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An Upper Devonian Kadzielnia-type carbonate buildup in Skrzelczyce Quarry, southern Holy Cross Mountains (Poland)

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ABSTRACT:

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In Skrzelczyce Quarry, located in the southern part of the Holy Cross Mountains in central Poland, a large Upper Devonian carbonate mound is exposed. The Skrzelczyce mound, developed as massive and faintly bedded limestones, measures nearly 100 m in lateral extent and over 20 m in thickness, and laterally passes into coral-rich biostromal limestones belonging to the Sitkówka Beds. Four facies have been identified within the massive limestone unit: stromatactis-bearing limestones with scarce macrofossils (M1), macrofossil-rich limestones (M2), stromatoporoid-microbial limestones (M3), and limestones with fenestral structures (M4). These facies indicate varying depositional conditions and microbial activity, reflecting a complex interplay of environmental factors. The mound's lithological features and spatial facies distribution resemble the late development stage of Devonian atolls in the Ardennes. This analogy suggests that the initial mound setting at Skrzelczyce might have been at depths of 30–60 m, in a moderate energy zone. The mound, composed predominantly of polygenetic biomicrite with a significant presence of laminar stromatoporoids and corals, features various forms of stromatactis, some typical and others related to sediment winnowing or to shelter cavities. The foraminiferal assemblages, along with lithostratigraphic correlation, suggest that the Skrzelczyce mound may belong to the lower to middle Frasnian, although the precise age remains uncertain due to the lack of conodont dating. The Skrzelczyce mound aligns with the definition of the Kadzielnia Member, and particular facies from Skrzelczyce can be matched with those described from the Kadzielnia Quarry. The structure outcropping in Skrzelczyce is the second largest Upper Devonian carbonate buildup after Kadzielnia in the Holy Cross Mountains, and the largest on the southern edge of the Kielce carbonate platform.

Key words: Devonian; Holy Cross Mountains; Kadzielnia limestone; Mud mound.

INTRODUCTION

The Devonian represents a crucial period in the Earth's history, distinguished by significant carbonate production and by the formation of vast reef ecosystems. These ecosystems, reflecting temperate climates, elevated sea levels and expansion of shallow epicontinental seas, are represented by an extraordinary variety of carbonate structures (Copper 2002). Some of the best documented Devonian reefs are known from the Ardennes in Belgium (Tsien 1975; Da Silva and Boulvain 2004), the Rhenish Massif in

Germany (Krebs 1974), Alberta in Canada (Klovan 1974; MacNeil and Jones 2016), the Anti Atlas in Morocco (Kaufmann 1998), and the Canning Basin in Australia (Playford *et al*. 2009). The Devonian reefs occurred in a wide array of morpho-ecotypes, such as platform reefs, barriers, atolls and mounds, showcasing the advanced development of varied carbonate environments (Copper 2002). These environments were characterized by clear zonal distinctions related to depth and associated energy levels, ranging from high-energy shoals to low-energy deeper basins, each hosting unique sedimentary structures and biotic assemblages (Wilson 1975; Machel and Hunter 1994; Da Silva and Boulvain 2004).

In the Holy Cross Mountains (HCM), the emergence and development of a Middle to Upper Devonian carbonate platform has been marked by distinct facies and evolutionary phases. Interestingly, the depositional history of the area shares many similarities with the Ardennes and the Rhenish Massif in terms of facies and development stages, as evidenced by comparisons between the works of Krebs (1974) for the Rhenish Massif, Tsien (1975) and Da Silva and Boulvain (2004) for the Ardennes, and Racki (1993) for the HCM, and which is also noted in a comprehensive overview of the Devonian in Central Europe by Bełka and Narkiewicz (2008). Despite these similarities, the HCM platform differs from other well-documented Devonian carbonate systems along the southern shelf of Laurussia, particularly in the occurrence and preservation of reefal structures. The HCM platform notably lacks a well-preserved reef framework (Narkiewicz 1988; Racki 1993; Szulczewski 1995). According to Bednarczyk *et al.* (1997), the edge of the platform was dominated by a microbial-algal association rather than by massive stromatoporoids, as in classic Devonian reef models, however a very large stromatoporoid has also been described (Racki and Sobstel 2004). The primary reason behind this absence remains elusive, although most likely it is linked to the specific tectono-environmental history of the area. Furthermore, significant erosion that has led to the loss of many potential outcrops, particularly in the central part of the Devonian carbonate platform, further complicates the understanding of the region's geological history.

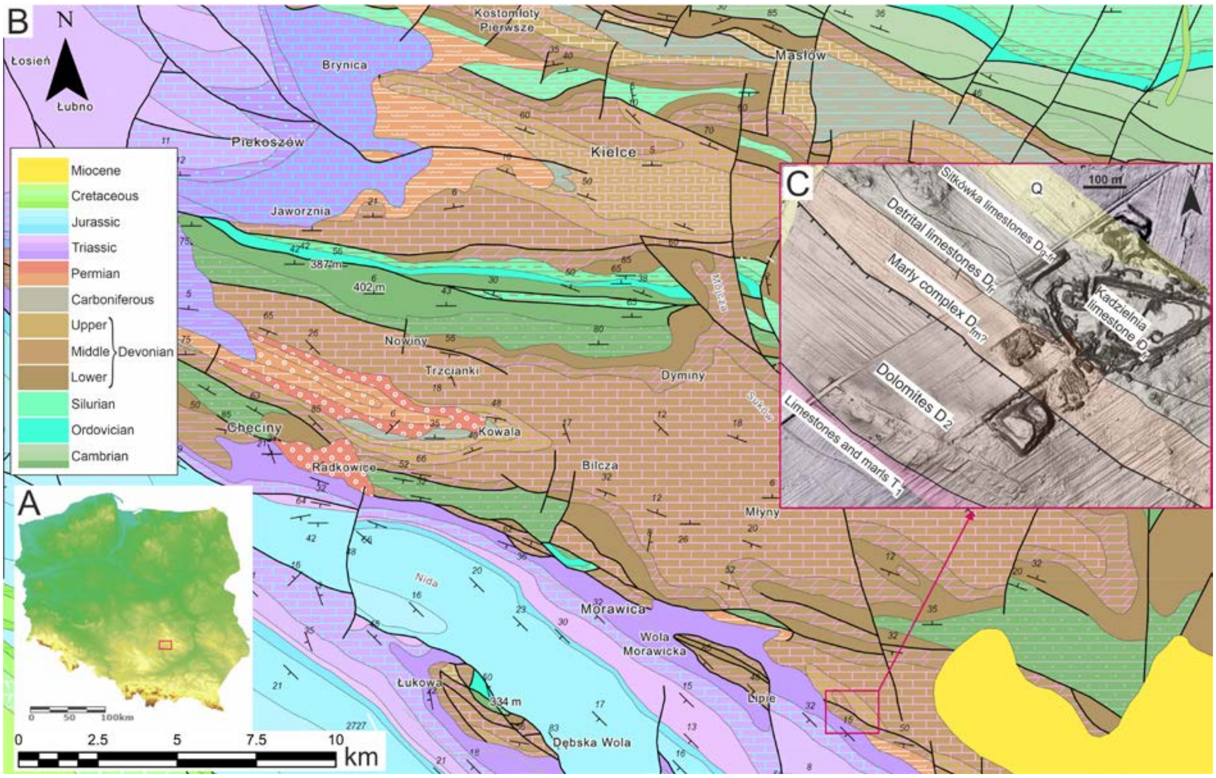
Another distinct feature, setting the Devonian of the HCM area apart from other regions, is the notably sparse distribution of carbonate mud mounds. Globally, the Devonian, and particularly the Frasnian, is marked by the formation of carbonate mud mounds (Boulvain and Wood 2007), including impressive atoll-like structures in Belgium (Boulvain *et al.* 2004). In contrast, the HCM feature only a limited number of mounds, with the Kadzielnia mound being the largest and best described, accompanied by a very few other less evident and/or distinctly smaller structures (Szulczewski and Racki 1981; Narkiewicz *et al.* 1990; Łuczyński 1998). The present paper aims to contribute to the Devonian carbonate platform puzzle by unveiling a previously unreported, impressively sized carbonate mound located on the southern edge of the HCM Devonian carbonate platform, akin to the Kadzielnia type.

When discussing the occurrence of Kadzielnia-type organic buildups in the HCM, it is crucial to recognize Professor Michał Szulczewski's significant contributions to understanding the geological history of the Devonian of the HCM area. His detailed facies and sedimentological studies of the carbonate succession combined with precise conodont stratigraphy (Szulczewski 1971, 1977, 1979, 1981a) have laid the groundwork for all subsequent geological studies on the Devonian in the region. The nature and bathymetrical position of the Kadzielnia-type limestones still remain the focus and centre of his professional interests, and thus we hope that this contribution may add some new data in this matter.

GEOLOGICAL BACKGROUND OF THE STUDY AREA

The study area is located in the south of the HCM, in central Poland (Text-fig. 1A). The Skrzelczyce Quarry (50º43'14.7"N, 20º44'14.9"E) is situated within the Chęciny-Klimontów Anticlinorium and lies in the southern limb of the eastern part of the Chęciny Anticline. The subordinate unit, to which the quarry area belongs, is the Radomice Anticline (Radomicki Fold according to Czarnocki 1925 as referenced by Filonowicz 1968). A few hundred metres southwest of the quarry, the Palaeozoic formations are unconformably overlain by the Triassic (Text-fig. 1B, C).

The Palaeozoic sequence of the HCM belongs to two main tectonic units: the southern Kielce Region and the northern Łysogóry Region. The separation runs along the Holy Cross Fault, which serves as a geological boundary highlighted by distinct differences between the two units in facies evolution, thickness of particular stratigraphic units, and completeness of the sedimentary record. Disparities between the two regions are profoundly manifested in the clastic succession of the Lower Devonian (Szulczewski 1995, 2006). A shift to the dominance of carbonate sedimentation commencing in the lower

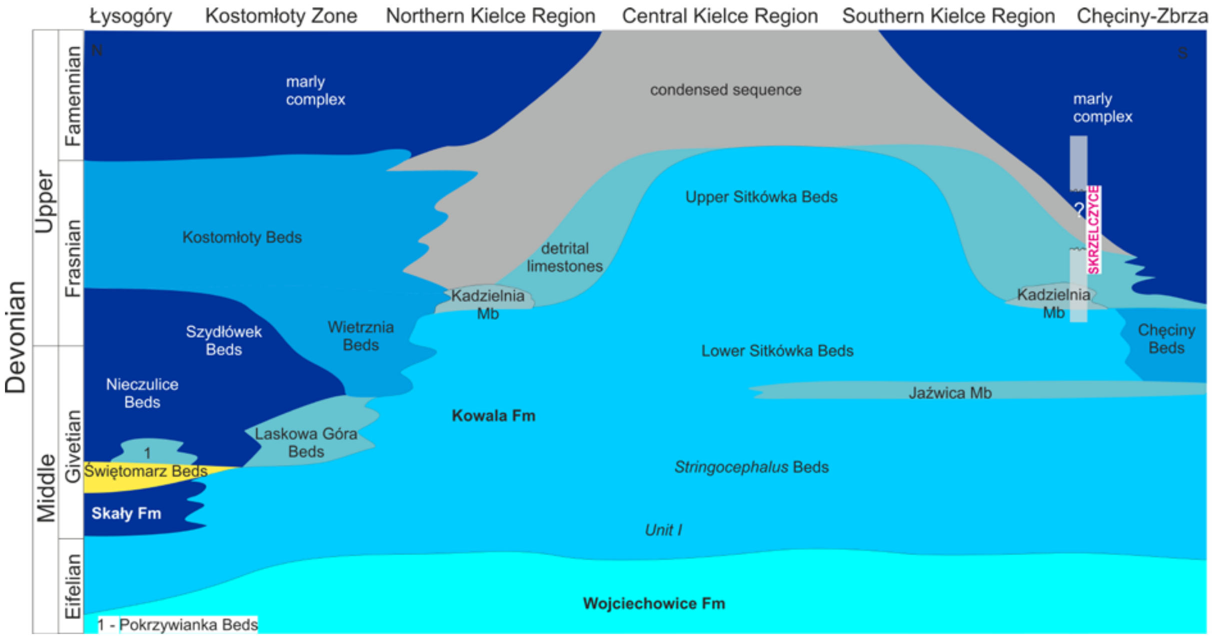


Text-fig. 1. Location of the study area. A – Map of Poland with the location of the Holy Cross Mountains; B – Geological map of the western part of the Holy Cross Mountains (after Filonowicz 1981 and Romanek 2008; for detailed explanations, see Romanek 2008); C – Detailed geological map of the Skrzelczyce Quarry area on a digital elevation model.

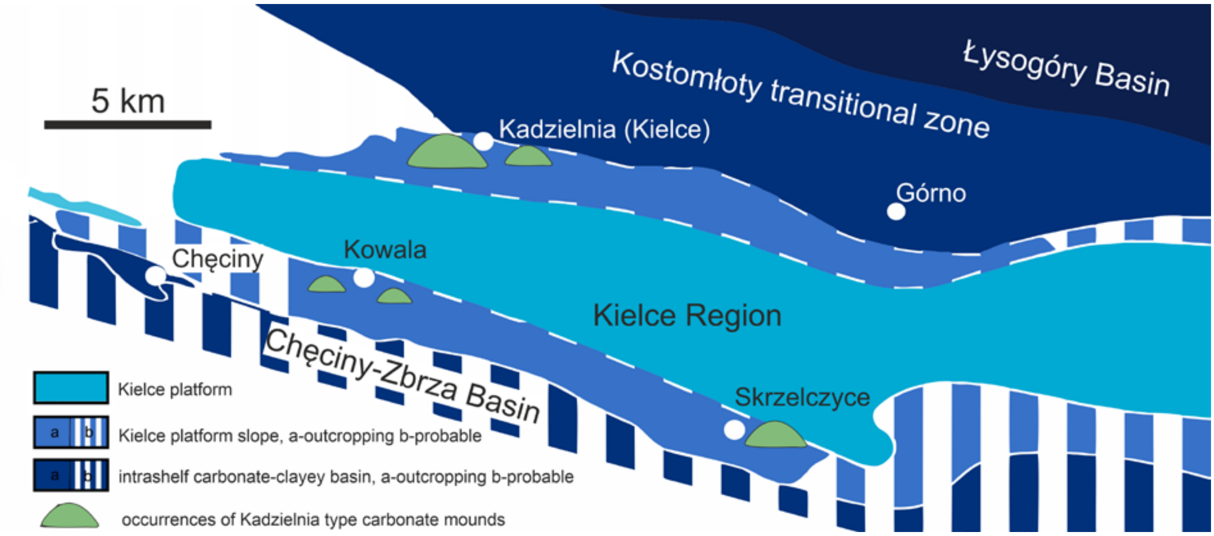
Eifelian signals a unification across the HCM domain, marked by extensive coverage of the area by a shallow dolomitic sea (Narkiewicz 1991; Wójcik 2015). The termination of the Eifelian phase of hypersaline dolomitic deposition most likely took place due to climatic shifts towards more humid conditions and/or due to transgressive pulses, with cyclicity primarily governed by eustatic sea level changes (Racki 1993; Szulczewski 1995). The subsequent development of a carbonate platform, influenced by the ongoing transgression, became facies-differentiated into the northern (Łysogóry), central (Kielce), and southern (Chęciny-Zbrza) zones (Szulczewski 1977). The central zone represents an elevated, isolated carbonate platform fringed by deeper intrashelf basins. Consecutive deepening pulses have led to the rapid submergence of the carbonate platform, followed by faunal colonization, which resulted in the replacement of a simple bank complex by the more diverse Sitkówka biostromal complex, and subsequently by the Dyminy reef complex. Growth of the reef in the central Dyminy zone was driven by the accelerating rate of transgression in the early Frasnian (Racki 1993). The ultimate decline of the reef stage was a consequence of combined eustatic and tectonic movements (Szulczewski 1995, 2006; Szulczewski *et al.* 1996; Racki and Narkiewicz 2000).

In the lithostratigraphic scheme of the HCM Devonian, the deposits of the central (Kielce) carbonate platform belong mostly to the Kowala Formation (Text-fig. 2), which is developed mainly as biostromal shallow marine coral-stromatoporoid dolostones and limestones (Narkiewicz *et al.* 1990). Its thickness ranges between 330 and 800 m. This platform is predominantly characterized by *in situ* benthic fauna accumulations alongside inorganic sediments, though notably excluding the organodetrital limestones that usually form the fore-reef and reef-cap facies (Narkiewicz *et al.* 1990; Racki 1993). The stratigraphic extent of this formation is not isochronous throughout the region, with its first occurrence in the upper Eifelian in the northern part and reaching its maximum range in the central part, extending to the upper Frasnian.

The Devonian deposits exposed in Skrzelczyce Quarry and in its direct vicinity are represented by



Text-fig. 2. Middle–Upper Devonian lithostratigraphy of the Holy Cross Mountains (after Narkiewicz *et al.* 1990, 2006; Wójcik 2015; Racki *et al.* 2022). The stratigraphic interval exposed in Skrzelczyce Quarry is marked with a vertical bar.



Text-fig. 3. Simplified palaeogeographic map of the Holy Cross Mountains area in the Frasnian (after Racki 1993).

Frasnian massive limestones of the Kowala Formation (Text-fig. 2), overlain by the so-called detrital limestone cap facies (traditional local nomenclature used in the HCM) and subsequently by probably Famennian marly shales. In the Frasnian, the area was located close to the platform edge positioned along a gradual slope transitioning towards the Chęciny-Zbrza basin (Text-fig. 3). The slopes of the Dyminy reef complex exhibit evidence of an enhanced tectonic activity and of the frequent occurrence of high energy sedimentary events (Vierek 2013). Tsunamites have also been reported on the southern slope of the Kielce platform (Łuczyński 2022). Furthermore, it is recognised that these slopes contain middle Frasnian biohermal structures (Szulczewski and Racki 1981; Łuczyński 1998).

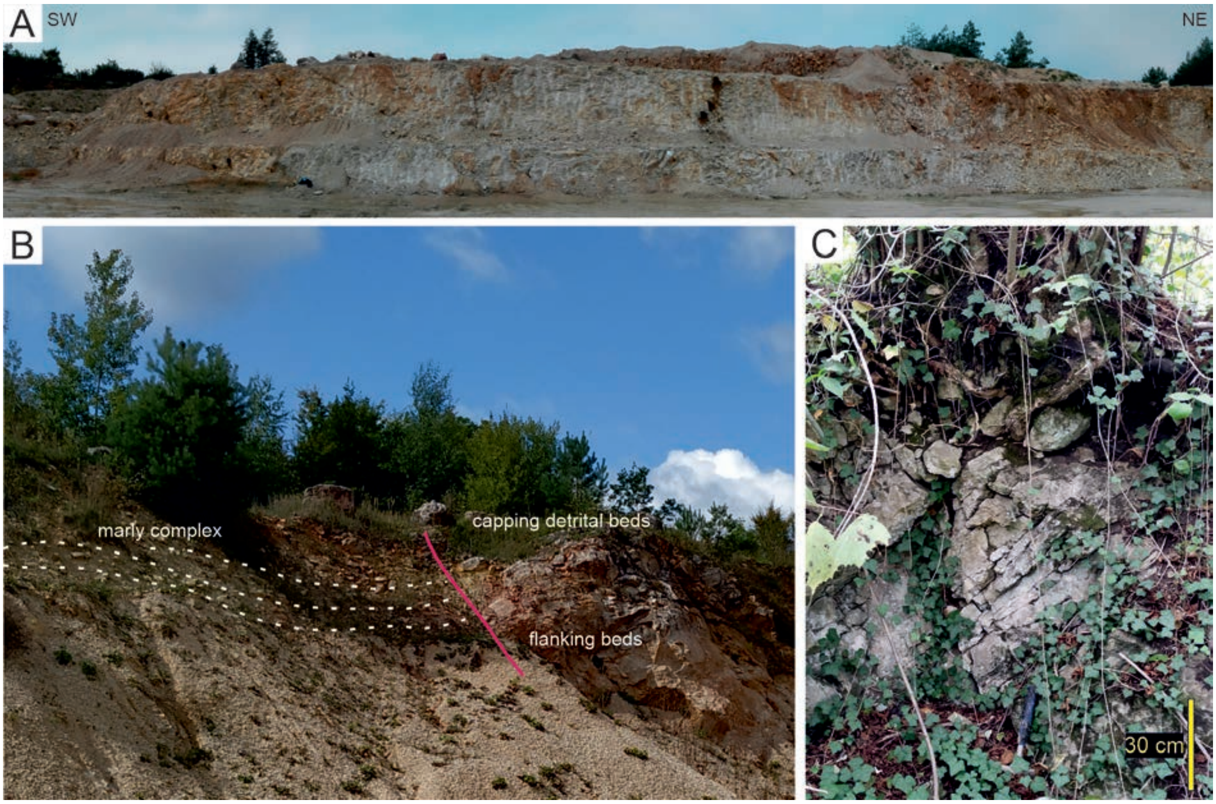
MATERIALS AND METHODS

Fieldwork was conducted in 2018, at a time when Skrzelczyce Quarry was active, and all exploitation levels (today partly buried and/or flooded) were accessible and available for studies. Representative lithofacies have been distinguished and their spatial distribution within the outcrop has been determined. Thin sections for microfacies analysis were prepared from all characteristic rock types occurring in the quarry. Particular microfacies have been determined according to the schemes provided in Flügel (2010), based on the concepts and classifications of Dunham (1962), Embry and Klovan (1971), and Wright (1992). Attempts to find conodonts did not give positive results, and thus the tentative stratigraphical ascription of the described deposits is based on determinations of cross sections of foraminifera seen in thin sections and on lithological analogues, mainly to the Kadzielnia limestones. Additional observations using cathodoluminescence were conducted at the Institute of Paleobiology, Polish Academy of Sciences, in Warsaw. Thin plates and rock samples are housed at the Museum of the Faculty of Geology, University of Warsaw, collection acronym MWGUW ZI/116.

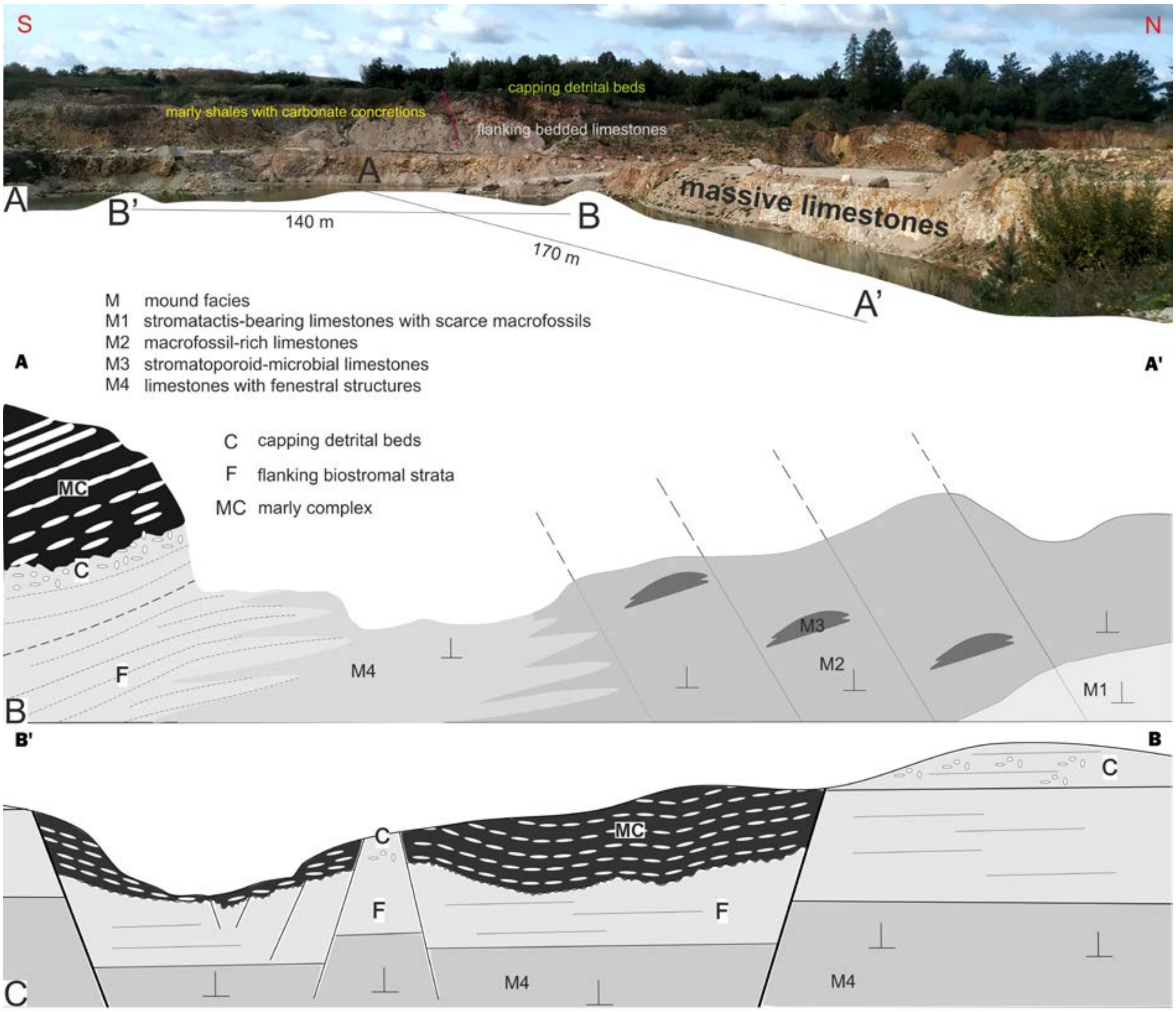
RESULTS

Two primary limestone lithological units outcrop in Skrzelczyce Quarry: massive limestones (Text-fig. 4A) and thin-layered limestones (Text-fig. 4B, C). Four distinct facies have been recognized within the massive limestone unit: stromatactis-bearing limestones with scarce macrofossils (M1), macrofossil-rich limestones (M2), stromatoporoid-microbial organogenic limestones (M3), and limestones with fenestral structures (M4). The thin-layered limestones are categorized into two series of layers: biostromal flanking and detrital capping.

The massive limestone facies are predominantly found in the central and lower parts of the quarry (Text-fig. 5A), with facies M1 at the base, followed by M2, M3, and M4 in ascending order (Text-fig. 5B). There are no sharp boundaries between particular varieties of the massive limestones. Facies M1, represented by stromatactis-bearing



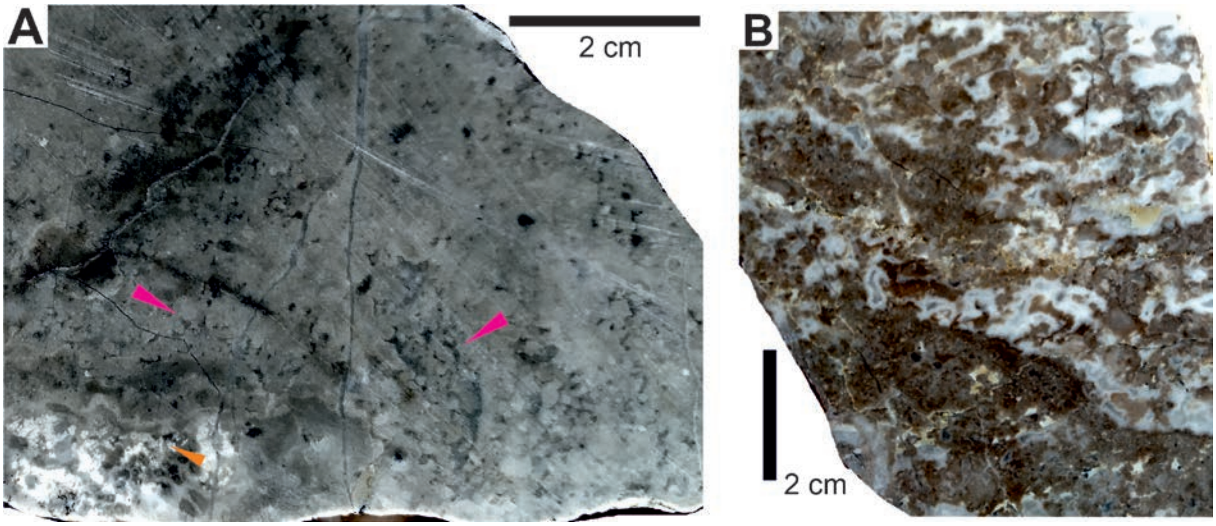
Text-fig. 4. General appearance of the lithotypes in Skrzelczyce Quarry. A – Northwestern quarry wall composed of massive limestones; the section is 90 m long and about 10 m high; B – Tectonic contact between the flanking and capping detrital beds and the marly complex (SW wall of the quarry); height of the escarpment is about 7 m; C – Capping detrital beds outcropping in a small pit southwest of the quarry.



Text-fig. 5. Spatial distribution of the lithotypes in Skrzelczyce Quarry. A – View of the northeastern and southern walls of the quarry; B, C – Schematic cross-sections.

light grey limestones, forms the basal part of the succession. Above it, facies M2, developed as macrofossil-rich light grey limestones, hosts lenses of facies M3, consisting of stromatoporoid-microbial bindstones. Upwards facies M2 gradually passes into facies M4, characterized by the occurrence of fenestral structures. In areas where these fenestral structures occur, as well as in areas based on *in situ* stromatoporoids, a slight tilt of the massive limestones to the south can be observed, with the dip not exceeding 15–20º.

The contact between the flanking strata and the massive limestones is not well exposed in the quarry, but most likely it has an overlapping character. The flanking strata, oriented at 120/45º S, are found in the south-western part of the quarry, and are overlain by capping detrital limestones. The capping detrital beds are exposed only in two small pits located several dozen metres west of the main quarry on a slight elevation, and they also form the upper part of one of the small-scale horsts, where they lie above the flanking biostromal strata, reaching a thickness of a few metres. It is likely that the thickness of the detrital beds increases with distance from the location of the mound, probably due to the post-mound relief (by analogy to the Kadzielnia section, Szulczewski 1971). The capping strata are covered with an erosional contact by dark-coloured marls with carbonate concretions, preserved only in the small-scale grabens (Text-fig. 5C).



Text-fig. 6. Polished samples of the mound facies M1 (stromatactis-bearing limestones with scarce macrofossils). A – Macroscopically visible thrombolitic structures (pink arrows) organized in mesoclots and stromatactis-like features beneath the wavy remnants of a laminar stromatoporoid (orange arrow); B – Reddish stromatactis-bearing limestone.

FACIES DESCRIPTIONS OF FRASNIAN DEPOSITS

Stromatactis-bearing limestones with scarce macrofossils (M1)

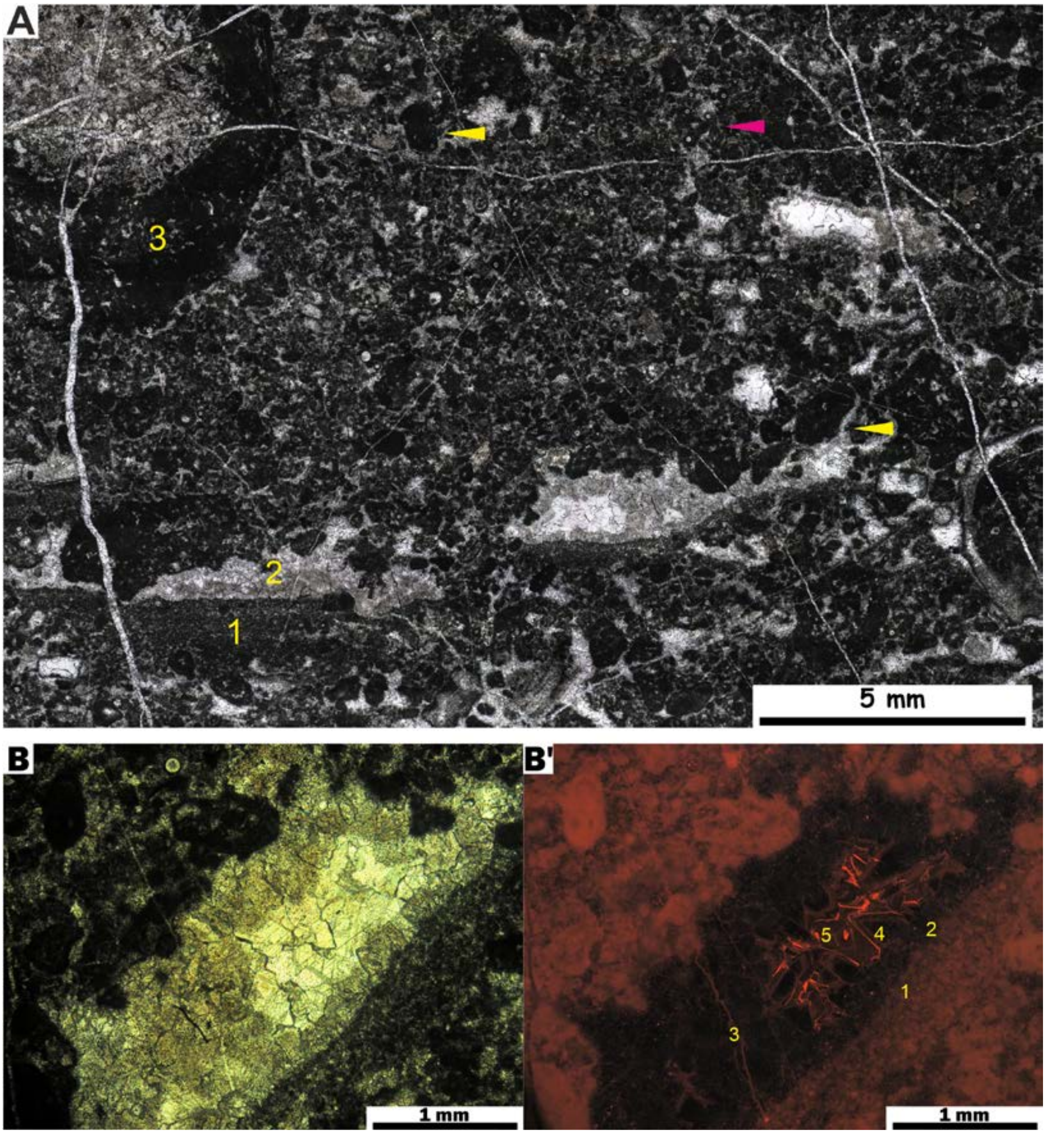
Stromatactis-bearing limestones are exposed in the lowermost part of the quarry. The transition between the massive limestone body and the neighbouring biostromal limestones is not clearly observable in the quarry, and can be visible only in its north-eastern corner (Text-fig. 5B). This facies is characterized by stromatactis-bearing light grey to reddish limestones (Text-fig. 6A, B) with macroscopically identifiable thrombolitic structures (Text-fig. 6A). Despite the overall sparse occurrence of macrofossils in this facies, when present, they primarily include laminar stromatoporoids, bryozoans, and various bioclasts such as molluscs and brachiopods. In terms of microfacies, facies M1 is primarily represented by peloidal wackestones (Text-fig. 7A), with evidence of *Renalcis* sp. calcimicrobe activity (Text-fig. 8B), occasional oncoidal coatings (Text-fig. 7A), *Girvanella* sp. filaments (Text-fig. 8A), and calcispheres. The stromatactis structures are horizontally elongated, with flat bottoms and ragged roofs, and all range in size up to a few centimetres. The basal parts of the stromatactis structures are mostly filled with laminar biopeloidal micrite, while the remaining parts of the cavities contain early diagenetic, multi-generation spar (Text-fig. 7B, B').

Macrofossil-rich limestones (M2)

This facies is widespread throughout the quarry, exhibiting a consistent light grey colour, without reddish alterations. It is distinguished from other facies by a higher abundance of macrofossils, particularly laminar and domical stromatoporoids with ragged surfaces, branching *Stachyodes* sp., and solitary tabulate corals (Text-fig. 9A). These elements are organized in a floatstone texture. Irregular cavities are filled with light grey micrite (Text-fig. 9B, C). The microfacies varies from crinoidal wackstones to packstones, with a peloidal matrix, clotted structures, and small-scale laminites. Foraminifera, including *Nanicella* Henbest, 1935 and Parathuramminida, are also observed (Text-fig. 8D, G). Diverse types of peloids, including those originating from reworked bioclasts, mud peloids, and cyanobacterial peloids, are identified within this facies (Text-fig. 9C). Additionally, micritic envelopes are commonly observed around bioclasts (Text-fig. 9A).

Stromatoporoid-microbial limestones (M3)

This facies forms discrete patches or lenses, not exceeding 1 m in diameter, localized within Facies M2, and comprises stromatoporoid-microbial bindstones (Text-fig. 10A, A'). Microscopically, it is characterized by laminar and low-domal stromatoporoids intercalated with laminated biomicrites and stromatolites (Text-fig. 10B, C). The matrix of these frame-

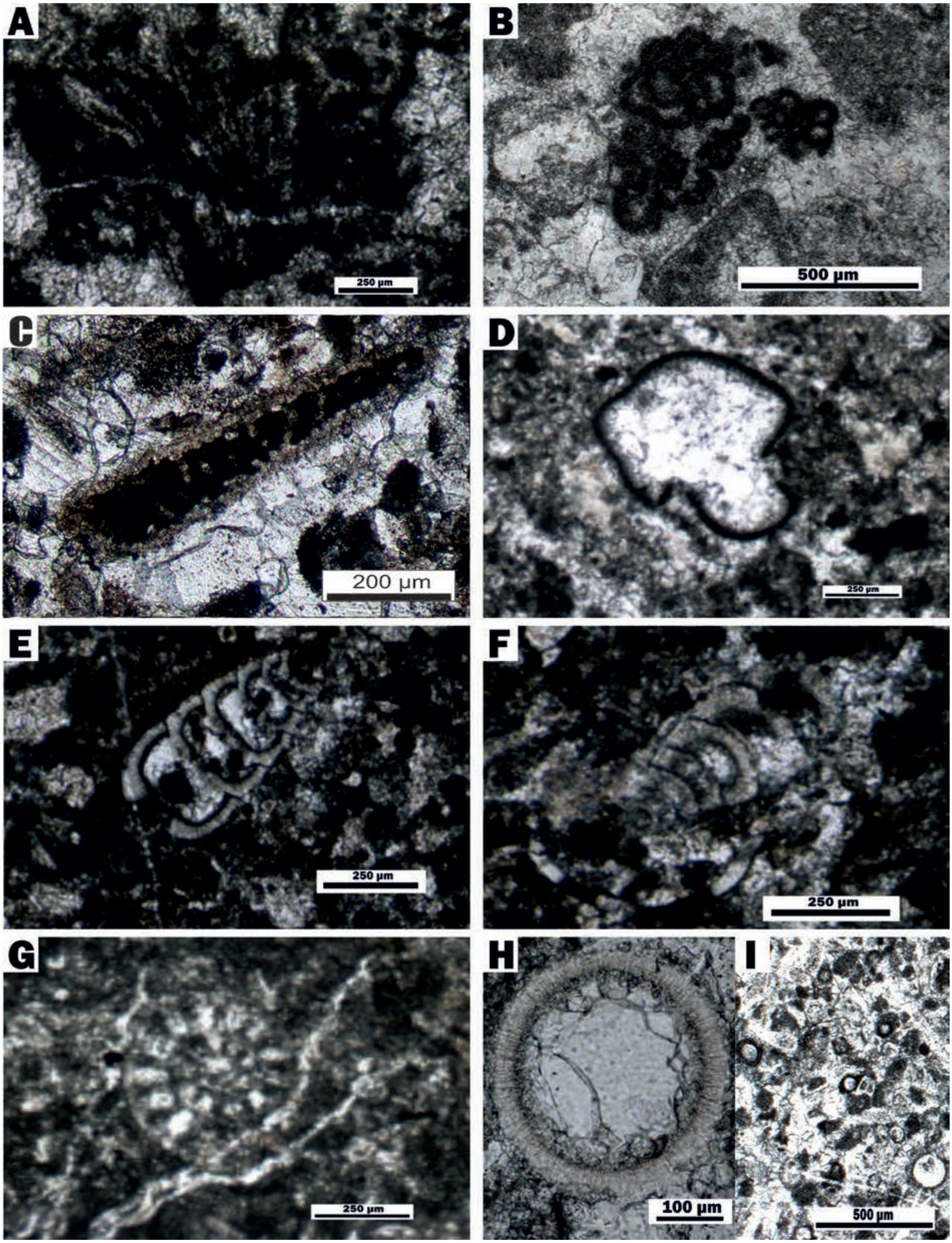


Text-fig. 7. Representative examples of facies M1 (stromatactis-bearing limestones with scarce macrofossils). A – Microscopic image of facies M1 in polarized light; biomicritic infill (1) of the bottom part of a stromatactis structure with a multigenerational spar roof (2); oncoid-like microbial (probably *Girvanella* sp.) coating (3) on a large bioclast; all within a peloidal matrix with clotted structures (yellow arrows) and calcispheres (pink arrow); B, B' – Microphotographs of a stromatactis structure in polarized light (B) and under cathodoluminescence (B') showing various generations of cements: micritic-peloidal (1), radiaxial fibrous (2), drusy and granular (3), dog-teeth (4), and granular (5).

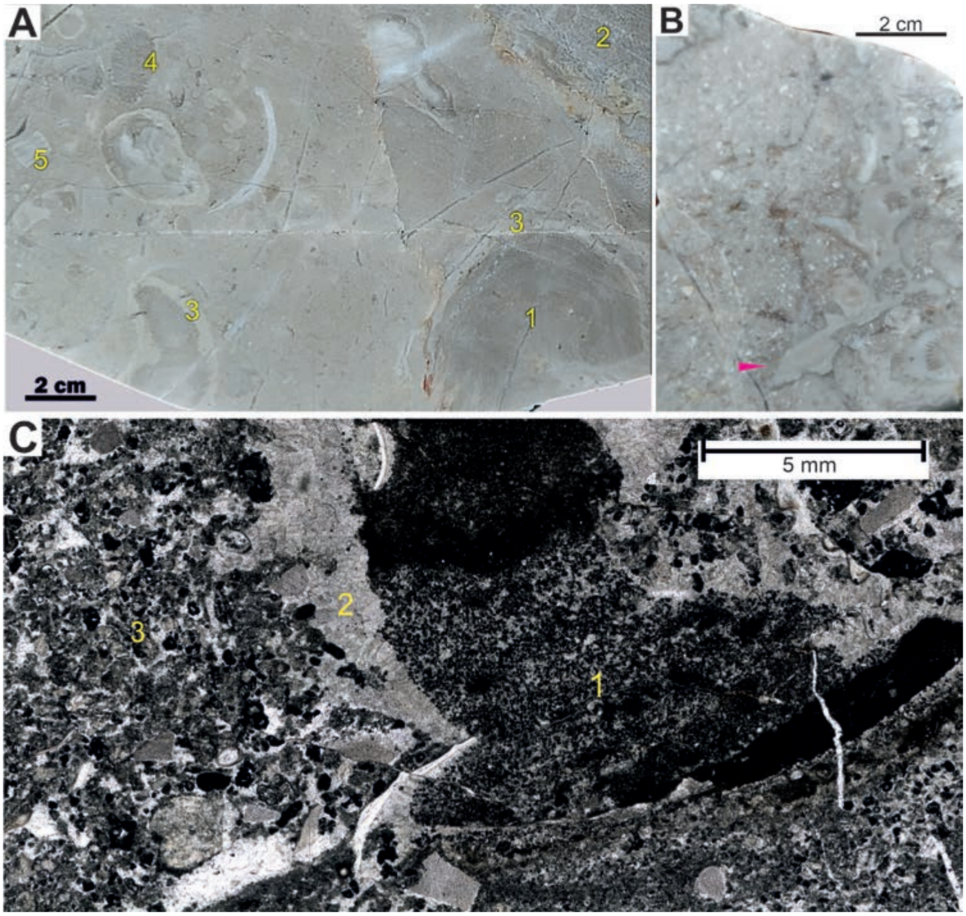
works contains trapped small bioclasts, primarily fragments of crinoids, and occasional benthic foraminifera.

Limestones with fenestral structures (M4)

This facies is characterized by significant primary cavities, up to 40% by volume, with both irregularly shaped and parallel-aligned fenestrae (Text-fig. 11A, C). These fenestrae are predominantly lined with a micritic cement followed by sparry calcite cements, and only a few contain layered lime mud, with scarce fossil debris at their bases (Text-fig. 11B). The structures often show evidence of synsedimentary deformation resulting in their irregular, wavy outline. Some of the horizontal cemented cavities are directly associated with shelter cavities, as indicated by their occurrence beneath laminar stromatoporoids and corals (Text-fig. 11B). Other macrocrystalline wavy structures of uncertain origin (see interpreta-



Text-fig. 8. Microscopic images in polarized light of the characteristic Upper Devonian microfossil assemblage from Skrzelczyce Quarry. Examples of calcified cyanobacteria (A – *Girvanella* sp.; B – *Renalcis* sp.); dasycladacean algae (C); foraminifera (D – Parathuramminida indet.; E, F – *Eogeinitzina* sp.; G – *Nanicella* sp.); radiosphere (H); other calcispheres (I).



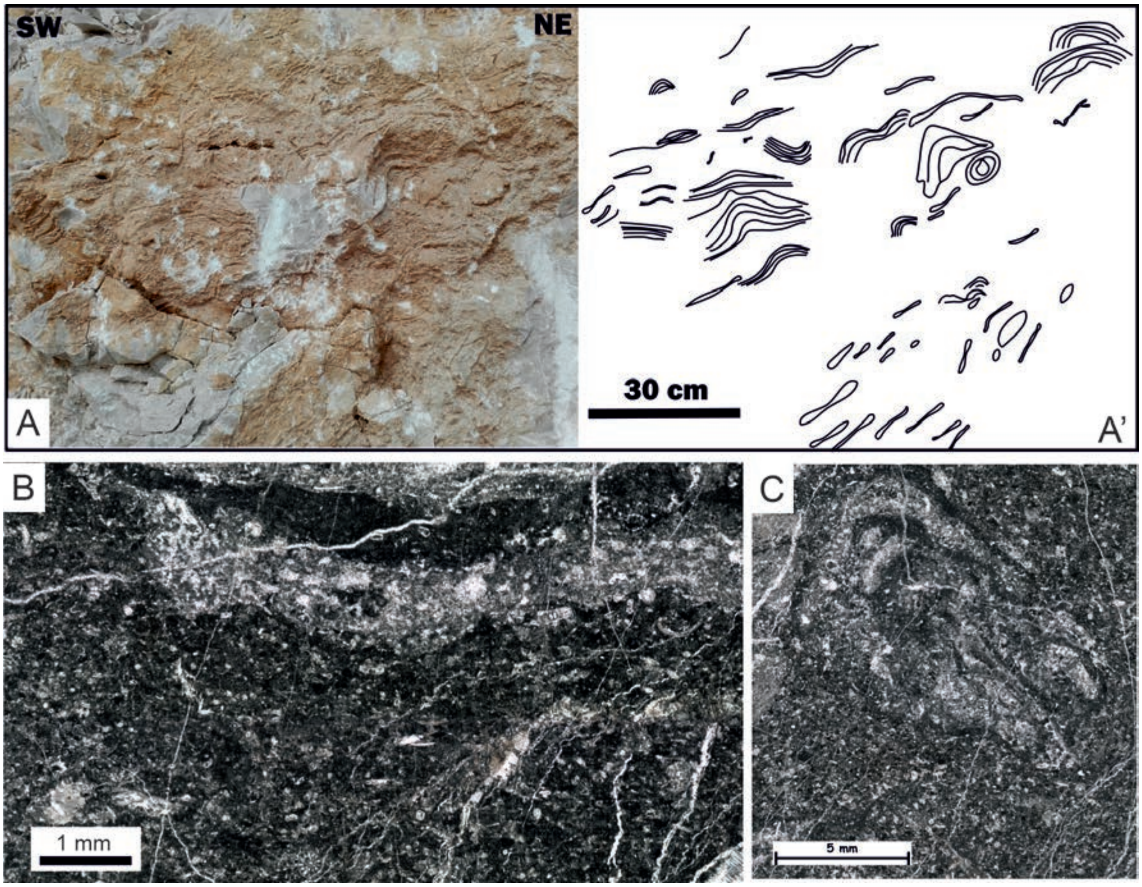
Text-fig. 9. Representative examples of facies M2 (macrofossil-rich limestones). A – Stromatoporoid specimens: domical form (1) with a ragged left margin, and a potentially redeposited, low-domical form (2); micritic envelopes evident around most clasts (3); matrix includes lithoclastic and bioclastic material with tabulate corals (4), shell and crinoid debris (5); B – Winnowed space filled with carbonate mud (pink arrow); the surrounding matrix is mostly biodetritic with a solitary coral in the lower left corner; C – Thin section from sample (B) viewed under plane-polarized light (PPL); biomicritic infill (1) of a stromatactis-like cavity with spar walls (2); the matrix is a crinoidal wackestone to packstone, with diverse types of peloids, and clotted structures (3).

tion) consist of an early marine radiaxial fibrous cement followed by granular cement (Text-fig. 11D, D'). Their final appearance may have been influenced by neomorphic processes. In terms of microfacies the surrounding matrix is represented by mudstones to wackstones, with ostracodes, crinoidal fragments, and echinoid spines.

Flanking and capping strata

South-westwards, the massive limestones laterally pass into flanking facies characterized by slightly enhanced layering. The contact between the flanking strata and the massive facies is not sharp. Microscopically the facies are represented by floatstones and rudstones with diverse stromatoporoids and massive corals, accompanied by brachiopods, ostracods, crinoids, calcispheres (Text-fig. 8H, I), sponge spicules, tentaculites, and dasycladacean algae (Text-fig. 8C), all set within a bioclastic-rich matrix.

The flanking strata are overlain by the capping strata, exposed in two small pits and also present on one of the horsts. The capping strata are darker, grey, occasionally greenish, and are developed as detrital facies (Text-fig. 2). The capping strata consist of reworked bioclastic material and lithoclasts (Text-fig. 12), incorporated within a wackestone matrix with common calcispheres, accompanied by foraminifera, predominantly by *Eogeinitzina* Lipina, 1950 (Text-fig. 8E, F). Additionally, bioturbated layers and erosional surfaces are found within the capping strata.

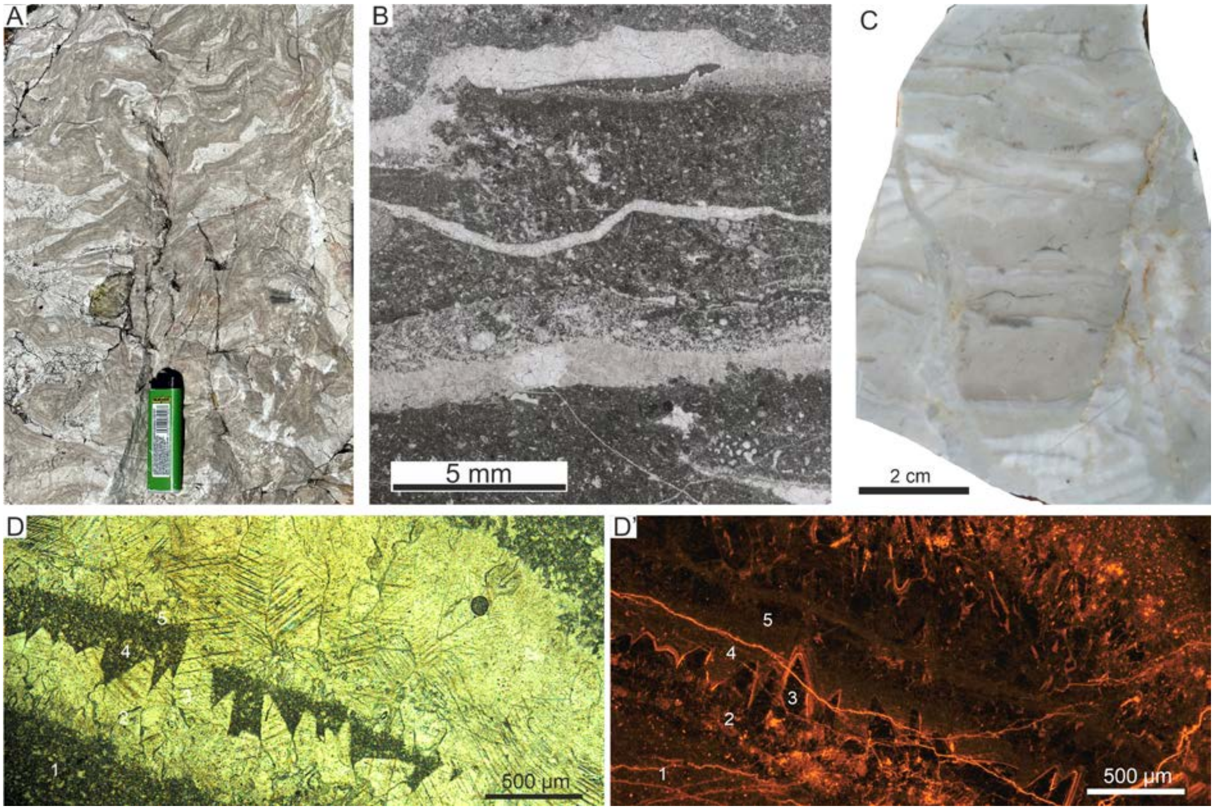


Text-fig. 10. Representative examples of facies M3 (stromatoporoid-microbial limestones). A, A' – Stromatoporoid bindstone observed on a weathered surface; B – Laminar stromatoporoid meshwork with stromatolite-like oriented biomicrite; C – Domal stromatoporoid meshwork with intercalated microbial incrustations.

The overall spatial relationship of particular lithosomes exposed in the quarry suggests that the flanking strata were deposited adjacent to the massive facies of the mud mound, while the capping strata represent a later stage of deposition that postdates both the flanking strata and parts of the massive limestones.

AGE OF THE BUILDUP

Despite multiple attempts, the samples dissolved for conodonts did not yield positive results, making precise stratigraphical positioning of the Skrzelczyce mound challenging. However, when comparing the microbiota assemblage from the mound facies and the flanking strata, particularly the occurrence of *Nanicella* foraminifera (found in facies M2 and M3), with other studies devoted to the HCM Devonian carbonates (Racki 1993; Racki and Soboń-Podgórska 1993; Bełka *et al.* 1996), there is strong evidence suggesting that the mound dates to the Frasnian. Additionally, the age of the capping detrital beds, indicated by the occurrence of *Eogeinitzina*, is most likely middle to late Frasnian (Kalvoda 1990; Racki and Soboń-Podgórska 1993). Lithostratigraphically, the Kadzielnia Limestone Member, to which the potential affinity of the mound facies outcropping in Skrzelczyce is discussed in this paper, is positioned in the lower to middle Frasnian (Narkiewicz *et al.* 1990). While these data suggest a Frasnian age for the mound, the precise age of the Skrzelczyce carbonate mound remains uncertain and should be the subject of further biostratigraphical studies. Consequently, there is a possibility that the Skrzelczyce mound is somewhat younger than other known mounds from the HCM area.

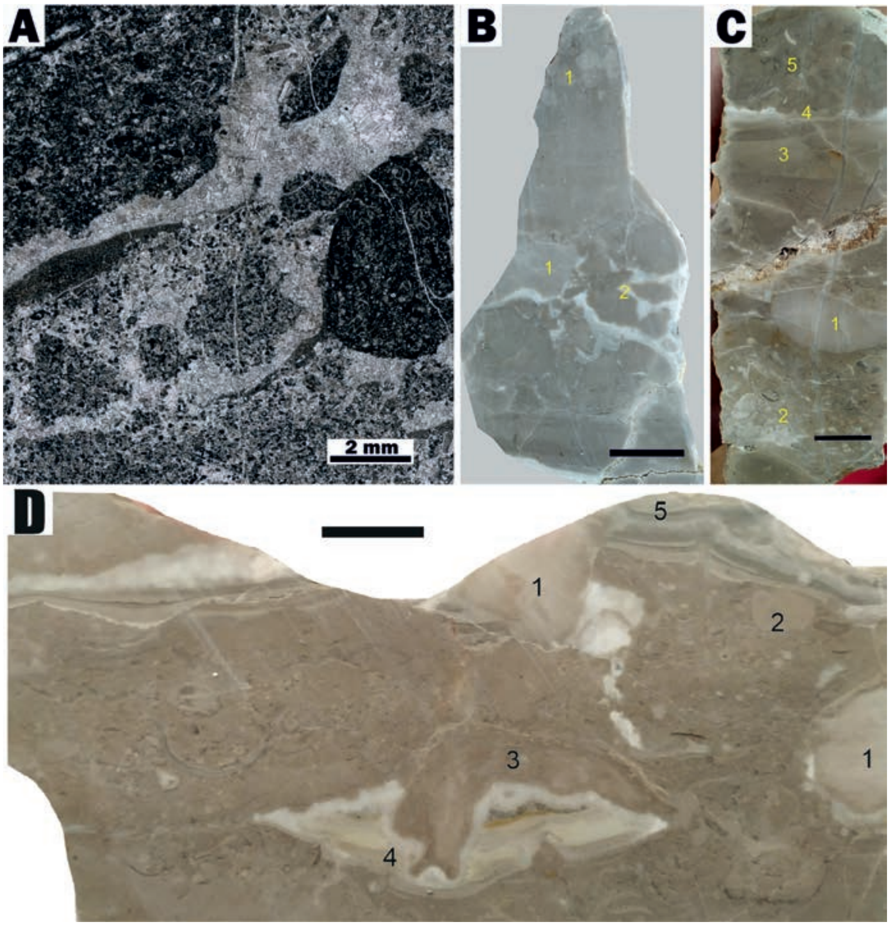


Text-fig. 11. Representative examples of facies M4 (limestones with fenestral structures). A – wavy fenestrae likely resulting from synsedimentary deformations of partially cemented carbonate mud; B – Thin section view, displaying three shelter cavities; C – primary shelter cavities beneath laminar organisms, such as stromatoporoids or tabulate corals; the cavities are filled with multigenerational carbonate cements; D, D' – Shelter cavity in polarized light (D) and under cathodoluminescence (D'), showing various generations of cements: micritic lining (1), radiaxial fibrous (2), bladed (3), break in macrocrystalline cementation followed by micritic sedimentation (4), and radiaxial fibrous (5).

ENVIRONMENTAL INTERPRETATION AND DEPOSITIONAL EVOLUTION

The lowest observable part of the Skrzelczyce Quarry section is represented by Facies M1 (stromatactis-bearing limestones with scarce macrofossils), which forms the basal part of the stratigraphic sequence. This facies is characterized by light grey to reddish limestones with stromatactis structures, indicative of a low-energy, subtidal environment, in which microbial activity played a significant role in sediment stabilization (Aitken 1967; Riding 2000). The presence of thrombolitic structures (Text-fig. 6A) and the limited occurrence of macrofossils, suggests deposition in a calm setting with the occasional development of microbial mats (Pratt 1982, 2000).

Following the initial stage, the conditions became more favourable for the development of diverse benthic communities, leading to the deposition of Facies M2 (macrofossil-rich limestones). This facies is characterized by a higher abundance of macrofossils, including laminar and domical stromatoporoids, branching *Stachyodes* sp., and tabulate corals. These macrofossils are organized within a floatstone texture, with microfacies ranging from peloidal wackestones to packstones. The transition to Facies M2 indicates a shift to a higher-energy environment, potentially characterized by better nutrient supply and increased water movement. This may have been facilitated by the development of low relief structures after the initial stage, allowing for enhanced current activity and nutrient distribution. Diverse types of peloids, including cyanobacterial peloids, reworked bioclasts, and mud clasts (Text-fig. 9C), highlight a polygenetic origin of the primary carbonate mud, which indicates both autochthonous (automicrite) and allochthonous (allomicrite) carbonate production. The presence of such diverse peloids suggests active bioturbation and microbial reworking of sediments, further supporting the notion of a dynamic,



Text-fig. 12. Capping and flanking beds. A – Microscopic image under plane-polarized light (PPL) of a thin section from a polished sample (B); lens-shaped marly insert representing sedimentary infill of a cavity later overgrown by calcite cement; B – Capping detrital beds displaying intraclastic pelitic limestone with indistinct bedding; intraclasts (1) and intraformational breccia with crystalline matrix (2); C – Lower capping beds; distinct layering: bioclastic layer (2) with fragments of shells, corals, and bulbous stromatoporoids (1); mudstone layer (3) with visible disturbances, jagged sharp boundary with possible escape structures (4); intraclastic limestone with traces of bioturbation (5); D – Polished section of flanking strata layers; vague layering and significant bioclast content are visible; bulbous stromatoporoids (1), intraclasts (2); microbial structure (3); cavity filled with carbonate mud (4), laminar stromatoporoid with shelter cavity beneath filled with carbonate mud (5). Scale bars in B–D equal to 2 cm.

nutrient-rich environment. Such a polygenetic origin of carbonate mud is a typical feature of mud mounds (Pratt 1995; Riding 2002).

Patches and lenses of Facies M3 (stromatoporoid-microbial limestones), localized within Facies M2, represent microenvironments with lower sedimentation rates. The stromatoporoid frameworks intercalate with stromatolites in these patches, indicating areas of reduced sedimentation and enhanced microbial activity. The limited clast content in Facies M3, contrasted with the high clast content in the surrounding Facies M2, suggests that these patches were slightly elevated. Water movement, such as currents or wave action, likely transported sediment away from these elevated patches, contributing to their composition. The ragged surfaces of some stromatoporoids within Facies M2 (Text-fig. 9A) indicate variable sediment supply with overall high deposition rates (Kershaw 1984; Łuczyński 1998). Therefore, the co-occurrence of Facies M2 and M3 can be attributed to the varied morphology of the mud mound surface, with even minor elevations leading to such facies diversification.

Facies M4 (limestones with fenestral structures) represents the gentle slopes of the mound, forming its most external parts. Although it retains the massive nature, characteristic of mound facies, some horizontal organization of its texture is visible. It features a higher abundance of laminar stromatoporoids and corals, with common shelter cavities beneath (Text-fig. 11B, C). The environment on the mound's periphery seems to be characterized by favourable conditions for laminar stromatoporoids and corals, with reduced sedimentation rates. Additionally, Facies M4 exhibits traces of syndepositional deformation, such as microfaulting (Text-fig. 11C) and convolute deformation structures (Text-fig. 11A). These features suggest that despite the mound's overall low relief, minor gravity-driven or seismically induced movements occurred on its gentle flanks.

The mud mound facies yields various types of fenestral structures. It is not an objective of this paper to delve into the terminology debate over whether these structures should be called fenestrae, stromatactis, or simply cavities. Instead, the focus is on their forms and origins. These structures exhibit a variety of types, sometimes aligning to create a zebra-like texture. Generally, three distinct forms can be distinguished: millimetre-sized stromatactis-like structures in Facies M1, irregular fenestrae in Facies M2, and wavy zebra-like fenestral structures in Facies M4. Each type appears to have a slightly different origin. The small stromatactis-like structures from facies M1, with flat bottoms and ragged roofs, partially filled with geopetal biomicrite followed by diagenetic marine cements (Text-fig. 7A, B), seem to result from physical collapse. Such a collapse could have been caused by various factors, such as changes in sediment load, or dissolution of the supporting material (Bathurst 1982; Pratt 1982; Bourque and Boulvain 1993). The irregular fenestrae, found mostly in Facies M2, are filled with biopeloidal micrite and contain shell fragments (Text-fig. 9B, C). Their walls are often lined with cements. These fenestrae are likely related to the winnowing of unconsolidated material, indicating subtle differentiation in cementation rates within the mud mound (Szulczewski and Racki 1981). Uneven distribution of microbial colonies, which contributed to cementation processes through organomineralization, is a probable factor. The third type, forming the zebra-like wavy fenestral structures in Facies M4, often features remnants of laminar metazoans, such as stromatoporoids or *Alveolites* sp. corals. These structures appear to be primary fenestrae, predominantly related to shelter cavities (Text-fig. 11B), some of which were later enlarged. This enlargement may have been caused by deformations resulting from *in situ* brecciation or dewatering of partially cemented crust-like surfaces, followed by winnowing (Bathurst 1982; Pratt 1982). These deformations could have been tectonically induced or caused by local mass flow due to destabilization on the flanks and opening of a gel-like sediment by lateral compression. This is supported by evidence of secondary reopening, as indicated by the phase of micrite infill observed in some cavities after initial cement crystallization (Text-fig. 11D). Additionally, the decay of soft-bodied organisms, such as sponges (Bourque and Boulvain 1993) or thick microbial mats, which is a common texture in similar environments, could also explain this peculiar texture. However, there is no direct evidence of this, except for the superficial similarity in texture. The spatial distribution of the various types of fenestral structures in Skrzelczyce resembles the pattern proposed by Pratt (1982), in which laterally extended stromatactis are preferably found on the flanks of the mud-mound, while the more scattered and irregularly shaped forms are predominantly present in its central part.

Direct contact between the capping facies and the mud mound facies, marking the termination of the mound growth cannot be observed in Skrzelczyce Quarry. However, there is a continuous profile of flanking facies transitioning into capping facies. These capping strata, which can be ascribed to the so-called detrital beds (Szulczewski 1971), consist of reworked carbonate deposits formed through denudation and erosion of the carbonate platform. The termination of mud-mound growth was generally related to an ongoing transgressive trend. However, at this time interval, several globally reported periods of rapid sea level drops took place (Johnson *et al.* 1985; Sandberg *et al.* 2002) and there is also regional evidence of such events (Szulczewski *et al.* 1996). It is challenging to determine whether the overall deepening trend, or rather these brief shallowing episodes were more detrimental to the growth of the carbonate mound. In Skrzelczyce Quarry, the upper capping strata reflect evidence of shallowing, as indicated by the presence of tempestite layers. Additionally, some erosional surfaces, likely related to emergent karstic episodes, have also been reported in the capping profile (Pedrycz and Łuczyński 2023).

DISCUSSION

The question arises as to whether the Skrzelczyce mound can be classified as a part of the Kadzielnia Limestone Member (Narkiewicz *et al.* 1990) in the lithostratigraphic scheme of the HCM Devonian. This member is characterized by its organogenic bindstone texture, significant occurrence of mostly laminar stromatoporoids and tabulate corals, and by adopting a form of isolated biohermal structures with thicknesses up to 50 m (Kaźmierczak 1971; Szulczewski 1971; Szulczewski and Racki 1981; Narkiewicz *et al*. 1990). The Kadzielnia Limestone features a micritic matrix with stromatactis structures and a significant microbial activity stabilizing these structures (Hoffmann and Paszkowski 1992; Racki 1993; Bednarczyk *et al*. 1997). Although the investigations presented here indicate that the mound facies outcropping in Skrzelczyce Quarry share close affinities with the Kadzielnia Limestone Member, it remains an open question whether they should be fully classified as such.

The massive limestones from Skrzelczyce are similar to the Kadzielnia Limestone Member, but they also display many biosedimentary similarities with the microbial associations observed in the detrital limestones of Kadzielnia (Bednarczyk *et al.* 1997). This raises the possibility that the Skrzelczyce mound may represent a slightly younger equivalent, perhaps corresponding to the age of the detrital beds at Kadzielnia, rather than the Kadzielnia bioherm itself. Therefore, the differences observed could either be due to variations in age between the carbonate mounds or subtle environmental differences during their formation. Nonetheless, the Skrzelczyce mound represents the largest known structure of this kind on the southern slope of the Kielce carbonate platform.

The facies described in Kadzielnia Quarry can be matched with those from Skrzelczyce Quarry, demonstrating similar sedimentological characteristics and depositional environments. The ‘stromatoporoid limestone’ described by Szulczewski (1971) corresponds to the ‘massive stromatoporoid limestones’ (Facies R-3) of Racki (1993), encompassing all the massive M facies from Skrzelczyce. In more detail, the stromatoporoid bindstones (R-3b) described by Racki (1993) are likely represented by Facies M1, M3, and M4 in Skrzelczyce. These facies exhibit occurrences of mostly laminar stromatoporoids, micritic matrix, and stromatactis structures. The reefoid stromatoporoid limestones (R-3r) align with the macrofossil-rich limestones (M2) at Skrzelczyce, with reworked bioclastic material and lithoclasts occurring along with diverse bioclasts and non-skeletal particles. The bulbous stromatoporoid floatstones (R-3f) described by Racki (1993), with their bioturbated peloidal-bioclastic matrix, can most likely be matched with the flanking strata in Skrzelczyce. This reflects the ambiguous character of the transition between the mound and the surrounding sediments, with the presence or absence of slight layering determining their classification as either part of the mound or of the flanking units

More distinct differences between Kadzielnia and Skrzelczyce involve the capping and flanking facies accompanying the mounds. In Skrzelczyce, the massive limestones of the mound facies laterally transition into thick-bedded biostromal limestones (flanking strata) that contain similar biotic components as those within the mound. Both units are covered by capping detrital beds, likely deposited after the mound relief was compensated. The Kadzielnia mound also laterally passes into coral-rich biostromal beds, best exposed on the so called Geologists’ Rock. On its basinward side (eastern wall of the quarry), the mound is flanked by detrital units. Szulczewski (1981b) suggested that the latter formed after termination of a ‘living’ mound, with the top surface providing favourable space for benthic fauna, periodically transported down the slopes. Bednarczyk *et al.* (1997) interpreted these facies as a reef apron. Together, these interpretations suggest that the Kadzielnia carbonate mound had a considerably high relief, as is also supported by studies of stromatoporoid orientation (Łuczyński 2009).

The well-known Upper Devonian carbonate mounds of the Ardennes in Belgium developed in a similar general palaeogeographic setting as the Kadzielnia-type mounds of the HCM – on the southern carbonate shelves of Laurussia. The middle Frasnian Arche and Lion buildups from the Dinant Synclinorium (Boulvain 2001, 2007; Boulvain *et al.* 2004) may share some elements with the Kadzielnia-type mound exposed in Skrzelczyce. Facies M1 (stromatactis-bearing limestones with scarce macrofossils) from Skrzelczyce can be considered an equivalent to facies A2/L2 (red, greenish, or pinkish mudstones and floatstones with stromatactis, corals, and crinoids) described by Boulvain *et al.* (2004) and Boulvain (2007), however characterized by less microbial features. Both are characterized by the occurrence of stromatactis, platy tabulate corals, and stromatoporoids, with cavities filled with carbonate mud and cements. Similarly, facies M2 (macrofossil-rich limestones) and M4 (limestones with fenestral structures) can be compared to facies A3/L3 and A4/L4 (grey, pinkish, or greenish limestone with stromatactis, corals, and stromatoporoids; and grey limestone with algae, fenestrae, branching tabulate corals, stromatoporoids, and brachiopods). Both feature wackestones and floatstones with stromatactis and stromatactoid fenestrae, abundant branching tabulate corals, brachiopods, crinoids, and stromatoporoids, with peloids, lithoclasts, and microbial coatings. Facies M3 (stromatoporoid-microbial limestones) is comparable to facies A5/L5 (grey microbial limestone), both consisting of thrombolitic and stromatolitic bindstones and bafflestones. These facies are characterized by the occurrence of *Renalcis* sp., stromatoporoids, tabulate corals, and by the presence of microbial laminae rich in peloids, occurring as metre-scale lenses, indicating localized microbial and metazoan interactions.

The general lithological features of the mound exposed in Skrzelczyce, as well as its spatial facies distribution, in spite of not adopting an overall form of an atoll, resemble the late development stage of the atolls from the Ardennes, particularly their basinward crown parts. This suggests that the initial mound setting might have been shallower than that of its Belgian counterparts. By comparison with Belgian bathymetric estimations (Boulvain *et al.* 2004; Boulvain 2007), it can be estimated that the Skrzelczyce mound grew at depths of 30–60 m, in a moderate-energy setting within the photic zone. In the bathymetric reconstructions of the Kadzielnia mound (Racki 1993) its position was settled at a depth of about 20 m, which is noticeably shallower.

The Kadzielnia-type mounds of the HCM fit the definition of a mud mound due to their biosedimentary buildup dominated by fine-grained carbonates and polygenetic matrix-supported fabrics, such as stromatactis and fenestral structures, consistent with typical mud mounds formed by microbial activity and early cementation processes (Riding 2002). However, these are not typical mud mounds, which are usually considerably muddier, such as those described from the Upper Devonian, of the southern Rocky Mountains, western Canada (Zhou and Pratt 2019a, b). The Kadzielnia-type mounds contain numerous microbial structures and tend to have a higher abundance of metazoans, including stromatoporoids and corals, and a high bioclast content in some parts of the buildup, indicating complex biotic interactions compared to more microbially dominated mud mounds elsewhere. This higher metazoan content suggests a deviation from the classic mud mound model, which is predominantly microbial (Pratt 1982; Riding 2002; Rodríguez-Martínez 2011).

FINAL CONCLUSIONS

The results of studies performed at Skrzelczyce Quarry allow us to present the following main conclusions:

- A previously unreported large carbonate mound occurred in the Frasnian on the southern slope of a shallow water Kielce carbonate platform.
- The massive mound facies from Skrzelczyce Quarry show significant similarities to those described from Kadzielnia, suggesting a close affinity with the Kadzielnia Member of the Kowala Formation. However, their full inclusion within this member remains open to further investigation.
- The Skrzelczyce mound's lithological features and spatial facies distribution resemble the late development stage of Devonian atolls in the Ardennes. This analogy suggests the initial mound setting at Skrzelczyce might have been at depths of 30–60 m, in a moderate energy zone.

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REFERENCES

Aitken, J.D. 1967. Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta. *Journal of Sedimentary Petrology*, **37**, 1163–1178.

Bathurst, R.G.C. 1982. Genesis of stromatactis cavities between submarine crusts in Paleozoic mud-mounds. *Journal of the Geological Society*, **139**, 165–181.

Bednarczyk, J., Hoffman, M. and Paszkowski, M. 1997. The Upper Devonian cryptomicrobial-algal-stromatoporoid buildups from the Holy Cross Mountains, Poland. Stop 10. Kadzielnia, abandoned quarry. The Holy Cross Mountains. In: 3rd IFAA Regional Symposium & IGCP 380 International Meeting, Guidebook, 3–7, 47–48. Institute of Geological Sciences, Jagiellonian University; Cracow.

Bełka, Z. and Narkiewicz, M. 2008. Devonian. In: McCann, T. (Ed.), The Geology of Central Europe. Volume 1: Precambrian and Palaeozoic, 315–373. Geological Society; London.

Bełka, Z., Skompski, S. and Soboń-Podgórska, J. 1996. Reconstruction of a lost carbonate platform on the shelf of Fennosarmatia: evidence from Visean polymictic debrite, Holy Cross Mts., Poland. *Geological Society Special Publications*, **107**, 315–329.

Boulvain, F. 2001. Facies architecture and diagenesis of Belgian Late Frasnian carbonate mounds (Petit-Mont Member). *Sedimentary Geology*, **145**, 269–294.

Boulvain, F. 2007. Frasnian carbonate mounds from Belgium: Sedimentology and palaeoceanography. *Geological Society of London, Special Publication*, **275**, 125–142.

Boulvain, F., Cornet, P., Da Silva, A.-C., Delaite, G., Demany, B., Humblet, M., Renard, M. and Coen-Aubert, M. 2004. Reconstructing atoll-like mounds from the Frasnian of Belgium. *Facies*, **50**, 313–326.

Boulvain, F. and Wood, R. 2007. Devonian. In: Vennin, E., Aretz, M., Boulvain, F. and Munnecke, A. (Eds.), Facies from Palaeozoic reefs and bioaccumulations, 171–223. Muséum national d'Histoire naturelle; Paris.

Bourque, P.-A. and Boulvain, F. 1993. A model for the origin and petrogenesis of the red stromatactis limestone of Paleozoic carbonate mounds. *Journal of Sedimentary Petrology*, **63**, 607–619.

Copper, P. 2002. Silurian and Devonian reefs: 80 million years of global greenhouse between two ice ages. In: Kiessling, W., Flügel, E. and Golonka, J. (Eds), Phanerozoic Reef Patterns. *SEPM Special Publication*, **72**, 181–238.

Czarnocki, J. 1925. Wyniki badań geologicznych dokonanych w r. 1924 na obszarze mezozoicznym zachodniej części Gór Świętokrzyskich. *Posiedzenia Naukowe Państwowego Instytutu Geologicznego*, **11**, 11–14.

Da Silva, A.C. and Boulvain, F. 2004. From paleosols to carbonate mounds: facies and environments of the Middle Frasnian platform in Belgium. *Geological Quarterly*, **48**, 253–266.

Dunham, R.J. 1962. Classification of carbonate rocks according to depositional texture. In: Ham, W.E. (Ed.), Classification of Carbonate Rocks – A Symposium, 108–121. American Association of Petroleum Geologists; Tulsa.

Embry, A.F. and Klovan, J.E. 1971. A late Devonian reef tract on northeastern Banks Island, Northwest Territories. *Bulletin of Canadian Petroleum Geology*, **19**, 730–781.

Filonowicz, P. 1968. Objaśnienia do Szczegółowej Mapy Geologicznej Polski 1:50 000 Arkusz Morawica, 100 pp. Instytut Geologiczny; Warszawa.

Filonowicz, P. 1981. Mapa Geologiczna Polski 1:200 000. Arkusz Kielce. Wyd. B, Wydawnictwa Geologiczne; Warszawa.

Flügel, E. 2010. Microfacies of Carbonate Rocks: Analysis, Interpretation and Application, 976 pp. Springer; Berlin.

Henbest, L.G. 1935. *Nanicella*, a new genus of Devonian foraminifera. *Journal of the Washington Academy of Sciences*, **25**, 34–35.

Hoffmann, M. and Paszkowski, M. 1992. Mikrobialne budowle organiczne górnego dewonu w synklinie kieleckiej. *Przegląd Geologiczny*, **40**, 606–607.

Johnson, J.G., Klapper, G. and Sandberg, C.A. 1985. Devonian eustatic fluctuations in Euramerica. *Geological Society of America Bulletin*, **96** (5), 567–587.

Kalvoda, J. 1990. Foraminiferal zonation of the Upper Devonian and Lower Carboniferous in Moravia (Czechoslovakia). *Acta Musei Moraviae*, **75**, 71–93.

Kaufmann, B. 1998. Middle Devonian reef and mud mounds on a carbonate ramp: Mader Basin (eastern Anti-Atlas, Morocco). In: Wright, V.P. and Burchette, T.P. (Eds), *Geological Society of London Special Publications*, **149**, 417–435.

Kaźmierczak, J. 1971. Morphogenesis and systematics of the Devonian Stromatoporoidea from the Holy Cross Mountains, Poland. *Palaeontologica Polonica*, **26**, 1–146.

Kershaw, S. 1984. Patterns of stromatoporoid growth in level-bottom environments. *Palaeontology*, **27**, 113–130.

Klovan, J.E. 1974. Development of western Canadian Devonian reefs and comparison with Holocene analogies. *American Association of Petroleum Geologists Bulletin*, **58**, 787–799.

Krebs, W. 1974. Devonian carbonate complexes of Central Europe. *Paleontologists and Mineralogists Special Publication*, **18**, 155–208.

Lipina, O.A. 1950. Foraminifera from the Upper Devonian of the Russian Platform. *Trudy Instituta Geologicheskikh Nauk Akademii Nauk SSSR*, **119**, 110–133.

Łuczyński, P. 1998. Stromatoporoid morphology in the Devonian of the Holy Cross Mountains, Poland. *Acta Palaeontologica Polonica*, **43**, 653–663.

Łuczyński, P. 2009. Stromatoporoid growth orientation as a tool in palaeotopography: A case study from the Kadzielnia Quarry, Holy Cross Mountains, central Poland. *Acta Geologica Polonica*, **59**, 319–340.

Łuczyński, P. 2022. Tsunamites versus tempestites: Various types of redeposited stromatoporoid beds in the Devonian of the Holy Cross Mountains (Poland), a case study from the Ołowianka Quarry. *PLOS ONE*, **17(5)**.

Machel, H.G. and Hunter, I.G. 1994. Facies model for Middle to Late Devonian shallow-marine carbonates, with comparisons to modern reefs: a guide for facies analysis. *Facies*, **30**, 155–176.

MacNeil, A. and Jones, B. 2016. Stromatoporoid growth forms and Devonian reef fabrics in the Upper Devonian Alexandra Reef System, Canada – Insight on the challenges of applying Devonian reef facies models. *Sedimentology*, **63**, 1425–1457.

Narkiewicz, M. 1988. Turning points in sedimentary development in the Late Devonian in southern Poland. In: McMillan, N.J., Embry, A.F. and Glass, D.J. (Eds), Devonian of the World. *Canadian Society of Petroleum Geologists, Memoir*, **14**, 619–635.

Narkiewicz, M. 1991. Mesogenetic dolomitization processes: an example from the Givetian to Frasnian of the Holy Cross Mts, Poland. *Prace Państwowego Instytutu Geologicznego*, **132**, 1–54. [In Polish with English summary]

Narkiewicz, M., Racki, G. and Wrzołek, T. 1990. Lithostratigraphy of the Devonian stromatoporoid-coral sequence in the Holy Cross Mts. *Geological Quarterly*, **34**, 433–456. [In Polish with English summary]

Narkiewicz, M., Racki, G., Skompski, S. and Szulczewski, M. 2006. Zapis procesów i zdarzeń w dewonie i karbonie Gór Świętokrzyskich. In: Skompski, S. and Żylińska, A. (Eds), Procesy i zdarzenia w historii geologicznej Gór Świętokrzyskich: Materiały konferencyjne LXXVII Zjazdu Naukowego Polskiego Towarzystwa Geologicznego, 51–77. Państwowy Instytut Geologiczny; Warszawa

Pedrycz, O. and Łuczyński, P. 2023. Charakterystyka sedymentologiczna dewonu rejonu Skrzelczyc (Góry Świętokrzyskie). In: Bojanowski, M., Jarzynka, A. and Wróblewski, W. (Eds), Materiały Konferencyjne 'POKOS 8', 126. Polish Geological Society; Chęciny. [In Polish]

Playford, P., Hocking, R., Cockbain, A., Becker, R. and House, M. 2009. Devonian reef complexes of the Canning Basin, Western Australia. *Geological Survey of Western Australia Bulletin*, **145**, 1–444.

Pratt, B.R. 1982. Stromatolitic framework of carbonate mud-mounds. *Journal of Sedimentary Petrology*, **52**, 1203–1227.

Pratt, B.R. 1995. The origin, biota and evolution of deepwater mud-mounds. In: Monty, C.L.V., Bosence, D.W.J., Bridges, P.H. and Pratt, B.R. (Eds), Carbonate Mud Mounds, Their Origin and Evolution. *IAS Special Publications*, **23**, 49–126.

Pratt, B.R. 2000. Microbial contribution to reefal mud-mounds in ancient deep-water settings: evidence from Cambrian. In: Riding, R.E. and Awramik, S.M. (Eds), Microbial Sediments, 282–287. Springer; Berlin.

Racki, G. 1993. Evolution of the bank to reef complex in the Devonian of the Holy Cross Mountains. *Acta Palaeontologica Polonica*, **37**, 87–182.

Racki, G. and Narkiewicz, M. 2000. Tectonic versus eustatic controls of sedimentary development of the Devonian in the Holy Cross Mts., Central Poland. *Przegląd Geologiczny*, **48**(1), 65–76. [In Polish]

Racki, G. and Soboń-Podgórska, J. 1993. Givetian and Frasnian calcareous microbiotas of the Holy Cross Mountains. *Acta Palaeontologica Polonica*, **37**, 255–289.

Racki, G. and Sobstel, M. 2004. Very large stromatoporoid indicating Early Frasnian reef core (Holy Cross Mts, Poland). *Geological Quarterly*, **48**, 83–88.

Racki, G., Wójcik, K., Halamski, A.T. and Narkiewicz, M. 2022. Middle Devonian Skały Formation in the Holy Cross Mountains (Poland) – formal description and subdivision based on new field data. *Annales Societatis Geologorum Poloniae*, **92**, 425–444.

Riding, R. 2002. Structure and composition of organic reef and carbonate mud mounds: concepts and categories. *Earth-Science Reviews*, **58**, 163–231.

Rodríguez-Martínez, M. 2011. Mud mounds. In: Reitner, J. and Thiel, V. (Eds), Encyclopedia of Geobiology, 667–675. Springer; Dordrecht.

Romanek, A. 2008. Mapa Geologiczna Polski 1:200 000, ark. 58 – Kielce, B – Mapa Bez utworów czwartorzędowych – Reambulacja. Państwowy Instytut Geologiczny; Warszawa.

Sandberg, C.A., Morrow, J.R. and Ziegler, W. 2002. Late Devonian sea-level changes, catastrophic events, and mass extinctions. *Geological Society of America Special Paper*, **356**, 473–487.

Szulczewski, M. 1971. Upper Devonian conodonts, stratigraphy and facial development in the Holy Cross Mts. *Acta Geologica Polonica*, **21**, 1–129.

Szulczewski, M. 1977. Main facial regions in the Paleozoic of the Holy Cross Mountains. *Przegląd Geologiczny*, **8–9**, 428–432. [In Polish]

Szulczewski, M. 1979. Devonian carbonate platform of the Holy Cross Mts. In: Fedorowski, J., Morycowa, E. and Roniewicz, E. (Eds), 3rd International Symposium on Fossil Cnidarians, Guidebook, 5–36. Wydawnictwa Geologiczne; Warszawa.

Szulczewski, M. 1981a. Dewon środkowy i górny zachodniej części Gór Świętokrzyskich. In: Żakowa, H. (Ed.), Przewodnik LIII Zjazdu PTG, Kielce, 6–8.IX.1981, 68–82. Wydawnictwa Geologiczne; Warszawa.

Szulczewski, M. 1981b. Kadzielnia (wycieczka). In: Żakowa, H. (Ed.), Przewodnik LIII Zjazdu Polskiego Towarzystwa Geologicznego, 110–115. Wydawnictwa Geologiczne; Warszawa.

Szulczewski, M. 1995. Depositional evolution of the Holy Cross Mts. (Poland) in the Devonian and Carboniferous – a review. *Geological Quarterly*, **39**, 471–488.

Szulczewski, M. 2006. Ewolucja środowisk depozycyjnych w dewonie świętokrzyskim i jej uwarunkowania. In: Skompski, S. and Żylińska, A. (Eds), Procesy i zdarzenia w historii geologicznej Gór Świętokrzyskich: Materiały konferencyjne LXXVII Zjazdu Naukowego Polskiego Towarzystwa Geologicznego, 56–62. Państwowy Instytut Geologiczny; Warszawa.

Szulczewski, M., Belka, Z. and Skompski, S. 1996. The drowning of a carbonate platform: an example from the Devonian–Carboniferous of the southern Holy Cross Mountains, Poland. *Sedimentary Geology*, **106**, 21–49.

Szulczewski, M. and Racki, G. 1981. Early Frasnian bioherms in the Holy Cross Mts. *Acta Geologica Polonica*, **31**, 147–162.

Tsien, H.H. 1975. Introduction to the Devonian reef development in Belgium. In: Conil, R., Groessens, E., Lejeune-Carpentier, M., Pel, J. and Tsien, H.H. (Eds), 2nd International Symposium on Corals and Fossil Coral Reefs, Paris, Livret-Guide Excursions, C, 3–43. Service géologique de Belgique; Paris.

Vierek, A. 2013. The palaeogeographical background of Late Devonian storm events in the western part of the Holy Cross Mountains (Poland). *Geologos*, **19**, 257–272.

Wilson, J.L. 1975. Carbonate facies in geologic history, 471 pp. Springer-Verlag; Berlin, Heidelberg, New York.

Wójcik, K. 2015. The uppermost Emsian and lower Eifelian in the Kielce Region of the Holy Cross Mts. Part I: Lithostratigraphy. *Acta Geologica Polonica*, **65**, 141–179.

Wright, V.P. 1992. A revised classification of limestones. *Sedimentary Geology*, **76**, 177–185.

Zhou, K. and Pratt, B. 2019a. Composition and origin of stromatactis-bearing mud-mounds (Upper Devonian, Frasnian), southern Rocky Mountains, western Canada. *Sedimentology*, **66**, 2455–2489.

Zhou, K. and Pratt, B. 2019b. Upper Devonian (Frasnian) stromatactis-bearing mud mounds, western Alberta, Canada: reef framework dominated by peloidal microcrystalline calcite. *Journal of Sedimentary Research*, **89**, 833–848.

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