

The Lower Badenian (Middle Miocene) coral patch reef at Grobie (southern slopes of the Holy Cross Mountains, Central Poland), its origin, development and demise

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ABSTRACT:

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The Lower Badenian (Middle Miocene) patch reef of Grobie (southern slopes of the Holy Cross Mountains, Central Poland) is the only coral buildup in the Polish Miocene. It contains four hermatypic coral taxa, of which *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME) and *Porites collegniana* MICHELIN dominate, whereas *Montastraea* sp. and *Stylophora reussiana* MONTANARO-GALLITELLI & TACOLI are subordinate. Wide diversities of colony shapes in this coral assemblage reflect natural development of the reefal structure and/or energy of environment; it varies from platy colonies (first settlers on an unconsolidated, pebble-strewn substrate), through branching, to massive forms. Wave activity was the most significant factor that influenced the reef core and distribution of associated facies. Disintegration and removal of reef core sediment led to the formation of crack crevices in freshly lithified deposits. Redeposited sediment formed the back-reef talus, where its composition varied with distance from the reef core. Reef-associated molluscs and decapods are abundant, the bivalves being represented by high-energy resistant borers (*Lithophaga* sp., *Jouannetia* (*J.*) *semicaudata* DES MOULINS) and the squatter *Sphenia* (*S.*) *anatina* (BASTEROT). Among 21 decapod taxa, the species *Dardanus hungaricus* (LÖRENTHEY, 1929) is reported from Poland for the first time. Recognition of the diversity of facies and their distribution enabled reconstruction of Grobie area during the Early Badenian transgression. Slowing and/or stopping of sea-level rise encouraged development of the patch reef, while the subsequent, rapid transgressive pulse caused its demise. Shortly after all reefal deposits were buried, diagenetic processes of neomorphisation and/or dissolution of aragonitic skeletal elements took place. This diagenesis could have continued till the Late Miocene and Pliocene, synchronously with rapid erosion that progressed since the Early Sarmatian until the Pleistocene glaciations.

Key-words: Coral patch reef, Hermatypic corals, Badenian, Miocene, Holy Cross Mountains, Poland.

INTRODUCTION

The Miocene deposits of the northern part of the Carpathian Foredeep in Poland display strongly diversified development of facies that was controlled by palaeo-

geographic conditions during the Middle Miocene marine transgression (RADWAŃSKI 1969). Their faunal diversity is locally typified by organic buildups, such as algal-vermetid, cryptalgal-serpulid and oyster reefs (PISERA 1978, 1985, 1996), while the corals, either solitary

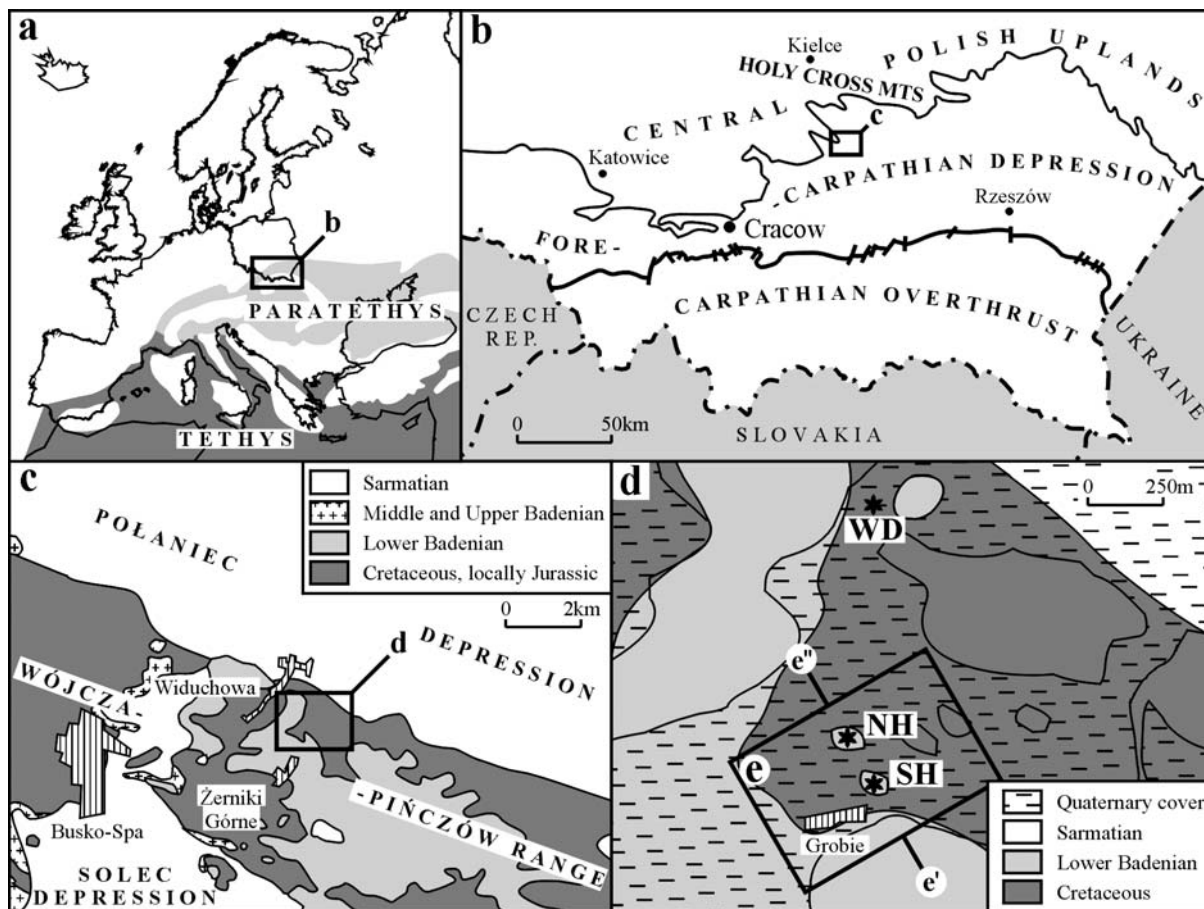


Fig. 1. Location of described sites: NH – Northern Hill at Grobie, SH – Southern Hill at Grobie, WD – outcrop at Widuchowa-Doły, e – range of reconstructed Early Badenian scenery (Text-fig. 8), e'-e'' – line of cross-section (Text-fig. 4); a-c adopted from: RADWAŃSKI (1977), STUPNICKA (1989), CZARNOCKI (1950)

or colonial, have always been noted as single specimens (see DEMBIŃSKA-RÓZKOWSKA 1932, STOLARSKI 1991, RONIEWICZ & STOLARSKI 1991). The purpose of this paper is to describe the unique structure of the only Polish coral patch reef of Miocene age which has been recorded so far; its development and demise, distribution of related facies, and associated fauna.

PREVIOUS WORKS

WRONA (1970), who gave the description of the exposure and paid special attention to the contained fauna, discovered the coral-bearing locality of Grobie. The decapods he collected were passed to Reinhard FÖRSTER, who recognised three taxa (FÖRSTER 1979a). MÜLLER (1984, 1996) who described 17 taxa (of which 5 are new to science) and revised FÖRSTER's assignments, subsequently studied his own decapod collection. He has also presented some environmental and climat-

ic conclusions and postulated a patch reef character for the coral buildup. The patch reef was mentioned briefly by STUDENCKI (1979) and the associated bivalves were studied by STUDENCKA & STUDENCKI (1988).

GEOLOGICAL SETTING

The studied patch reef is located on the southern slopes of the Holy Cross Mountains (Text-fig. 1a-1b) on the northern margin of the Wójcza-Pińczów Range, close to its border with the Polaniec Depression. These local tectonic units of Miocene age (Wójcza-Pińczów Horst and Polaniec Graben) belong to a system of tectonic blocks building the central and the northern part of the Carpathian Foredeep in Poland (ŁYCZEWSKA 1975a, b; KUBICA 1992).

The Miocene reef-associated deposits are located some 6 kilometres ENE of Busko-Spa, where they build two small hills, named here the Northern and the

Southern Hill, situated north of the village of Grobie (Text-fig. 1d, 3-4). The distance between the hills exceeds some 200 metres. The character of the coral-bearing buildup is recognisable in the regolith on the surface of arable fields, whereas the non-weathered parts of the buildup are not exposed.

The Miocene deposits exposed along the Wójcza-Pińczów Range overlie with an angular unconformity the Mesozoic basement, which is built predominantly of Upper Cretaceous marls and siliceous marls passing occasionally into sandy limestones; the latter are called the common name “gaizes” (see Text-fig. 1c). The underlying rocks, such as Cenomanian glauconitic sandstones and Upper Jurassic limestones, are exposed locally along the southern margin of the range, a few kilometres south of Grobie (see RADWAŃSKI 1969). The transgressive Miocene succession (Text-fig. 2) starts with Lower Badenian deposits of the Pińczów Formation, which is divided into two lithofacies members. The lower part of the succession has only a local distribution, and is commonly called the “Sublithothamnian Level”. It is com-

posed mainly of marls and sandy marls, about 5 metres thick. Younger deposits, rich in coralline-algal material, represent the “Lithothamnian Level” (also known as the Pińczów Limestone), which exceeds 50 metres in thickness and totally overlies older strata. The distribution of these Lower Badenian strata is strongly controlled by the palaeogeography and lithology of the substrate during the Middle Miocene transgression (RADWAŃSKI 1969; STUDENCKI 1979, 1988). The studied reef structure occurs in the upper part of the “Sublithothamnian Level”, and extends to the lowermost part of younger deposits. The core reef part, due to its organodetrital calcareous character, may be considered as a counterpart of the Pińczów Limestone (see STUDENCKI 1988).

STUDENCKA & STUDENCKI (1988) inferred a Badenian age for most of the bivalves of the Pińczów Limestone. The presence of the coral *Turbellastraea reussiana* (MILNE EDWARDS & HAIME) in the studied site also indicates its Badenian age, as well as for the other Paratethyan occurrences of this species (see e.g. BUDD & al. 1996). According to MÜLLER (1984), the Grobie patch reef corresponds to the Langhian Stage of the Mediterranean (approximately Lower Badenian of the Paratethys), or to the NN5-NN6 nannofossil zones. Stratigraphic studies of the Korytnica Clay (GEDL 1996), which is believed to be coeval deposit (RADWAŃSKI 1969), determined them as belonging to the NN5 zone (Lower Badenian). Summarising, it may be stated that the age of the studied patch reef is Lower Badenian (Langhian, or NN5 zone).

Younger Miocene strata in the studied area are present locally as erosional remnants. Sandy clays and marls (Skawina Formation) followed by Middle Badenian gypsum (Krzyżanowice Formation), both reaching up to 20 metres, are exposed in the vicinity of Busko-Spa, some 4 kilometres west of Grobie (see Text-fig. 1c). Upper Badenian and Lower Sarmatian marly clays (Machów Formation) occur mainly in small tectonic grabens with thicknesses probably exceeding 20 metres. The youngest Miocene deposits of the Lower Sarmatian are regressive carbonate conglomerates, several metres thick (Chmielnik Formation). The Quaternary cover of glacial sands and loess, a dozen or so metres thick, appears locally.

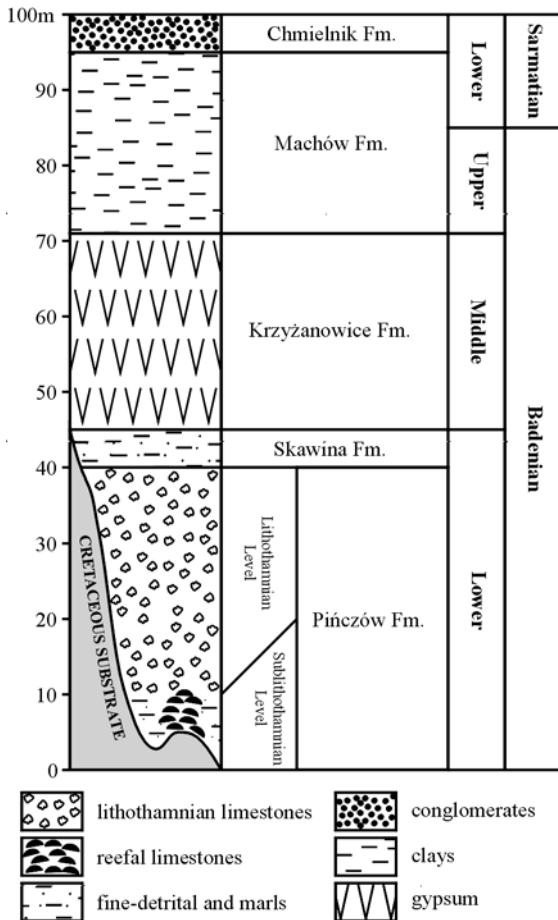


Fig. 2. Stratigraphic framework of Miocene deposits of Grobie area; lithostratigraphic units after ALEXANDROWICZ & al. (1982)

PATCH REEF DEPOSITS AND ASSOCIATED FACIES

The Lower Badenian deposits exposed in the study area can be observed all over both of the two hills. Vertical and horizontal differentiation of the deposits allows four types of facies to be distinguished here: (1) reef base; (2)

reef core; (3) back-reef talus with two subfacies, proximal and distal; (4) reef cover, overlying reefal deposits.

Reef base facies. This occurs at the base of the Miocene sequence as a basal conglomerate directly underlying the reef core deposits. It may be observed in the weathered material around the Northern Hill. Huge pebbles (long axes over 20 centimetres) of Upper Cretaceous gaizes may be collected there, but nothing is known about the cementing material. The pebbles are composed of quartz grains (about 60 %), glauconite (up to 20 %), and sponge spicules (5-10 %), all in a micritic matrix.

Reef core facies. Remnants of a reefal buildup, a few metres thick and some tens of metres across which may be considered as a patch reef, are exposed in the highest part of the Northern Hill. A mass-occurrence of hermatypic corals, with dominant *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME) and *Porites collegniana* MICHELIN, characterise this buildup, while *Montastraea* sp. is present in small numbers (Pl. 1, Figs 1-3). Moreover, rare occurrences of *Stylophora reussiana* MONTANARO-GALLITELLI & TACOLI were reported by MÜLLER (1996), and *Heliastrea* sp. was recorded by WRONA (1970) [the latter item probably refers to *T. reussiana*]. The deposits that are considered as the reef core facies are developed as light-grey cavernous limestones. The coral colonies are usually dissolved, leaving void cavities, only some neomorphised calcitic specimens of *T. reussiana* and *P. collegniana* were found.

The reef core facies may be studied only in weathered material from the field-brash, which is generally smaller in size than a single coral colony. This means that the general petrographic characters are difficult to determine. Nevertheless, it can be concluded that microfacies change from dominant framestone to local rudstone. The framestone is built of the biggest

colonies of massive *T. reussiana* and platy/encrusting and stick-like forms of *P. collegniana*. In blocks from the field-brash they are usually oriented in one direction, independently of their shape or taxonomy, suggesting preservation in life position. Their total amount varies from about 10 to 40 percent of the entire rock. Broken and reoriented Colony fragments of variable size form the rudstone parts of the rock. Crusts of coralline algae *Lithophyllum* sp., several millimetre thick, commonly encrust the coral colonies.

The intercolonial material of the framestone parts is dominantly packstone with local grainstone and/or wacke-packstone, and comprises quartz grains (about 30%) and glauconite (about 1%) derived from Upper Cretaceous gaizes, as well as hash of Miocene mollusc shells and echinoderm skeletons. These elements are generally less than a millimetre across. Only the fragments of coralline-algal thalli and bryozoan colonies of *Cellepora* sp. reach larger dimensions, up to 1 centimetre. The other important components are micritic peloids of varied structure and genesis. Some of them contain small amounts of quartz grains, while the texture of others suggests them to be micritised debris of coralline-algal thalli. The content of peloids varies from a few up to 50 % (Pl. 2, Fig. 1).

The regular and fine-detrital composition of the intercolonial material changes locally. In some places, it is a conglomerate built of irregular rubble bonded with micritic matrix. The rubble is built of the dominant packstone, while the matrix contains a small amount of quartz grains (about 1%) and angular coralline-algal debris (Pl. 2, Fig. 2).

Also noteworthy is the presence of crevices cutting the intercolonial packstone (Pl. 1, Fig. 1) and filled with a micritic matrix that includes small amounts of quartz



Fig. 3. General view of Lower Badenian reefal deposits exposed at Grobie, to show distribution of facies: **b** – reef base, **r** – reef core, **p** – proximal back-reef talus, **d** – distal back-reef talus, **c** – reef cover; **NH** – Northern Hill, **SH** – Southern Hill

grains. This resembles the matrix of the conglomerate, differing only in the lack of coarser grains. In some cases, microbial lamination in the infilling sediment may be observed (Pl. 2, Fig. 3). Crevices are generally curved or rectilinear, several centimetres long and up to few millimetres wide. Some are wedge-shaped, about 2 centimetres long and extend into thin rectilinear crevices. Very thin (< 1mm) fissures that have not been filled with any sediment are also present.

Back-reef talus facies. These deposits are exposed on the SE part of the Northern Hill directly adjacent to the reef core facies, and they are also present on the Southern Hill. Their composition changes gradually as the distance from the reef core increases. In its immediate neighbourhood, that is the proximal back-reef talus, they have a floatstone structure (locally wacke-packstone or packstone) built of quartz grains (approx. 35%), glauconite (1%), and biogenic debris (Pl. 2, Fig. 4). The latter are variously shaped fragments of coralline-algal thalli and molluscs, and *Cellepora* sp. colonies. Fragments of *T. reussiana* and *P. collegniana* colonies (up to 1 cm) and small quantities of Upper Cretaceous echinoids (*Micraster* sp.) and inoceramid prisms derived from substratal rocks can also be found. Micritic peloids and micritised debris of coralline-algae reach 20% of the total grain amount. These deposits are generally similar to the intercolonial material of the reef core facies, differing in the higher proportion of biogenic clasts, often of large dimensions, and in the rare occurrence of small coral rubble. The colour of the entire rock is distinctly yellowish.

Deposits of the distal back-reef talus form the Southern Hill, where they are composed of packstone,

locally grainstone, and show no sedimentary structures. A mass occurrence of fine-grained material, such as quartz grains (40-50%), glauconite (up to 2%), foraminifers (mainly Textulariidae), and peloids, was observed. Coralline-algal and echinoderm skeletal particles are present, but do not reach more than 1.5 mm across (Pl. 2, Fig. 5).

Reef cover facies. The reef core deposits are covered by coralline-algal limestones of the "Lithothamnian Level", which are developed at the base as the branching-algae subfacies (STUDENCKI 1988). The transition between the reef core facies and the branching-algae subfacies seems to be extremely sharp as it was observed in pieces of a cobble from the field-brash in the NW part of the Northern Hill. Main rock components (up to 60 %) of these rudstones are fragments of branching coralline-algae, *Lithophyllum* sp., some of which overcrust *Cellepora* sp. colonies. The matrix consists of micrite with quartz grains (app. 3%), micritic peloids, shell debris, and common foraminifers (Pl. 2, Fig. 6). It is followed by algal-bryozoan subfacies of the "Lithothamnian Level" which has been removed from the hills under discussion but is still present on the surrounding highs.

REMARKS ON SYNDEPOSITIONAL LITHIFICATION

The intercolonial deposits of the reef-core frame-stone are built generally of a packstone of a uniform composition. However, some parts of the rock are conglomerates of packstone rubble in matrix, what suggests

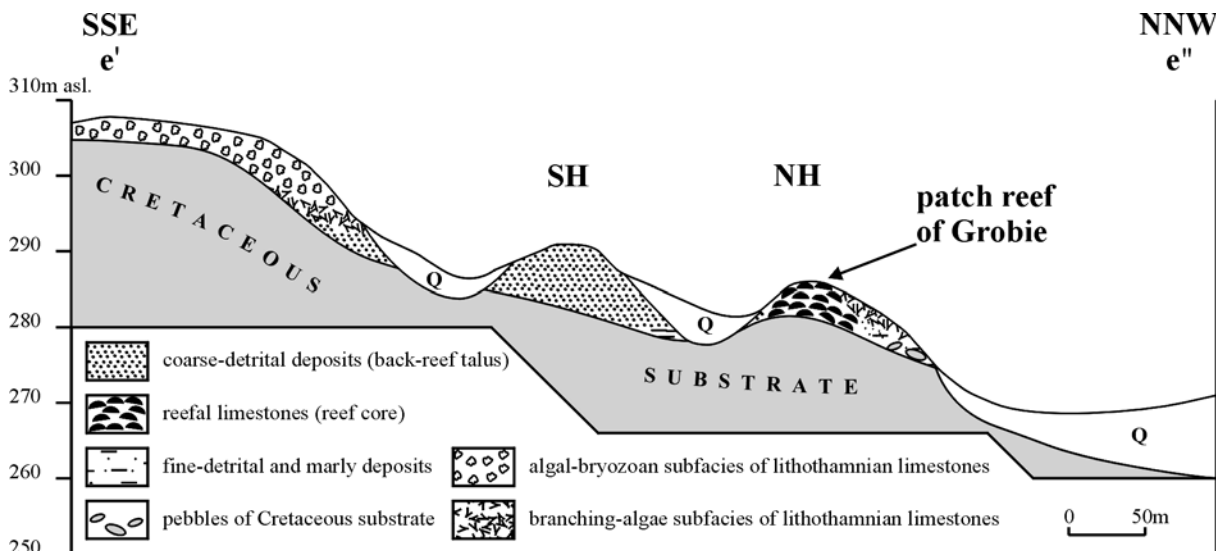


Fig. 4. Cross-section through Lower Badenian deposits of Grobie area, to show facies distribution; NH – Northern Hill, SH – Southern Hill, Q – Quaternary cover

at least two stages of deposition and a fast rate of lithification. The origin of the conglomerates could be explained by a process of mechanical disintegration of freshly lithified sediment of the reef core within a high-energy, turbulent environment. Strong wave action crushed the reef framework and intercolonial deposits, and the products of the break-up were deposited in intra- and intercolonial space or in newly originated crevices, and then bonded by further sediments.

Within the buildup of Grobie, the lithification of reef-core deposits was certainly very fast. Wave-originated crushing and agitation of the highest, non-lithified parts of the reef buildup led to the creation of crevices in its lower, freshly lithified parts. The same result could also have been caused by complete removal of some overlying top-reef deposits by wave activity, which effected in extensional cracking of the lower parts of the buildup. The crushed/desintegrated and/or removed portion of the loose sediment at the surface of the buildup could have been relatively thin, as may be inferred from observations on recent reefs where lithified parts may occur as shallow as 1 m below the living surface (BATHURST 1971).

The shape of the crevices in the reefal buildup was controlled by the degree of lithification. In weakly lithified parts, curved crevices developed as a result of deformation. Well-lithified areas were places in which more regular, wedge-shaped forms developed. A "sieve effect" prevented larger quantities of coarser grains, such as coralline-algal debris, from filling the crevices. Some of the larger grains are clasts of packstone

derived from the walls of crevices that formed when the rigid deposit originally cracked.

The following succession of deposition and further lithification and disintegration of the sediment could be distinguished:

1) The main mass of intercolonial sediment (the main packstone of about 30% of quartz grains), representing the first stage of deposition and lithification.

2) Formation of crevices in main packstone and local conglomerates of packstone rubble, both as a result of cracking and disintegration of freshly lithified sediment.

3) Micritic matrix with scattered quartz grains (about 1%) and angular coralline-algal debris that bonds the packstone rubble and infills the crack crevices, representing the next stage of deposition and lithification of previously lithified and crushed afterwards material.

PATCH REEF-ASSOCIATED FAUNA AND ENVIRONMENTAL IMPLICATIONS

Apart from hermatypic corals, coralline-algae, foraminifers, bryozoans, echinoderms, brachiopods, molluscs, decapods and fishes have been found in the patch reef deposits. The three most important groups for the determination of environmental conditions are briefly discussed below.

Corals. As already mentioned at least four coral species were recognized in the studied deposits. The diversity of

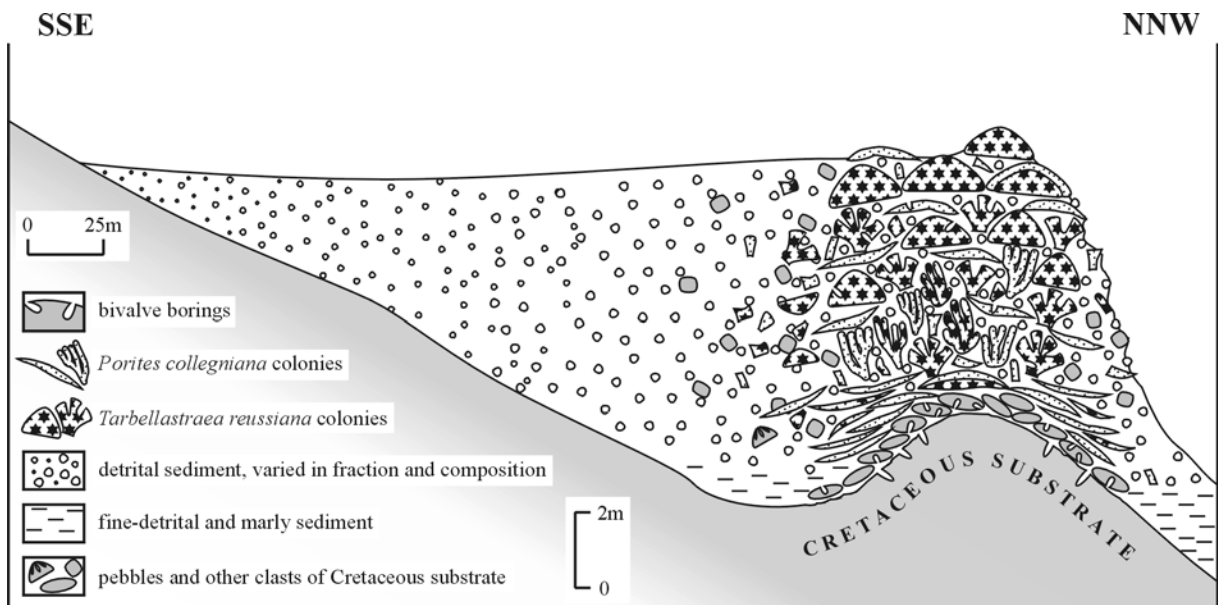


Fig. 5. Schematic cross-section through reconstructed Lower Badenian patch-reef at Grobie, to show its dimensions, succession and variety of coral colony shapes, and distribution of associated deposits. Coral colonies and other detrital elements not to scale. Further details in text

colony morphology, however, could be studied only in the *Tarbellastraea reussiana* and *Porites collegniana* colonies because of the large quantity of specimen available. Analysis of the other species was rendered difficult because of their rarity. Of the massive colonies of *T. reussiana*, those exceeding 10 centimetres in height and 15 cm wide predominate. Branching forms of *T. reussiana* are much more diversified. Stick-like branches up to 3 cm in diameter and over 10 cm in length are present but flat, antler-like branches that reach 10 cm in length are more numerous. Platy and encrusting forms, up to 5 centimetres thick, are abundant and they usually cover older deposits (intercolonial sediment or dead colonies).

The colonies of *P. collegniana* are morphologically less diversified. Platy and encrusting forms, up to 4 (usually 2.5) centimetres thick, predominate. Mostly, they overgrow *T. reussiana* specimens covered previously by a thin coralline-algal crust, while colonies of *P. collegniana* covering other sediments are less common (Pl. 1, Fig 2). Branching colonies built of several parallel sticks, each over 10 centimetres high and 3 centimetres across, are rare.

Despite the poor state of preservation it may be concluded that the diversity of coral colony morphology was the result of the natural development of the reef. The vertical profile of the reef buildup may be reconstructed, based on a model presented by ESTEBAN & *al.* (1996), according to which platy colonies represent an initial stage of the reef development. In this particular case, the corals settled sea bottom that was covered with littoral gravels derived from disintegrated Upper Cretaceous deposits. As the reef core started to develop, the platy colonies were succeeded by branching colonies. Rising of the reef buildup into shallower water would have been accompanied by a gradual increase in hydrodynamic energy and would have resulted in the occurrence of more robust, massive forms (Text-fig. 5).

Molluscs. Remains of molluscs are the second commonest group of macrofossils that occur in this locality. The most common representatives are bivalves, whereas only two gastropod species were found. The bivalves represent forms characteristic of different ecological niches. Free-living scallops *Chlamys (Aequipecten) scabrella* (LAMARCK) and *Chlamys cf. multistriata* POLI are numerous in the talus facies, while massive *Chlamys (Macrochlamis) latissima nodosiformis* (DE SERRES in PUSCH) is common in the reef core facies. Burrowing *Acanthocardia (A.) paucicostata* (SOWERBY) and *Glycymeris (G.) deshayesi* (MAYER) are present in both types of deposits, though they are more abundant in the talus facies, as is the vagile gastropod *Conus* sp.

WRONA (1970) also described *Pelecypora (Cordiopsis) cf. gigas* (LAMARCK) and *Atrina* sp. (cf.

JAKUBOWSKI 1977). Although the debris of the latter was probably found in the reef core facies, this particular species lived in the sandy deposits of back-reef talus.

Molluscs typical of a high-energy environment occur abundantly. Except for the vagile gastropod *Diodora (D.) graeca* (LINNAEUS), sessile bivalves such as *Barbatia barbata* (LINNAEUS), *Spondylus crassicosta* LAMARCK and *Anomia ephippium* LINNAEUS were found. Specimens of the latter occur commonly between the *Tarbellastraea reussiana* colonies. The most extreme examples of sessile bivalves are the borers. Their borings are particularly common in *T. reussiana* colonies and were produced mainly by *Lithophaga* sp. Some of the *P. collegniana* colonies also have traces of such bioerosion. STUDENCKA & STUDENCKI (1988) reported shell impressions of another boring bivalve, *Jouannetia (J.) semicaudata* DES MOULINS. Strongly abraded borings of undetermined bivalves are also present in pebbles of Upper Cretaceous gaizes gathered from the reef base facies of the lowermost part of the Miocene succession (Text-fig. 5). Special attention should be paid to the fact that in some borings shells of the squat bivalve *Sphenia (S.) anatina* (BASTEROT) were found. They occur in empty borings of different bivalves, made in both *T. reussiana* and *P. collegniana* colonies. In one case, two specimens of *S. (S.) anatina*, one living after another in the same boring of *Lithophaga* sp. (ecotype *lithophagicola* according to BAŁUK & RADWAŃSKI 1979), were discovered (Pl. 1, Fig 1). This is the third record of this species in the Miocene of Poland, following Małoszów (FRIEDBERG 1934, RADWAŃSKI 1969) and Korytnica (BAŁUK & RADWAŃSKI 1979).

Decapods. Although decapods are abundant in both reef core and proximal back-reef talus deposits, they are strongly dismembered and/or crushed. In reef core deposits carapaces and claw fingers are the most common. Other elements, such as limb segments, are present in lesser quantities. According to MÜLLER (1996), the high-energy environment caused fragmentation. Only those remains that were trapped in reefal crevices are well preserved. Detrital sediment of the back-reef talus also created good conditions for preservation, probably due to the high rate of deposition. Non-resistant pieces, such as limb segments are very frequent there. Twenty-one taxa of decapods have been recorded in the studied strata by various authors (see Text-fig. 6). During preparation of this paper, the presence of the species *Dardanus hungaricus* (LÖRENTHEY, 1929) has been recorded based on a fragment of its right propodus (see Text-fig. 7), in back-reef talus deposits. This is the first report of this species in the Miocene of Poland. It is significant that the Miocene decapod assemblage of Grobie is the richest of all Polish localities (cf. FÖRSTER 1979a, b; MÜLLER 1996).

DECAPOD SPECIES	FÖRSTER (1979a)	MÜLLER (1996)	GÓRKA (this paper)	I	II	III	IV
<i>“Pylopagurus” corallinus</i> MÜLLER, 1996		R					
<i>Dardanus hungaricus</i> (LÖRENTHEY, 1929)			D	+	+		
<i>Petrochirus</i> sp.			D				
<i>Galathea weinfurteri</i> BACHMAYER, 1950		R		+	+	+	R1
<i>Petrolisthes haydri</i> MÜLLER, 1984		R	R,D	+	+	+	R1
<i>Pisidia</i> aff. <i>vai</i> MÜLLER, 1984		R		+			R2
<i>Kromtitis koberi</i> (BACHMAYER & TOLLMANN, 1953)		R			+		
<i>Dynomene emiliae</i> MÜLLER, 1979	R	R	R,D			+	
<i>Calappa praelata</i> LÖRENTHEY, 1929		D				+	D1
<i>Cancer</i> cf. <i>styriacus</i> BITTNER, 1884			R				R1,D2
<i>Liocarcinus</i> sp.		D	D				D2
<i>Rakosia rectifrons</i> MÜLLER, 1996		R		+			
<i>Carpilius antiquus</i> GLAESSNER, 1928		R		+		+	R1
<i>Panopeus wronai</i> MÜLLER, 1984	R	R	R,D	+	+		R1
<i>Daira speciosa</i> (REUSS, 1871)	R	R	R,D	+	+		R1
<i>Chlorodiella mediterranea</i> (LÖRENTHEY, 1929)		R	R,D	+		+	R1
<i>Haydnella steingeri</i> MÜLLER, 1984		R					
<i>Pilodius</i> sp.		R		+		+	
<i>Maldivia plana</i> MÜLLER, 1996		R					
<i>Pilumnus</i> sp.	R			+			R2
<i>Glabropilumnus fossatus</i> MÜLLER, 1996		R				+	

Fig. 6. Decapods found at Grobie locality by various authors: FÖRSTER (1979a), later revised by MÜLLER (1984), MÜLLER (1996), GÓRKA (*this paper*) in reef core (R) and/or detrital (D) facies. I–III – coral-associated genera: I – after MÜLLER (1993), II – after MÜLLER & COLLINS (1991), III – after KARASAWA (2000), IV – ecological groups of decapods (R1, R2 – reef core-associated genera; D1, D2 – back-reef talus-associated genera) after MÜLLER (1984). Further details in text

Analysis of the ecological complexes of the decapods, based on the scheme presented by MÜLLER (1984), shows that forms inhabiting four types of biotopes dominated the assemblage (Text-fig. 6). The first group (R1) is typical of tropical patch reefs and sea depths no greater than 10 metres. The second group (R2) consists of species preferring extremely shallow water (0–2 m) and coarse, inhomogeneous, partly hard and creviced substrates of tem-

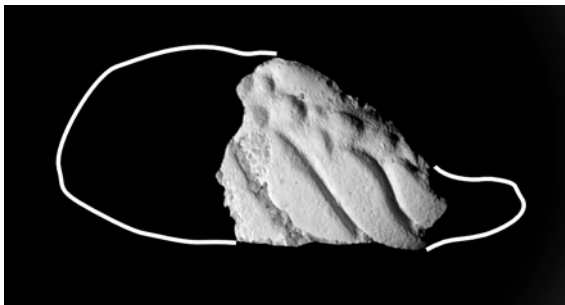


Fig. 7. *Dardanus hungaricus* (LÖRENTHEY, 1929) from back-reef talus deposits at Grobie; fragment of right propodus, oblique-lateral view, $\times 5$

perate climates and variable salinity. Except for the two latter cases, these requirements are consistent with a reef core environment. The two last groups (D1, D2), represented by three genera only, appear typical of talus deposits as they are believed to exist on sandy/calcarene floors, over 20 m deep. D1 is characterised by oceanic salinity and loose substrates in a warm-temperate climate, while for D2 slight changes of salinity, a partly hard substrate, and a temperate climate are typical.

Other studies, based on observations of coral-associated decapods of Japan, Hungary and Spain, suggest that the decapod assemblage of Grobie consists almost exclusively of taxa favouring coral reef environments (Text-fig. 6), and that some of the anomalies may be considered as having been caused by local hydrodynamic conditions. Wave activity certainly removed decapod remains and other sediment from the reef core, to form the back-reef talus deposits. The reverse process was also possible, when violent, storm-originated waves suspended any loose grains from the talus and drove them into reef core crevices.

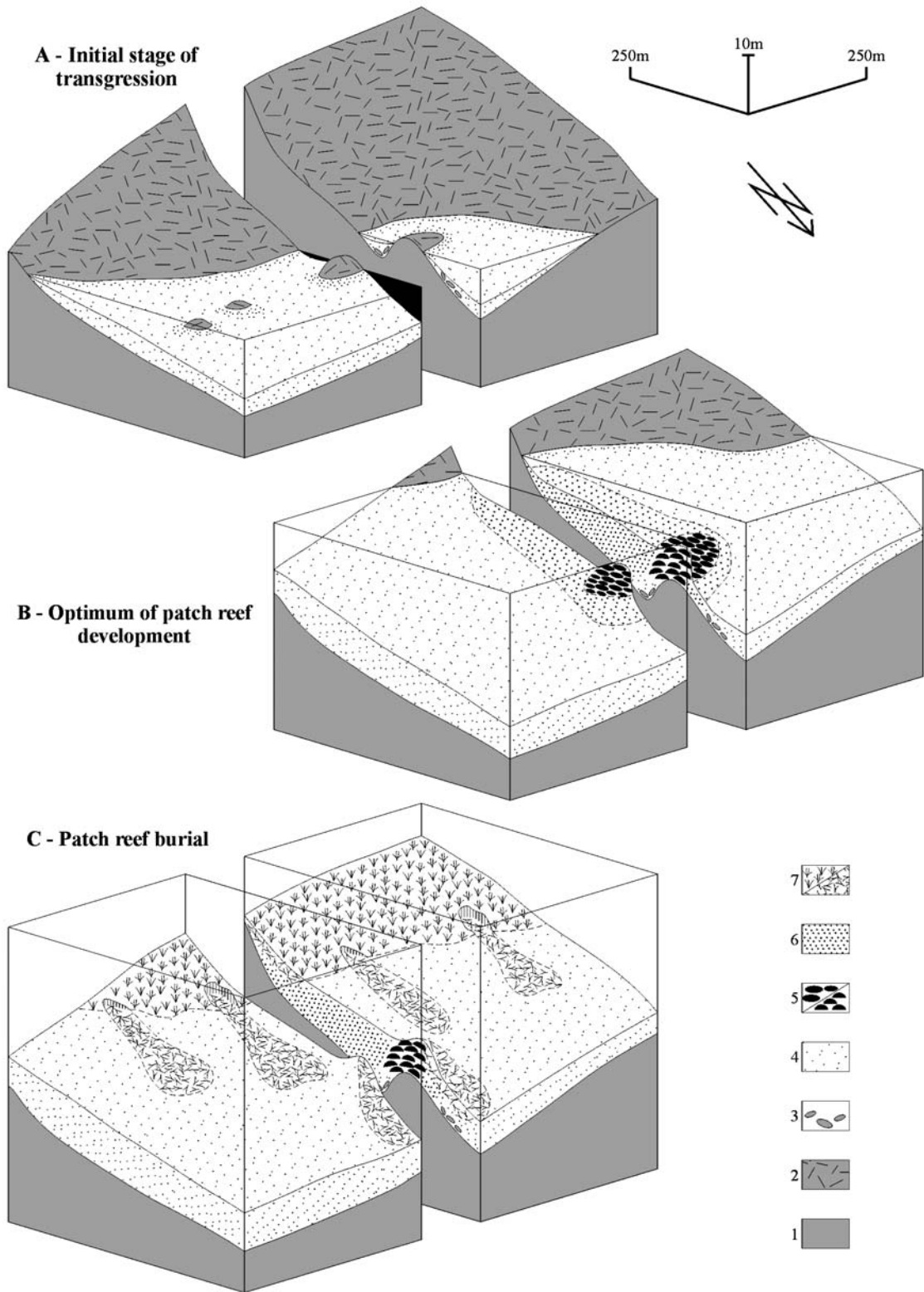


Fig. 8. Reconstruction of Grobie area (see Text-fig. 1d) during Early Badenian transgression and development of the patch reef studied. 1 – Cretaceous basement, 2 – emerged areas, 3 – pebble of Cretaceous substrate, 4 – fine-detrital and marly deposits, 5 – reef core deposits, 6 – coarse detrital (back-reef reef talus) deposits, 7 – branching-algae subfacies. Further details in text

PATCH REEF DEVELOPMENT

Marine sedimentation in the study area started with its flooding during the Early Badenian transgression (RADWAŃSKI 1969). A package of varied littoral sediments developed, dependent on the lithology of the substrate and its morphology. In relatively flat areas, underlain by marls and siliceous marls of the Upper Cretaceous, littoral marly sandstones and marls originated. Coarser deposits, such as littoral gravels, appeared in the elevated zone built of gaizes. Although the gravels may be observed only on the Northern Hill at Grobie, they were probably also present in the neighbouring knolls that created a chain of islands during the transgression (see Text-fig. 8a). Such a palaeotopography was peculiar for this region (RADWAŃSKI 1969) in which the Grobie area was situated in a transitional zone between the highest elevations of the Wójcza-Pińczów Range and the deeper, northern parts of the basin. Corals inhabited at least one of the islands when these became completely submerged.

In the initial stage of reef development, platy colonies covered the gaize pebbles. Such a shape of the colonies together with the lithology of the substrate may suggest a turbulent environment (Brian ROSEN, *personal communication*). The first settler was certainly *Porites collegniana*, which is a species tolerant of broad environmental conditions (see FRIEBE 1991, ESTEBAN 1996, INSALACO 1998). As the transgression progressed and the substrate became stabilised, branching colonies of *Tarbellastraea reussiana* and some *P. collegniana* appeared. The common occurrence of flat branches could indicate that the energy of the environment became relatively lower, probably because of sea-level rise, though not enough for the predominance of more delicate, stick-like branches. The further development of predominantly massive forms of *T. reussiana* suggests that up-growth of the coral buildup led to achieving a shallower zone, with renewed turbulent conditions. Massive colonies were the forms most able to resist destructive waves, while the others often became fragmented and removed. Such a succession shows that during the reef development the rate of transgression decreased extremely hence at a distinctly slower rate than the up-growth of the reef (or even that sea-level rise stopped).

Wave activity also influenced facies distribution. Relatively fine material was washed out from the reef core and deposited in the back-reef talus. Coarser pieces accumulated in the immediate neighbourhood of the reef, while finer ones were transported into the distal zone of back-reef talus (Text-fig. 8b). The finest material was carried out into more distant areas. Destructive activity of waves led also to reconstruction

of the freshly lithified deposits of the reefal buildup, causing its cracking and the appearance of rubble and crevices. Similar processes of disintegration and/or dismembering affected other organic remains as well.

Wave action was also an agent forcing changes in the coral assemblages, causing suspension of sediment that was significant for individual species. Representatives of *Porites* are generally more resistant and may survive episodes of the increased suspension of fine sediment (see MÜLLER 1984, MCCALL & *al.* 1994, ESTEBAN 1996). Such occurrences were fatal for faviids but tolerated by *P. collegniana*. Specimens of *T. reussiana* overgrown by *P. collegniana* (Pl. 1, fig. 2) testify to such episodes, which resulted in the death of less tolerant species.

Although destructive, wave action is not blamed for the demise of the reef. This was probably caused by a rapid rise in sea-level linked with increased input of terrigenous material, as the sharp junction between the reef core facies and the overlying strata shows. As the decapod assemblage and composition of corals indicate (see MÜLLER 1984, MCCALL & *al.* 1994), the reef rose up in relatively shallow water, not deeper than 10 metres. According to STUDENCKI (1988), the coralline-algal deposits of the Pińczów Formation developed at depths of at least 30 m which indicates that sea-level rose at least 20 metres. The occurrence of the branching-algae subfacies in the transitional zone is not typical, as this subfacies usually originated in the highest parts of submerged highs (see STUDENCKI 1988). In the present case, deposits of this subfacies probably represent a bank that was formed behind the dead reef, which existed as a submarine elevation. Material transported from the central parts of the Wójcza-Pińczów Range into deeper areas was deposited as a particular kind of a "fore-reef talus" (Text-fig. 8c).

Further sedimentation gave way to the creation of the sequence typical of the Pińczów Limestone: deposits of branching-algae subfacies were covered by algal-bryozoan subfacies, while in neighbouring deeper parts the detrital coralline-algal subfacies appeared (cf. STUDENCKI 1988). These younger strata were eroded from the study area, but can still be observed *in situ* on the surrounding highs.

PALAEOCLIMATIC AND PALAEOGEOGRAPHIC SIGNIFICANCE

The described patch reef is located approximately at 50°30'N latitude, over 100 kilometres north of the northern limit of the Middle Miocene hermatypic reefs of Europe presented by ESTEBAN (1996). As previously suggested by MÜLLER (1996), the patch reef at Grobie

appears to be the world's northernmost Neogene coral buildup. The closest coral reef occurrences in the Central Paratethys are located approximately 300 km (Pannonian, Styrian, and Vienna Basins of Austria and Hungary) to the south (e.g. FRIEBE 1991, 1993; PISERA 1996, RIEGL & PILLER 2000). Other Middle Miocene coral reefs do not extend beyond 48°N (see FRANSEEN & *al.* 1996).

The development of the coral patch reef of Grobie so far to the north was probably due to the Middle Miocene (Early Badenian) climatic optimum (ITOIGAWA 1989, MÜLLER 1996) associated with a global rise in sea-level (STANDKE & *al.* 1993, PERRIN & *al.* 1998). However, it is hard to determine the exact climatic conditions. BALUK & RADWAŃSKI (1977) established a subtropical and/or tropical character for the faunal assemblage of the coeval deposits of the Korytnica basin. The decapods of Grobie are represented by genera typical of warm-temperate (*R1* and *D1* ecological groups) and temperate climate (*R2* and *D2*) conditions, similar to the present-day ones of the Adriatic Sea (see MÜLLER 1984, 1996). Such climatic conditions and the relative isolation of the marine basin of Carpathian Foredeep during the Middle Miocene (see Text-fig 1a) were supposedly responsible for the taxonomic composition of the corals (almost exclusively two species only). The assemblage of hermatypic corals is much scarcer than those of other coral reef occurrences in the Central Paratethys.

The studied patch reef shows significant dependence on the terrigenous input. The distribution of material from subsequently flooded areas influenced not only the rise of the coral buildup, but also its biotic assemblage, and, finally, caused its death.

The patch reef at Grobie shows many resemblances to other reefal buildups of the Central Paratethys (see MÜLLER 1984; FRIEBE 1991, 1993; PISERA 1996) which are usually developed in transgressive sequences, dominated by clastic sedimentation, and appear on elevated parts of the substrate (see e.g. FRIEBE 1991). The dimensions of these reefs do not generally exceed more than a few tens of metres in width and a few metres in thickness. The composition of the hermatypic coral assemblage is also similar, with the genera *Tarbellastraea* and *Porites* predominating.

Despite these resemblances, the Grobie patch reef also appears very similar to some of the Late Miocene reef complexes of the Tethys. In these cases, the reefs are developed on clastic substrate and often show convergence of reef flanking (especially back-reef) facies (see e.g. GRASSO & PEDLEY 1988). The closest similarities are found in the case of the Late Miocene (Tortonian to ?Messinian) Tethyan coral reefs of SW

Turkey reported by HAYWARD & *al.* (1996). Comparison between these reefs and the Grobie patch reef shows numerous similarities, including deposition in terrigenously-dominated settings. The closest resemblance is seen in the vertical section, which begins with coarse pebble with bivalve borings, followed by a coral-bearing sequence of a succession starting from platy, then branching, and finally massive colonies. There is also a strong similarity in the off-reef flanking facies, where the grain size and contribution of coral debris decrease, while foraminifer quantity increases with distance from the reef core. The dimensions of the Turkish reefs, described as mounds up to 8 m high and 40-50 m across, correspond closely to those of the reef at Grobie. Summarising the observations on reef dimensions, taxonomic diversity of the corals and reef-associated facies it can be stated that the Grobie reef represents a relatively small, species-poor coral buildup developed within a mixed carbonate/siliciclastic facies. According to that description, the reef fits well into reef-type VI of the scheme for Oxfordian reefal facies (INSALACO & *al.* 1997).

REMARKS ON DIAGENESIS

The most impressive effect of diagenetic processes is the dissolution of the majority of the primarily aragonitic skeletal elements, such as mollusc shells and most of the coral colonies, which are preserved as moulds or void cavities. Some of the major coral colonies, predominantly massive *Tarbellastraea reussiana*, were not completely affected by dissolution, so all remnants of aragonite are replaced there by neomorphic calcite (Pl. 1, Figs 1-2). In some cases, only the external part of the colony was dissolved while the internal one was neomorphised. Effects of dissolution are present both in the reef core and in the talus facies. In the latter, no traces of replacement by calcite were found.

The diagenesis of the deposits at Grobie generally resembles that of the reefal buildups of the Roztocze Hills (Lublin Upland, SE Poland) described by PISERA (1985). Such a comparison is possible, as the post-Badenian, tectonic history of both regions is very similar.

Initially, after burial, the aragonitic elements began to be neomorphised into calcite. Such a process could continue until the Early Sarmatian when the Wójcza-Pińczów Horst was tectonically uplifted above sea-level (RUTKOWSKI 1981, GÓRKA 1999). The porous reefal deposits were then relocated into the fresh-water phreatic zone that originated due to cover of younger, clayey strata, and further replacement of the aragonitic elements by calcite took place.

Tectonic uplift of the Wójcza-Pińczów Horst was followed by rapid erosion that exhumed the porous Lower Badenian strata even in the Early Sarmatian (GÓRKA 1999). This caused the appearance of the fresh-water vadose zone in which the major dissolution of the remaining aragonite took place. Rapid erosion is shown by the occurrence of *T. reussiana* colonies that are both neomorphised as well as dissolved (see Pl. 1, fig. 1).

The Early Sarmatian was probably the first time when a hydrogeological system appeared that is similar to the present one. Its standard feature is a groundwater table that occurs between low permeable Upper Cretaceous and highly porous Miocene rocks (WALCZOWSKI 1976). There, in the cementation zone, speleothem-like calcitic structures originated. Pieces of this material are common in the field-brash, close to the supposed Cretaceous/Miocene contact. The main source of the calcium carbonate that forms these structures is believed to be the aragonitic elements, now completely dissolved away.

All the described processes took place before the Pleistocene glaciations, perhaps as early as the Late Miocene, as suggested by PISERA (1985) for the Roztocze Hills. Products of the further erosion of reefal deposits of the Grobie area could be found in its neighbourhood. Coral colonies (Pl. 1, Fig. 4) together with speleothem-like structures, undoubtedly coming from the studied locality at Grobie, are present in Widuchowa-Doły (GÓRKA 1999), some 1 km north of Grobie (see Text-fig. 1d). They occur in Quaternary sands and rubble filling a small valley there, where they were redeposited.

FINAL REMARKS

The studied patch reef at Grobie is the only known Polish occurrence of Middle Miocene coral buildups, and is the northernmost Neogene coral reef example of the Northern Hemisphere (cf. MÜLLER 1996). Its coral assemblage is composed almost exclusively of two species, *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME) and *Porites collegniana* MICHELIN, associated with rare *Montastraea* sp. and *Stylophora reussiana* MONTANARO-GALLITELLI & TACOLI. Two of these taxa, *P. collegniana* and *Montastraea* sp., have not hitherto been reported from other Middle Miocene localities of Poland. The low taxonomic diversity of the hermatypic corals in the patch reef of Grobie indicates unfavourable environmental conditions, while the variety of coral colony shapes, from laminar and platy, to branching and finally massive forms, reflects a natural succession in the rising patch reef.

Other organic remains in the studied deposits represent a wide variety of forms typical of a reefal biocoenosis. The sessile molluscs are the most common and significant, especially the rock-borers (*Lithophaga* sp.) and squatters [*Sphenia* (*S.*) *anatina*]. Abundant decapods belonging to varied ecological groups indicate that the Early Badenian climate was comparable to that of the present-day Adriatic Sea.

A wide variety of sedimentological structures in the studied patch reef appeared as a cause of wave activity. High-energy water movement often removed and reoriented sediment clasts, and encouraged the development of crack crevices. It was also the main agent that formed back-reef talus and distributed detrital and muddy material around, and off the coral buildup.

The development of the reefal buildup within a Lower Badenian transgressive sequence marks a relatively short stillstand or slowing of the sea-level rise. A further, rapid rise of sea-level caused an increase in the supply of terrigenous sediment and the demise of the patch reef, due to its burial by detrital deposits.

Diagenetic processes of dissolution or neomorphisation of originally aragonitic skeletal elements affected the deposits shortly after burial (Early Badenian–Early Sarmatian). After exhumation during the Early Sarmatian to Early Pliocene, intensive erosion destroyed the major part of the patch reef and redeposited some of its elements into Quaternary deposits around the Grobie site.

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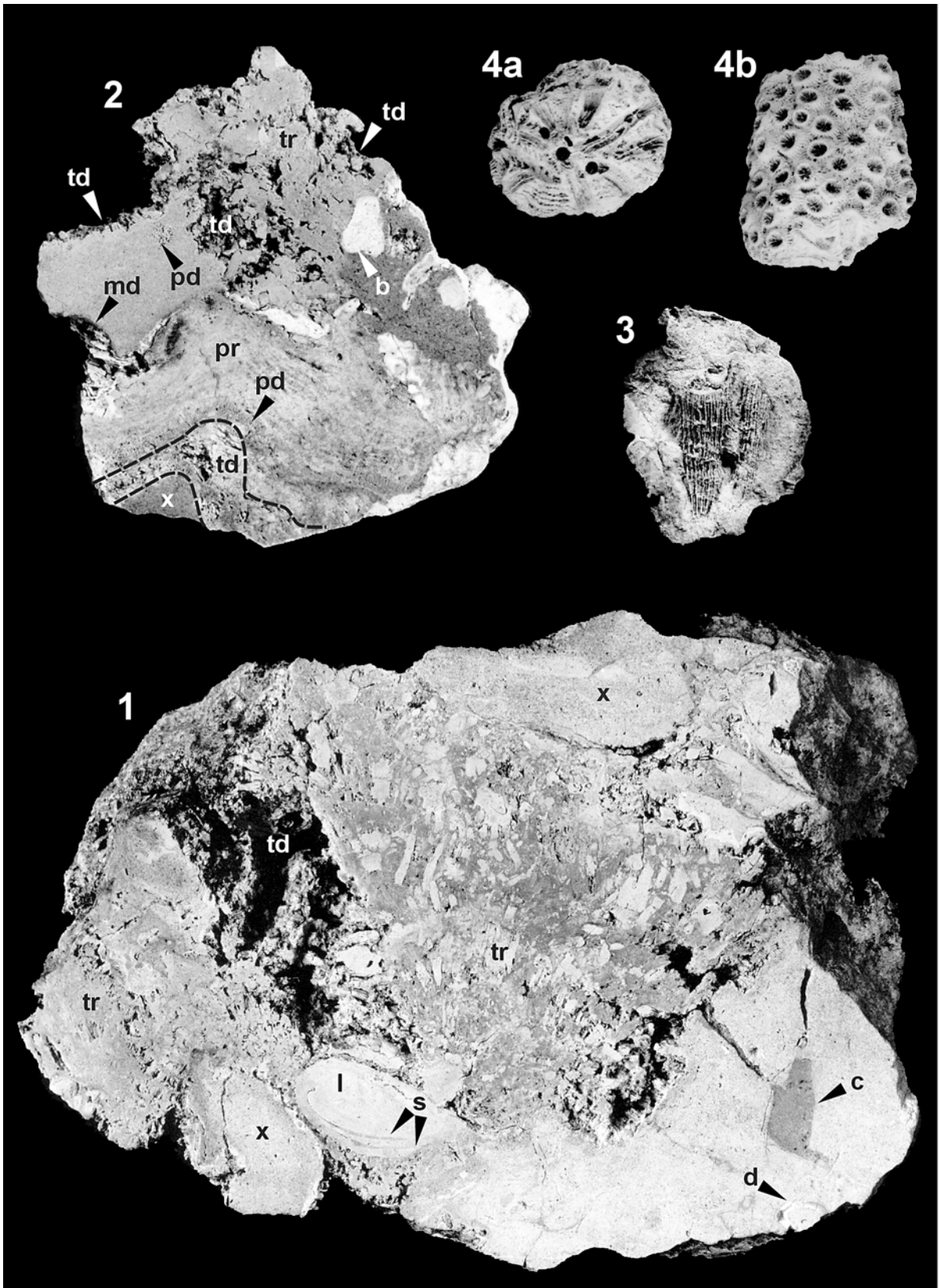
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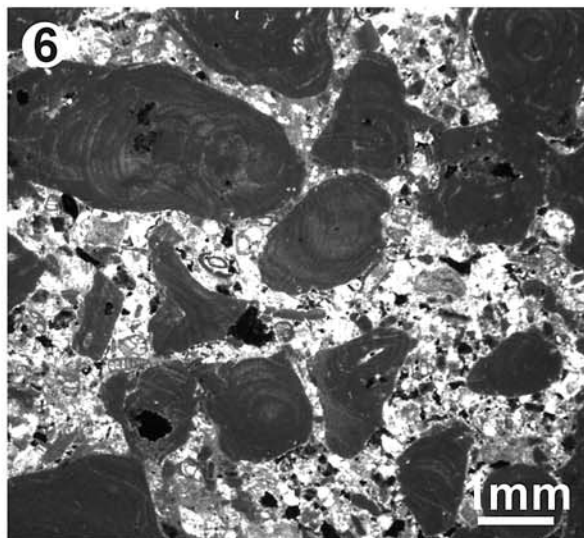
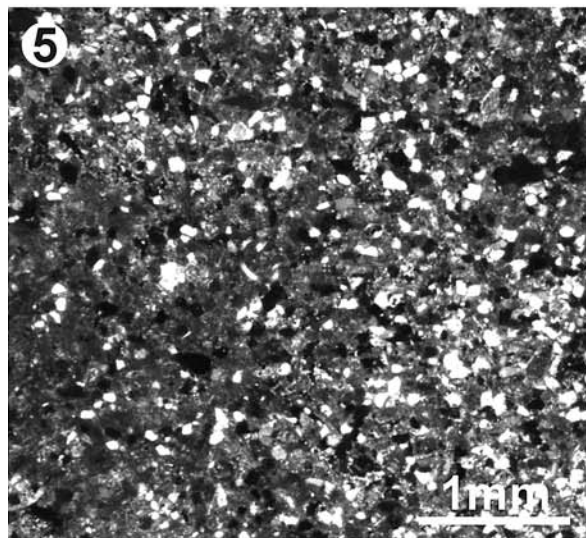
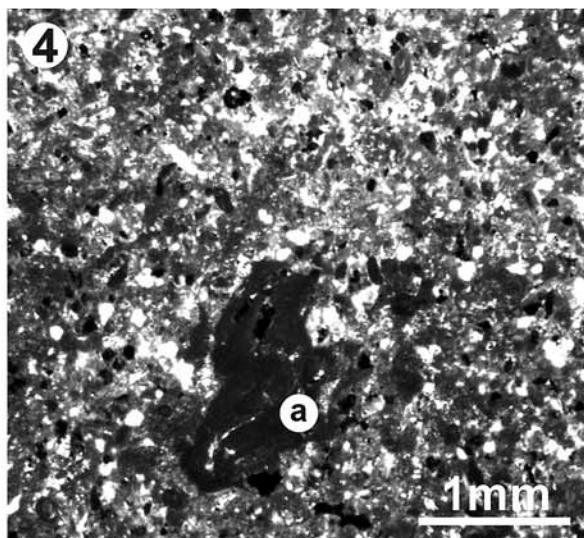
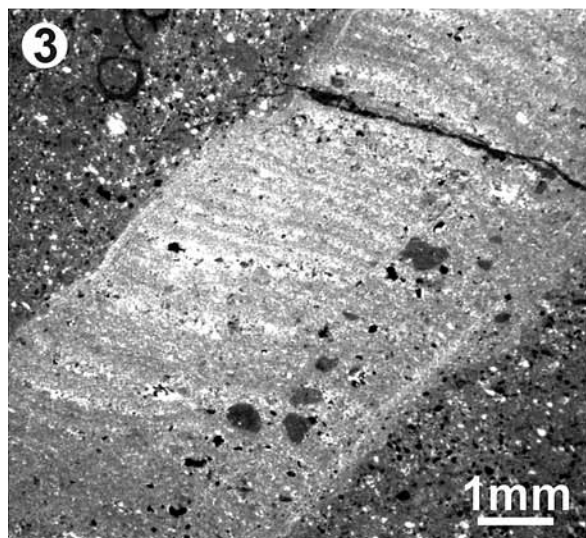
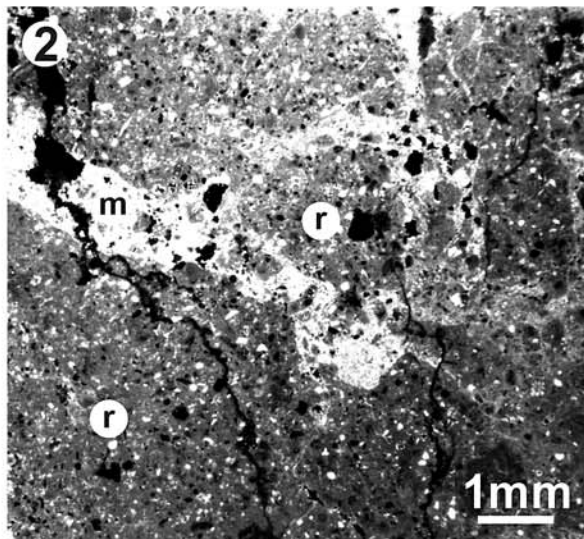
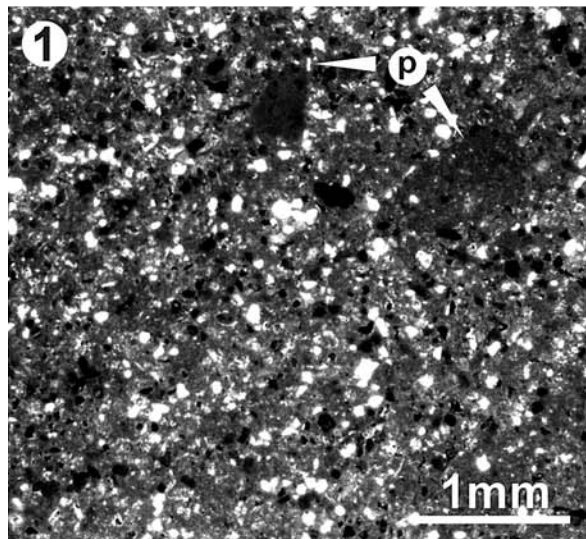
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1-2 – Corals, other organisms, and associated sedimentary structures of reef core facies at Grobie: **tn**, **td**, **pn**, **pd**, **md**: – neomorphised (**n**) and dissolved (**d**) colonies of *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME) (**t**), *Porites collegniana* MICHELIN (**p**), and *Montastraea* sp. (**m**), **l** – boring of *Lithophaga* sp. squatted by *Sphenia* (*S.*) *anatina* (BASTEROT) (**s**), **b** – *Cellepora* sp. colony, **d** – finger of decapod (probably *Cancer* sp.), **x** – clasts of packstone, **c** – crack crevice (see Pl. 2, fig. 3); polished slabs, natural size; **3** – *Montastraea* sp. (rubber cast) from reef core facies at Grobie; natural size; **4a-4b** – Fragment of stick-like colony of *Tarbellastraea reussiana* (MILNE EDWARDS & HAIME) redeposited into Quaternary deposits at Widuchowa-Doly; **4a** – top view, **4b** – lateral view; natural size



1 – Reef core facies, intercolonial deposits; packstone with micritic peloids (p); × 20; 2 – Reef core facies, intercolonial deposits; rubbles of packstone (r) within low-quartz matrix (m); × 10; 3 – Reef core facies, intercolonial deposits; crevice with microbial lamination within the main packstone; × 10; 4 – Proximal reef talus facies; coralline-algal debris (a) within quartz-organodetrital matrix; × 20; 5 – Distal reef talus facies; fine-detrital packstone, note almost complete lack of coarser grains; × 20; 6 – Reef cover facies, branching-algae subfacies; debris of branching coralline-algal thalli in organodetrital matrix; × 10