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# Offshore redeposited coralline algae as evidence of Paleocene shallow-water carbonate sedimentation in the Magura Basin (Outer Carpathians)

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ABSTRACT:

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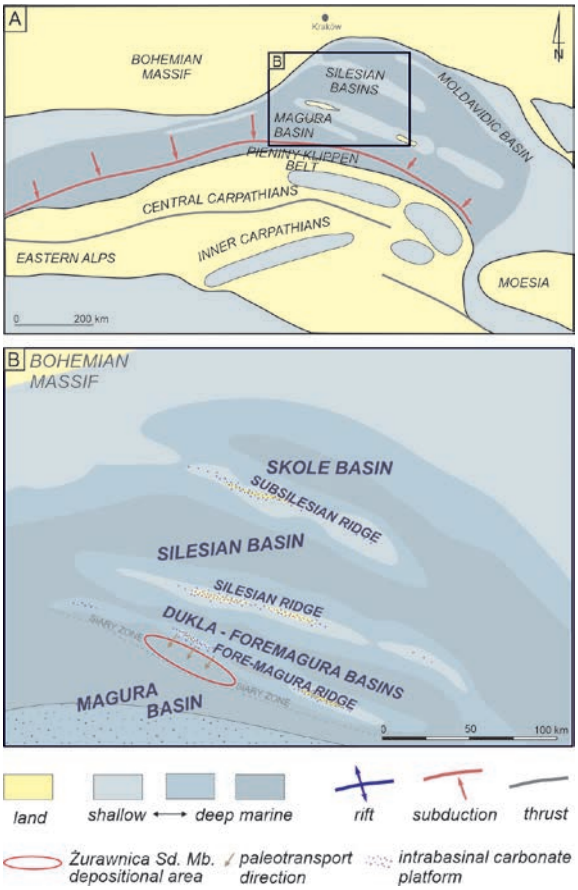
Within the upper Paleocene (Thanetian) flysch conglomeratic sandstones of the Magura Nappe, a bed characterized by dominant coralline red algae, with subordinate benthic foraminifera, corals, bryozoans, and molluscs has been identified. It is the only known site showing evidence of rarely explored Paleocene shallow-water areas in the Magura Basin. Corallines occur as abraded coralline algal debris and rhodoliths. The upper Paleocene coralline algal debris consists of rounded, sand- to pebble-size clasts. Two types of rhodoliths were distinguished: abraded sub-spheroidal boxwork up to 0.5 cm in diameter, and irregular boxwork rhodoliths larger than 1 cm in diameter. In the coralline algal assemblage, the most abundant component is *Sporolithon* sp., with subordinate *Lithothamnion* sp. and *Mesophyllum* sp. *Karpathia sphaerocellulosa* and *Spongites* sp. are also present. Bioerosions, such as *Entobia* isp., *Gastrochaenolites* isp., *Trypanites* isp., and microborings are common in the coralline debris. This assemblage documents the shallow-water carbonate biogenic sedimentation in the northern Magura Basin during the Thanetian. These corallines formed above the storm wave base and were redeposited offshore in the inner part of the Magura Basin by sediment gravity flows.

**Key words:** Taphonomy; Allochthonous assemblage; Flysch; Thanetian; Carpathian Tethys.

## INTRODUCTION

Allochthonous coralline debris and rhodolith deposits result from either offshore or onshore transport from the coralline algal factory (e.g., Johnson *et al.* 2017; Puga-Bernabéu and Aguirre 2017). Coralline debris and crushed rhodoliths may be incorporated into offshore deposits derived from living rhodolith beds during extremely high-energy events like storms, hurricanes and tsunami. These events might form sedimentary shell and coralline algal beds due to either landward-incoming waves or basin-ward backwash flows (e.g., Martín *et al.* 2004; Braga *et al.* 2006; Gramigna *et al.* 2012; Brandano and Ronca 2014; Johnson *et al.* 2017; Puga-Bernabéu and Aguirre 2017). On the whole, in these settings a significant part of the fossil benthic communities represents re-mobilized skeletal debris and only a minor part of the produced skeletal grains is normally preserved *in situ*. That material exhibits high




Text-fig. 1. Paleogeographical sketch-maps of the Outer Carpathian basins in the Early Paleogene. **A** – Carpathian region (Golonka *et al.* 2021). **B** – Western Outer Carpathians (Kowal-Kasprzyk *et al.* 2021) (Sd. Mb. – sandstone member).

mobility and it is moved from shelves to the more inner part of the basins (Johnson *et al.* 2017; Puga-Bernabéu and Aguirre 2017). Submarine channels are ways also for offshore transport as well as point-sourced and/or line-sourced mixed siliciclastic-carbonate submarine fans and/or channels (e.g., Bassi *et al.* 2017).

The sedimentary rocks of the Outer Carpathians formed in the western, marginal part of the closing Tethyan Ocean from the Jurassic to the Miocene. They developed within basins separated by intrabasinal ridges (e.g., Golonka and Picha 2006; Leszczyński *et al.*, 2012; Golonka *et al.* 2019; Text-fig. 1), which resulted in the occurrence of a wide range of depositional environments, from shallow- to deep-marine settings. As a consequence of the Miocene folding, a structural reorganization took place and, in their present form, the Outer Carpathians are composed of nappes (Text-fig. 2) built predominantly of deep-marine deposits, whereas their shallow-marine counterparts were buried and nowadays are not exposed. The sedimentary history of shallow-marine environments within the Outer Carpathian basins remains, therefore, relatively poorly understood. In these basins Paleocene coralline debris and rhodoliths have been interpreted as allochthonous components of deep-water siliciclastic deposits (e.g., Bieda 1968; Leszczyński 1978; Leszczński *et al.* 2012; Kowal-Kasprzyk *et al.*, 2021; Cieszkowski 1992; Szymakowska 1966; Rajchel and Myszkowska, 1998; Cieszkowski *et al.* 2005). Corallines have been also reported from a few findings of re-sedimented limestone blocks (Kowal-Kasprzyk *et al.* 2021). Coralline algal factories locally developed in the early Paleogene Outer Carpathian basins constituting the *Lithothamnion*-bryozoan facies (Kowal-Kasprzyk *et al.* 2021). In the marginal zone of the Tethys (i.e., the Silesian Domain) occurrences of late Paleocene coralline red algae are rare (e.g., Leszczyński 1978; Cieszkowski *et al.* 2012; Leszczyński *et al.* 2012; Minor-Wróblewska 2018; Kowal-Kasprzyk *et al.* 2021; Text-fig. 1). The deposits formed in the Silesian Domain are today incorporated in the Silesian, Skole, and Subsilesian nappes and partly in the Fore-Magura group of nappes. They originated in the area north of the Silesian Ridge. The Silesian Ridge was an intrabasinal long-lasting uplift, which stably divided the Carpathian Tethys into an internal (Magura) and an external (Silesian) domain (e.g., Unrug 1968; Książkiewicz 1975; Eliáš *et al.* 2003; Golonka and Piacha 2006; Golonka *et al.* 2019). In the Magura Domain (today incorporated in the Magura Nappe), located further south of the ridge, the oldest corallines are known from the Żurawnica Sandstone Member (deposited in the northern part of the Magura Basin; Książkiewicz 1974b; Cieszkowski *et al.* 2006; Geroch *et al.* 1967) and from the Szczawnica Formation (deposited in the southern part of the Magura Basin; Alexandrowicz *et al.* 1966; Chrustek *et al.* 2005), Paleocene in age (Kowal-Kasprzyk *et al.* 2021).

In this study we investigate the late Paleocene coralline algae from the type locality of the Żurawnica Sandstone Member. The coralline algae are major biotic components in a unique mixed siliciclastic-carbonate bed within a conglomeratic sandstone deposit. The coralline taxonomic composition, growth forms, and taphonomic features were assessed to infer the paleoenvironmental setting in which they grew. This study provides information about these rarely explored shallow-water areas in the Magura Basin.

## GEOLOGICAL SETTING

The studied section is located in the upper part of Żurawnica Hill (49.761°N, 19.514°E) (NW of Sucha Beskidzka town) in the Kozie Skały Reserve and belongs to the Łabowa Formation (Text-figs 2, 3) occurring in the Outer Carpathians. The Outer Carpathians constitute the externides of the Carpathian Orogen (e.g., Golonka and Waśkowska-Oliwa 2007; Golonka *et al.* 2019). To the north, the externides border the European Platform, onto which they have been thrust. To the south, they adjoin more internal Carpathian units (Pieniny Klippen Belt), which separate the Outer Carpathians from the Inner Carpathians (Text-fig. 2A). The Outer Carpathians have a nappe structure formed as a result of tectonic activity associated with the Alpine orogeny. The main structural units in the Polish segment of the Outer Carpathians include the Magura Nappe (the highest), the Fore-Magura group of nappes, and the Silesian, Subsilesian, and Skole nappes (e.g., Książkiewicz 1962, 1972; Oszczypko *et al.* 2006; Text-fig. 2A). These nappes are successively thrust over one another and together onto the European Platform (e.g., Żytko *et al.* 1989; Golonka and Picha 2006).

The studied deposits belong to the sedimentary succession of the widest extended Magura Nappe. This consists predominantly of deep-water clastic flysch successions, deposited from the Jurassic to the Miocene within the Magura Basin (e.g., Książkiewicz 1962, 1975; Golonka and Waśkowska-Oliwa 2007; Kowal-Kasprzyk *et al.* 2021; Text-fig. 1). The study area lies within the Siary Zone, which represents the northern structural-tectonic unit of the Magura Nappe (Książkiewicz 1974a, b; Cieszkowski *et al.* 2006; Text-fig. 2). It corresponds to the outer northern part of the Magura Basin supplied by clastic material delivered from the northern side of the Fore-Magura Ridge (Cieszkowski and Waśkowska-Oliwa 2001; Text-fig. 1). In the study area the Łabowa Shale Formation comprises upper Paleocene–middle Eocene, mudstone-dominated variegated shales with two complexes of thick-bedded sandstone and conglomeratic sandstone: the Żurawnica Sandstone Member (200 m in thickness, Thanetian) and the Skawce Sandstone Member (150 m in thickness, lower Eocene; Książkiewicz 1974a, b; Cieszkowski and Waśkowska 2001, 2011; Cieszkowski *et al.* 2006; Waśkowska 2012; Text-fig. 3). Research was conducted on the type section of the Żurawnica Sandstone Member (Text-figs 2, 3) in a 12 m-thick landslide cliff (Text-figs 2, 3).

The foraminiferal assemblages studied from the type locality of the Żurawnica Sandstone Member in Kozie Skały Reserve are typical of the upper part of the Rzehakina fissistomata Zone (Cieszkowski and Waśkowska 2011; Waśkowska-Oliwa 2000) and indicate a Thanetian age.

## MATERIAL AND METHODS

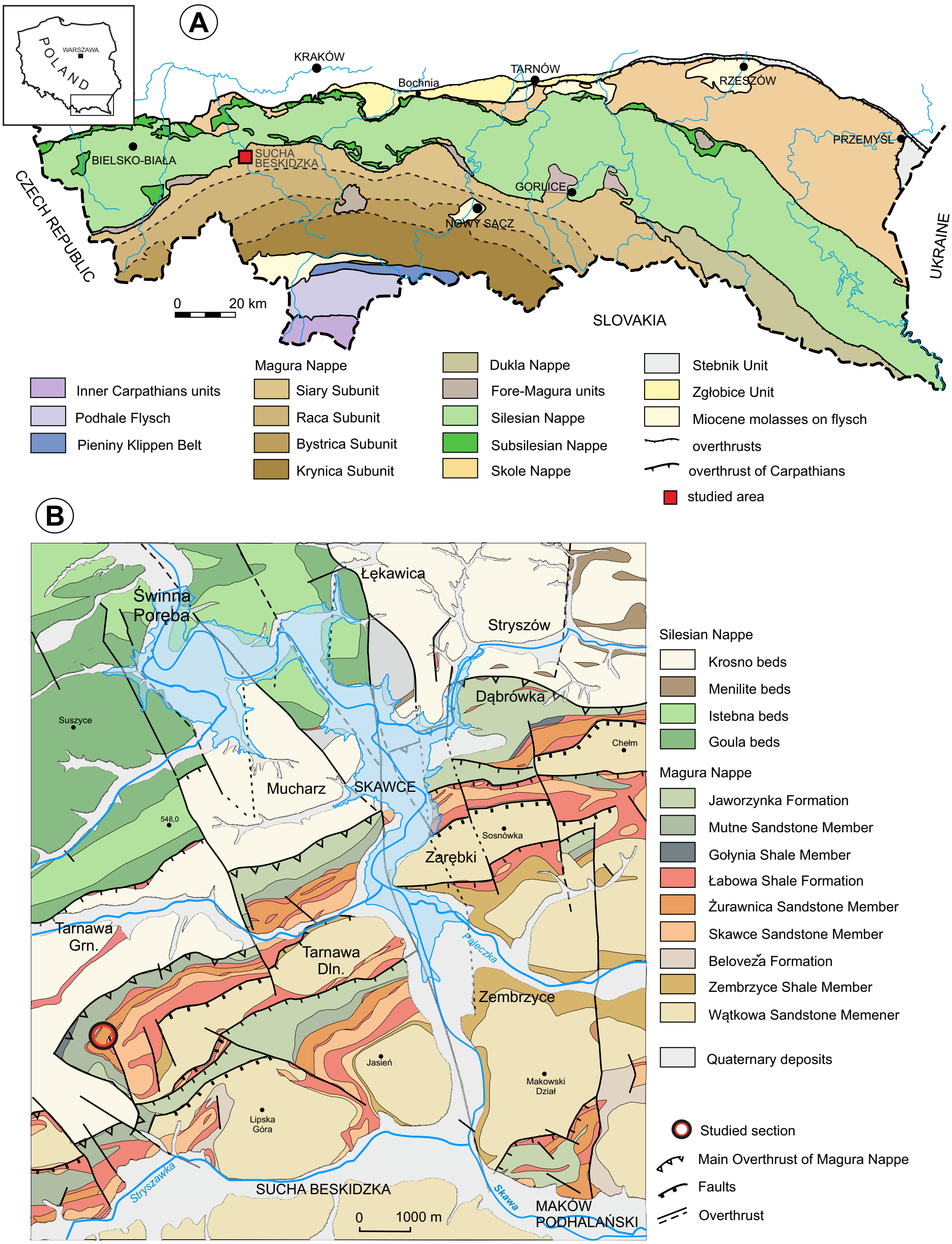
The studied section was documented using the standard sedimentological logging method, including descriptions of beds in terms of thickness, type of bed surfaces, sedimentary structures, grain size fraction, grain shape, and mineral composition of grains. For the coralline algal analysis, ten samples of rocks (up to 20 cm in diameter) containing carbonate clasts were selected, and 57 thin sections were prepared. All research was conducted at the Faculty of Geology, Geophysics, and Environmental Protection of the AGH University of Krakow. Characteristics of the coralline algae include the assessment of coralline growth forms, taxonomy, and taphonomic signatures (abrasion, bioerosion, fragmentation). Coralline algae were identified to the lowest taxonomic level possible. Open nomenclature was applied to coralline specimens whose morpho-anatomical diagnostic characters were not completely preserved (e.g., reproductive features) or could not be confidently assigned to a previously described species. Taxonomic subdivisions of coralline algae follow the most recent molecular phylogenetic schemes (Peña *et al.* 2020; Jeong *et al.* 2021; Aguirre *et al.* 2022). The terminology for coralline algal growth forms follows Woelkerling *et al.* (1993). Bioerosion traces were identified at the ichnogenus level (Bromley and D'Alessandro 1983, 1984; Kelly and Bromley 1984; Edinger and Risk 1996). The degree of bioerosion was estimated in thin sections using the bioerosion index (BI), ranging from no bioerosion (BI 1) to complete bioerosion (BI 6; where the inner structure of the grain is indistinguishable; Bassi *et al.* 2012).

The studied samples are stored at the Faculty of Geology, Geophysics, and Environmental Protection, AGH University, Kraków.

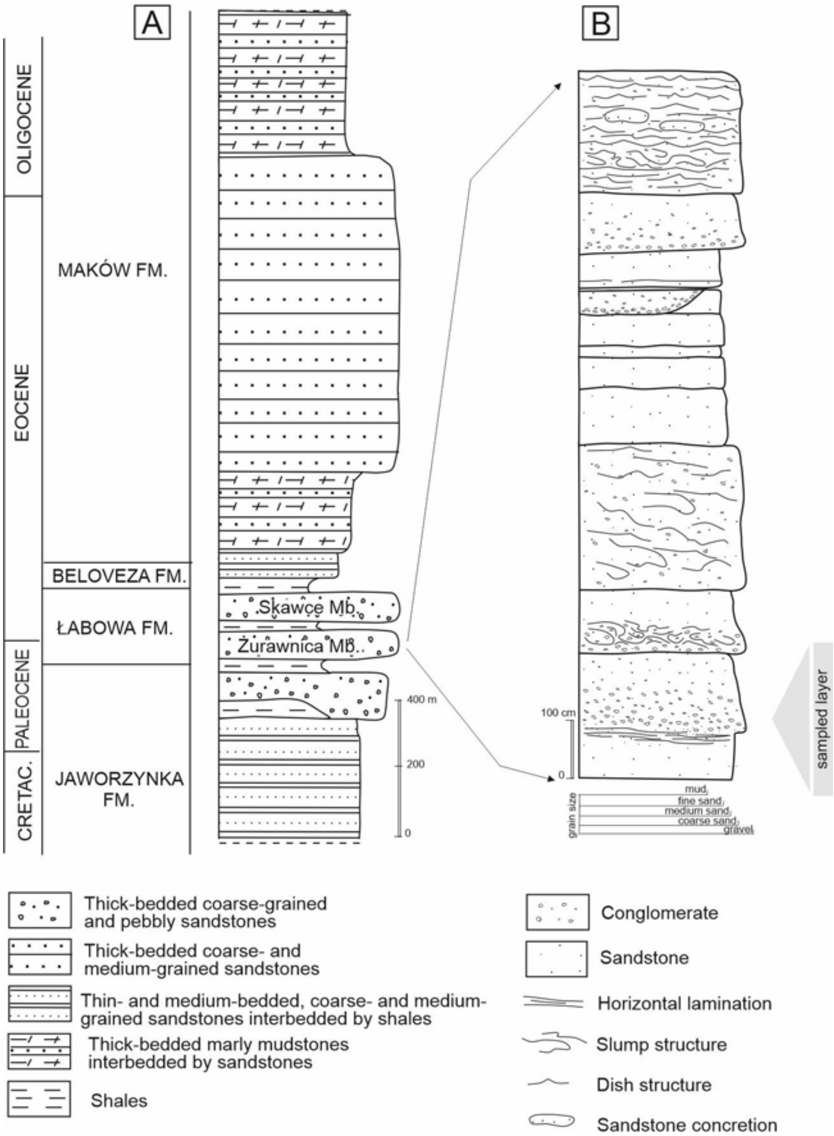
## RESULTS

### Lithology

The section consists of a dozen very thick sandstone beds, normal or reverse graded with erosive lower surfaces and slump deformation structures (Text-fig. 3B). The sandstone is grey, poorly sorted,




Text-fig. 2. **A** – Tectonic-sketch map of the Polish part of Carpathians (modified from Żytko *et al.* 1989). **B** – Geological map of Sucha Beskidzka-Skawce area (Książkiewicz *et al.* 1974a; Cieszkowski *et al.* 2006, modified).

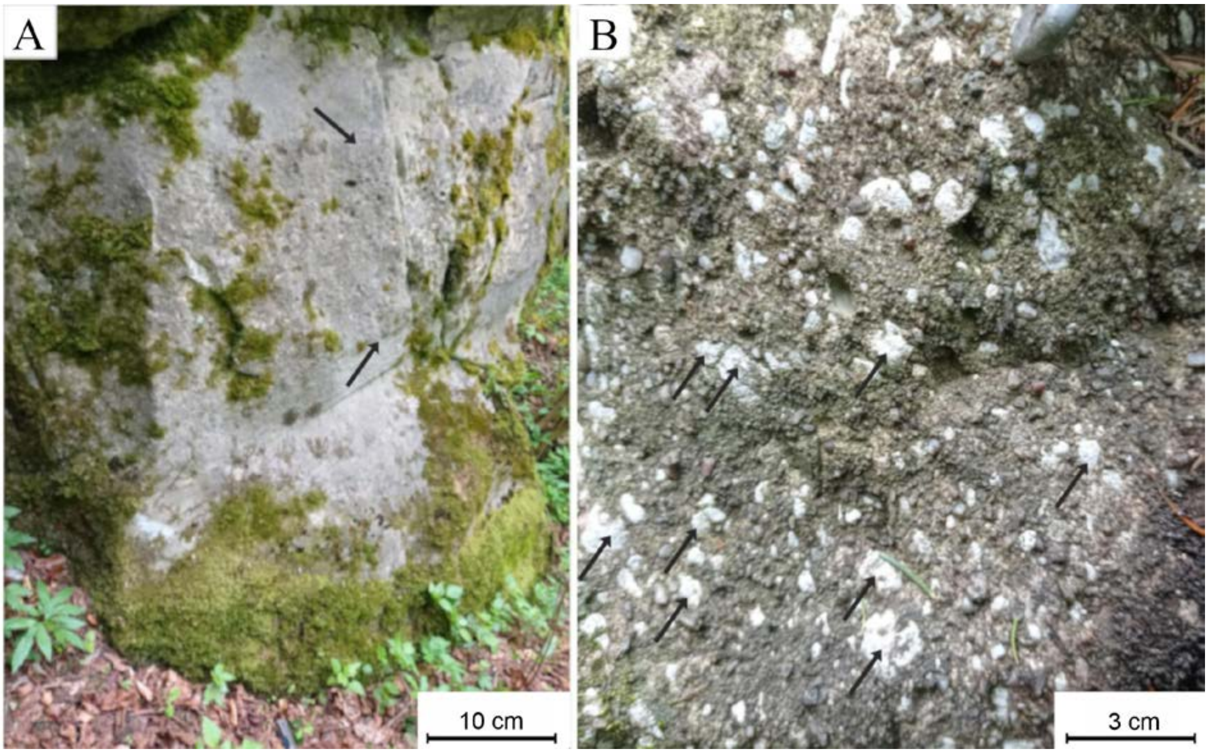



Text-fig. 3. **A** – Lithostratigraphical log of the Magura Nappe in Sucha Beskidzka area (modified from Cieszkowski and Waśkowska 2011). **B** – Detailed lithological log section in the landslide cliff in uppermost part of the Żurawnica Hill (Fm. – formation; Mb. – member).

coarse- and medium-grained, locally conglomeratic. It consists of very well-rounded quartz grains, with a subordinate amount of sand to pebble-size grains of limestone, metamorphic schists, feldspar and mica in a siliciclastic matrix.

Coralline algae occur in a single very thick bed, exposed at the base of the landslide cliff, which consists of three layers (stratigraphical order): 80 cm-thick medium-grained sandstone with parallel lamination in its upper part, 50–60 cm-thick normal graded conglomeratic sandstone with grains up to 3 cm in diameter, and 50–70 cm-thick normal graded coarse and medium grained sandstone (Text-figs 3B, 4). The bed thickness varies laterally.

The quartz and carbonate grains are the main components of that bed; mica, feldspar, and metamorphic schist are very rare. The carbonate clasts range from sand-size to pebbles, including lithoclasts (micritic limestones) and bioclasts (such as coralline algae, benthic foraminiferal tests, coral and bryozoan fragments, and bivalve shells). The coralline algae are dominant components. Their accumulation occurs in the middle part of the bed, in a normal-graded conglomeratic sandstone, which is characterized predom-




Text-fig. 4. A – Studied conglomeratic sandstone bed in the landslide cliff in the Żurawnica Hill, Kozie Skały Reserve (narrows point the range of studied conglomeratic sandstone bed). B – Detail of the studied horizon (carbonate clasts are highlighted in white, narrow points the biger rodoliths). For stratigraphical location see Text-fig. 3.

inantly by mixed sand and pebble sized siliciclastic clasts dispersed in a siliciclastic matrix (Text-fig. 4).

The bioclasts vary in size and shape, ranging from less than 1 mm up to more than 3 cm. The gravel grains are rare, and they are unevenly distributed (average 1–3 grains per 1 $cm^2$). Apart from coralline grains, small fragments of other bioclasts occur in the sediment matrix as well and they are coated by corallines contributing to the rhodolith formation. Larger benthic foraminifera are represented by rare *Nummulites* sp., *Heterostegina* sp., and orthophragminids.

**Type of coralline algal grains**

The coralline red algae occur as abraded fragments of encrusting and fruticose thalli as well as fragmented and entire rhodoliths (Text-figs 5–8).

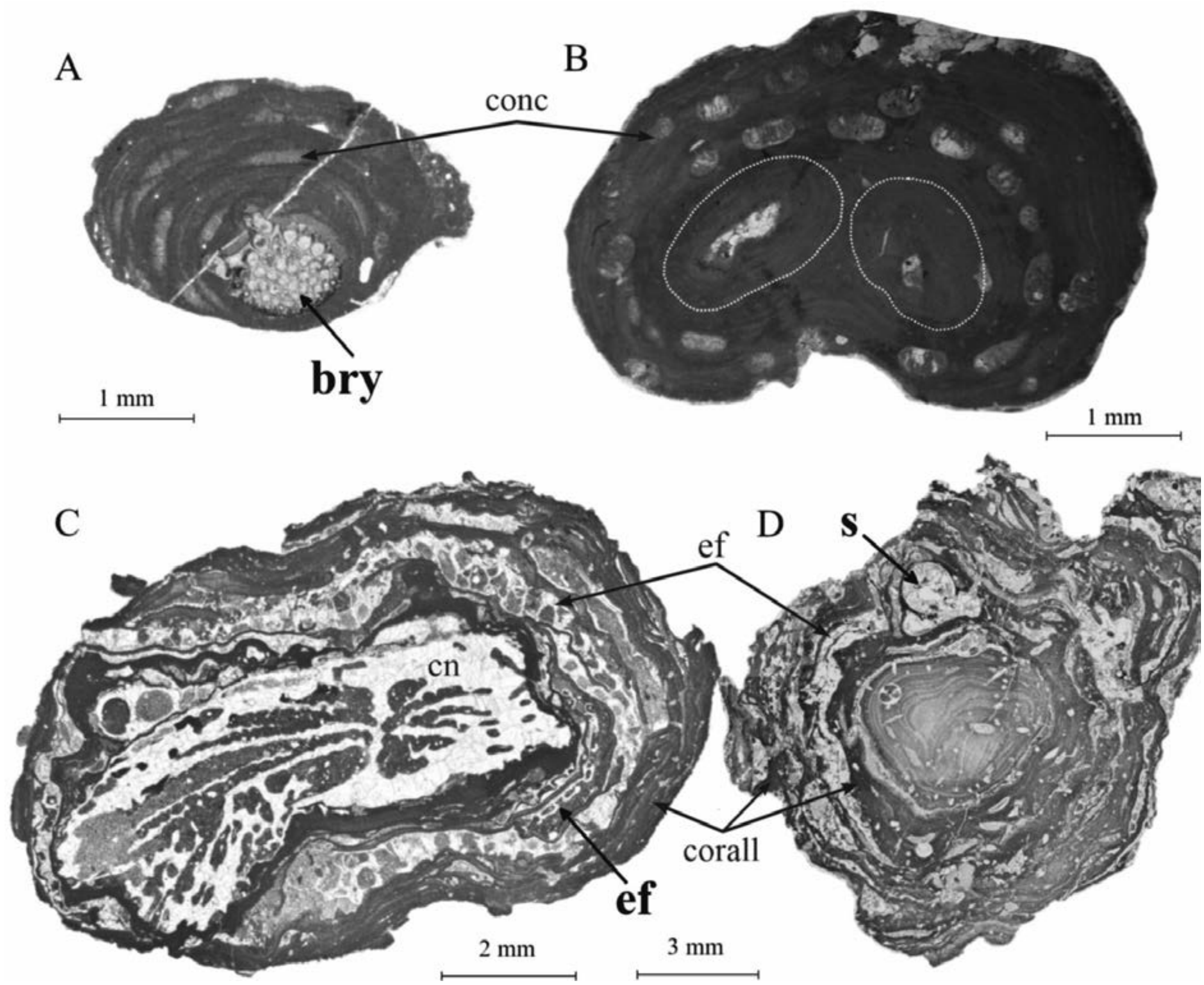
Coralline debris ranges in size from sand-size grains to pebbles. The sand-sized coralline fragments are abraded and show a good degree of roundness: (a) the fine sand (up to 0.25 mm in size) is spheroidal or close to spheroidal in general outline, well rounded, irregular-shaped coralline fragments are rare; (b) the medium sand (0.25–0.5 mm) consists of abraded ellipsoidal or irregularly shaped coralline fragments; (c) the coarse and very coarse sand (0.5–2 mm) are more ellipsoidal, discoidal or irregular, generally well rounded, with rare fragments with sharp-edged surface.

Pebble-sized grains (2–25 mm in size) are abraded and the majority are highly bioeroded; they do not show diagnostic characters for coralline species identification. Broken rhodoliths also belong to that group.

Rhodoliths, constituting about 15% of the carbonate components, are made up of encrusting (Text-figs 6A, 7A, B, E), warty (Text-fig. 7D), and rare lumpy (Text-fig. 8F) coralline algae. Two type types are distinguished: sub-spheroidal boxwork rhodoliths and irregular boxwork rhodoliths.

The sub-spheroidal boxwork rhodoliths, very common in the studied material, are made up by thick, internally compact encrusting thalli, with small carbonate nuclei (Text-fig. 5A). They are abraded, with smooth outer surfaces, and are up to 5 mm in diameter.

The irregular boxwork rhodoliths (Text-fig. 5B–D), larger than 1 cm in diameter, show uneven outer




Tex-fig. 5. Microphotographs of rhodoliths, Żurawnica locality. **A** – Small sub-spheroidal boxwork rhodolith with bryozoan (bry) nucleus. **B** – Two-nuclei rodolith. **C**–**D** – Large irregular boxwork rhodolith with coral nucleus (cn) and encrusting foraminifera (ef), and serpulids (s). conc, conceptacle; corall, coralline red algae.

surfaces and are formed by superimposed very thin loosely-packed coralline thalli coating a large nucleus which is usually a fragment of coral or oyster shell (Text-fig. 5C). The ratio of cover thickness/nucleus size is usually less than 1. With such thin thalli, the irregular rhodolith shape is inherited by the nucleus shape. Rhodoliths with two nuclei are rare (Text-fig. 5B). They are formed by the bounding of two small separate rhodoliths in a single nodule by coralline algae overgrowing them. Generally, irregular boxwork rhodoliths are much bigger than sub-spheroidal ones: their sizes are larger than 1 cm in diameter. They are slightly abraded with uneven surfaces. This type of rhodolith is rare in the studied material. The highest diversity occurs in these rhodoliths, since they are intergrown with encrusting foraminifera (acervulinids), bryozoans, and serpulids (Text-fig. 5C, D). Acervulinids occur as single or superimposed specimens among coralline thalli. The encrusting agglutinated foraminifer *Haddonia* sp. is also present. Fragments of corals occurs within the rhodoliths.

**Taxonomic composition**

Five species of coralline algae were identified, with representatives of three orders: Sporolithales, Hapalidiales, and Corallinales (Text-fig. 6). The most abundant forming species is *Sporolithon* sp. (Table 1, Text-fig. 6A) yielding about 40% of the total identified coralline specimens, whereas Hapalidiales (*Lithothamnion* sp. more common than *Mesophyllum* sp.) are subordinate (30% of identified specimens;

| Species | Coralline algal debris | Rhodoliths sub-spheroidal box | Rhodoliths irregular box |
|---|---|---|---|
| Sporolithales | | | |
| *Sporolithon* sp. | +++ | +++ | +++ |
| Hapalidiales | | | |
| *Lithothamnion* sp. | ++ | +++ | |
| *Mesophyllum* sp. | | + | |
| Corallinales | | | |
| *Karpathia sphaerocellulosa* | ++ | + | + |
| *Spongites* sp. | ++ | + | +? |

Table 1. Relative abundance of the distinguished coralline red algal species in the coralline agal debris and rhodoliths. +++, abundant; ++, common; +, rare.

Text-fig. 6B, C). Among the Corallinales, about 10% of the recognised specimens represent *Karpathia sphaerocellulosa* Maslov, 1962 (Text-fig. 6E, F; Bassi *et al.* 2005), whereas *Spongites* sp. (Text-fig. 6D) is a subordinate component.

*Sporolithon* sp. is the dominant species in the large irregular boxwork rhodoliths, and some of them are made up of *Karpathia sphaerocellulosa* and *Spongites* sp. (Table 1). Small sub-spheroidal boxwork rhodoliths are monospecific and made up of encrusting Sporolithales (*Spongites* sp.; Text-fig. 7A, E) and Hapalidiales (mainly *Lithothamnion* sp.; Text-fig. 7B–D). The highest coralline diversity occurs in the algal debris. All taxa, except *Mesophyllum* sp., were identified, with *Sporolithon* sp. representing the dominant component (Table 1). No relationship between genus and growth form was observed, except for *Karpathia sphaerocellulosa*, which occurs only as encrusting growth forms.

**Bioerosions**

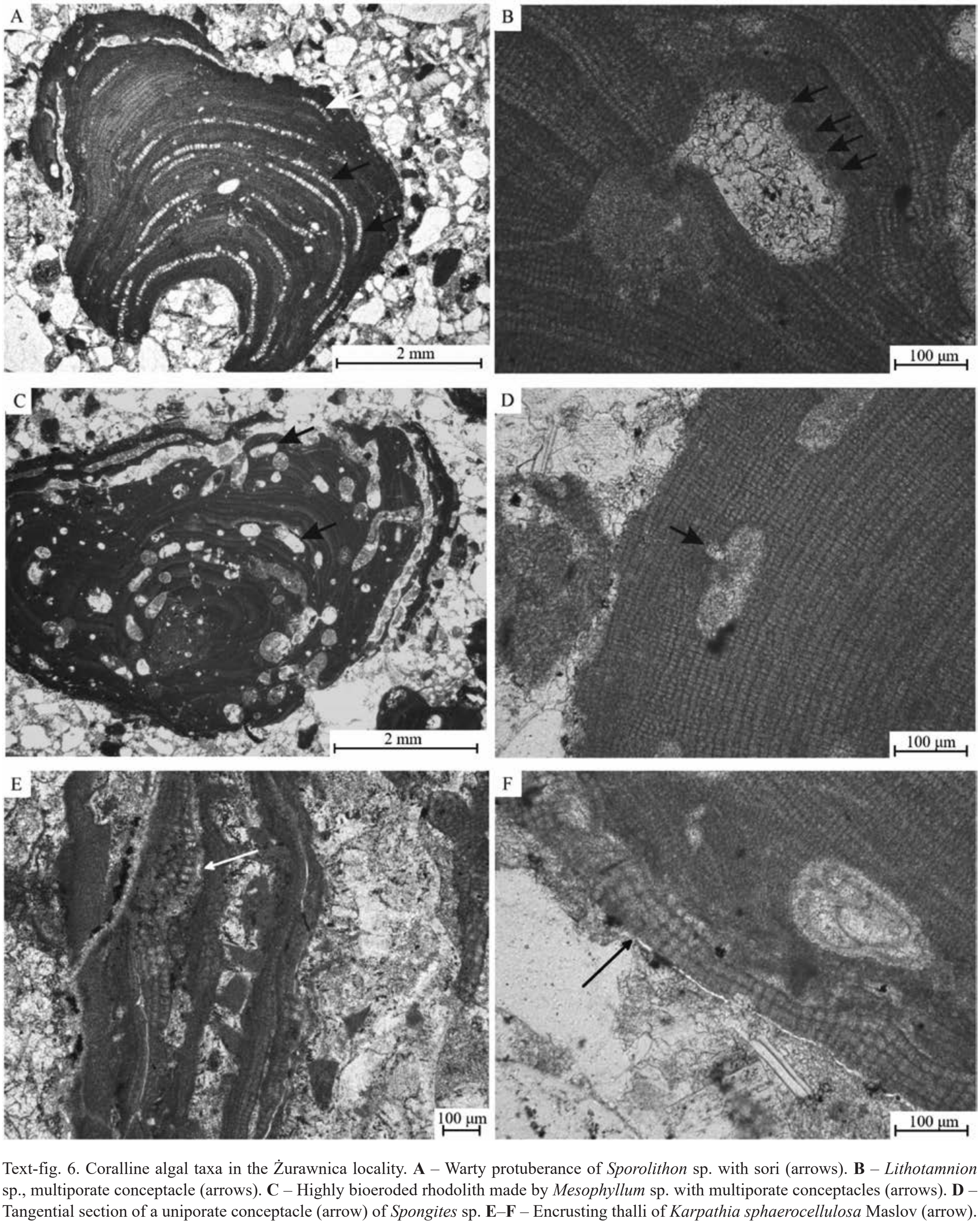
Bioerosions occur in single coralline fragments of the algal debris as well as in the rhodoliths (Text-fig. 8). The highest bioerosion was found in encrusting *Sporolithon* sp., *Mesophyllum* sp., and *Spongites* sp., whereas no or rare bioerosion was observed in warty specimens of Hapalidiales and *Sporolithon* sp. In large irregular boxwork rhodoliths the BI ranges from 1 to 3, whereas in small sub-spheroidal boxwork rhodoliths bioerosion is very rare: BI is 1 (rare 2).

The traces can be assigned to four different ichnospecies: *Entobia* isp. (made by etching sponges), *Gastrochaenolites* isp. (by bivalves; Text-fig. 8D), *Trypanites* isp. (by worms; Text-fig. 8A), and microborings. The largest borings represent *Gastrochaenolites* isp., with its bivalve preserved in the hole, in large irregular boxwork rhodoliths. *Entobia* isp. is filled with sparry calcite cement or micrite matrix with benthic and planktonic foraminiferal tests. *Trypanites* isp. is present in coralline debris and sporadically in small sub-spheroidal boxwork rhodoliths. Microborings (similar to those described by Checconi *et al.* 2010) occur in coralline algal debris and in rhodoliths.

## DISCUSSION

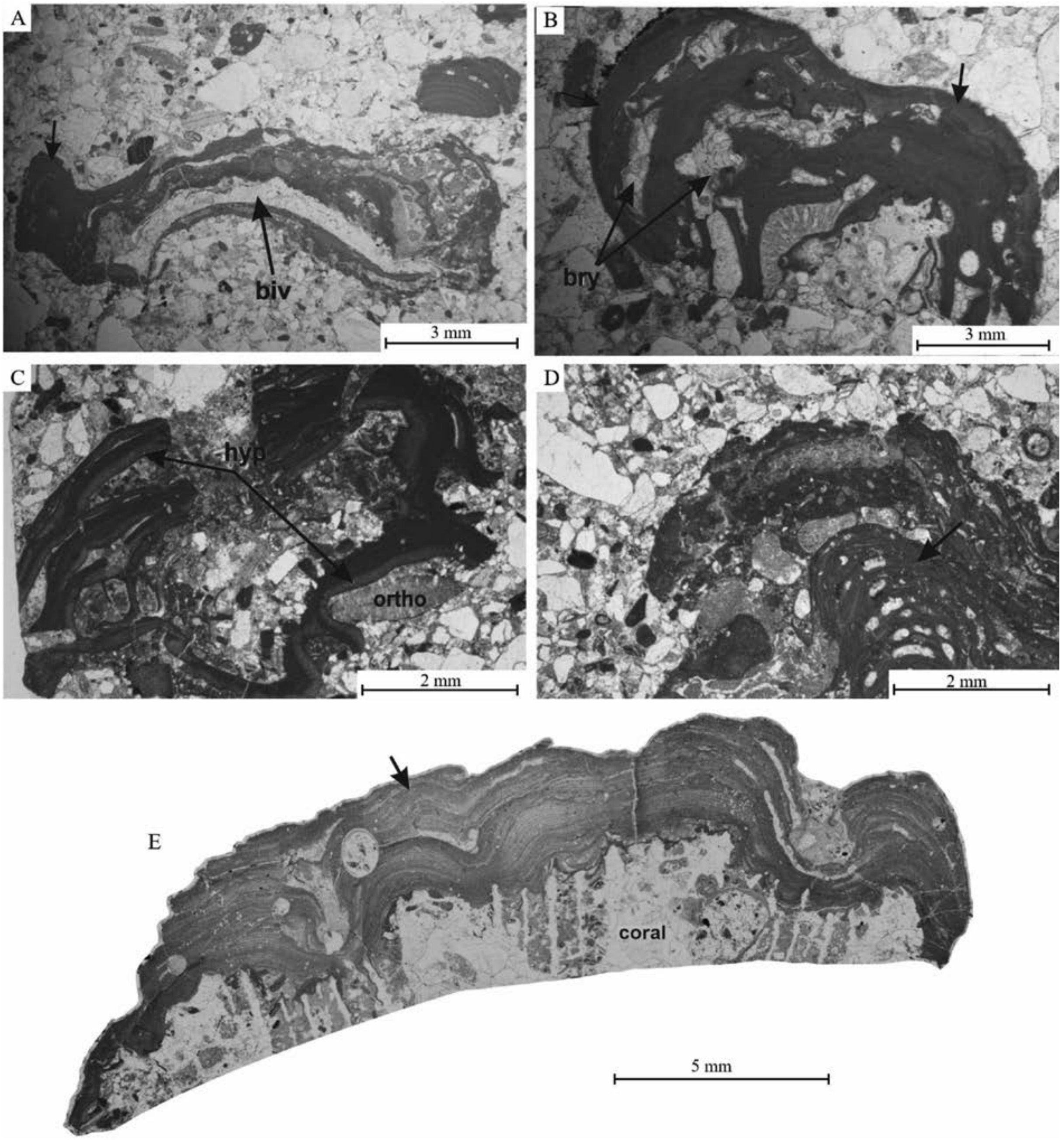
Within the Magura Nappe the studied succession in the landslide cliff on Żurawnica Hill represents unique evidence of shallow-water coralline algae in the Magura Basin offshore-transported into deeper settings (Text-figs 3, 4). This is actually the single known site of this type within the Magura Nappe.

The production of coralline algal debris and the rhodolith characteristics are related to the sedimentation rate and hydrodynamic conditions in the source area (e.g., Bosence 1983; Checconi *et al.* 2007; Aguirre *et al.* 2017). The studied corallines show an encrustation/bioerosion pathway characteristic of areas on the shelf-margin (Bassi *et al.* 2017). The identified ichnogenera (*Entobia*, *Gastrochaenolites*, *Trypanites*) preferentially inhabited settings with low sedimentation rates (Bromley and D'Alessandro 1983, 1984; Bassi *et al.* 2020). The low BI (i.e., BI 1–3) assessed in the studied rhodoliths indicates relatively short residence times of rhodoliths on the seafloor before burial (Bassi *et al.* 2012). The growth of large irregular boxwork rhodoliths was promoted by a relative low sedimentation rate and low energy conditions. These conditions are confirmed by the occurrence of rhodoliths with two nuclei (Text-fig. 5B). These rhodoliths were exposed on the sediment-water interface for enough time to allow corallines to overgrow two small coalescent rhodoliths. Their large size, the inner loosely-packed arrangement of the thalli, as well as the uneven outer surface, point to a low overturning rate (Aguirre *et al.* 2017). This inner loosely-packed arrangement characterised by a high proportion of constructional voids has been considered indicative of quiet waters (Nitsch *et al.* 2015; Brasileiro *et al.* 2018; Vale *et al.* 2022).



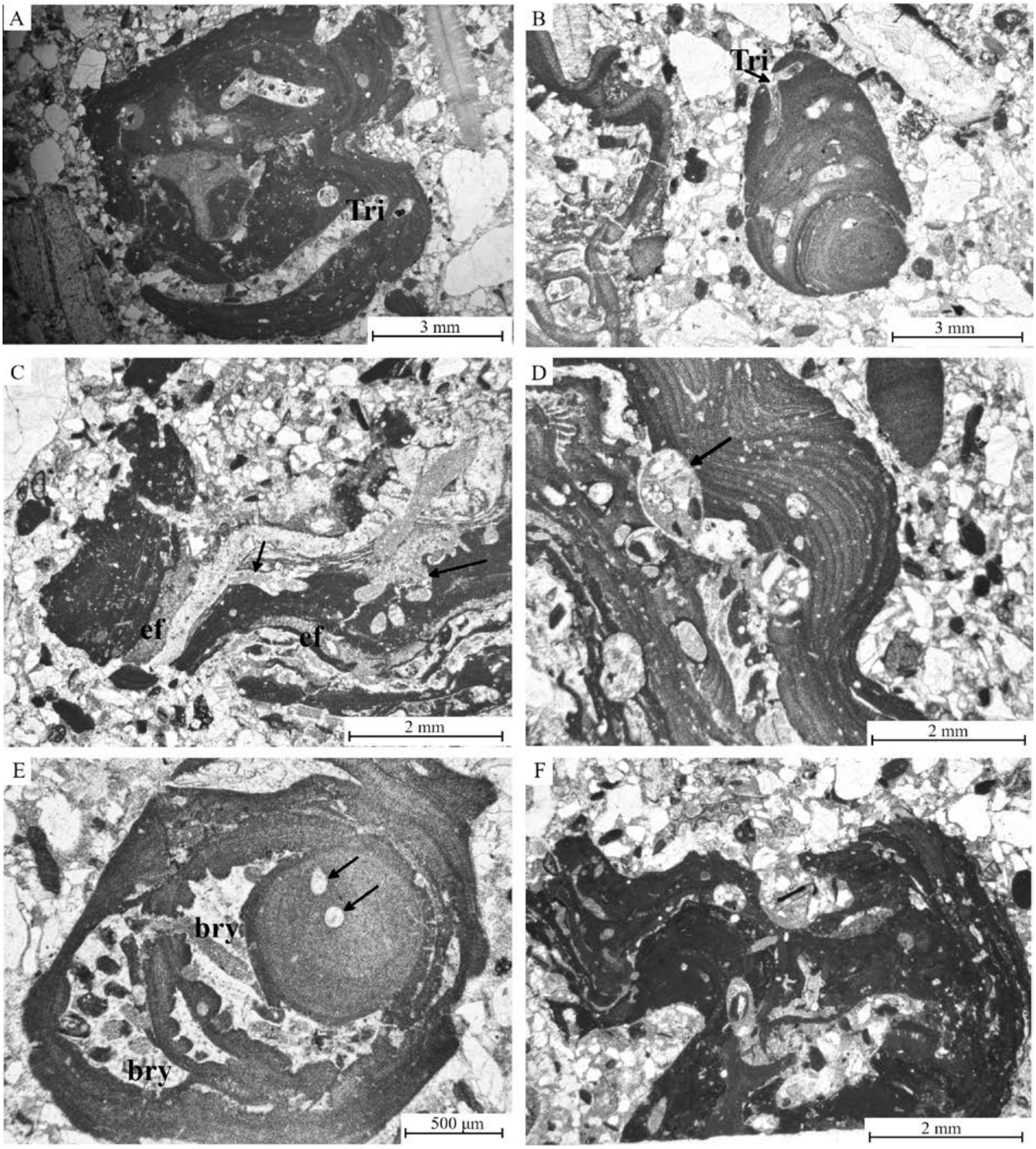

Text-fig. 6. Coralline algal taxa in the Żurawnica locality. **A** – Warty protuberance of *Sporolithon* sp. with sori (arrows). **B** – *Lithotamnion* sp., multiporate conceptacle (arrows). **C** – Highly bioeroded rhodolith made by *Mesophyllum* sp. with multiporate conceptacles (arrows). **D** – Tangential section of a uniporate conceptacle (arrow) of *Spongites* sp. **E**–**F** – Encrusting thalli of *Karpathia sphaerocellulosa* Maslov (arrow).

In terms of taxonomic composition, the most abundant rhodolith-forming is *Sporolithon*, which has been recorded from shallow to deeper-water settings in Recent and fossil deposits (e.g., Adey 1979; Basso *et al.* 2009), with the abundance of Sporolithales increasing with water depth (e.g., Braga *et al.* 2009;




Text-fig. 7. Coralline algal taxa in the Żurawnica locality. **A** – Disarticulated bivalve shell (biv) encrusted by *Sporolithon* sp. (arrow). **B** – Encrusting *Lithothamnion* sp. (arrows) with bryozoans (bry). **C** – Encrusting Hapalidiales thallus with coaxial cell arrangement in the hypothallus (hyp) and a larger foraminiferal rthphragminid test (ortho). **D** – Lumpy protuberance of Hapalidiales thallus (arrow) encrusted by undetermined coralline thallus. **E** – Bioeroded warty *Sporolithon* sp. (arrow) on abraded coral fragment.

Aguirre *et al.* 2022). From the earliest Danian record to the Thanetian, the relative proportion of Sporolithales increased to the detriment of the Hapalidiales, which were initially the most abundant corallines (Aguirre *et al.* 2007). Red algal debris and small sub-spherical rhodoliths are built up by a significant amount of *Lithothamnion*, which lives in shallow settings, at tens of meters of water depth, mainly below 30 m depth (e.g., Basso 1995; Rendina *et al.* 2020). *Mesophyllum* has a wider depth range, from a few meters down to c. 100 m (e.g., Adey 1984; Athanasiadis and Neto 2010), but the highest abundance is known at c. 40 m (Basso




Text-fig. 8. Ichnotaxa identified in coralline debris and rhodoliths in the Żurawnica locality. **A** – Highly bioeroded coralline fragment with *Trypanites* isp. (Tri). **B** – *Trypanites* isp. (Tri) in an abraded and bioeroded fragment of Hapalidiales. **C** – Encrusting acervulinid foraminifer (ef) on an encrusting coralline thallus with *Entobia* isp. filled with sparry calcite cement (arrow). **D** – Microborings in warty coralline protuberance with *Gastrochaenolites* isp. (arrow). **E** – Sub-spheroidal boxwork rhodolith with *Entobia* isp. (arrow) and bryozoans (bry). **F** – Highly bioeroded coralline fragment.

1995). *Karpathia* has been identified in shallow-water paleoenvironments (Aguirre *et al.* 2022). *Spongites* tends to occur in shallow-water settings of fossil tropical and temperate seas (e.g., Braga and Aguirre 2001, 2004; Braga 2017; Aguirre and Braga 2022). The shallow-water origin of the studied coralline assemblage is confirmed by similar Paleocene assemblages (Leszczynski *et al.* 2012; Aguirre *et al.* 2022), and by late Eocene and Oligocene possible counterparts of the Western Tethys (e.g., Bassi and Nebelsick 2010; Nebelsick *et al.* 2000; Rasser and Nebelsick 2003).

The abraded fragments of encrusting and fruticose corallines (debris), sub-spheroidal boxwork and large irregular boxwork rhodoliths, together with the presence of coral and oyster shell fragments, account for the allochthonous nature of the algae. The coralline algal debris and rhodoliths, taphonomically altered (fragmented and abraded) and colonized by epi- or infaunal organisms (encrusting and borings), are likely related to storm-reworked material. This material derived from exposed or only shallowly buried zones within the taphonomic active zone, favouring taphonomic feedback due to colonization by encrusters (e.g., bryozoans, serpulids) and borers (bivalves, sponges). Abrasion and fragmentation affected coralline debris and rhodoliths in the shallower settings where the corallines grew or partially acted during the offshore transportation into deeper-water substrates where the corallines were finally buried. The analyzed coralline algal assemblage was, therefore, formed above the storm wave base (Braga and Martin 1988; Braga *et al.* 2010). High-energy events redeposited offshore these shallow-water carbonate components and fragments of benthic organisms (i.e., corals, oysters), along with siliciclastic grains of variable sizes, to the deeper-water low-energy settings (e.g., Simone and Carannante 1988; Braga *et al.* 2001, 2006; Garcia-Garcia *et al.* 2009; Bassi *et al.* 2017; Aguirre and Braga 2022; Poyatos-Moré *et al.* 2022).

Storm events selected the studied rhodoliths from shallower areas and the smaller ones (i.e., the studied material) were able to travel longer distances offshore. Comparable study cases of rhodolith-size selection by storms have been reported from fossil and modern accumulations (Toscano *et al.* 2006; Bassi *et al.* 2017; Aguirre and Braga 2022). Storm beds show higher proportions of fragmentation, abrasion and biotic interactions (presence of borings and encrusting organisms) (Yesares-García and Aguirre 2004; Aguirre and Méndez-Chazarra 2010; Joshi *et al.* 2017) as evidenced in the material from Żurawnica. Tsunamis represent another common agent responsible for sediment transport in shallow-water settings. The absence of a diverse shell composition and the low abrasion and fragmentation as described from fossil offshore backflow tsunami deposits exclude a tsunami event as a possible transport mechanism for the studied Żurawnica coralline bed (Puga-Bernabéu and Aguirre 2017). Tsunamiites would contain in fact a major proportion of unbored and non-encrusted skeletal remains (Caron 2012; Puga-Bernabéu and Aguirre 2017).

The Magura Basin was characterised by a siliciclastic sedimentary regime (e.g., Oszczypko *et al.* 2006; Golonka and Picha 2006). The intra-basin sandy and conglomeratic deposits generally are devoid of carbonate grains or contain them in a small amount. The occurrence of coralline algal debris and rhodoliths in the sandstones from Żurawnica Hill documents the shallow-water carbonate production which took place locally in the northern edge of the basin. From the Fore-Magura Ridge the siliciclastic deposits with carbonate components were prone to mobilization as they were subordinately constituted of loose, unlithified skeletal grains. They formed within the reach of storms and were transported offshore by gravity flows and deposited with siliciclastic material in the inner part of the basin. The basinward transport mechanisms for these coralline debris and rhodoliths by sediment gravity flows were related to major Paleocene relative sea-level changes (Leszczyński 1978; Leszczyński *et al.* 2012; Minor-Wróblewska 2018; Kowal-Kasprzyk *et al.* 2021).

Lower Paleogene deposits with coralline algae are not common in the Outer Carpathians (e.g., Bieda 1968; Leszczyński 1978; Cieszkowski 1992; Leszczyński *et al.* 2012; Minor-Wróblewska 2018; Kowal-Kasprzyk *et al.* 2021). Next to the Żurawnica Hill site, upper Paleocene coralline assemblages have been reported from three localities in the Istebna Sandstone (from Upper Sandstone) in the Silesian Nappe, a few localities in the Ciężkowice Sandstone (from the lower Sandstone III) in the Silesian Nappe, and from Czerwin Sandstones in the Subsilesian Nappe (Leszczyński 1978; Cieszkowski *et al.* 2005; Leszczyński *et al.* 2012; Minor-Wróblewska 2018). This case study documents the existence of a coralline algal factory that developed in late Paleocene shallow-water settings of the Silesian Basin situated to the north of the Magura Basin. The rhodoliths are common in the upper Paleocene Istebna and Ciężkowice sandstones in the Silesian Nappe. The locality of Harńczykowa Range in Beskid Mały mountains is described as being particularly rich in rhodoliths (Leszczyński 1978). It is located close to the Magura Thrust, only 3 km from the Żurawnica locality, and represents the Ciężkowice Sandstone III. The sedimentary factory of sandstones as well to the other localities of the Istebna and Ciężkowice sandstones was located on the southern part of the Silesian Ridge (Text-fig. 1B). These coralline assemblages share many similarities in terms of depositional setting, taxonomic composition, taphonomic features, and age with those of the Żurawnica Hill locality which originated on the southern part the Fore-magura Ridge, developed along northern site Silesian Ridge (Text-fig. 1B).

## CONCLUSIONS

The coralline algae of the Thanetian flysch conglomeratic sandstone (Żurawnica Sandstone Member) cropping out in Żurawnica Hill (Kozie Skały Reserve) consist of abraded fragments of encrusting and fruticose corallines (debris), sub-spheroidal boxwork and large irregular boxwork rhodoliths in an allochthonous context.

Sub-spheroidal boxwork rhodoliths, up to 5 mm in diameter, are made up by thick, internally compact encrusting thalli, with small carbonate nucleus. The large irregular boxwork rhodoliths are formed by superimposed very thin loosely-packed coralline thalli usually coating a large fragment of coral or oyster shell. Both types of rhodoliths show abraded outer surfaces.

Rhodolith-forming species are dominated by Sporolithales (*Sporolithon* sp.), with subordinate Hapalidiales (*Lithothamnion* sp., *Mesophyllum* sp.), and Corallinales (*Karpathia sphaerocellulosa*, *Spongites* sp.). Boring traces are ascribed to *Entobia*, *Gastrochaenolites*, *Trypanites*, and microborings.

The coralline assemblages are interpreted as elements formed in shallower-water settings characterised by low sedimentation rates and low-energy conditions, above the storm wave base. In the northern part of the Magura Basin the smaller coralline debris and rhodoliths were finally moved by gravity flows, related to major Paleocene relative sea-level changes, to the inner part of the basin and were deposited with siliciclastic flysch material in deeper-water environments.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