

SEDIMENTATION AND DIAGENESIS OF THE UPPER OXFORDIAN CYANOBACTERIAL-SPONGE LIMESTONES IN PIEKARY NEAR KRAKÓW

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Abstract: Components of cyanobacterial origin and siliceous sponges are the main rock-forming components of the limestones studied. Massive limestone occurs in the rigid-framework cyanobacterial-sponge buildups that formed elevations on the basin floor. Bedded limestone was laid down in extensive depressions between the elevations. Sedimentation took place in a quiet environment where intense water movements occurred only sporadically. There are numerous indications of the shallowness of the sea, which meant that elevated areas of the bottom were episodically emerged. Chert horizons have formed along the surfaces of synsedimentary stratification where the clay content was locally elevated. The bedding of the limestones is of diagenetic origin and is related to the diagenetic redistribution of calcium carbonate during burial.

Key words: massive limestone (Felsenkalk), bedded limestone, cyanobacterial-sponge buildup, microfacies, sedimentation, silification, bedding, Upper Oxfordian, Southern Poland.

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INTRODUCTION

The Upper Jurassic carbonate rocks cropping out in the Kraków-Wieluń Upland belong to a large tectonic unit known as the Silesia-Kraków monocline which comprises Triassic, Jurassic and Cretaceous rocks.

The Upper Jurassic rocks in the southern part of the Kraków-Wieluń Upland are Oxfordian limestones and marls, about 200 m thick. In the vicinities of Kraków there are three main facies of Upper Oxfordian limestones: massive limestone (also *rocky* or *budden limestone*; locally called – *wapień skalisty*, German equivalent – *Felsenkalk*), bedded limestone and platy limestone (Dżułyński, 1952).

The massive limestone does not form a continuous horizon, it forms massive bodies of various shape, size and stratigraphical extent throughout the

Upper Jurassic sequence. It has continuous lateral transitions to bedded limestones, while within the platy limestone it forms irregular distinctly separate bodies (Dżułyński, 1952). Due to the extensive cover of Quaternary sediments, transitions of the massive to bedded limestone can be observed only in a few exposures.

The depth of the sedimentary basin is one of the main questions in the reconstruction of the conditions of sedimentation of the Upper Oxfordian limestone facies in the vicinity of Kraków. Several different hypotheses have been proposed with respect to this.

Pusch (1836) and Alth (1872) considered the bodies of massive limestone to be fossil coral reefs, while Lewiński (1912) regarded the limestone as a bathyal sediment. According to Dżułyński (1952) and Wieczorek (1982) it was laid down in the deeper part of the shelf. A different opinion has been expressed by Golonka & Haczewski (1971) and Golonka (1978) who considered that the massive limestone was laid down in a basin that included zones as shallow as 30–50 meters.

The present author studied an exposure in Piekary near Kraków, in the southern part of the Kraków-Wieluń Upland in detail (Fig. 1). This exposure shows the lateral transition from massive limestone to bedded limestone very well.

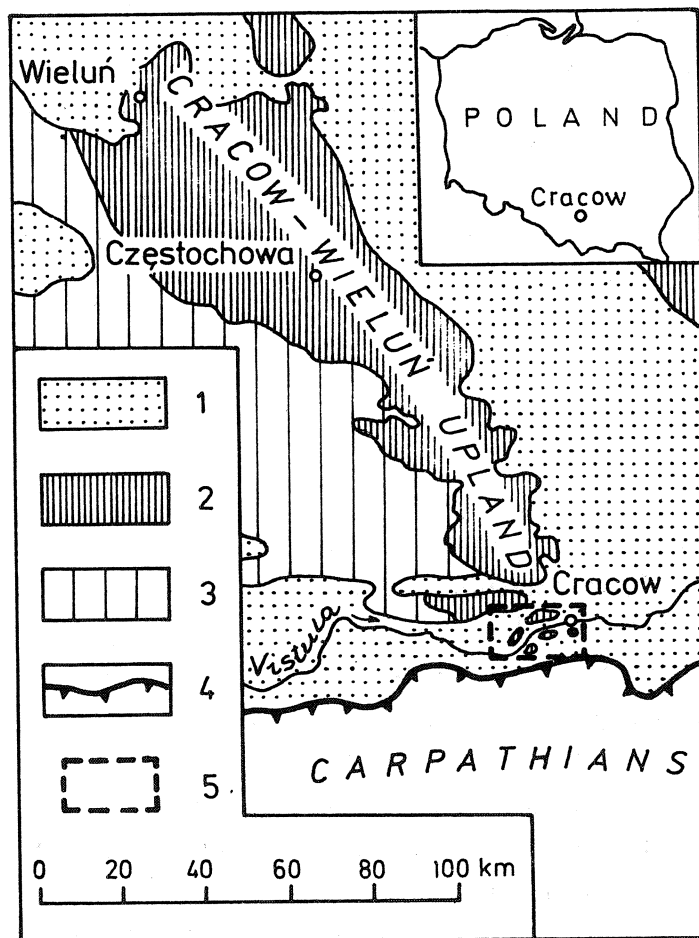


Fig. 1. Situation of study area. 1 — post-Jurassic deposits; 2 — Jurassic; 3 — pre-Jurassic deposits; 4 — front of Carpathian overthrust; 5 — study area

A detailed microfacies analysis of the massive and bedded limestone in Piekary served as a basis for the reconstruction of their sedimentary environment. The results of investigations and observations of Upper Oxfordian limestones near Tyniec, and in Kostrze and Pychowice, c. four kilometers to the east (Fig. 2) were also used for the same purpose.

METHODS AND TERMINOLOGY

The main method of study was microfacies analysis, supplemented by mesoscopic observations of the rocks in outcrop, of polished sections, and surfaces etched with acetic acid. The microfacies analysis was performed on 134 thin sections of standard size and on five thin sections of dimensions 5 × 5 cm.

The classification and terminology used for the microfacies description is Folk's (1959, 1962) and Dunham's (1962), supplemented by Embry and Klovan's (1972). Only the terms *crust* and *tuberoid* need explanation.

The term *crust* is used in this paper for planar or dome-like structures built of dark micrite and observed mainly on the upper surfaces of sponges and on surfaces of sedimentary discontinuity. Only the forms that occur *in situ* are termed *crust* in this paper. Redeposited fragments of crusts are considered as *oncoids* or *peloids*, depending on their size and structure.

Many, mainly German, authors have described various crusts that are not stromatolites (cf. Wolf, 1965; Aitken, 1967; Wagenplast, 1972, p. 30; Nitzopoulos, 1973, p. 15; Gwinner, 1976, p. 23; Flügel & Steiger, 1981, p. 378; Schorr & Koch, 1985, p. 239).

In the light of the studies by Behr & Behr (1976), crusts and stromatolites have similar origins. Both are built of cyanobacteria, mainly of the family Rivulariaceae, and the main difference is the rhythmic occurrence in the stromatolites of laminae: (i) dark (in transmitted light) built of densely packed, fine spherules of rivularia (up to about 20 µm in diameter) and (ii) light, including spheres of greater diameter. Moreover, only the crusts commonly include organic encrustations (mainly by foraminifers) and coccolith debris (Behr & Behr, 1976, p. 290). Some authors question the usefulness of distinguishing between crusts and stromatolites (cf. Gaillard, 1983, p. 268).

In this paper the term *tuberoid* is used for those carbonate grains which have recognizable traces of sponge structures in them.

The name *tuberoid* was introduced by Fritz (1958) for carbonate grains of various shapes, dimensions and internal structure. Flügel & Steiger (1981) and Gaillard (1983) used this term for the grains which originated from the disintegration of sponges, often overgrown by cyanobacteria. A somewhat different meaning has been accepted for *tuberoids* by Kutek *et al.* (1977) who considered them to be those aggregates of calcium carbonate whose origin is related to the decay of organic matter. The putridal calcium carbonate originating in this way (cf. Matyja, 1978) is manifest on the outer surface of the limestone in the form of dark spots (cf. spotted limestones — Peszat, 1964).

DESCRIPTION OF EXPOSURE

The exposure of Upper Oxfordian limestones in Piekary is situated on the left bank of the Vistula, opposite to Tyniec Abbey (Fig. 2). It is the wall of an abandoned quarry, about 16 m high and about 250 m long. In the northern

part, there occurs bedded limestone with cherts, and in the southern part — massive limestone (cf. Alexandrowicz, 1955; Rajchel, 1970; Fig. 3; Pl. I).

The lateral transition of the massive limestone to the bedded limestone is gradual and occurs within a transition zone about 10 m wide. The deposits studied occur about 150 m above the sole of the Oxfordian and they belong to the *Epipeltoceras bimammatum* or *Idoceras planula* zone (Tarkowski, 1982).

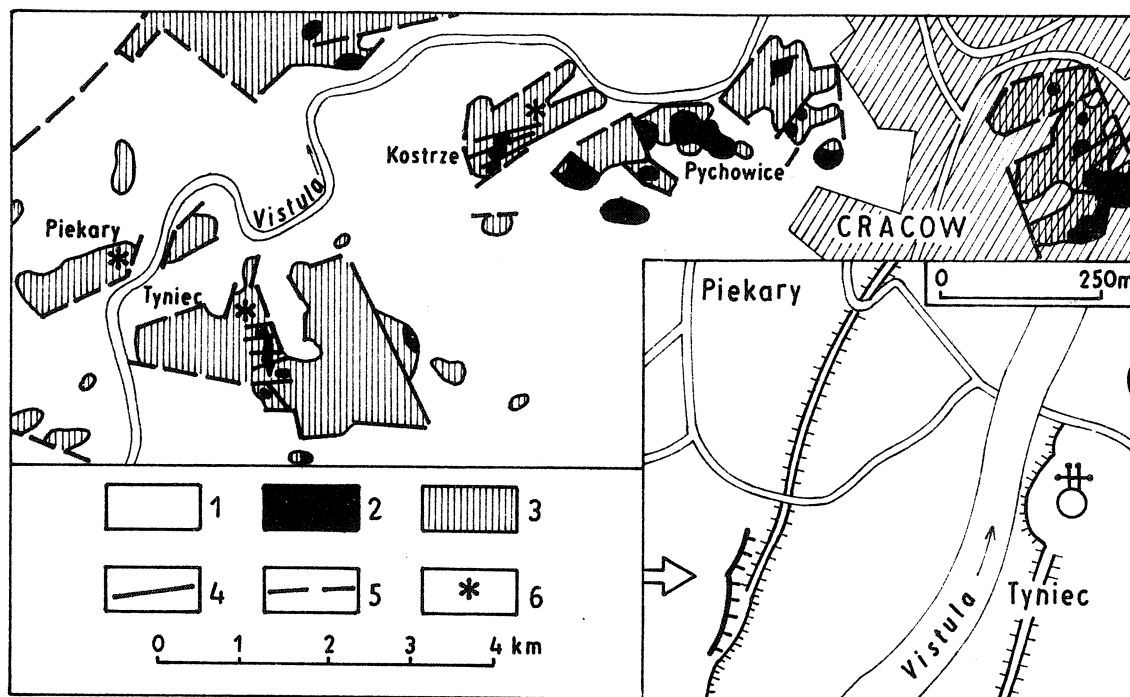


Fig. 2. Situation of studied exposures. Geology according to Gradziński (1972). 1 — Miocene; 2 — Cretaceous; 3 — Jurassic; 4 — proven faults; 5 — probable faults; 6 — described exposures

Bedded limestone

The beds are 0.9–2.5 m thick and are persistent laterally (Pl. I). The beds are separated by bedding joints up to 3 centimetres wide. The limestone is white, varying in shade; it has uneven or splintery fracture. Cherts are common and are distributed in layer-parallel horizons. The bedding is less distinct in those places where the cherts are chaotically distributed in the rock. Numerous dish-like and cup-shaped sponges are visible on slightly weathered surfaces. They occur both in life position and overturned (Pl. II: 1). Brachiopod shells, a few sea-urchin spines and fragments of bryozoans and gastropods are also visible.

Transition zone

Bedding fades in the transition zone, and the cherts are sporadic. The bedding joints of the bedded limestone pass laterally to layers of nodules, 5–16 cm in thickness (Pl. II: 2; Pl. III: 1). Sponge fragments are penetrated by the boundaries of the nodules (Pl. III: 2). The layers of nodules have numerous

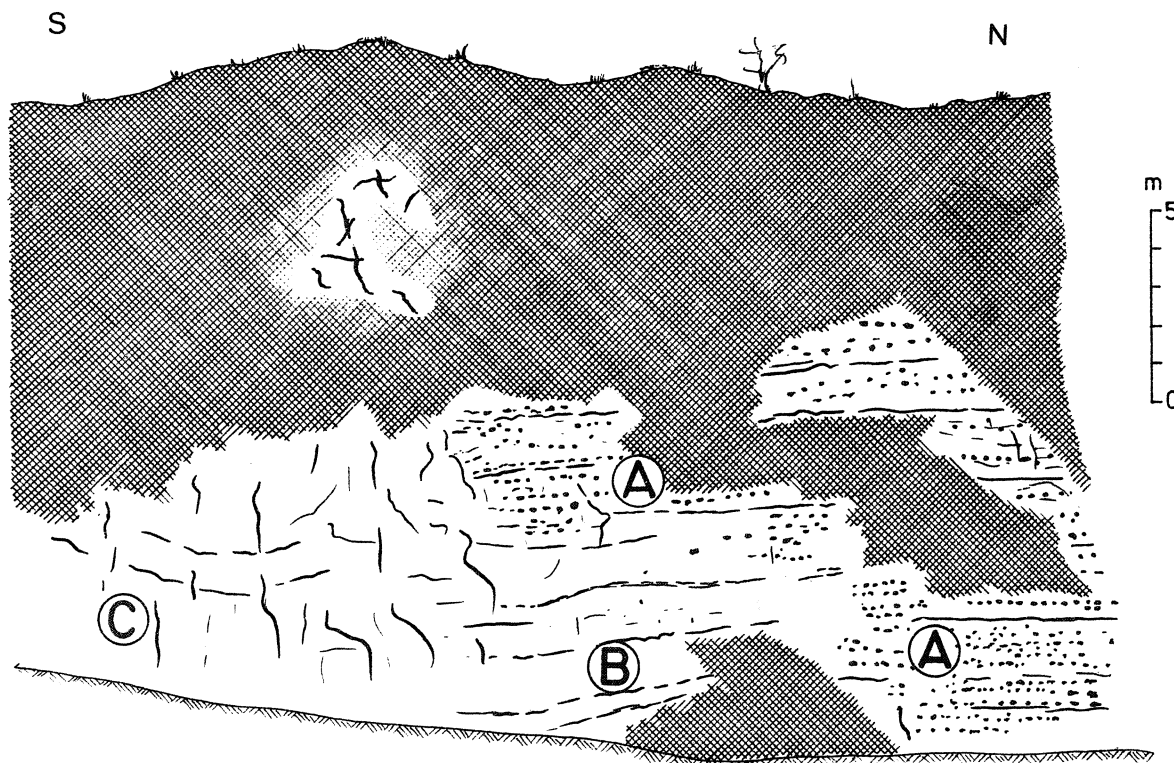


Fig. 3. Fragment of exposure wall. *A* — bedded limestone with cherts; *B* — transitional zone; *C* — massive limestone. The fragments of wall covered with vegetation are shown hatched

bendings characteristic of a peri-bioherm zone. The limestone “layers” separated by such layers of nodules increase in thickness nearer the massive limestone.

Cherts are visible in the transition zone only in one place, over an area of several square metres (Pl. I). The cherts are arranged there in horizons parallel to the bedding which is distinct in this place. The fauna is identical to that in the bedded limestone.

Massive limestone

This limestone lacks almost entirely the regular bedding and cherts. In some places there appear thin (up to c. 5 cm) layers of nodules, inclined at about 10° to the north or south. The massive limestone is white, in some places slightly cream-coloured, varying in shade, with uneven fracture. Numerous sponges are visible on polished sections, mainly in life positions. The contact of the massive limestone with the bedded limestone in the transition zone is oblique to the bedding and is inclined towards the massive limestone (Fig. 3).

ORGANOGENIC COMPONENTS

The mesoscopically recognizable organogenic components of the massive and bedded limestone are for the greater part sponges, and in smaller quantities brachiopods. Gastropods, sea-urchin spines and bryozoan fragments are observed sporadically.

Sponges

Sponges are one of the main constituents of the massive limestone. They are also numerous in the bedded limestone, especially near the bioherms. The distribution and positions of the sponges in the rock were observed mainly on joint surfaces in the bedded limestone, near the transition zone. The sponges are poorly visible on very uneven, at places nodular, surfaces of the massive limestone.

The sponges are encountered in two morphological varieties: (i) extensive, flat dish-like forms, up to 20 cm in diameter and, less frequently, (ii) cup-shaped sponges. The dish-like sponges in the bedded limestones occur in life position as well as overturned. The cup-shaped sponges have not been observed in life position. The sponges are mostly preserved as whole, intact specimens (Pl. II). Their concentration attains scores of specimens per square metre of exposure surface.

The mesoscopic observations of the sponges were also performed on polished sections and on surfaces etched with dilute acetic acid. The etched surfaces show a clear difference between the nature of the sediment directly adjoining the upper surface of a sponge and the remaining sediment. The limestone above the upper surface of a sponge has compact texture, and the remaining rock has flocky texture. Microscopic observations have shown that the compact texture above the upper surfaces of sponges is related to the occurrence of cyanobacterial crusts and stromatolites on these surfaces, which were subject to stronger compaction than the remaining part of the sediment.

The siliceous sponges Hexactinellida and Lithistida dominate in the limestones (Pl. IV: 1–3; Pl. VII: 6, 7; Pl. XII; Pl. XIII; Pl. XIV). Calcareous sponges are less frequent (Pl. IV: 4, 5).

Hexactinellida include *Lychniscosa* with open cross-shaped spicules (Pl. IV: 2) and *Hexactinosa* with completely filled cross-shaped spicules (Pl. IV: 3). The skeletons of siliceous sponges are completely calcified — the silica is substituted by sparite.

Some of the sponges reveal distinct borings, either with the shell of the borer preserved or filled with internal sediments (Pl. XII). In many sponges, the details of their internal structure were obliterated more in their lower parts. Spiculite was found in only one thin section (Pl. XVI: 3).

The outer surfaces of sponges and their internal canals were settled by other organisms. Dome-shaped and cushion-shaped cyanobacterial crusts and stromatolites developed on the sponge upsides (Pl. IV: 1; Pl. XIV: 1). The lower surfaces of the sponges were settled by numerous epifauna, which mainly included bryozoans and polychaetes (Pl. VII: 6, 7; Pl. XII: 4; Pl. XIV: 1). The unitary sedimentary sequences: siliceous sponge (together with the encrusting epifauna) — cyanobacterial crust and (or) stromatolite — pelmicrite or biopelmicrite, overgrowing one another, are frequently separated by sliccolites, interpreted by Gaillard (1983) as stylolite seams. Sliccolites can also be observed on the outer surfaces of sponges (Pl. XIV: 2).

Foraminifers

The observations of foraminifers in thin sections permitted their approximate determinations only at the generic level.

The studied material includes mainly foraminifers of the family Nodosariidae (cf. *Lenticulina* sp., less numerous cf. *Nodosaria* sp., cf. *Lagena* sp.) and Nubeculariidae (cf. *Nubeculinella* sp., sporadically cf. *Ophtalmidium* sp.) but also foraminifers of the families Spirillinidae (cf. *Spirillina* sp., cf. *Patellina* sp.), Involutinidae (cf. *Paalzowella* sp., cf. *Trocholina* sp.), Lituolidae (cf. *Ammobaculites* sp.), and Hormosinidae (cf. *Rheophax* sp.) (Pl. V).

In the massive limestone, the most numerous foraminifers are cf. *Nubeculinella* sp., encrusting the cyanobacterial crusts and sometimes stromatolites. They are also the only organisms besides serpules to appear on both, the lower and upper surfaces of sponges (cf. Wagenplast, 1972). The foraminiferal crusts (cf. Flügel & Steiger, 1981) also occur with in cyanobacterial crusts developed on other bioclasts and in oncoids (organism-bearing lamination, cf. Dahanayake, 1977) (Pl. VII: 2; Pl. IX: 1–5), as well as on local surfaces of sedimentary discontinuities (Pl. V: 6).

In the bedded limestone the most numerous foraminifers are those of the family Nodosariidae; Spirillinidae and Nubeculariidae are less numerous.

Within the canals of siliceous sponges, in both limestone facies, there occur fairly numerous foraminifers of the family Ammodiscidae (cf. *Tolypammina* sp.) and sporadically Polymorphinidae (cf. *Bullopore* sp.) (Pl. V: 1, 3).

Brachiopods

Thin-shelled forms have been observed in the sections; they have smooth or sculptured shells, some of them with characteristic spines (Pl. VI: 1–4). Crusts are locally present on shell fragments (Pl. VI: 2). The interiors of unbroken shells are in some cases filled with fecal pellets and microoncooids.

Bryozoans

Bryozoans are common in the studied limestones. They occur as: (i) encrusting, together with other epifauna, on the lower surface of a sponge protected from the light, (ii) encrusting cryptohardground-type surfaces (see p. 177) and (iii) rounded fragments of zoaria randomly distributed in sediment, in some cases with boring, often surrounded by a cyanobacterial envelope encrusted with foraminifers (Pl. VII; Pl. XII: 4; Pl. XIV: 1).

Echinoderms

Echinoderms are one of most numerous groups of microfauna in the limestones from Piekary (Pl. VIII). They are mainly represented by segments of crinoids, both planktonic, cf. *Saccocoma* sp. and benthic. Locally, the accumulation of crinoids is so large that „crinoid limestone” is observed. The planktonic forms are somewhat more numerous in bedded limestone, as are the benthic in massive limestone. Plates and spines of sea urchins are also

common and vertebrae of brittle stars and holoturian sclerites appear sporadically.

Most echinoderm fragments have micritic envelopes (Pl. VIII: 4). Syntaxial calcite on echinoderm plates (Pl. VIII: 5, 7, 8) occurs almost exclusively in those thin sections in which internal sediments have been found.

Polychaetes

In the limestones studied, serpules are not a rock-forming element. They occur *in situ* only among the epifauna on the lower sides of sponges and on shell fragments (Pl. VI: 1). They occur also as nuclei of some oncoids (Pl. VII: 3).

The forms which have built micritic, agglutinated tubes 0.3–1 mm in diameter, are attributed to polychaetes cf. *Terebella lapilloides* (Pl. VI: 7, 8; cf. Klieber, 1985; Brachert, 1986).

Other groups of fauna

Ostracodes, oyster fragments and hydrozoa have been sporadically encountered in the limestones from Piekary. In one case an aptychus, a juvenile form of ammonite and a coral fragment were found. Some organic remains could not be determined because of their poor preservation.

Cyanobacterial structures

Cyanobacterial products are the most important rock-forming elements in the limestones studied. They constitute more than half of the rock volume in the massive limestone in Piekary. This value is close to that given by Behr & Behr (1976) for the reef limestones in the Upper Jurassic of southern Germany.

The structures related to the activity of cyanobacteria include: crusts, stromatolites, oncoids, peloids and to some extent tuberoids.

Crusts and stromatolites

In Piekary, the cyanobacterial crusts are especially numerous in the massive limestone. They are most common on the upper surfaces of sponges where they form cushion-like structures, amply encrusted, mainly by foraminifers of the nebeculariid-type (Pl. IV: 1; Pl. XIV: 1). Similar forms have also developed on other bioclasts, especially on the large ones (Pl. VI: 2). Small, light organic fragments are in most cases encrusted on all sides (usually several stages of growth can be seen), so they may become oncoids. Cyanobacterial crusts are also common on local surfaces of sedimentary discontinuities (Pl. XI: 1; Pl. XIV: 2).

Some cyanobacterial crusts grade upwards into stromatolites (Pl. XIV: 1; cf. Wagenplast, 1972; Meyer, 1975). Stromatolites occur also directly on sponge mummies. Rare, redeposited fragments of LN-type stromatolites (cf. Gaillard, 1983), randomly scattered are characteristic of the limestone in the transitional zone.

The light, sparitic laminae of stromatolites include numerous peloids, microoncooids and sporadically even fine (0.1–0.2 mm) ooids. The dark laminae consist almost exclusively of peloids (Pl. X: 2).

A crust with a distinct, filamentous structure has been observed in one thin section (Pl. IX: 5, 6: cf. Flügel & Steiger, 1981; Brachert, 1986).

Oncoids

Two groups of oncoids have been distinguished. One includes large forms (up to c. 3 mm in diameter), usually irregular, in some cases nearly elliptical (Pl. IX; Pl. X: 4). Some oncoids have several nuclei. The nuclei are usually bioclasts. The cortices around the nuclei are relatively thick and grumose; micritic and organism-bearing laminations may be observed within them (cf. Dahanayake, 1977). Foraminiferal lamination with nubeculariid-type foraminifers (nubeculariid oncoids, cf. Gaillard, 1983) is especially frequent. The oncoids discussed belong mainly to types III and IVC in Dahanayake's classification (1977) and in a lesser degree to types I and II. Those lacking a central nucleus and distinct lamination correspond to type IVS (pseudooncooids). Some of the forms described resemble *Tubiphytes* sp. (cf. Maslov, 1956; Morycowa & Moryc, 1976; Flügel, 1981). The oncoids included in the first group occur in both micrite and sparite, but mainly in the transition zone from massive to bedded limestone.

The second group of oncoids comprises small (0.1–0.3 mm), spherical forms of concentric structure (Pl. X: 1–3). This cortex thickness is variable. These oncoids occur almost exclusively in sparite, on surfaces of sedimentary discontinuities or in stromatolites (cf. Gwinner, 1976; Schorr & Koch, 1985) together with peloids and ooids, where they form distinctive, graded laminae (Pl. X: 2). These forms correspond to microoncooids (cf. Radwański, 1968) and they somewhat resemble the pelagic ooids (cf. Jenkyns, 1972) in their morphology. There also occur gradual transitions between peloids, microoncooids and ooids (Pl. X: 1, 3, 5). The discussed forms belong to Dahanayake's type I (1977).

Peloids

Peloids are one of the most common constituents of the massive and the bedded limestone. This class embraces grains up to 0.2 mm in diameter, built of dark micrite, and embedded in sparite or lighter micrite. They occur either in isolation or in aggregates of several peloids (cf. Illing, 1954; Kutek, 1969). The peloids have been found in the matrix as well as in stromatolites, where they form separate, well sorted laminae together with microoncooids and ooids (Pl. X: 2).

Tuberoids

The observed tuberoids vary in size from a few tenths of a millimetre to a few millimetres (Pl. VI: 5, 6; Pl. IX: 4; Pl. XVI: 2). Their shapes are irregular;

some are rounded, especially those that occur in the sparite matrix on washed out surfaces. Tuberooids which occur in accumulations are usually poorly sorted. The conditions of their origin are discussed on p. 219.

Ooids

Small (0.1–0.3 mm), usually single-envelope ooids, occur in sparite, mainly on surfaces of sedimentary discontinuity or in stromatolites (cf. Gwinner, 1976; Schorr & Koch, 1985). One can distinguish among them forms with very thin envelopes (Pl. X: 5), somewhat similar to the surface ooids (oolitic film; cf. Bathurst, 1967) and ooids with non-concentric envelopes (Pl. X: 6; cf. Gąsiewicz, 1984). The radial structures, characteristic of ooids, are indistinct and the transition to microoncooids is gradual. The envelopes are in some cases incomplete. The micritic inter-envelopes are several times thicker than the sparitic laminae. In some ooids the central parts are dissolved, and the outer envelopes of the cortices are preserved (Pl. X: 5).

Intraclasts

Intraclasts have been observed sporadically, but only on local wash-out surfaces, where they are accompanied by tuberooids, bioclasts, oncoids and ooids. Intraclasts are fragments of earlier lithified sediment (biopelmicrite or biomicrite), slightly rounded and partly encrusted with nebeculariid-type foraminifers (Pl. XV: 3). They are about a millimetre in diameter; the absence of smaller forms may result from difficulty in their identification and confusion with peloids.

Cements

Micritic cement distinctly dominates (above 95%) in massive and bedded limestone. Isopachous and mosaic cement also occur. Equant calcite and syntaxial cement occur in massive limestone only.

Isopachous cement forms thin (up to c. 0.2 mm) rims on grains and it occurs mainly in grainstone.

Drusy mosaic cement fills joints and large (above 3 mm) voids. It consists of grains 0.2–0.5 mm in diameter. It occurs in all limestone microfacies.

Equant calcite fills voids up to 1–2 mm in diameter or it occurs together with internal sediment. Crystal size in this type of cement increases towards the centre of the field occupied by it (Pl. XII: 4; Pl. XIII: 2, 3; Pl. XV: 4).

Syntaxial calcite occurs on those echinoderm plates which have no micritic envelope. It occurs in biolithites and biopelmicrites (Pl. VIII: 5, 7, 8; Pl. XIII: 1).

Surfaces of sedimentary discontinuity

Numerous, mesoscopically invisible, surfaces of sedimentary discontinuity occur in massive and bedded limestone. Two basic types of such surfaces have been distinguished: cryptohardgrounds and erosional surfaces. Sporadically surfaces of softground features occur.

Cryptohardgrounds (Flügel & Steiger, 1981) are marked by cyanobacterial crusts and numerous encrusting fauna — foraminifers (mainly of nubeculariid type), bryozoans and serpules (Pl. V: 6; Pl. XIV: 2). Surfaces of this type are usually relatively flat. They occur frequently in sets consisting of several superimposed surfaces. Cryptohardgrounds are observed mainly in biolithites. It should be stressed that the same microfacies is present below and above a cryptohardground surface. Intraclasts or redeposited bioclasts are almost absent on cryptohardground surfaces.

Erosional surfaces are covered with sediment microfacies indicative of the high energy of the environment (numerous tuberoids, oncoids, ooids, large bioclasts and intraclasts embedded in sparite; Pl. XI: 1). Surfaces of this type are also settled by fauna and crust-forming cyanobacteria.

Surfaces of soft-ground type have been observed only as an exception. Their distinctive features are: the lack of crusts and encrusting fauna, as well as the occurrence of gentle bends and irregularities. Surfaces of this type are overlain with sediment typical of deposition in conditions of high water-energy (Pl. XI: 2).

Graded sediments

Graded sediments have not been found in the exposure in Piekary, but they occur nearby in Tyniec (Fig. 1). Thin graded beds (3–20 mm) occur in bedded greyish-yellow micritic limestone, indistinctly horizontally laminated. The largest grains, mainly bioclasts, are about 1.5 mm in diameter.

The bottoms of graded beds are in some cases erosional and then the boundary with micrite limestone is sharp. The tops of graded beds are hardly recognizable, due to gradual transition of the fining-upwards sediment to micrite.

Internal sediments

Internal sediments occur mainly in massive limestone. They correspond to (i) micropelletal grainstone (packstone) and (ii) vadose crystal silt (cf. Aissaoui & Purser, 1983) and fill voids 1–2 mm in diameter.

Micropelletal grainstone or packstone fills voids in sponges (Pl. XII: 1–5; Pl. XIII: 1, 2). Some of these voids are pelecypod borings. It seems also, that the sediments occasionally observed in fills of solution pores or in intergranular voids of intraclasts (Pl. XV: 3), belong to this type. Micropelletal grainstone (packstone) is built of peloids, ooids, microoncoids and some bioclasts (0.1–0.2 mm) cemented with sparite. Sorting is fairly good and inverse grading is present in some cases.

Vadose crystal silt is built of fine crystals of yellowish calcite (up. to c. 0.01 mm in diameter) and bioclasts (Pl. XIII; Pl. XV: 1). It fills voids of different origin in sediment and in some cases occurs together with internal sediment of the grainstone (packstone) type. Vadose crystal silt is in some cases slightly coarser in the lower parts of the filled voids.

Dolomitization and dedolomitization

Only small fragments of massive limestone in Piekary are dolomitized. The dolomitized fragments are built of hipidiomorphic dolomite crystals about 0.8 mm in size. Relics of original limestone texture are preserved within the crystals. The dolomitized fragments were found in samples from Piekary only in those thin sections in which there were also internal sediments or syntaxial calcite on echinoderm plates (Pl. XIII: 2; Pl. XV: 4).

The occurrence of dolomite is known from exposures near Kostrze and Pychowice, situated c. 4 km to the east (Fig. 2; cf. Gawel, 1948; Łaptaś, 1974).

The exposure in Kostrze, not hitherto described, seems to be especially important for the reconstruction of the sedimentary environment. Dedolomitization and internal sediments have been found there. Bedding is distinctly visible in the limestone exposed there, although the cherts, typical of this bedded limestone, are absent. Isolated rhomboedres calcified after dolomite occur in biopelmicrite or biomicrite. The upper parts of dedolomitized rhomboedres are built of euhedral calcite crystals and the lower parts — of vadose crystal silt (Pl. XV: 1; cf. Meder, 1987).

MICROFACIES

Similar types of microfacies occur in massive and bedded limestone. The essential difference between the two types of limestone consists in the relative frequency of the occurrence of individual microfacies (Table 1).

In the massive limestone, biolithites and biopelmicrites are the most frequent; oncobiomicrites/sparites with tuberooids and biopelmicrites with tuberooids are also numerous. Biomicrites with tuberooids and oncobiopelsparites with intraclasts are sporadic. Biomicrites have not been observed.

Table 1
Observed frequency of microfacies types in various facies of the Upper Oxfordian limestones in Piekary

	Massive limestone	Transitional zone	Bedded limestone	
			near bioherm < 40 m	far from bioherm > 40 m
Biolithite	+++	++	+	—
Biopelmicrite	+++	+++	+++	+++
Oncobiomicrite/sparite with tuberooids	++	+++	++	+
Biopelmicrite with tuberooids	++	++	+++	++
Biomicrite with tuberooids	+	++	++	++
Biomicrite	—	+	++	+++
Oncobiopelsparite with intraclasts	+	+	++	+

+++ > 25% thin sections of this facies; ++ 10–25%; < 10%: — 0%

In the bedded limestone, the microfacies varies laterally with increasing distance from the bioherm. As the distance from the bioherm increases, the biomicrites become more numerous and oncobiomicrites/sparites with tubero-ids, biopelmicrites with tuberooids and oncobiopelsparites with intraclasts become less numerous. Biolithites are rare in bedded limestone and they occur only close to the bioherms.

All microfacies observed in massive and bedded limestone also occur in the transition zone. The distinctive features of the microfacies in the transition zone are: the presence of numerous, small aggregates of silica, the predominance of tuberooids and the occurrence of redeposited stromatolites randomly distributed in sediment.

The names of microfacies are given according to Folk (1959, 1962). Equivalents in the classifications of Dunham (1962) and Embry & Klovan (1972) are given in brackets.

Biolithites (boundstone: bindstone-framestone)

(Pl. IV: 1; Pl. XIII: 1; Pl. XIV)

The main constituent of biolithites is cyanobacterial crusts, transitional upwards to stromatolites. They are present on bioclasts, mainly on sponges, where they form the unitary sedimentary sequences described above. Algal crusts are usually encrusted by nubecularian-type foraminifers. The voids that sporadically occur within the sponges are in most cases due to borings, and they are often filled with internal sediments. Other, greater bioclasts, are almost entirely absent in the investigated biolithites; brachiopod and oyster shells occur sporadically. Microfauna is represented by foraminifers (mainly of the family Nodosariidae) and echinoderms. Biocenoses on sponge downsides — bryozoans and polychaetes, are also important rock-forming elements. Local surfaces of sedimentary discontinuity of cryptohardground type are common in biolithites.

Biopelmicrites (wackstone, floatstone)

(Pl. XI: 1)

Biopelmicrites are distinguished by having bioclasts up to c. 1 cm in diameter and peloids embedded in micrite as their main constituents. Brachiopods, echinoderms, bryozoans and agglutinating foraminifers dominate among the bioclasts. The bioclasts are usually overgrown with cyanobacteria. Sponge fragments and polychaetes cf. *Terebella lapilloides* which usually occur near the sponges are relatively rare. Apart from peloids and bioclasts, some composite oncoids and tuberooids also occur. Cryptohardground-type surfaces are also present in biopelmicrites. One case has been observed of authigenic glauconite impregnating bioclasts (cf. Łacka, 1986).

Oncobiomicrites/sparites with tuberooids
(tuberolitic packstone/grainstone)
(Pl. XI; Pl. XVI: 1)

The main constituents of this microfacies are tuberooids and microoncooids. Brachiopods and crinoids dominate among the bioclasts. Most bioclasts are covered with cyanobacterial envelopes. Tuberooids are mostly rounded and usually poorly sorted. They occur mainly in micrite, in contrast to microoncooids which are related to sparite. Continuous transition to ooids has been observed in many cases, as well as typical ooids, some of them with dissolved centres.

Biopelmicrites and biomicrites with tuberooids
(tuberolitic wackestone), biomicrites (wackestone)
(Pl. XVI: 3)

Micrite includes numerous bioclasts, mainly sponges and fragments of bryozoans, brachiopods and echinoderms. Foraminifers (Nodosariidae) are also numerous. Biopelmicrites with tuberooids include large, individual, composed oncooids, similar to *Tubiphytes* sp. Tuberooids of various shape and size are especially numerous in bedded limestone and near the transition zone to bedded limestone. The proportion of biomicrites increases in the opposite direction. A specific variety of biomicrites are sporadically occurring spiculites.

Oncobiopelsparites with intraclasts (grainstone)
(Pl. XI: 1)

This variety of microfacies is related to the surfaces of sedimentary discontinuity and erosional surfaces occasionally observed, mainly in bedded limestone. Sparite includes numerous well sorted spherical tuberooids, large composite oncooids, microoncooids, ooids, disintegrated fragments of bioclasts and even large redeposited bioclasts, not found elsewhere.

SEDIMENTATION AND DIAGENESIS

The reconstruction of the sedimentary environment is based mainly on indirect evidence and is based on the discussion of the following questions: (I) the role of cyanobacteria and their influence on the low-energy state of the environment, (II) conditions of sponge fossilization, (III) fauna as an indicator of basin depth and the sedimentation rate, (IV) bottom morphology, (V) indications of subaerial exposure of the limestones during early diagenesis, (VI) processes of silicification, dolomitization and dedolomitization and (VII) the origin of the bedding.

(I) The sedimentation of limestones in Piekary took place in an environment dominated by cyanobacteria and siliceous sponges. Though not all cyanobacteria are photosynthetic organisms, the numerous cyanobacterial

crusts growing exclusively on sponge upsides (oriented towards the light?) suggest that the growth of the cyanobacteria took place within the photic zone. The upward transition of the cyanobacterial crusts into stromatolites is, according to Meyer (1975), an indication of the shallowing of the sedimentary basin.

Ooids and intraclasts are few in the limestones in Piekary. This indicates the low energy of water and seemingly excludes the shallow-water environment. However, if in a shallow water environment the intense water movement occurs only sporadically, then the conditions of sedimentation will be similar to that in the deeper zones, below the wave-base. The marked dominance of the microfacies formed in conditions of low energy may be explained by the abundance of cyanobacteria forming extensive and dense cyanobacterial mats.

The cyanobacterial mats inhibited the wave action and at the same time they bound all free grains on the sediment surface (cf. Meyer, 1975) and favoured the accelerated lithification of sediment, resulting in increased resistance of the sediment to the wave action (cf. Neumann *et al.*, 1970). The sediments accumulating in such an environment were eroded only during strong storms. The oncoids and fragments of redeposited stromatolites prove that intense water movement occurred occasionally in the basin and disrupted the cyanobacterial mats. The presence of composite oncoids (IVC) seems to be an additional indication of shallow-water conditions of sedimentation (cf. Dahanayake, 1978). One can not, however, exclude the possibility that these oncoids have been redeposited to the deeper zone from the tidal zone (cf. Kutek, 1969). Numerous microoncoids, related mainly to sparite, also indicate sporadically occurring high-energy conditions of sedimentation. These forms, however, do not determine the depth of the depositional basin.

The cyanobacterial activity may also be responsible for the common occurrence of peloids together with the small quantity of mainly single-envelope ooids. The studies of Behr & Behr (1976) indicated that peloids in the Upper Jurassic limestones in southern Germany are of cyanobacterial origin. A similar origin may be accepted for the major part of the peloids in Piekary. The sponge ectoderma has been completely micritized (grain diminution) by the action of rivularia (cf. Behr & Behr, 1976). A certain part of the micrite which originated thus might still have been too weakly lithified during the early diagenetical dissolution of the siliceous sponge skeletons, and could have been transformed into a mass of structureless micrite, and they could only be preserved in local sedimentary voids in the form of peloids (Pl. XII: 1; cf. Schorr & Koch, 1985). Other sources of peloids such as local point recrystallization of micrite (structure grumeleuse; cf. Cayeux, 1935) or fecal pellets (cf. Kutek, 1969), although they are encountered in the limestones studied, are of marginal importance.

The cyanobacteria which stabilized the sediment formed micrite envelopes on ooids (micrite envelopes; cf. Kobluk & Risk, 1977). A grain which fall to the bottom would be quickly overgrown by cyanobacteria and could be

oolitized again only in the case of a sudden increase in water energy that occurred before the grain became stabilized. Thus, the process of oolitization a single grain occurred only once in most cases. The ooids originated in this way are hardly distinguishable from microoncooids. Most of the ooids have probably been completely micritized (cf. Dravis, 1979) and this makes them indistinguishable from peloids.

(II) The fossilization of sponges and the origin of the "sponge mummies" have been described in the papers by Fritz (1958), Flügel & Steiger (1981), Gaillard (1983), Matyja (1978) and Matyja & Wierzbowski (1985). Two factors are mainly responsible for this process: water movement and the amount of clay in suspension. Only in the case of weak water movements, with a low concentration of clay the "sponge mummies", common in the limestones studied can be formed (Fig. 4). The weak water movements permit the shape of the sponge ectoderm to be preserved during the internal decay of organic matter and the diagenetic dissolution of the siliceous skeleton. The small amount of clay allows for the processes of early diagenesis occurring. Slightly stronger water movement, with low clay content results in tuberoids forming, and in the remaining cases spiculites form. The presence of spiculites has been ascertained in only one case (Pl. XVI: 3).

The details of the internal structure of "sponge mummies" are much more obliterated in the lower parts of the sponges from Piekary. This fact indicates

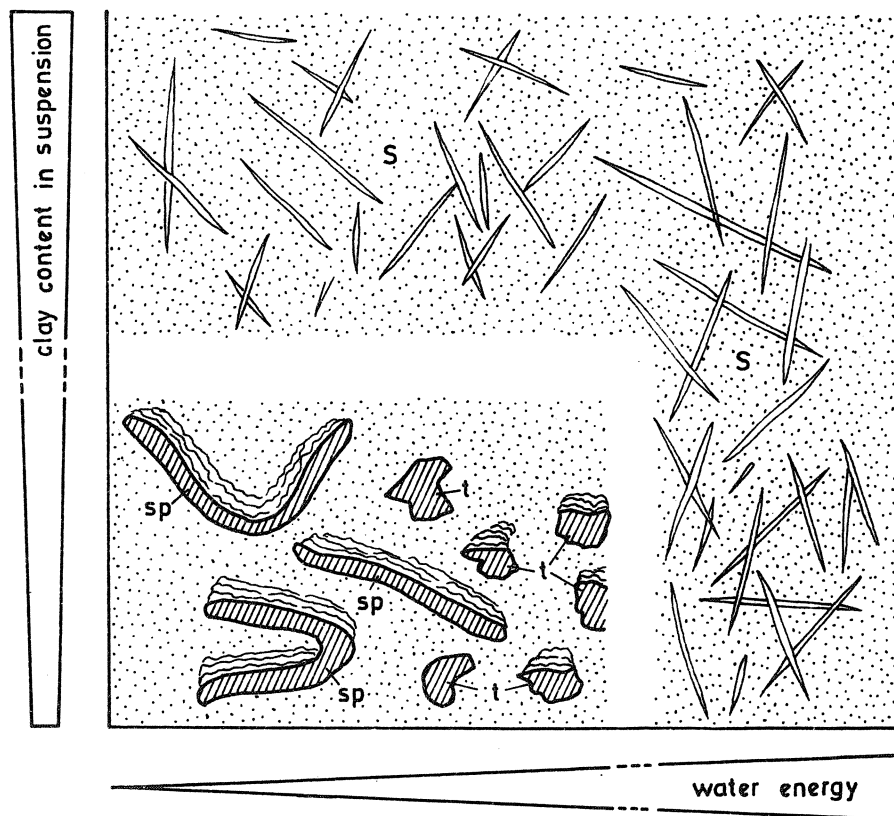


Fig. 4. Conditions of origin of sponge mummies (sp), tuberoids (t), and spiculites (s)

the rapidity and high intensity of the early diagenetic process which took place before the complete burial of the sponges by the sediment (cf. Palmer & Fürsich, 1981). The distinct traces of boring in "sponge mummies", with preserved borer shells or filled with internal sediment (Pl. XII: 1–5) indicate that a rigid framework was present during the bioherm growth (framestone; cf. Embry & Klovan, 1972).

(III) Neither the sponges nor the other fauna provides a basis for the determination of the basin depth. Siliceous sponges may occur to a depth of 1.000 meters. Fossil sponge bioherms attributed to a shallow-water environment are known in Normandy and England (Palmer & Fürsich, 1981), and modern ones — from the Bahamas (Wiedenmayer, 1978).

Earlier opinions on the situation of the sedimentary environment in the deeper part of shelf (Dzuleński, 1952; Wieczorek, 1982) are based on negative evidence, namely the lack of the assemblage of organisms and sedimentary structures typical of shallow-water conditions. The lack of the assemblage of organisms characteristic of a shallow-water environment (e.g. of corals which are very scarce in the Kraków area) may not necessarily be the result of great depth, but of the action of other factors: the lack of food, inadequate temperature, the turbidity of the water etc. The shallow-water environment of deposition is indicated by green algae — Dasycladaceae — found in the massive limestone in the Kraków area by Golonka & Haczewski (1971) and by crabs of the family Dromioidea and brachiopods (Dallinidae) from the bedded limestone (Krobicki, 1986).

The common occurrence of agglutinated foraminifers cf. *Tolypammina* sp. seems to indicate a temporary increase in the rate of deposition of terrigenous material, in conditions of increased water movement (Kazmierczak, 1973). The low rate of deposition is suggested by the presence of numerous nubeculariid-type foraminifers and some foraminifers of the genus *Ophtalmidium* sp. (Gaillard, 1983, p. 318).

(IV) The occurrence of graded sediments in the bedded limestone in Tyniec (Fig. 2) indicates the existence of sea bottom denivelation (cf. Marcinowski, 1970) whose origin was related to the cyanobacterial-sponge rigid-framework buildups. Occasional intense water movements resulted in their partial destruction.

The material removed by erosion was deposited in extensive depressions between the cyanobacterial-sponge buildups.

A genetical interpretation of the observed graded sediments is not possible, because they could be either tempestites, i.e. storm-generated clouds of suspension transported to a zone situated below the wave-base, or classical turbidites, i.e. deposits of turbidity currents, generally unrelated to bathymetry (cf. Aigner, 1982; Dott, 1983).

In a shallow basin, the bottom irregularities are one of the decisive factors in extinguishing the energy of waves.

(V) The shallow-water sedimentation of the limestones from Piekary, with

the possibility of short-lasting subaerial exposure of the bioherm culminations, seems to be indicated by the internal sediments-micropelletal grainstone (packstone) and vadose crystal silt (cf. Dunham, 1969; Aissaoui & Purser, 1983).

The possibility of episodic subaerial exposure is indicated by the presence of syntaxial calcite on echinoderm plates. Waldken & Berry (1984), using cathodoluminescence, ascertained that the existence of corona solution in the syntaxial calcite originated during the early diagenesis in fresh water. Syntaxial calcite on echinoderm plates usually forms in a freshwater phreatic zone or in a freshwater vadose zone, but these are rarely found around echinoderm plates (Longman, 1980). Syntaxial calcite may also originate in a mixing zone of marine and fresh water (cf. Brachert, 1986). There are also known occurrences of syntaxially developed calcite which originated in deep-sea zones, and only the use of the cathodoluminescence methods permits unequivocal interpretation.

The meteoric conditions of early diagenesis seem to be indicated by the presence of equant calcite which reveals a trend to increasing crystal size towards the centre of the occupied field. According to Loucks (1977; *vide* Peryt, 1984, p. 23) and Longman (1980), this type of cement forms usually in the shallow-water phreatic zone. The isopachous cement is typical of early submarine diagenesis, whereas the micrite cement may be formed in various conditions.

Similarly, the dissolution of originally aragonitic ooids is interpreted by Robinson (1967) and Peryt (1984) as occurring due to the action of fresh water. This phenomenon is rare in the limestones studied. It seems that the lack of distinct oomoldic porosity (cf. Choquette & Pray, 1970) is related to: (i) the originally small number of ooids, due to the lack of conditions favouring oolitization because free grains were bound by cyanobacteria, and (ii) micritization of oolitized grains (cf. Dravis, 1979; Richter, 1983) which occurred during a low rate of deposition (cf. Peryt, 1984; Fig. 5).

(VI) The beginning of the formation of cherts, common in bedded limestone, is related to the early diagenetic stage. The probably main source of silica was sponges, though the siliceous skeleton only constitutes less than ten percent of their weight.

The decay of the ectoderme of the sponges that built the bioherm led to an increase in pH. Then, the opaline sponge skeletons were being dissolved in the highly alkaline environment, when at the same time they were being substituted with calcite secreted in abundance, resulting in the formation of "sponge mummies" (Newell *et al.*, 1953; Fritz, 1958; Wiedenmayer, 1980).

Similar processes were taking place in the sediment around the bioherms, from which the bedded limestone was formed. Zonal changes of pH occurred in the strongly watery sediment, which had, in general, a slightly elevated clay content due to the depressional position relative to the bioherm (cf. Flügel & Steiger, 1981; Matyja & Wierzbowski, 1985; Schorr & Koch, 1985).

They led to the migration of silica from the spicules of sponges, which were decaying on the spot, as well as from the spicules supplied from the bioherm. Migration of silica in the locally highly porous sediment followed the morphological slope: from the bioherm towards the depression where the original sediment of the bedded limestone was being accumulated.

The diagenetic processes had to occur longer in bedded limestone than in bioherm (cf. Flügel & Steiger, 1981), due to the higher content of clay. They led to the formation of siliceous gel horizons and ceased gradually due to the expulsion of water and decrease in sediment porosity by ongoing compaction.

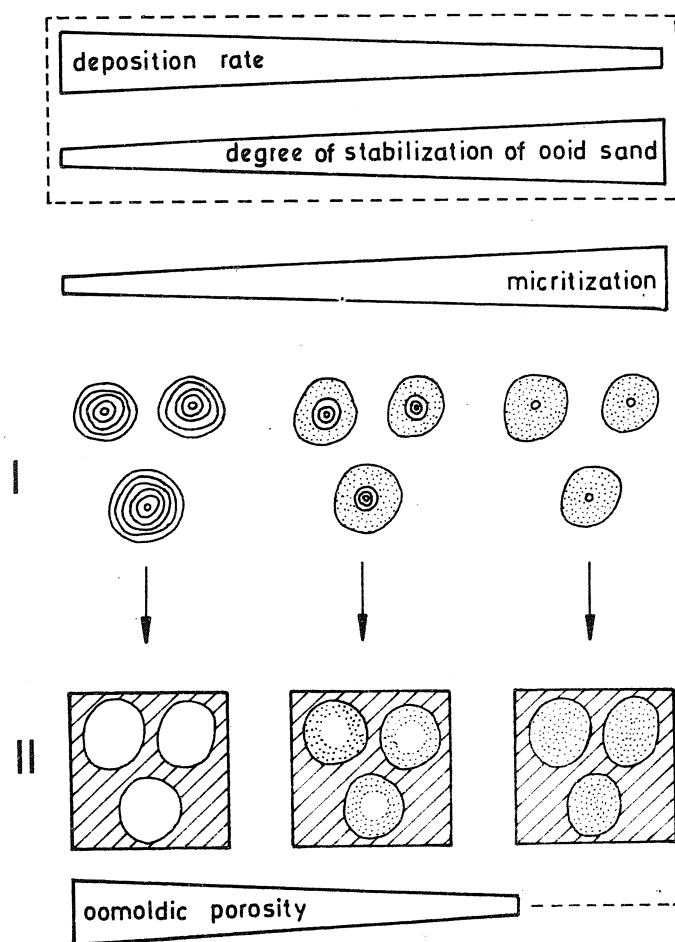


Fig. 5. The relation between micritization and ooid dissolution by fresh water during early diagenesis (according to Peryt, 1984; slightly modified). I — sedimentary textures; II — diagenetic textures

Probably, the chert horizons formed in bedded limestone on weakly marked, original stratification surfaces, i.e. where clay content was locally elevated. Some of these surfaces became transformed into bedding surfaces within some millions of years after deposition under the overburden of 100–150 metres (Ricken, 1985). Other surfaces became healed by calcium carbonate redistributed within the sediment. The only trace of these surfaces now is the postdiagenetic, mid-layer chert horizons.

The small amount of silica of unclear origin, which did not become

concentrated in cherts, occurs in the limestones in the form of small aggregates (Pl. XIV: 1; Pl. XV: 2). These aggregates could be one of the sources of silica for the epigenetic siliceous formations that occur at the top of the Oxfordian strata in the Kraków area (cf. Matyszkiewicz, 1987).

The lack of cherts in the dolomitized bedded limestones corroborates the supposition by Łaptaś (1974) of the early diagenetic nature of the dolomitization.

The observed early diagenetic dolomitization occurred probably in the zone of mixing of fresh and marine water. Dolomitization of this type is usually related to temporary emergence of the higher parts of the basin floor, resulting in the creation of several shallow isolated reservoirs of elevated salinity (cf. Geldsetzer, 1973). The course of the dolomitization processes seems to approximately follow the model of Dorag (Badiozamani, 1973; cf. Meder, 1987).

The observed early diagenetic dolomitization occurred probably in the zone occurring during the early diagenesis in surficial or nearly surficial conditions with the participation of meteoric water (cf. Evamy, 1967; Sha Quingan *et al.*, 1979; Peryt, 1984; Schorr & Koch, 1985; Wirsing & Koch, 1986; Meder, 1987).

(VII) That the origin of the bedding is early diagenetic and not synsedimentary is indicated by the presence of nodular interbeds in the transition zone, which contain sponge fragments cut by nodule boundaries. This indicates that the nodular layers, which are continuations of bedding joints, are not of conglomerate or breccia nature.

Hence, the bedding seems to be the result of diagenetic redistribution of calcium carbonate within the sediment, in condition of burial. This redistribution transformed some of the numerous, indistinct synsedimentary stratification surfaces into bedding surfaces with the participation of the processes of solution, compaction and weathering, and reduced the other ones by cementation (diagenetic bedding; cf. Ricken, 1985). The bedding of this origin is termed pseudobedding (Simpson, 1985). The formation of limestone nodules is, in this approach, an early diagenetic process that occurs just after deposition. The mechanism of this process seems to be similar to so called diagenetic segregation (cf. Hudson & Jenkyns, 1969).

The lack of regular bedding in the massive limestone is an obvious result of its internal structure. The relatively rapid lithification of bioherm mean that it behaved as a rigid body with respect to the more slowly lithified surrounding sediment (cf. Schorr & Koch, 1985). The result of this is the observed increase in thickness of the limestone "layers" bounded by nodular interbeds, towards the bioherms.

CONCLUSIONS

1. The bodies of massive limestone in Piekary are rigid-framework cyanobacterial-sponge build-ups. Cyanobacteria and sponges are also important builders of the bedded limestone.

2. The limestones from Piekary have been laid down in an environment of low energy, where intense water movements occurred sporadically. There are numerous indications that it was a shallow environment in which elevated fragments of basin floor were periodically emergent.

3. Chert horizons were formed where local, horizontal elevation of clay content occurred, apparently in relation to poorly marked, synsedimentary surfaces of stratification.

4. The bedding in the limestones is of diagenetic nature and is related to the redistribution of calcium carbonate within the sediment, in conditions of burial. As a result of this redistribution, part of the indistinct, synsedimentary stratification surfaces have been transformed, with the participation of solution, compaction and weathering processes, into bedding surfaces and the rest were reduced by cementation.

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Streszczenie

SEDYMENTACJA I DIAGENEZA SINICOWO-GĄBKOWYCH WAPIENI GÓRNEGO OKSFORDU W PIEKARACH KOŁO KRAKOWA

Jacek Matyszkiewicz

W pracy przedstawiono wyniki badań wapieni górnego oksfordu z Piekar koło Krakowa, uzupełnionych obserwacjami z Tyńca oraz Kostrza i Pychowic (Fig. 1, 2). Szczegółowymi badaniami objęto odsłonięcie położone na lewym brzegu Wisły, naprzeciw Opactwa Tynieckiego, w którym dobrze widoczne jest

przejście wapieni skalistych w wapienie uławiczone (Pl. I, Fig. 3). Odsłaniające się utwory znajdują się w profilu około 150 m nad spągiem oksfordu i należą do poziomu *Epipeltoceras bimammatum* lub *Idoceras planula* (Tarkowski, 1982).

CHARAKTERYSTYKA WAPIENI

Ściana odsłonięcia ma wysokość 16 m i długość około 250 m. W północnej części widoczne są wapienie uławiczone z krzemieniami o miąższościach ławic 0.9–2.5 m, które ku południowi, w strefie przejściowej, na odcinku około 10 m przechodzą w wapienie skaliste pozbawione uławiczenia i krzemieni. Kontynuacją fug międzylawicowych w strefie przejściowej są warstewki gruzłów o miąższości od 5 do 16 cm (Pl. II: 2; Pl. III: 1). W „ławicach” wapieni oddzielonych od siebie takimi warstewkami gruzłów ma miejsce wyraźny wzrost miąższości w kierunku wapieni skalistych. Na zglądach obserwuje się, że fragmenty gąbek przecięte są przez granice gruzłów (Pl. III: 2).

Fauna obserwowana mikroskopowo w wapieniach skalistych i w wapieniach uławiczonych jest identyczna i składa się głównie z gąbek krzemionkowych (Pl. II) i ramienionogów. Badania mikroskopowe wykazały, że najpospolitsze są gąbki krzemionkowe Hexactinellida i Lithistida (Pl. IV: 1–3; Pl. VII: 6–7; Pl. XII; Pl. XIV). Wśród ramienionogów stwierdzono formy cienkoskorupowe, o gładkiej lub urzeźbionej skorupie; niekiedy z charakterystycznymi kolcami (Pl. VI: 1–4). Ponadto obserwowano: gąbki wapienne (Pl. IV: 4, 5), szkarłupnie (Pl. VIII), otwornice (Pl. V), mszywioly (Pl. VII; Pl. XII: 4; Pl. XIV: 1), wieloszczety (Pl. VI: 1; Pl. VII: 3; Pl. VI: 7–8), małżoraczki i wyjątkowo ślimaki i stułbiopławy.

Najważniejszymi elementami skałotwórczymi badanych wapieni są produkty pochodzenia sinicowego. W wapieniach skalistych z Piekar ich udział wynosi ponad 50% objętości skały, co w przybliżeniu odpowiada wartościom podawanym przez Behr i Behr (1976) dla wapieni rafowych południowych Niemiec. Do struktur związanych z działalnością sinic zaliczono oskorupienia, stromatolity, onkoidy, peloidy i częściowo tuberoidy.

Oskorupienia sinicowe szczególnie licznie występują w wapieniach skalistych. Obserwowane są najczęściej na górnych powierzchniach gąbek, gdzie tworzą poduszkowate ciała obficie inkrustowane nubeculariami (Pl. IV: 1; Pl. XIV: 1). Podobne formy rozwinięte są także na innych, szczególnie dużych, bioklastach (Pl. VI: 2) i na lokalnych powierzchniach nieciągłości sedymentacyjnej (Pl. XI: 1; Pl. XIV: 2).

Oskorupienia sinicowe przechodzą niekiedy ku górze w stromatolity (Pl. XIV: 1). Nieliczne, redeponowane fragmenty stromatolitów typu LN (por. Gaillard, 1983) są charakterystyczne dla wapieni strefy przejściowej. W jasnych, sparytowych laminach stromatolitów stwierdzono obecność licznych peloidów, mikroonkoidów, a nawet sporadycznie drobnych ooidów. Ciemne, mikrytowe laminy zawierają natomiast prawie wyłącznie peloidy (Pl. X: 2).

W jednym z preparatów zaobserwowano oskorupienie charakteryzujące się wyraźną, nitkowatą strukturą (Pl. IX: 5, 6).

W obrębie onkoidów występują głównie formy duże (do około 3 mm) typu III, IV C i IV S (por. Dahanayake, 1977; Pl. IX; Pl. X: 4) oraz tzw. mikroonkoidy, czyli drobne (0.1–0.3 mm) kuliste ziarna o koncentrycznej budowie (Pl. X: 1–3).

Peloidy stanowią jeden z najpospolitszych składników wapieni skalistych i uławiconych. Zaliczono do nich ziarna ciemnego mikrytu o maksymalnej średnicy 0.2 mm.

Tuberoidy mają średnice od kilku dziesiątych mm do kilku mm, kształty nieregularne i są słabo wysortowane (Pl. VI: 5, 6; Pl. IX: 4; Pl. XVI: 2).

Drobne (0.1–0.3 mm), najczęściej jednopowłokowe, ooidy występują w sparycie, głównie na powierzchniach nieciągłości sedymentacyjnej lub w stromatolitach. Charakterystyczne dla ooidów struktury radialne są niewyraźne, a przejścia w mikroonkoidy płynne (Pl. X: 5, 6). W niektórych ooidach obserwuje się rozpuszczone środki ziarn, a zachowane zewnętrzne powłoki korteksu (Pl. X: 5).

Intraklasty obserwowano sporadycznie, wyłącznie na lokalnych powierzchniach rozmycia, gdzie występują z tuberoidami, bioklastami, onkoidami i ooidami (Pl. XV: 3).

Sedymenty wewnętrzne stwierdzono głównie w wapieniach skalistych, gdzie stanowią wypełnienia kawern o średnicy 1–2 mm. Odpowiadają one utworom typu micropelletal grainstone/packstone (Pl. XII; Pl. XIII: 1, 2; Pl. XV: 3) i vadose cristal silt (Pl. XIII; Pl. XV: 1; por. Aissaoui & Purser, 1983).

W wapieniach skalistych i wapieniach uławiconych zdecydowanie przeważa cement mikrytowy (ponad 95%), a ponadto obserwuje się cement izopachytowy i mozaikowy. Blokowy cement kalcytowy (Pl. XII: 4; Pl. XIII: 2, 3; Pl. XV: 4) i cement syntaksjalny (Pl. VIII: 5, 7, 8; Pl. XIII: 1) występują tylko w wapieniach skalistych.

W wapieniach skalistych i uławiconych rozwinięte są liczne, makroskopowo niewidoczne, powierzchnie nieciągłości sedymentacyjnej, wykształcone jako kryptohardgroundy (Pl. V: 6; XIV: 2; por. Flügel & Steiger, 1981) lub powierzchnie erozyjne (Pl. XI: 1). Wyjątkowo obserwowano powierzchnie o cechach miękkiego dna (Pl. XI: 2).

Dolomityzacja w wapieniach z Piekar obejmuje jedynie niewielkie fragmenty wapieni skalistych. Stwierdzono ją w tych preparatach, w których obserwowano sedymenty wewnętrzne i syntaksjalny kalcyt na płytkach szkarłupni (Pl. XIII: 2; Pl. XV: 4).

W rejonie Kostrza i Pychowic przejawy dolomityzacji i dedolomityzacji występują w wapieniach wykazujących makroskopowo wyraźne uławicenie, a jednocześnie brak typowych dla tej facji krzemieni. Izolowane od siebie, skalcyfikowane romboedry po dolomicie obserwuje się w biopelmikrycie lub biomikrycie. Górne części tych romboedrów budują ksenomorficzne kryształy kalcytu, a w dolnej części występuje vadose cristal silt (Pl. XV: 1, 2; por.

Meder, 1987). Ponadto w pobliskim Tyńcu stwierdzono osady uziarnione frakcjonalnie.

W wapieniach skalistych i uławiconych występują podobne typy mikrofacji, a istotne różnice między wapieniami skalistymi a uławiconymi polegają na częstotliwości występowania poszczególnych typów mikrofacji (Tab. 1).

W wapieniach skalistych najczęściej obserwowano biolityty (Pl. IV: 1; Pl. XIII: 1; Pl. XIV) i biopelmikryty (Pl. XI: 1); liczne są także onkobiomikryty/sparyty z tuberoidami (Pl. XI; Pl. XVI: 1) i biopelmikryty z tuberoidami. Znacznie rzadsze są biomikryty z tuberoidami i onkobiopelsparyty z intraklastami; nie stwierdzono występowania biomikrytów.

W wapieniach uławiconych zaznacza się pewne zróżnicowanie mikrofacjalne związane z odległością od biohermy. Wraz ze wzrostem odległości od biohermy liczniej występują biomikryty (Pl. XVI: 3), mniej liczne natomiast są onkobiomikryty/sparyty z tuberoidami, biopelmikryty z tuberoidami i onkobiopelsparyty z intraklastami (Pl. XI: 1). Nieliczne w wapieniach uławiconych biolityty ograniczone są tylko do bezpośredniej bliskości bioherm.

W strefie przejściowej spotyka się wszystkie z mikrofacji obserwowanych w wapieniach skalistych i uławiconych. Charakterystycznymi cechami mikrofacji strefy przejściowej są: obecność licznych, drobnych skupień krzemionki, obfitość tuberoidów oraz występowanie redeponowanych stromatolitów.

ŚRODOWISKO SEDYMENTACJI

Sedymentacja wapieni z Piekar zachodziła w środowisku o niskiej energii, w którym sporadycznie zachodziły intensywne ruchy wody. Znaczną przewagę mikrofacji tworzących się w warunkach niskiej energii wody można tłumaczyć przede wszystkim obfitością i gwałtownym rozwojem sinic budujących rozległe i bujne maty.

Maty sinicowe, wythumiając energię falowania, wiązały jednocześnie wszystkie wolne ziarna na powierzchni osadu (por. Meyer, 1975), a także przyczyniły się do jego szybkiej lityfikacji powodując dużą odporność sedymentu na działanie fal (por. Neumann *et al.*, 1970). Osady sedymentujące w takim środowisku były erodowane jedynie w przypadku silnych sztormów.

Niezbyt intensywny ruch wody, przy niskiej zawartości substancji ilastej w zawiesinie, sprzyjał tworzeniu się mumii gąbkowych; jedynie wyjątkowo tworzyły się spikulity (Fig. 4; Pl. XVI: 3).

Wyraźne ślady drażeń w mumiach gąbek z zachowaną skorupką skałotocza, lub wypełnione sedymentami wewnętrznymi (Pl. XII) wskazują na istnienie sztywnego szkieletu w czasie wzrostu biohermy (framestone; por. Embry & Klovan, 1972).

Znacznie większe zatarcie szczegółów wewnętrznej budowy gąbek w ich dolnych częściach świadczy o dużej szybkości i natężeniu procesów wczesnej diagenety zachodzących przed całkowitym zasypianiem osadem (por. Palmer & Fürsich, 1981).

Obecność osadów uziarnionych frakcjonalnie dowodzi istnienia deniwelacji dna zbiornika sedymentacyjnego (por. Marcinowski, 1970). Powstanie elewacji na dnie zbiornika było związane z rozwojem sinicowo-gąbkowych budowli o sztywnym szkielecie. Zachodzące niekiedy intensywne ruchy wody powodowały ich częściowe niszczenie. Materiał pochodzący z erozji był deponowany na obszarach rozległych obniżen między budowlami sinicowo-gąbkowymi.

Zarówno gąbki, jak i pozostała fauna nie dają podstaw do dokładnego określenia głębokości zbiornika. Dotychczasowe twierdzenia o sedymentacji zachodzącej w głębszej części szelfu (Dżułyński, 1952; Wieczorek, 1982) opierają się na kryteriach negatywnych, tj. braku zespołów organizmów typowych dla warunków płytkowodnych. Na płytkowodne środowisko sedymentacji wskazują natomiast pochodzące z wapieni skalistych okolic Krakowa zielenice z rodziny Dasycladaceae (Golonka & Haczewski, 1971) oraz kraby z rodziny Dromioidea i ramienionogi (Dallinidae) z wapieni uławiconych (Krobicki, 1986).

Na sedymentację w płytkim zbiorniku, którego elewacje dna mogły ulegać epizodycznym wynurzeniom wskazują także liczne pośrednie przesłanki. Chodzi tu zwłaszcza o: sedymenty wewnętrzne (Dunham, 1969; Aissaoui & Purser, 1983) i obecność blokowego cementu kalcytowego wykazującego tendencję do zwiększania wielkości kryształów ku centrum zajmowanego pola (Loucks, 1977, *fide* Peryt, 1984; Longman, 1980), występowanie cementu syntaksjalnego na płytkach szkarłupni (Waldken & Berry, 1984), zjawiska wczesnodiagenetycznej dolomityzacji (Geldsetzer, 1973; Badiozamani, 1973; Meder, 1987) i dedolomityzacji (Evamy, 1967; Sha Quingan *et al.*, 1979; Peryt, 1984; Schorr & Koch, 1985; Wirsing & Koch, 1986; Meder, 1987) oraz rozpuszczone środki ooidów (Robinson, 1967; Peryt, 1984). Brak wyraźnej porowatości oomoldycznej (Choquette & Pray, 1970) wynika przypuszczalnie z: (1) pierwotnej niewielkiej liczby ooidów związanej z brakiem odpowiednich warunków do oolityzacji na skutek szybkiej stabilizacji osadu przez dominujące w środowisku sinice; oraz (2) mikrytyzacji zoolityzowanych ziarn (Dravis, 1970; Richter, 1983) przy nieznacznym tempie sedymentacji (por. Peryt, 1984; Fig. 5).

SYLIFIKACJA I UŁAWICENIE

Z etapem wczesnej diagenety wiąże się początek procesu tworzenia się kongrecji krzemionkowych powszechnych w wapieniach uławiconych. Gąbki krzemionkowe były głównym, ale przypuszczalnie nie jedynym źródłem krzemionki.

Wydaje się, że horyzonty krzemieni utworzyły się w wapieniach uławiconych na słabo zaznaczonych, pierwotnych powierzchniach stratyfikacji, czyli tam, gdzie następowało lokalne, horyzontalne podwyższenie zawartości substancji ilastej. Część z tych powierzchni kilka milionów lat po depozycji i pod nadkładem 100–150 m (por. Ricken, 1985) przekształciła się w powierzchnie uławicenia; część zaś została zabliźniona przemieszczanym wewnątrz sedymen-

tu węglanem wapnia. Jedynym śladem istnienia tych powierzchni są obecnie postdiagenetyczne, śródlawicowe horyzonty krzemieni.

Niewielka ilość krzemionki, o niejasnej genezie, która nie uległa koncentracji w krzemieniach, występuje w wapieniach w postaci drobnych skupień (Pl. XIV: 1; Pl. XV: 2). Skupienia te mogły stanowić jedno ze źródeł krzemionki dla epigenetycznych utworów krzemionkowych występujących w stropie oksfordu, w rejonie Krakowa (Matyszkiewicz, 1987).

Na diagenetyczną, a nie sedymentacyjną genezę uławicenia wskazuje obecność w strefie przejściowej warstewek gruzłów, w których obserwuje się fragmenty gąbek przecięte przez granice gruzłów. Wynika stąd, że warstewki gruzłów stanowiące kontynuację fug międzylawicowych nie mają charakteru zlepieńca czy brekcji.

Uławicenie jest, jak się wydaje, zatem efektem, zachodzącej w warunkach pogrzebienia, diagenetycznej redystrybucji węglanu wapnia wewnątrz osadu. W wyniku tej redystrybucji część z licznych, niewyraźnych, synsedymentacyjnych powierzchni stratyfikacji została przy udziale procesów rozpuszczania, kompaktacji i wietrzenia przekształcona w powierzchnie uławicenia, a część zredukowana przez cementację (por. Ricken, 1985; Simpson, 1985).

Brak regularnego uławicenia w wapieniach skalistych jest oczywistym następstwem ich struktury wewnętrznej. Stosunkowo szybka lityfikacja biohermy powodowała, że w stosunku do wolniej lityfikowanego, otaczającego ją sedymentu zachowywała się ona jak ciało sztywne (por. Schorr & Koch, 1985). Efektem tego jest obserwowany wzrost miąższości „ławic” w kierunku biohermy.

EXPLANATIONS OF PLATES

Plate I

Exposure in Piekary near Tyniec. On the right bedded limestone with cherts (*A*) laterally passing to massive limestone without bedding and cherts (*C*). In the transitional zone (*B*) the cherts disappear, bedding planes become less distinct and pass to nodular horizons. The bedding is again distinct in the upper left on the photo and is accompanied by the appearance of cherts in parallel horizons

Plate II

- 1 — Bedded limestone with cherts. Siliceous sponges (*marked with black paint*) in life positions and overturned
- 2 — Transitional zone. Limestone is locally nodular (*in lower part of photo*). The limestone above has a smooth surface with sponges marked in black

Plate III

- 1 — Transitional zone. Nodular horizon in prolongation of bedding joint. The black circle is 5 cm in diameter

- 2 — Sponge fragments passing across nodule boundaries (*arrows*). Transitional zone; polished section

Plate IV

- 1 — Biolithite with calcified siliceous sponges (*sp*) and cyanobacterial crusts on its upper surfaces. Structural details are obliterated more in the lower parts of sponges. Massive limestone
- 2 — Siliceous sponge *Lychniscosa*. The cross-shaped calcified spicules are open. Bedded limestone
- 3 — Siliceous sponge *Hexactinosa*. The cross-shaped calcified spicules are filled. Massive limestone
- 4 — Calcareous sponge. Massive limestone
- 5 — Calcareous sponge. Bedded limestone

Plate V

- 1 — Numerous agglutinated foraminifers cf. *Tolypammina* sp. in canals of calcified siliceous sponge. Massive limestone
- 2 — Agglutinated foraminifer cf. *Rheophax* sp. Massive limestone
- 3 — Foraminifer cf. *Bullopore* sp. Calcified spicules of siliceous sponge are visible. Transitional zone
- 4 — Foraminifer cf. *Ammobaculites* sp. Transitional zone
- 5 — Foraminifer cf. *Trocholina* sp. Transitional zone
- 6 — Local surface of sedimentary discontinuity of cryptohardground type, encrusted with numerous foraminifers. Bedded limestone
- 7 — Foraminifer cf. *Lenticulina* sp. Transitional zone
- 8 — Foraminifer from the family Nodosariidae; cf. *Lenticulina* sp. Massive limestone
- 9 — Foraminifer of the family Nodosariidae. Bedded limestone
- 10 — Foraminifer of the family Nodosariidae. Massive limestone

Plate VI

- 1 — Fragment of brachiopod shell with attached serpulæ (*arrow*). Massive limestone
- 2 — Fragment of brachiopod shell with cyanobacterial crust (*arrow*). Bedded limestone
- 3 — Cross-section of brachiopod shell filled with peloids of fecal origin. Bedded limestone
- 4 — Fragment of brachiopod shell with spines. Massive limestone
- 5 — Nearly spherical tuberoid. Bedded limestone
- 6 — Irregular tuberoid. Fragment of calcified siliceous sponge visible within it. Transitional zone
- 7 — Polychaete cf. *Terebella lapilloides*; cross-section. Transitional zone
- 8 — Polychaete cf. *Terebella lapilloides*; cross-section. Massive limestone

Plate VII

- 1 — Fragment of bryozoan zoarium in biopelmicrite. Bedded limestone
- 2 — Fragment of bryozoan zoarium as an oncoid nucleus. Cyanobacterial envelopes of cortex encrusted with nubecularians (*arrows*). Massive limestone
- 3 — Serpula as an oncoid nucleus. Massive limestone
- 4 — Fragment of bryozoan zoarium with a distinct boring (*arrow*). Bedded limestone
- 5 — Fragment of bryozoan zoarium in biopelmicrite. Bedded limestone
- 6 — Bryozoans (*b*) growing on siliceous lithistidean sponge (*sp*). Transitional zone
- 7 — Bryozoans (*b*) growing on lower part of siliceous sponge (*sp*) whose internal structure is strongly obliterated in their lower part. Transitional zone

Plate VIII

- 1 — Crinoid in biopelmicrite. Bedded limestone
- 2 — Fragment of an echinoderm plate. Bedded limestone
- 3 — Crinoid in biopelmicrite. Bedded limestone
- 4 — Echinoderm plate with micritic envelope. Bedded limestone
- 5 — Echinoderm plate with syntaxial calcite overgrowth (*arrows*). Massive limestone
- 6 — Holothurian sclerite. Bedded limestone
- 7 — Echinoderm plate with syntaxial calcite overgrowth around it (*arrows*). Massive limestone
- 8 — Echinoderm plate with syntaxial calcite overgrowth (*arrows*). Transitional zone
- 9 — Planktonic crinoid cf. *Saccocoma* sp. Transitional zone
- 10 — Planktonic crinoid cf. *Saccocoma* sp. as an oncoid nucleus. Transitional zone

Plate IX

- 1 — Composite oncoid (pseudooncoid) encrusted with numerous nubecularians. Massive limestone
- 2 — Composite oncoid encrusted with numerous foraminifers, mainly nubecularians. Massive limestone
- 3 — Composite oncoid encrusted with nubecularians. Transitional zone
- 4 — Composite oncoid (*o*) and tuberoid (*t*) in biopelmicrite. Transitional zone
- 5 — Composite oncoid cf. *Tubiphytes* sp. (? cross-section). Filamentous algal crust on the right. Transitional zone
- 6 — Enlarged fragment of fibrous algal crust shown in Pl. IX: 5. Transitional zone

Plate X

- 1 — Microoncoid in pelsparite. Note the small thickness of the cortex relative to nucleus size. Massive limestone
- 2 — Fragment of stromatolite. The lighter laminae have sparitic matrix and include numerous peloids with microoncooids and rare small ooids. The darker micritic laminae include almost exclusively smaller peloids. Massive limestone
- 3 — Microoncooids (? micritized ooids) in pelsparite. Massive limestone
- 4 — Oncoids in sparite. On oncoid nucleus is probably a dasycladacean alga (*arrow*). Bedded limestone
- 5 — Ooids in sparite. The ooid with a dissolved centre is marked with an arrow. Other ooids are micritized. Transitional zone
- 6 — Form resembling an ooid with excentric envelopes. Transitional zone

Plate XI

- 1 — Surface of sedimentary discontinuity covered with cyanobacterial crust (*arrows*). The overlying sediment (oncobiosparite and oncobiopelsparite with intraclasts) indicates increased energy of water in the sedimentary environment. Sparite includes numerous tuberooids, oncoids, ooids, large lithoclasts and bioclasts. The sediment beneath the surface is biopelmicrite. Negative print. Bedded limestone
- 2 — Surfaces of sedimentary discontinuity of soft-ground type (*arrows*). The relief of the surface indicates violent erosion and rapid burial by sediment forming in an environment of increased water energy (oncobiosparite with tuberooids). Negative print. Bedded limestone

Plate XII

- 1 — Calcified siliceous sponge with void of unknown origin. Interior of void is occupied by a stromatolite (*s*). The accumulation of peloids in its upper part is probably internal sediment of micropelletal packstone/grainstone type (*arrow*). Massive limestone

- 2 — Boring in sponge with preserved borer shell (*arrow*). Massive limestone
- 3 — Boring in sponge filled with internal sediment of micropelletal packstone/grainstone type (*arrow*). Massive limestone
- 4 — Boring in sponge filled with internal sediment of micropelletal packstone/grainstone type. The boring is situated in the lower part of the calcified siliceous sponge overgrown by bryozoans on the downside. The internal sediment is overlain by equant calcite (*arrow*) whose crystals are greater towards the centre of the occupied field. Massive limestone
- 5 — Boring in sponge with internal sediment of micropelletal packstone/grainstone type (*arrow*). Massive limestone

Plate XIII

- 1 — Biolithite. A void filled with internal sediment (*is*) is visible in the calcified siliceous sponge with traces of early diagenetic dolomitization. On the right an echinoderm plate with syntaxial calcite overgrowth (*arrow*). The black arrow points upwards. Negative print. Massive limestone
- 2 — Internal sediment of vadose silt type consisting of fine calcite crystals. The top of the vadose silt truncated by (?) erosion is covered with biopelmicrite. Equant calcite with crystal size increasing towards the centre of the occupied field is present within the internal sediment and directly beneath. On the right, early diagenetic dolomite rhomboedres (*arrows*). Enlarged fragment of Pl. XIII: 1. Massive limestone
- 3 — Internal sediment of vadose silt type. Equant calcite is present directly beneath the internal sediment and within it (*arrows*). Enlarged fragment of Pl. XIII: 2. Massive limestone

Plate XIV

- 1 — Biolithite. Visible sedimentary sequences: siliceous sponge (*sp*) — cyanobacterial crust (*c*) — stromatolite (*s*) — biopelmicrite (*m*). The lower parts of sponges are overgrown with bryozoans (*b*) and other epifauna. The white irregular patches within sponges are silica concentrations. Massive limestone
 - 2 — Biolithite. Numerous surfaces of sedimentary discontinuity of cryptohardground type (*I–IV*), with occasional tuberoids (*t*) and bioclasts on them. An echinoderm spine on the left of the tuberoid. Outer surfaces of calcified siliceous sponges (*sp*) are commonly separated by
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Plate XV

- 1 — Calcified rhomboedres after dolomite. Vadose silt in lower parts of the rhomboedres (*arrow*). Bedded limestone without cherts. Kostrze
- 2 — Fine concentrations of silica (*q*) preserved in limestone. They could be one of the sources of silica for epigenetic silicifications. Transitional zone
- 3 — Intraclasts. Micropelletal packstone/grainstone (*arrow*) is present in intergranular space. Massive limestone
- 4 — Void in siliceous sponge. Two generations of cements filling the void. Equant calcite with crystal size increasing towards the centre of the occupied field in the lower part, and late diagenetic cement in the upper part. Traces of early diagenetic dolomitization (*arrows*) are visible around the void in the form of hipidiomorphic dolomite crystals with preserved relicts of the original structure of the limestone. Massive limestone

Plate XVI

- 1 — Oncobiomicroite (sparite) with tuberoids. Numerous simple and composite oncoids. Negative print. Massive limestone
- 2 — Numerous tuberoids of nearly spherical form. Bedded limestone
- 3 — Spiculite. Bedded limestone

