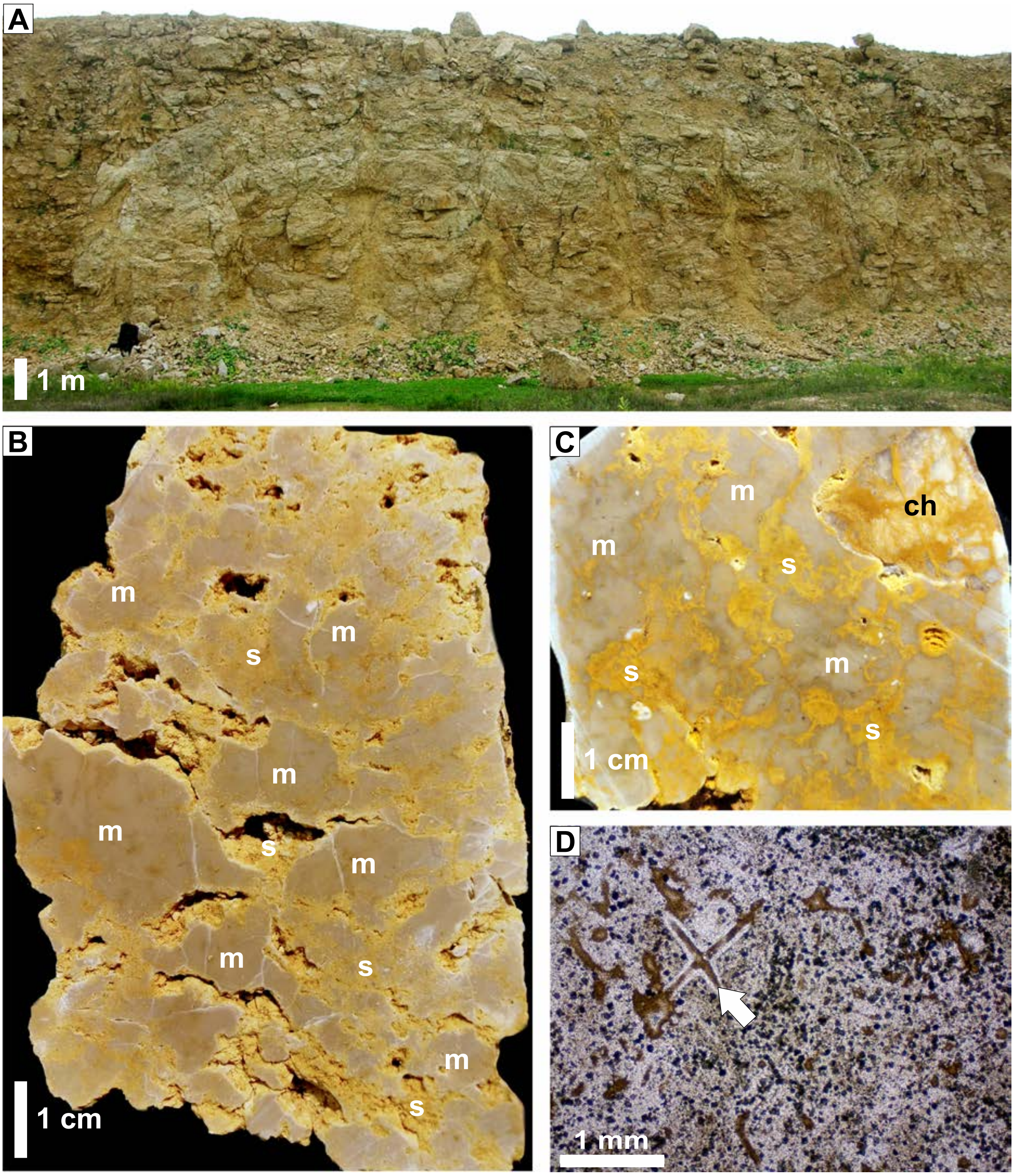

Fig. 6. Selected features of the lower reefs in the Karchowice Beds. **A**. Symmetrical isolated mound with hemispheroidal beds composed of sponge automicrite. The mound is onlapped by peloid-crinoid facies with horizontal bedding. Tarnów Opolski. Photo taken from Matysik (2016). **B**. Cavernous fabric of sponge buildup, showing cm-scale patches of pink sponge automicrite (m) and yellow dolomitized and partly dissolved intersponge sediment (s). Kamień Śląski. **C**. Fabric of sponge buildup, showing cm-scale patches of grey sponge automicrite (m) and yellow dolomitized intersponge sediment (s). Part of the fabric is replaced by silica concretion (ch). Kamień Śląski. **D**. Plane polarized view of silica concretion in C, showing relic of sponge spicule (arrow) in microquartz mass.

the bed thickness. This complex is twice thinner in the SE distal part (3 m) than in NW proximal part (7 m), which is the first sign of basin differentiation (Matysik 2010). Based on her conodont work, Zawidzka (1975) placed the Pelsonian-Illyrian boundary around 10 m above the base of the Karchowice Beds, which corresponds to the middle part of this cavernous complex, but it is not explicitly stated in her paper.

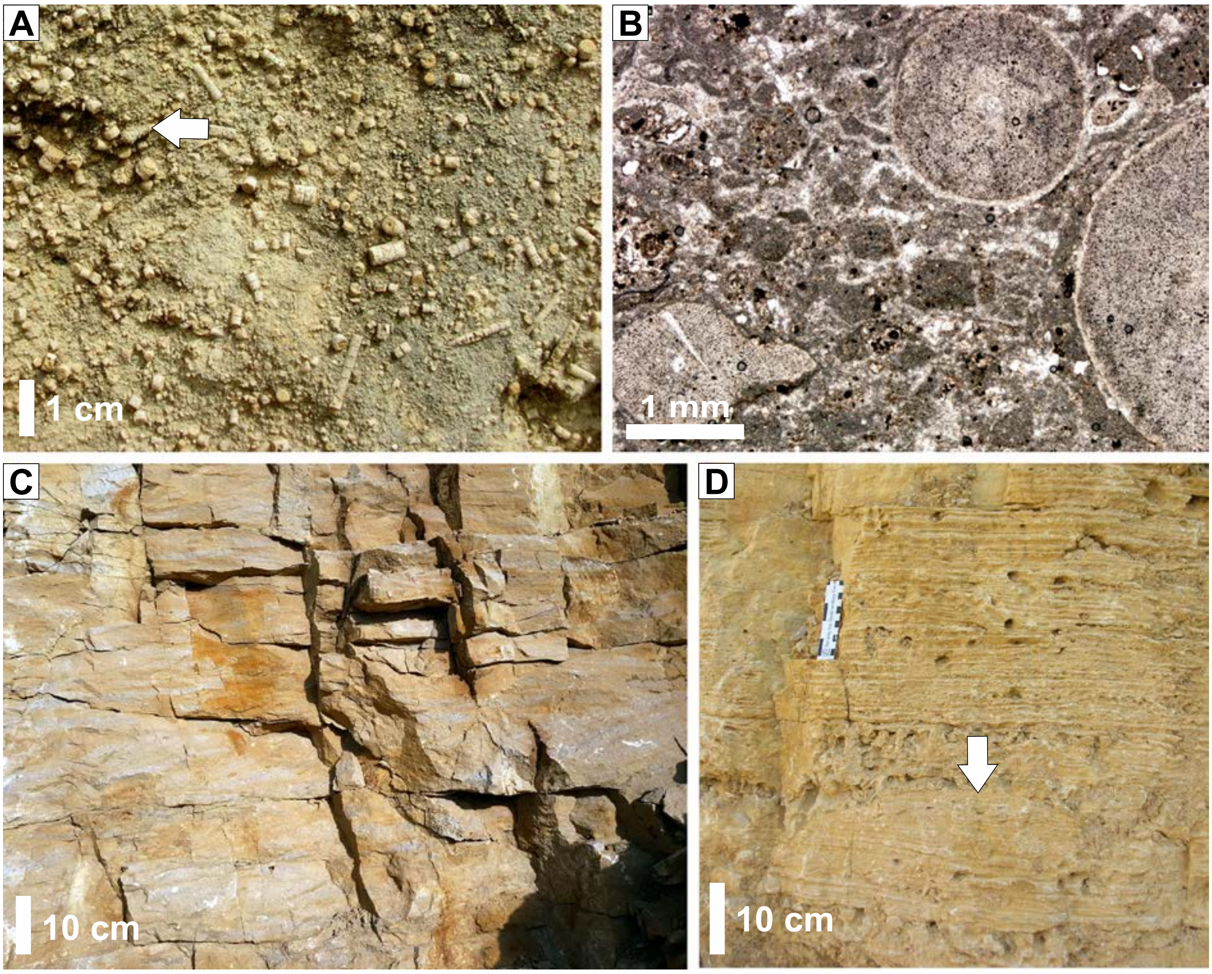

Fig. 7. Selected features of a high-energy sand complex onlapping the lower reefs in the Karchowice Beds. **A**. Bedding plane view of peloid-crinoid facies, with abundant articulated crinoid columnals and isolated echinoid spines (arrow). Kamień Śląski. Photo taken from Matysik (2010). **B**. Plane-polarized view of peloid-crinoid packstone-grainstone. Kamień Śląski. **C**. High-angle tabular cross-bedding in peloid-crinoid facies. Kamień Śląski. **D**. Subaqueous megaripple (arrow) covered with cavernous burrowed sediment that was previously intepreted as prostrate sponges. Tarnów Opolski. Photo taken from Matysik (2010).

The major differentiation of the Opole sub-region starts immediately above this complex, as sponge-coral reefs appear in the NW proximal part. The reefs occur in two levels enclosed by detrital carbonate facies (Fig. 2). This repetition of the succession is interpreted to have resulted from a short-term deepening of the basin within an overall shallowing trend (Szulc 2000). The reefs and the adjacent facies from the two levels differing in some aspects and thus they are described separately below (in the stratigraphic order). The lower reefs occur as isolated, semicircular mounds 6–8 m high and 20–30 m across, with spacing ranging from c. 10 to 100 m. Most reefs consists of distinct beds <1 m thick that follow the general buildup shape, but are thinner on the sides (Fig. 6A), indicating that the reefs grew mainly vertically (aggradation), formed distinct elevations above the seafloor, and were not largely covered with sediment during their growth. Less common are reefs comprising irregular lenses and wedges or a massive structure (see Fig. 13A) – in their case it is difficult to conclude about their growth patterns. Regardless of the shape, the reef fabric is a mass of cm-scale, irregularly shaped bodies of beige-pink micrite with isolated bioclasts, which are separated by caverns or yellow dolomitized patches (Fig. 6B, C). Under the microscope, the beige-pink micrite is homogeneous to clotted and sometimes contains calcite- or silica-filled molds after siliceous sponge spicules (Fig. 6D) – therefore is interpreted as automicrite formed by bacterial decaying of sponge tissues. The surrounding yellow dolomitized patches are probably detrital micrite and bioclastic wackestone deposited between the sponges. In some of those reefs,

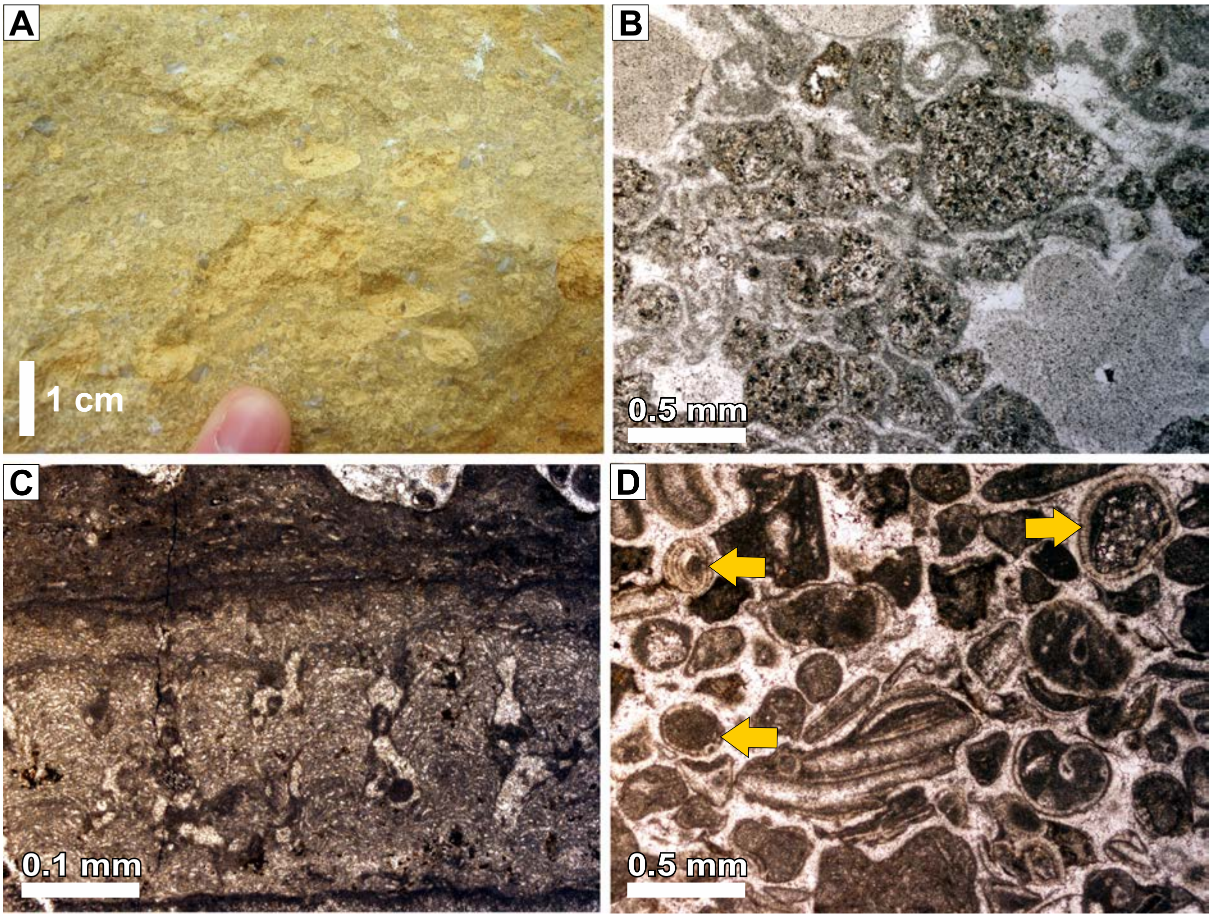

Fig. 8. Selected features of high-energy facies capping the lower reefs in the Karchowice Beds. **A**. Peloid-oncoid-crinoid grainstone. Kamień Śląski. **B**. Detailed plane-polarized view of A, showing peloid-crinoid grainstone, with selective dolomitization of peloid central parts. **C**. Plane-polarized view of oncoid cortex formed by Girvanella. Tarnów Opolski. **D**. Plane-polarized view of grainstone with cortoids, gastropods, peloids and superficial ooids (arrows). Tarnów Opolski.

sponges are replaced towards the reef top by corals (more details in section ‘Corals’). This shift is interpreted to reflect a gradual shallowing of the basin. No conodonts were reported from the reefs (Zawidzka 1975), but they must be earliest Illyrian (possibly latest Pelsonian) in age, judging from the underlying and overlying facies with conodonts.

The lower reefs are onlapped by a 8-m-thick unit of medium-bedded peloid-crinoid packstones-grainstones with large-scale cross-bedding and megaripple cross-lamination (Figs. 2, 6A, 7). They most likely formed laterally migrating, high-energy subaqueous dunes at water depths of a few meters (Szulc 2000; Matysik 2010). They are interpreted to have covered the reefs after the reef development when the basin shallowed and intersected the fair-weather wave base, which is evidenced by the reef internal bedding that persists around the entire buildups. These peloid-crinoid packstones-grainstones are found only in the NW proximal part of the Opole sub-region where they are Illyrian in age according to conodont data (Zawidzka 1975). In the SE distal part, they are replaced by the same alternation of *Balanoglossites* firmgrounds and tempestites (Fig. 2) as observed in the basal part of the Karchowice Beds (Fig. 4D–F).

Some of the lower reefs are capped by <1-m-thick peloidal-oncoidal-cortoidal grainstone with *Girvanella* oncoids and superficial ooids (Figs. 2, 8). This facies is considered to record the shallowest environmental conditions before a short-term deepening and repetition of the succession (Szulc 2000; Matysik 2010).

The repeated succession starts with the same highly cavernous, recrystallized and patchily dolomitized thin-bedded limestones as observed below (Figs. 2, 9). The thickness of this complex

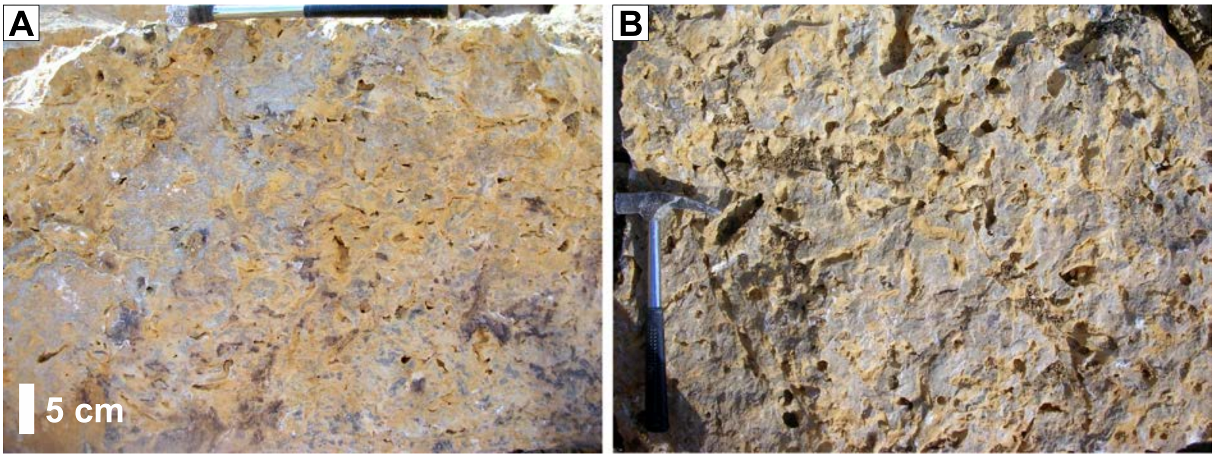

Fig. 9. Upper cavernous limestone in the Karchowice Beds, Tarnów Opolski. **A**. Highly burrowed fine-grained limestone, with most burrow infills being selectively dissolved by late karstification to form caverns. **B**. Bedding plane view of A.

increases from 7 m in the SE distal zone to 10 m in the NW proximal zone where the uppermost part of these cavernous limestones is interfingered with reefs of the upper reef level (Figs. 2, 9A, B). Those reefs have similar shapes, dimensions, spacing and sponge-dominated fabric as the lower reefs, but their structure is only massive and their relief above the seafloor was only c. 4 m. They must have also formed in a much shallower environment of probably only several meters, as the reef flanks are onlapped with various grainstones. The lowermost 2 m of these grainstones are dominated by peloids and oncoids, the latter observed only in meter-scale depressions between two nearby sponge buildups (Fig. 10A, D, E). The oncoids are microbial and frequently developed around coral fragments (Fig. 10D). The majority of these corals are badly preserved, but some were classified as *Volzeia* cf. *szulci* and ?*Retiophyllia* sp. (Matysik 2010). Their presence shows that at least some reefs of the upper level were co-created by corals, albeit in situ preserved corals have not been found so far. This grainstone package ends the Karchowice Beds (Fig. 2). This entire repeated succession belongs to the Illyrian (Zawidzka 1975).

The peloid-oncoid grainstone package – along with the tops of the highest reefs – is directly overlain by 2 m of white ooidal grainstones of the basal Diplopora Beds (Figs. 2, 10A, C, 11A, B). Scarce crinoids, brachiopods and undetermined coral colonies indicate stenohaline conditions of these high-energy oolitic shoals (Fig. 11C–F). Higher up, c. 5 m of lagoonal green algae-peloid packstones-grainstones occur and mark the final filling of accommodation space during the prolonged highstand of Sequence 3 (Figs. 2, 10A, 11G–I). The Diplopora Beds must have prograded from the NW onto the Karchowice Beds.

Corals

Middle Triassic corals from Upper Silesia, mostly from the visited Opole sub-region, have been described or mentioned in the literature since the middle of 19th century (Beyrich 1852; Eck 1865, 1879; Roemer 1870; Ahlburg 1906; Schmidt 1928, 1938 - for bibliographic data see Morycowa 1988; Weissermel 1925; Assmann 1937; Morycowa 1988, 2018; Morycowa and Szulc 2000, 2006, 2007, 2010; Morycowa et al. 2006; Matysik 2010; Kołodziej et al. 2018). In terms of coral taxonomy most important are papers by Weissermel (1925) and Morycowa (1988). Various aspects of coral and reef paleoecology were described by Morycowa (1988), Bodzioch (1997a), Szulc (2000), Łabaj (2007), Morycowa and Szulc (2007, 2010), Matysik (2010), Kołodziej et al. (2018) and Hagdorn et al. (2021).

The corals belong to 16 species and 14 genera (Table 3; Figs. 12–15). Three genera (*Eckastraea*, *Silesiastraea*, *Opolestraea*) and four species described by Morycowa (1988, 2018) are new. Most specimens and also the largest specimens were collected from the Karchowice and Diplopora Beds in two localities in the Opole sub-region: Tarnów Opolski and Kamień Śląski (both localities will be visited during this fieldtrip). Less common specimens were found in the Kraków-Silesia

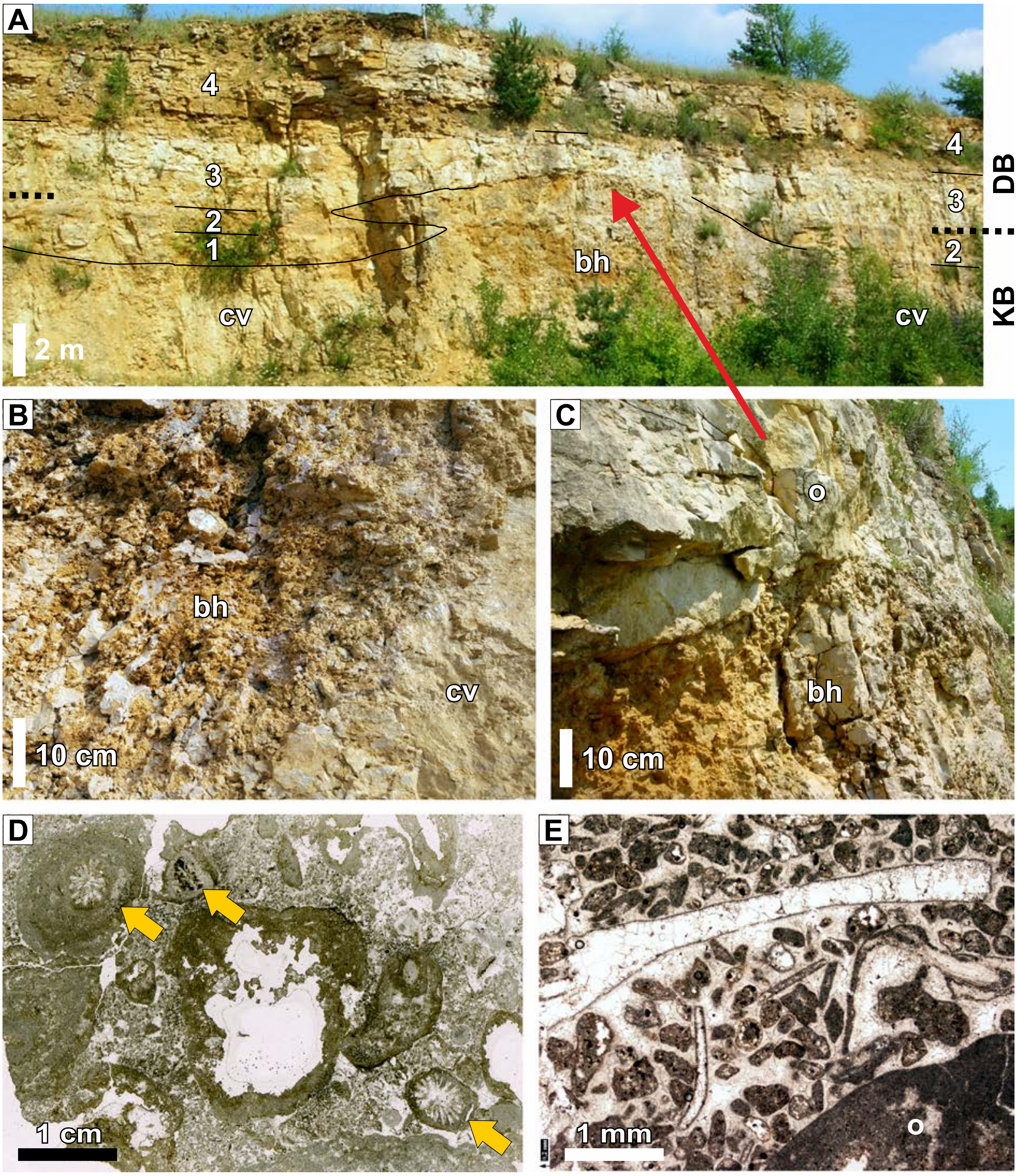

Fig. 10. Selected features of the upper reefs and the adjacent facies at the transition from the Karchowice (KB) to Diplopora (DB) Beds. **A**. Spatial relationships between sponge bioherms (bh), cavernous limestones (cv), oncoid-peloid grainstones (1), peloid grainstones (2), ooid grainstones (3) and green algae-peloid grainstones (4). Kamień Śląski. **B**. Contact of sponge bioherm (bh) and cavernous limestone (cv). Kamień Śląski. **C**. Detail of A, illustrating top of the bioherm (bh) onlapped by ooid grainstone (o). **D**. Detail of A, showing oncoid-peloid grainstone with some oncoids developed around fragments of phaceloid corals (arrows). **E**. Detail of A, illustrating peloid grainstone with bioclasts and oncoid (o).

sub-region in Stare Gliny, Zawiercie and Pogorzyce where they occur in the Diplopora Beds and never form reefs, only isolated colonies. For location of coral sites described by Weissermel (1925) see Morycowa (1988).

Morycowa (1988) interpreted the coral buildups from the Karchowice Beds in the Opole sub-region as originated in a warm, calm, shallow-water (probably less than 40 m deep) environment.

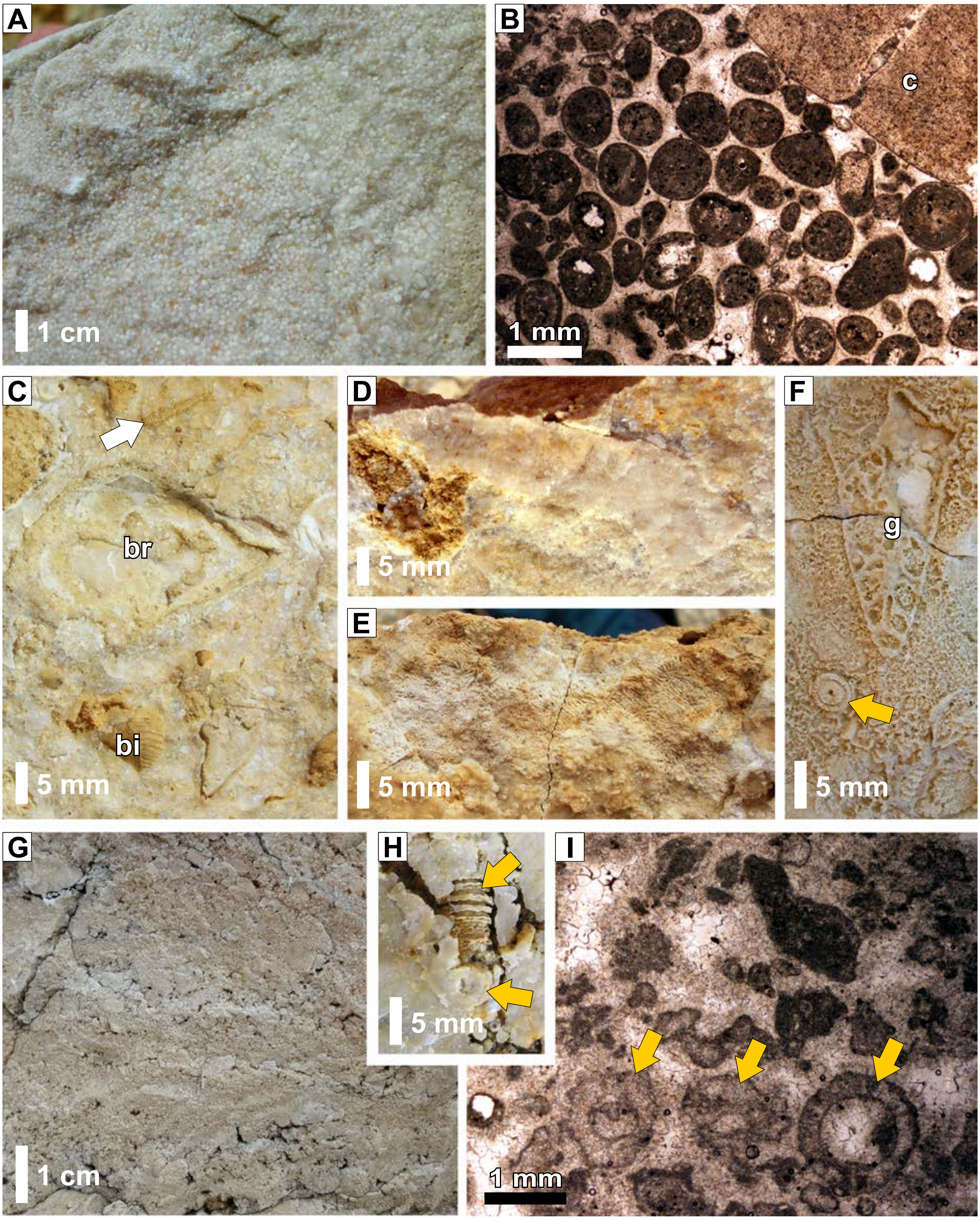

Fig. 11. Selected features of the late highstand systems tract represented by the Diplopora Beds. **A**. Ooid grainstone. Tarnów Opolski. **B**. Plane-polarized view of ooid grainstone with a single crinoid (c). Kamień Śląski. **C**. Brachiopod (br), bivalve (bi) and diplopore algae (arrow) in ooid grainstone. Tarnów Opolski. **D**, **E**. Cross-sectional and bedding-plane view of coral in ooid grainstone. Tarnów Opolski. **F**. Crinoid (arrow) and gastropod (g) in ooid grainstone. Tarnów Opolski. **G**. Green algal grainstone. Tarnów Opolski. **H**. Detailed view of G, illustrating diplopore green algae (arrows). **I**. Thin section view of green algae grainstone with diplopores (arrows) and peloids derived from desintegration of green algae. Kamień Śląski.

Currently, the best outcrop of corals is a large mound of the lower reefs in the Tarnów Opolski quarry (Fig. 13A). This mound starts with a sponge boundstone that is upwards replaced by corals: first by

Table 3. List of coral species from the Middle Triassic of Upper Silesia.

Coral species described by Morycowa (1988, 2018), Morycowa and Szulc (2006) and Morycowa et al. (2006)
Suborder Stylophyllina Beauvais, 1981
Family Stylophyllidae Volz, 1896 *Stylophyllopsis* sp.
Suborder Pachythecalina Eliášová, 1978
Family Volzeiidae Beauvais, 1981 *Volzeia szulci* Morycowa, 1988
Suborder Archaeocoeniina Alloiteau, 1952
Family uncertain *Coelocoenia* cf. *decipiens* (Laube, 1865) *Cyathocoenia* sp.
Suborder Faviina Vaughan et Wells, 1943
Family Pamiroseriidae Melnikova, 1984 *Pamiroseris silesiaca* (Beyrich, 1852) *Pamiroseris* sp. *Morycastraea opoliensis* Morycowa, 1988
Family Cuifastraeidae Melnikova, 1983 *Silesiastraea weissermeli* Morycowa, 1988
Family Tropiastraeidae Melnikova, 1984 ?*Chevalieria tenuiseptata* Morycowa, 1988
Suborder Caryophyliina Vaughan et Wells, 1943
Family Eckastraeaidae Morycowa, 2006 *Eckastraea prisca* (Weissermel, 1925) *Opolestraea exporrecta* (Weissermel, 1925)
Coral species described by Weissermel (1925) and in older papers (see Morycowa 1988, 2018)
Family Conophylliidae Alloiteau, 1952 *Omphallophyllia triasina* (Dunker, 1851)
Family Thecosmiliidae Duncan, 1884 *Montlivaltia chonocalyx* Weissermel, 1925 *Thecosmilia compressa* Weissermel, 1925 *Thecosmilia caespitosa* Reuss, 1865
Family uncertain *Phyllocoeniella globosa* Weissermel, 1925

Volzeia szulci (Figs. 12A, B, 13B, C) and higher up by *Pamiroseris silesiaca* (Figs. 12C, 14, 15). The two corals show contrasting growth forms, suggesting they grew in different sedimentary regimes.

Thin branching colonies of *Volzeia szulci* attain up to 40 cm in hight. The unbroken character of the branches, co-occurrence with sponges, mainly pure micritic matrix and occurrence directly over the sponge facies suggest that the basal part of the mound originated in a slightly deeper platform environment and under rapid sedimentation conditions. In contrast, the sedimentary environment of *P. silesiaca* in the higher part of the reef was interpreted as very shallow, periodically influenced by turbulent high-energy events, leading to mud in suspension and influx of sediments that interrupted coral growth (Morycowa and Szulc 2010). Differences in sedimentation rates during the growth of both coral species are also indicated by rare epibionts and microbial crusts on branches of *V. szulci* (Fig. 13B) and their common presence on the skeletons of *P. silesiaca* (figs. 5, 6, 8, 9 in Kołodziej et al. 2018 and Fig. 15A in the present paper).

Recently, platy corals *P. silesiaca* from Tarnów Opolski were the subject of morpho-functional analysis (Kołodziej et al. 2018). Coral plates – up to 24 cm wide (mostly up to 12 cm) and 1–1.5 cm thick – were studied in the outcrop where they constructed two platestone layers, each up to 50 cm thick. *Pamiroseris silesiaca* was interlayered with crinoidal wackestone-packstone, mudstone and microbialites (Figs. 14, 15). Undersides of the coral plates were encrusted by epibionts, mainly by serpulid-like worms. The sedimentary environment in which *P. silesiaca* grew was interpreted as a shallow, turbid-water environment with dominantly moderate hydrodynamics and low net sedimentation. Based on the euphotic floor model of Rosen et al. (2002), platy morphology of *P. silesiaca* was interpreted as an optimal growth form in a low-light environment, not because of depth,

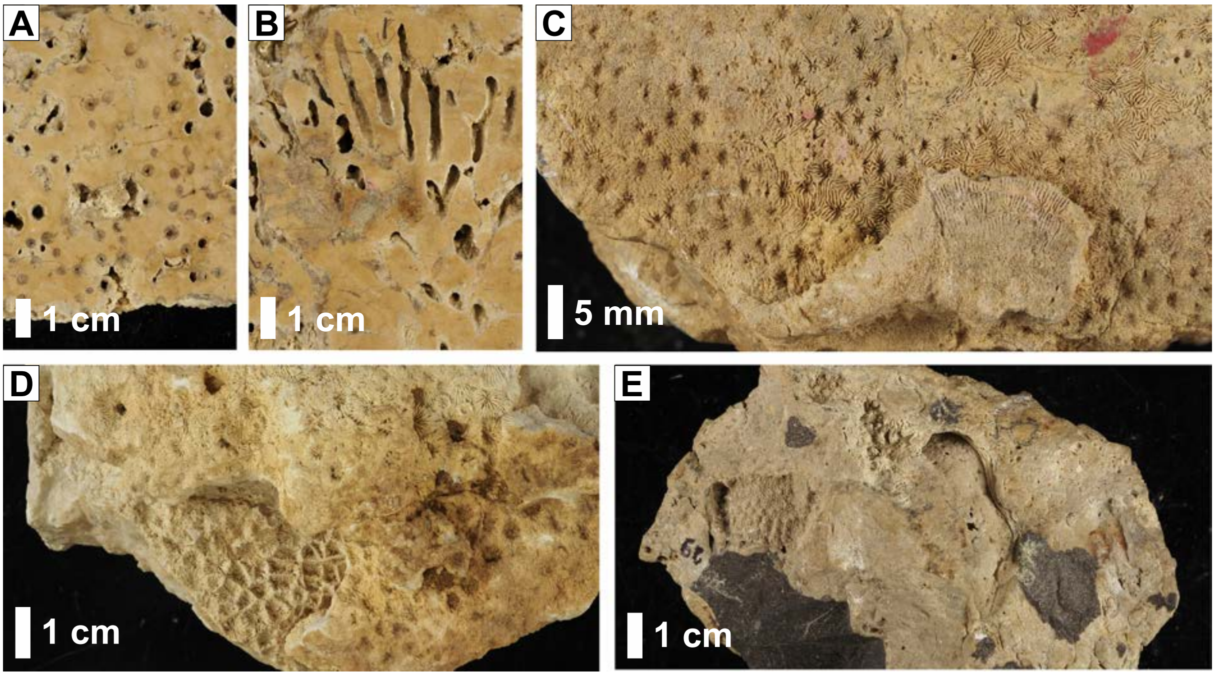

Fig. 12. Main corals from the Middle Triassic of Tarnów Opolski (A–D) and Stare Gliny (E). **A**, **B**. *Volzeia szulci* Morycowa, 1988 in transverse and vertical sections. Most of corallites are dissolved. **C.** Upper surface of platy coral *Pamiroseris silesiaca* (Beyrich, 1852). **D**. Various calicular morphology of *Eckastraea prisca* (Weissermel, 1925). **E**. Cliff breccia with corals between and encrusting clasts of Devonian dolostones. All illustrated corals are from the collection of Elżbieta Morycowa (see Morycowa 1988) housed at the Nature Education Center of the Jagiellonian University in Kraków (coll. UJ 34P/2).

but due to turbidity. Resuspension of carbonate mud during storm events resulted in growth-interruptions of corals and decreased light levels. Epibionts on the aboral surfaces of *P. silesiaca* imply that flattened coral morphology was not an adaptation to the substrate conditions (soft or hard substrate). This supports the hypothesis that at least some of the earliest scleractinian corals had photosymbionts like modern zooxanthellae. *Pamiroseris silesiaca* has formed platy assemblages also in the neighboring Kamień Śląski quarry (Morycowa 1988), but presently they are not visible. Photosymbiotic status of the Late Triassic corals is based on isotopic compositions of the skeleton and intra-skeletal organic matrix as well as fine-scale skeletal banding (Stanley and Swart 1995; Tornabene et al. 2017; Frankowiak et al. 2017, 2021).

Assemblages of *P. silesiaca* are regarded as a fossil example of modern shallow-water mesophotic reefs developed in a nearshore, turbid-water environment (Morgan et al. 2017). However, mesophotic coral ecosystems (MCEs) are typically developed in a deeper environment (30–150 m; Lesser et al. 2009). *Leptoseris fragilis* Milne Edwards and Haime, 1849, a modern zooxanthellate coral with a plate-like morphology is the best known example of the coral adapted to poorly-lit conditions. Its skeleton morphology, showing similarities to the Jurassic–Cretaceous suborder Microsolenina (Morycowa and Roniewicz 1995; Insalaco 1996), enhanced heterotrophic nutrition and some physiological adaptations enable the growth of this coral in such an environment.

Platy coral assemblages occur also in the Paleozoic. Flattened morphology of some Silurian and Devonian tabulates and rugose corals from Gotland (Sweden) and the Holy Cross Mts. (Poland), respectively, have been interpreted as an adaptation not to the substrate conditions, but to efficient light harvesting to low-light environment. As a consequence, it may evidence photosymbiosis in some Paleozoic corals. The described Silurian and Devonian platy coral assemblages would be the oldest MCEs (Zapalski et al. 2017; Zapalski and Berkowski 2019). Fossil deep-water mesophotic coral ecosystems were more common in the Mesozoic and Cenozoic (Insalaco 1996; Rosen et al. 2000; Kołodziej and Bucur 2020; Wierzbowski and Stolarski 2023). Anisian platy coral assemblages from Tarnów Opolski are the oldest example of shallow-water MCEs (Kołodziej et al. 2018).

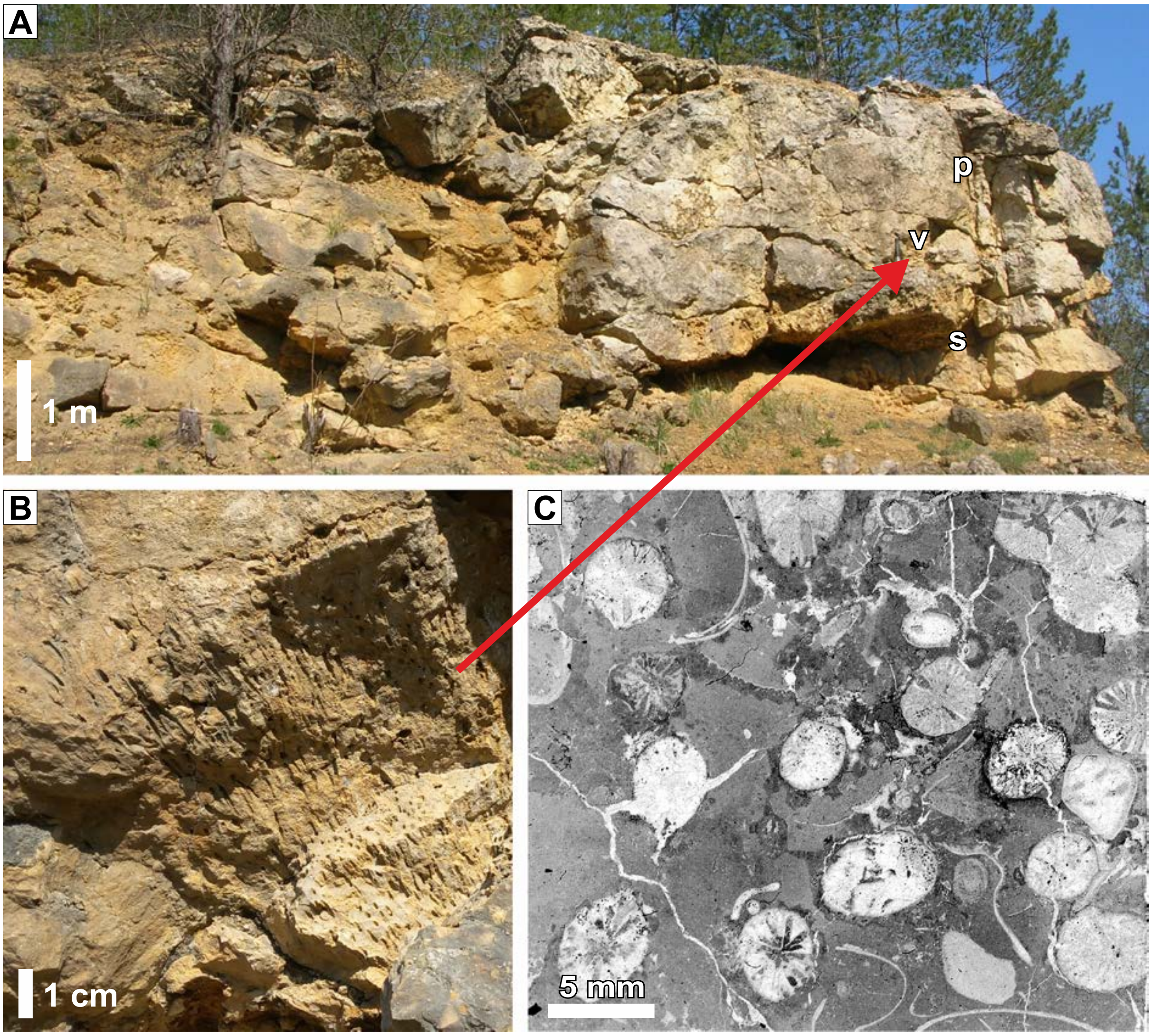

Fig. 13. **A**. General field view of the coral-dominated reef mound in Tarnów Opolski. The reef constructors change upwards from sponges (s), to phaceloid coral *Volzeia szulci* (v), to platy coral *Pamiroseris silesiaca* (p). **B**. Detailed field view of coral pillarstone formed by *V. szulci*, now being mostly dissolved. **C**. Thin section scan showing *V. szulci*. Dark micrite is probably of microbial origin.

Modern shallow and deep-water mesophotic coral ecosystems are proposed as potential refugia and/or propagule sources for reef corals and other organisms from shallow, clear-water reefs damaged by environmental stressors (Lesser et al. 2009). Corals from turbid coral reefs (mesophotic environment) exhibit high tolerance to bleaching (see Zweifler et al. 2021).

The discussed reef complex in Upper Silesia was ultimately killed by shallowing of the basin. This is evidenced by high-energy, micrite-free facies occurring above both reef levels (Szulc 2000; Matysik 2010; Morycowa and Szulc 2010).

Diagenesis

The visited reef-bearing Karchowice Beds and the overlying Diplopora Beds underwent complex diagenetic alterations, starting with early diagenesis, mainly (1) bacterially mediated decay of sponge tissues, (2) micritization of grains and (3) cementation of sediments with isopachous aragonitic rims around grains and microcrystalline cement within micrite. These processes are, however, overshadowed by later diagenesis: dolomization, stylolitization, recrystallization, cementation and dissolution, which significantly modified the former fabrics and often obliterated them completely.

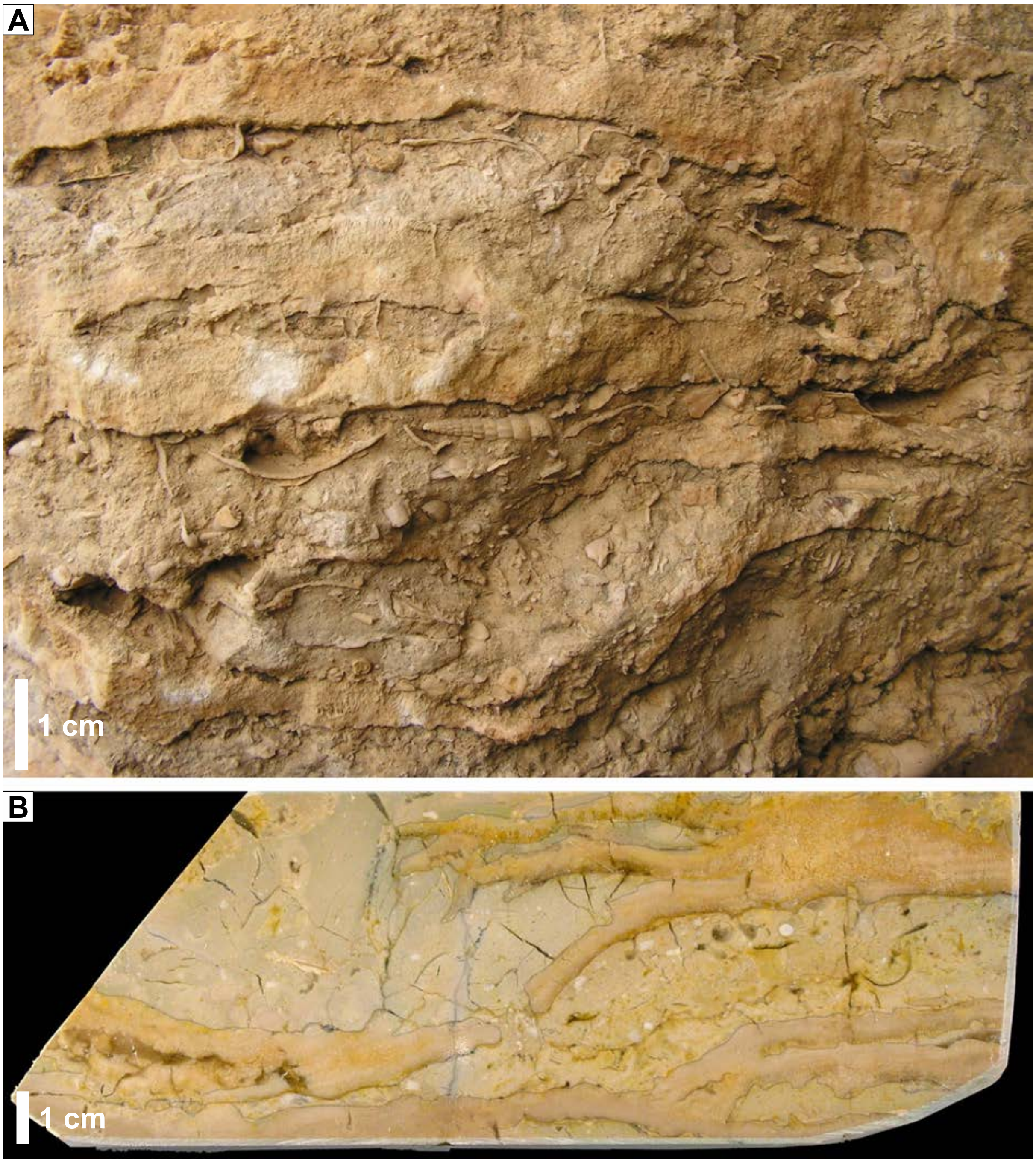

Fig. 14. **A**. Field photograph of coral platestone built by *Pamiroseris silesiaca*. Numerous bioclasts (crinoids, bivalves, large shell of gastropod) occur in the packstone matrix. **B**. Polished slab of *P. silesiaca* in a vertical section. Note coral growth-interruptions visible as ragged margins of the colonies.

The processes are described briefly below, but their parent fluids and relative timing are not well understood.

Dolomitization is generally patchy and follows primary fabrics. In the Karchowice Beds, it selectively affects (1) infill of *Balanoglossites* burrows (Figs. 4D, 5G, H) and (2) areas between sponge automicrite within the reefs (Fig. 6B, C). In the Diplopora Beds, it preferentially concentrates within green algae-peloid packstones-grainstones. The process was probably related to the reflux of evaporatively concentrated brines from the overlying lagoons of the Tarnowice Beds.

Recrystallization is much more pervasive than dolomitization, as it affects whole complexes. It is seen as (1) common microspar replacing primary fabrics and (2) blotchy cathodoluminescence

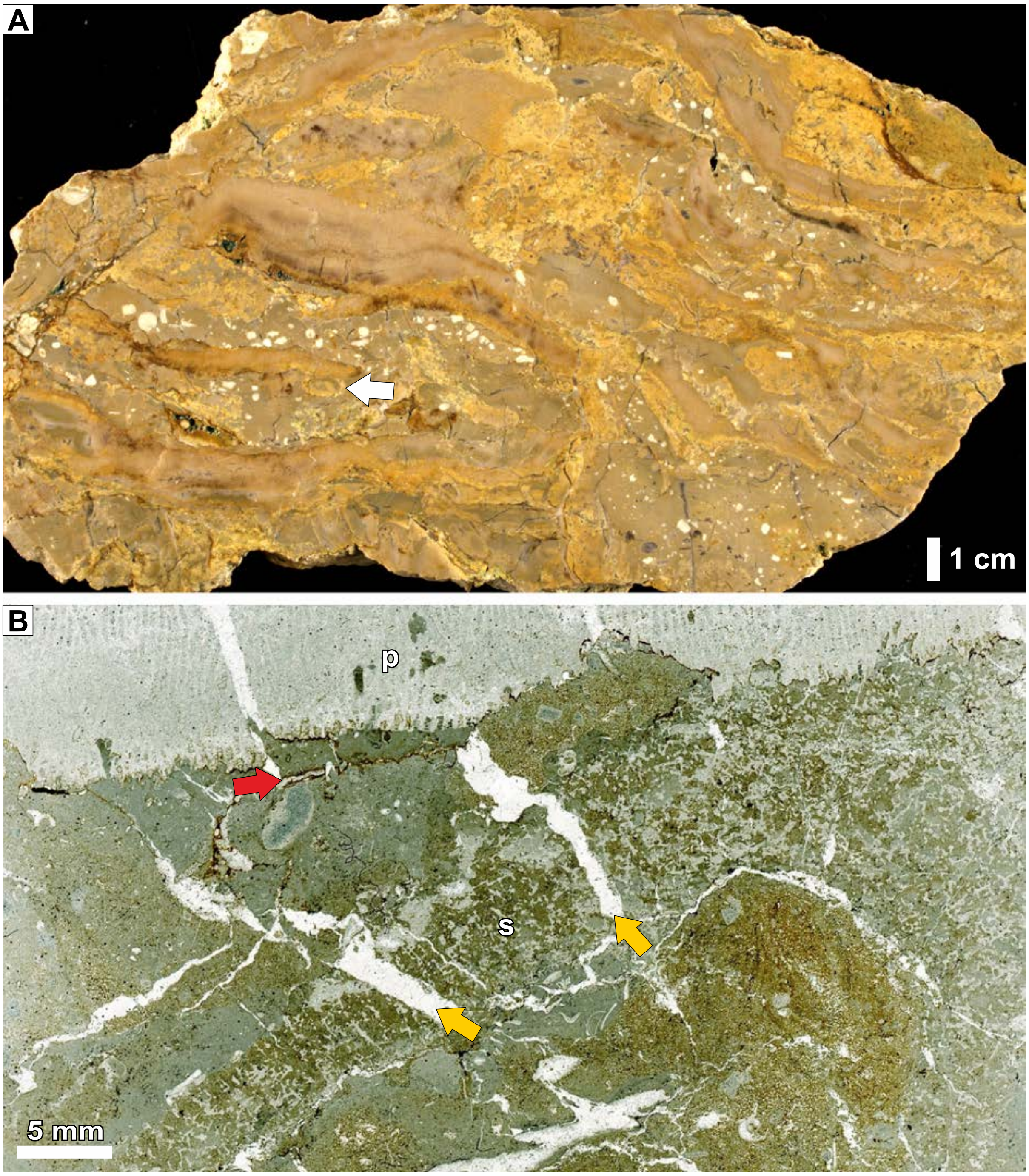

Fig. 15. **A**. Polished slab of *Pamiroseris silesiaca* in a vertical section. Note numerous crinoids. Arrow indicates *Terebella* sp. encrustation (agglutinated worm) on the lower coral surface. **B**. Thin section scan showing siliceous sponge (s) and lower surface of *P. silesiaca* (p). Both are pierced by calcite-filled veins (yellow arrows) which in turn are cut by stylolites (red arrow).

in most dolomite crystals. It also led to weakening of the rock and its disaggregation into a friable mass of crystals, producing a "sanded" or "powdered" fabric (Dżułyński and Kubicz 1971). Recrystallization clearly disappears in the lowermost Karchowice Beds, suggesting that the recrystallizing fluid penetrated the succession from the top. Such recrystallizing fluids are typically meteoric; if this was the case here the fluid could have theoretically penetrated the succession during the Early Jurassic, Early Cretaceous and Cenozoic emersion periods. Each of the three possibilities is problematic. The first two scenarios seem to be impossible because the strata were deeply buried under younger strata during these time intervals. The third scenario is implausible too because recrystallization would have to post-date late calcite cements which display no evidence for recrystallization.

The discussed calcite cements include drusy, blocky and poikilotopic varieties. They fill cm-scale dissolution vugs and fractures (Fig. 15B).

Dissolution is the most apparent process in the strata, manifested as ubiquitous voids of different sizes. The were at least two different dissolution events separated by calcite cementation. The pre-calcite dissolution produced cm-scale vugs scattered across the strata, with many vugs being now occluded with calcite cements. The dissolving fluid is unknown, but the process took place at some stage of burial which opens a possibility for aggressive hydrothermal or burial brines. In contrast, the post-calcite dissolution was related to meteoric water and occurred after telogenic uplift of the strata in the Cenozoic, as this karstification produced both subsurface and surface forms. The subsurface forms include vugs and caverns, many of which are developed by selective dissolution of dolomitized infill of *Balanoglossites* burrows (Figs. 5E–G, 9) and areas between sponge automicrite (Figs. 6B, C, 10B, C). The surface forms are decameter-scale sinkholes filled with terra rosa, Miocene lignites and Quaternary tills and sands (Szulc and Worobiec 2012).

Stylolites are the only evidence of chemical compaction in the strata. They are abundant and cut through calcite cements (Fig. 15B). Their relative timing with other diagenetic events is unknown, however.

DESCRIPTION OF OUTCROPS

STOP 1. Tarnów Opolski – active quarry of Zakłady Wapiennicze Lhoist S.A.

Internal structure and succession of a sponge-coral reef

The quarry exposes the uppermost part of the Terebratula Beds, the complete succession of the Karchowice Beds, and the basal part of Diplopora Beds. The quarry is currently in the process of recultivation and flooding, and hence only a single sponge-coral reef of the lower reef level is accessible, but luckily this reef contains the most spectacular corals found in situ in the region.

The reef consists of numerous lenses and wedges of different thicknesses (< 1 m) and lateral extent (<20 m). The lower half of the buildup is composed of sponge framestone interpreted to have developed in a slightly deeper platform setting. In contrast, the upper half of the reef is dominated by corals: first phaceloid *Volzeia szulci* forming a pillarstone and then platy *Pamiroseris silesiaca* forming a platestone. The corals are believed to have grown in a slightly shallower environment than sponges, reflecting the overall shallowing of the basin. More information about the corals is provided in section ‘Corals’.

STOP 2. Kamień Śląski – active quarry of Zakłady Wapiennicze Lhoist S.A.

Morphology, arrangement and fabric of the sponge-coral reefs and their relation to the adjacent facies

The quarry exposes a 30-m-thick shallowing-upward succession comprising both reef levels of the Karchowice Beds and the overlying Diplopora Beds. The outcrop provides an opportunity to observe the spatial relationships between the reefs and the onlapping facies. All the reefs are composed only of sponges, and so far no corals have been found in them. The lower reefs are onlapped by peloid-crinoid packstones-grainstones with large-scale cross-bedding interpreted as subaqueous dunes. In contrast, the upper reefs are onlapped by peloid-oncoid grainstones, which together with the reef tops are capped ooid grainstones succeeded by green algal-peloid grainstones marking the final phase of basin infilling.

Acknowledgements

The authors are grateful to the Management of Zakłady Wapiennicze Lhoist S.A. for granting permission to visit the quarries. Michał Stachacz (Jagiellonian University) greatly helped in elaborating one of the sponge-coral reefs.

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The Conference has been financially supported by the programme "Excellence Science" of Ministry of Education and Science Republic of Poland

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ISBN 978-83-969205-2-2

14th Symposium of the International Fossil Coral and Reef Society
Poland, 10-16 September 2023