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Development of the Turonian/Coniacian hardground boundary in the Cracow Swell area (Wielkanoc quarry, Southern Poland)

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During the Turonian and Coniacian, up to the early Santonian, the present-day Polish Jura Chain composed a positive submarine palaeotectonic feature referred to as the Cracow Swell, separating the deeper Opole Trough to the SW from the Danish-Polish Trough to the NE. At present the Turonian and Santonian deposits at the margin of the Polish Jura Chain and the Miechów Trough are fragmentarily preserved. They are characterised by numerous stratigraphic hiatuses and the occurrence of many unconformity surfaces. One of the most spectacular unconformities is a hardground at the Turonian/Coniacian boundary described herein from the vicinity of Wielkanoc. Its development took place in several stages. Three main stages can be distinguished with a composite middle stage. In the first stage during the early late Turonian, a gradual drowning of the carbonate Cracow Swell took place followed by eutrophication of the environment. The second stage from the latest Turonian to the earliest Coniacian was linked with a crisis of a carbonate sedimentation leading to its cessation. A firmground with *Thalassinoides* traces was formed, followed by a hardground with bivalve borings and *?Trypanites*. Carbonate-clastic sedimentation recommenced at least twice (with quartz arenites), followed by rejuventation of burrows and/or borings, lithification of the sediment, glauconitization and phosphatization, as well as the development of microbial mats undergoing early phosphatization. This led to the formation of phosphatic stromatolites. In consequence a composite hardground was formed. The third stage took place in the late early Coniacian. Carbonate-clastic sedimentation resumed. Deposits, developed as carbonate arenites with quartz and glauconite admixtures (non-phosphatized), filled the last generation of the rejuvenated burrows and finally covered the hardground.

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Key words: Cracow Swell, Turonian/Coniacian, phosphatic stromatolites, composite hardground.

INTRODUCTION

Turonian strata from the vicinity of Wolbrom were described in the 19th century (Zaręczny, 1878) and were often discussed in later papers (Sujkowski, 1926, 1934; Kowalski, 1948; Marcinowski, 1974; Walaszczyk, 1992; Olszewska-Nejbert, in prep.). Coniacian deposits from this area were documented for the first time by Walaszczyk (1992) based on inoceramid faunas. From the Wielkanoc quarry, Walaszczyk (1992) described a faunal assemblage indicating the *Cremnoceramus crassus* Zone, which represents in the most recent biostratigraphic schemes the uppermost zone of the lower Coniacian (Walaszczyk and Wood, 1998). Walaszczyk (1992), however, did not trace the succession of strata at the Turonian/Coniacian boundary at Wielkanoc.

During several field trips in 1993, 1999–2000 and 2002, I carried out detailed studies in the Wielkanoc quarry. While drawing a detailed lithostratigraphic column in 1993, I noticed an interesting bed rich in the echinoid *Conulus subrotundus* Mantell within the Turonian strata, which is described in a separate paper (Olszewska-Nejbert, in prep.). The upper part of the succession was not available for further studies at that time. Fortunately, in 1999 it became exposed. In pelitic limestones of the *Inoceramus costellatus* Zone (lower upper Turonian) a hardground is developed, which is overlain by calcarenites with admixtures of quartz and glauconite from the *Cremnoceramus crassus* Zone (upper lower Coniacian). Detailed observations carried out in 2002 confirmed the presence of this hardground at Wielkanoc. The sedimentary character of the Turonian-/Coniacian boundary, developed as a hardground, is documented in this paper for the first time.

GEOLOGICAL SETTING

Wielkanoc is a large abandoned quarry in the SW part of Wielkanoc village located *ca*. 31 km northwards from the cen-

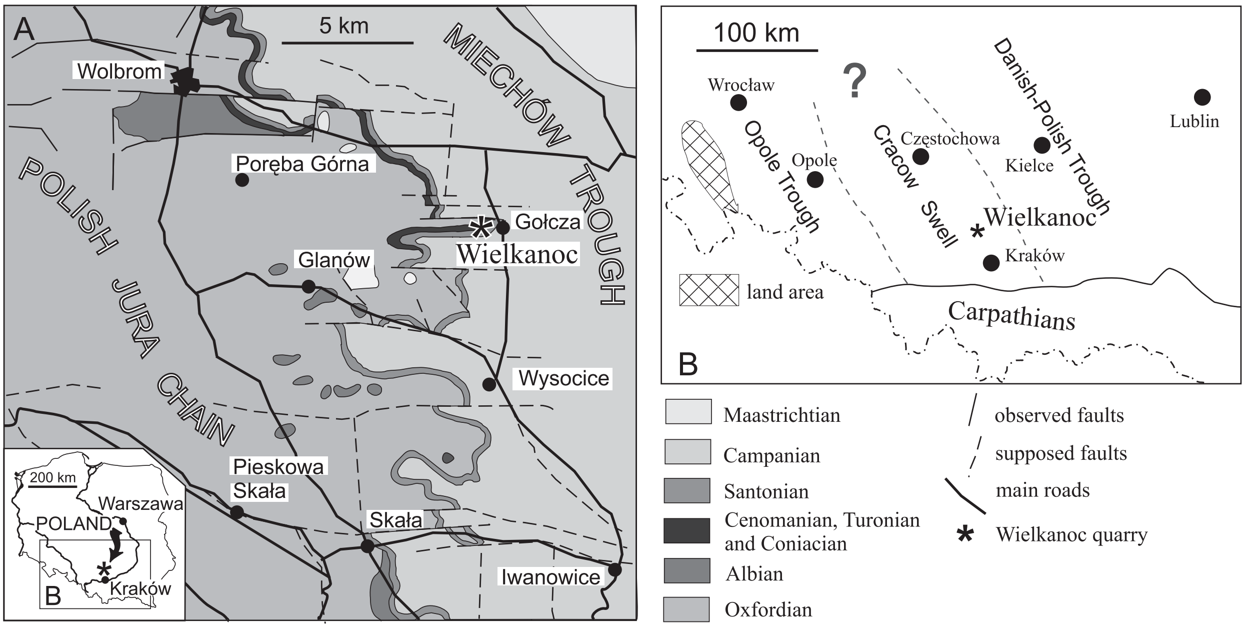

Fig. 1. A — geological sketch-map of the study area with location of Wielkanoc quarry (after Kaziuk, 1978; modified and simplified); B — palaeogeography of the south-west of Poland (without Carpathians) in the late Turonian and Coniacian (after Jaskowiak-Schoeneichowa and Krassowska, 1988; Walaszczyk, 1992; simplified and modified)

tre of Cracow (Fig. 1A). The Cretaceous deposits of this region are linked with the eastern margin of the Polish Jura Chain, situated in the central part of it, and border the Miechów Trough. Exposures of Cenomanian, Turonian and Coniacian deposits, where present, are narrow and generally strike NNW–SSE (Fig. 1A). Turonian deposits, commonly thin, are common in the Polish Jura at the boundary with the Miechów Trough. They either rest upon quartz conglomerates of Cenomanian age, or much more commonly directly onlap an abrasion surface topping Oxfordian limestones (Zaręczny, 1878; Smoleński, 1906; Sujkowski, 1926, 1934; Panow, 1934; Kowalski, 1948; Alexandrowicz, 1954; Barczyk, 1956; Bukowy, 1956; Rutkowski, 1965; Marcinowski, 1974; Marcinowski and Radwański, 1983, 1989; Walaszczyk, 1992; Kudrewicz and Olszewska-Nejbert, 1997). A separate issue is the presence of Coniacian deposits in the Polish Jura Chain. Walaszczyk (1992) for the first time recognised the presence of Coniacian deposits at Wielkanoc based on an inoceramid fauna which documents the *Cremnoceramus crassus* Zone from the upper part of the lower Coniacian (Walaszczyk and Wood, 1998). Coniacian deposits were noted at that time in the northern wall of the quarry in the form of breccias infilling erosional depressions in the Jurassic limestone. Revision of inoceramid faunas from Przychody, Solca and Zalesice, exposures located north-westwards from Wielkanoc (Walaszczyk, 1992), allowed us to consider as Coniacian those deposits which were earlier dated by Marcinowski (1974) as the lower part of the upper Turonian.

The Cracow Swell is a palaeogeographic unit representing a part of the present-day Great Monocline (Walaszczyk, 1992). The Cracow Swell was an elevated positive morphological unit from the early Turonian to the late Santonian. At that time it was a submarine area between the deeper basins of the Opole Trough to the south-west and the Danish-Polish Trough to the north-east (Fig. 1B). It was also a marginal part of the large epicontinental Late Cretaceous basin to the south (Jaskowiak-Schoeneichowa and Krassowska, 1988; Leszczyński, 1997).

MATERIALS AND METHODS OF STUDY

Several samples were taken from the hardground and associated deposits. Polished thin sections of the samples were prepared: one from pelitic limestone underlying the hardground, four from the hardground zone, three from the sandy glauconitic limestone overlying the hardground. Five polished slabs were made from the samples of the hardground zone, two of which are illustrated in this paper. The ternary graph of Zuffa (1980) was used to plot the modal data obtained by point counting. The 14 points on the ternary graph were counted from photomicrographs taken from 5 thin sections using a *Nikon* microscope equipped with the *Lucia Software*. One particular point on the graph is based on a total of 500 points counted within a counting distance of 0.1 mm.

LITHOLOGY AND STRATIGRAPHY OF THE HARDGROUND ZONE

A detailed succession of Cretaceous deposits was examined in the southern wall of the quarry. Turonian deposits reach here 10 m in thickness and are developed as sandy, sandy-organodetrital and organodetrital limestones as well as pelitic limestones (Olszewska-Nejbert, in prep.).

The uppermost bed of the Turonian is developed as a pelitic limestone, white or white-grey in colour, rather compact (Fig. 2). The thickness of this bed reaches 0.6 m. Stratigraphically the limestone represents the undivided *Inoceramus lamarcki* and *I. costellatus* Zones, that is the upper Middle and lower upper Turonian, respectively (Walaszczyk, 1992). A hardground is developed at the top of the pelitic limestones (Fig. 3). *Thalassinoides* burrows, *?Trypanites* and *Gastrochaenolites* borings can be observed in the pelitic limestone (Fig. 4). *Thalassinoides* burrows reach down to *ca*. 15–20 cm below the topmost surface into the pelitic limestone.

The hardground forms a distinct lithological contrast. Above it occur sandy-glauconitic calcarenites, green in colour and *ca*. 0.5–0.6 m thick (Figs. 2 and 3). This deposit fills also the borings and burrows within the hardground (Fig. 4), reaching down several to over a dozen cm into the pelitic limestone. The sandy-glauconitic calcarenite stratigraphically belongs to the *Cremnoceramus crassus* Zone (Walaszczyk, 1992), corresponding to the upper lower Coniacian (Walaszczyk and Wood, 1998). The biostratigraphic hiatus linked with the hardground at the Turonian/Coniacian boundary encompasses therefore the uppermost Turonian and lowermost Coniacian.

Furthermore, the hardground is accompanied by phosphatized fragments of the sandy-glauconitic calcarenite (Fig. 4D) and phosphatic stromatolites at the boundary between the pelitic limestone and the sandy-glauconitic calcarenite (Figs. 4 and 5). Phosphate stromatolites in Cretaceous deposits, not encountered previously at Wielkanoc, are known from many other localities within the Polish Jura Chain (Golonka and Rajchel, 1972; Marcinowski and Szulczewski, 1972; Marcinowski, 1974; Walaszczyk, 1992; Krajewski *et al*., 2000). At Wielkanoc the phosphatic stromatolites occur as discontinuous thin polygonal beds, maximally reaching 2–3 mm thick, or as almost smooth stromatolite layers encrusting the burrow walls; in the latter case their thickness does not exceed 1 mm. Thicker stromatolites, maximally up to 1 cm thick, are preserved only within larger oval borings (Fig. 4). They are black and possess a distinct lamination (Fig. 4C), and in most cases grown downwards from the top of the boring. Two types

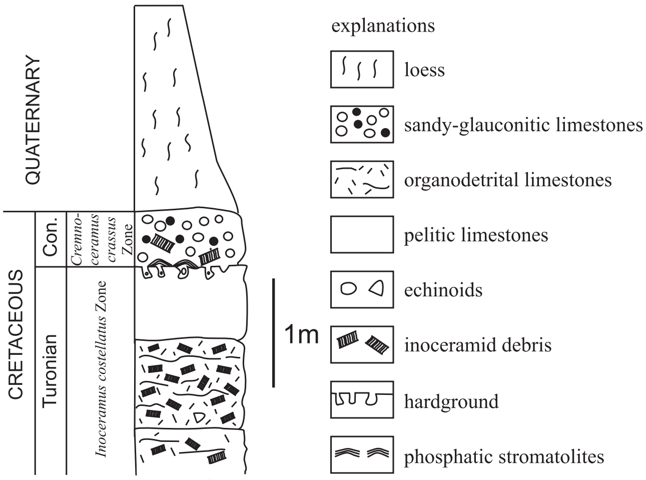

Fig. 2. Detailed lithological and stratigraphic column of the Turonian/Coniacian boundary zone of the Wielkanoc section exposed in the southern wall of the Wielkanoc quarry

of polygons formed by the stromatolite domes, higher and lower ones, can be observed on the stromatolite layer surface. Higher stromatolite domes are distinctly truncated, whereas the lower ones are completely preserved (Fig. 5).

Quaternary loess overlies the Coniacian deposits in the southern wall of the quarry (Figs. 2 and 3).

MICROFACIES ANALYSIS OF THE HARDGROUND ZONE

PELITIC LIMESTONE — LOWER UPPER TURONIAN

The lower upper Turonian deposits are developed as a foraminiferal or foraminiferal-calcisphere wackestone/packstone microfacies (Fig. 6). This microfacies will be referred to

Fig. 3. General view of the upper part of the southern wall in Wielkanoc quarry

OL — organodetrital limestone, Turonian; PL — pelitic limestone, Turonian; SGL — sandy-glauconitic limestone, Coniacian; LS — loess, Quaternary; author as a scale

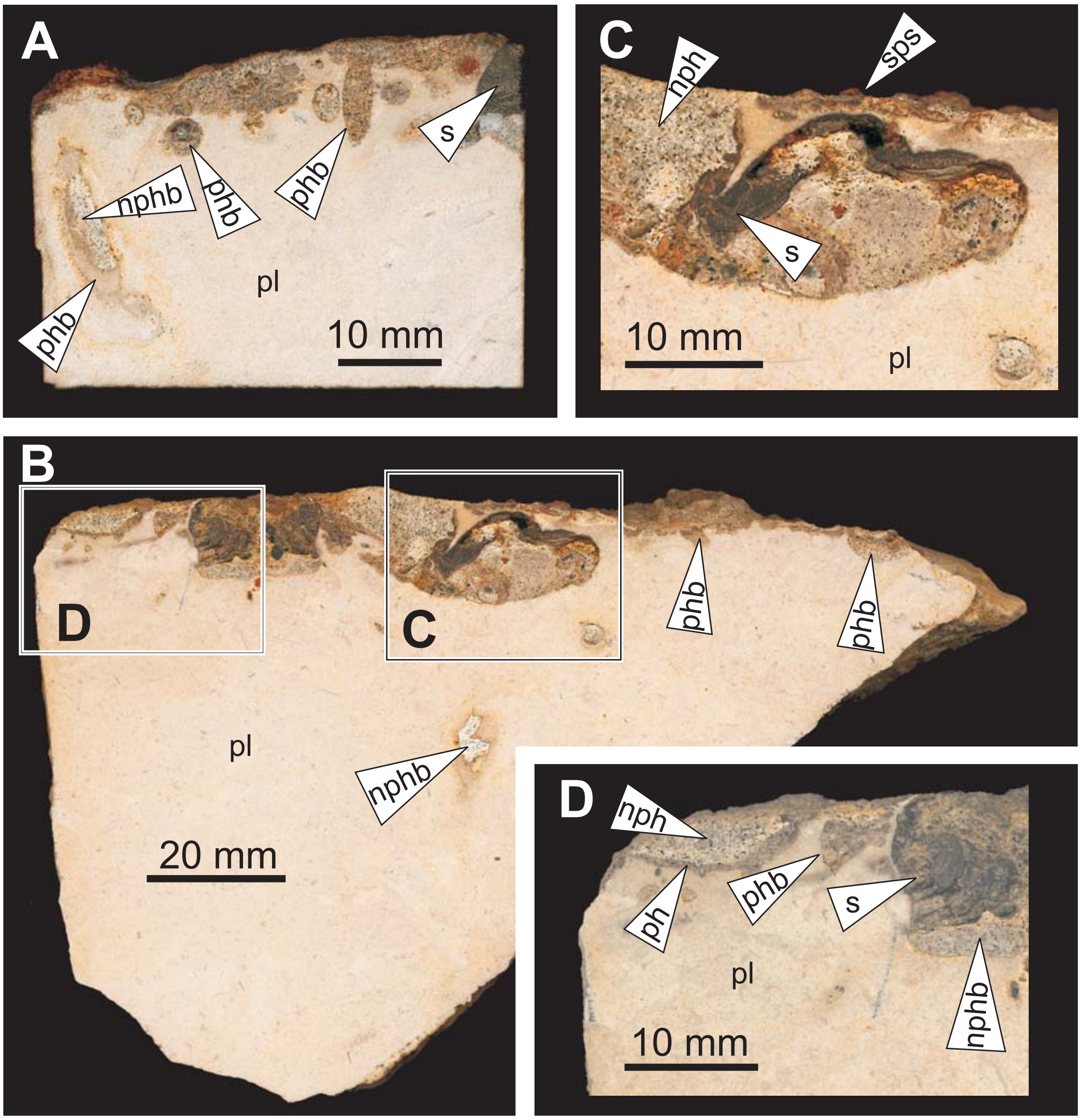

Fig. 4. Photographs of polished slabs of the Turonian–Coniacian hardground from Wielkanoc quarry

A, B — details of the hardground with burrows and borings; C, D — close-up views of the hardground fragments shown in Figure B; C — black phosphatic stromatolite growing downwards from the top of the borings; D — phosphatized layer of sandy-glauconitic limestone with underlying pelitic limestone of Turonian age and overlying non-phosphatized sandy glauconitic limestone of Coniacian age; pl — pelitic limestone, ph — phosphatized layer of sandy-glauconitic limestone, nph — non-phosphatized sandy-glauconitic limestone, s — black phosphatic stromatolite developed inside borings, phb — phosphatized sandy-glauconitic limestone infilling borings or burrows, nphb — non-phosphatized sandy-glauconite limestone infilling the rejuvenated burrows or borings, sps — small polygonal phosphatic stromatolite

as FCW/P. Additionally, fragments of echinoids and inoceramids occur in subordinate quantities, and bryozoan fragments are noted sporadically. Foraminifers observed in thin sections belong to the planktonic group. Benthic foraminifers are very rare. Most elements, i.e. single foraminifer chambers and calcispheres reach dimensions smaller than 0.1 mm, and so the limestone may be described macroscopically as pelitic. Fragments larger than 0.1 mm, that is complete foraminifers, inoceramid and echinoid fragments, are infrequent.

PELITIC LIMESTONE/SANDY-GLAUCONITE CALCARENITE BOUNDARY — LOWER UPPER TURONIAN/UPPER LOWER CONIACIAN BOUNDARY

Deposits at the pelitic limestone/sandy-glauconite calcarenite boundary are variable with reference to their microfacies. The following microfacies can be distinguished in this interval:

— limestones of the FCW/P microfacies are overlain by a thin, discontinuous and phosphatized limestone bed developed as the foraminiferal microfacies with a distinct admixture of

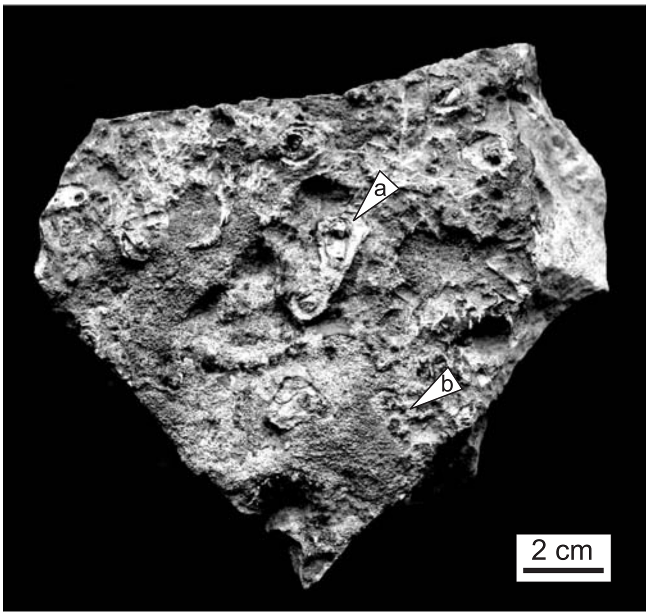

Fig. 5. Top view of a stromatolitic layer

a — higher polygonal stromatolites clearly truncated, b —lower polygonal stromatolites preserved

quartz and glauconite (PhFW+QG) (Fig. 7), macroscopically visible as a darker grey bed (Fig. 4D), and in some cases infilling entirely the burrows or borings (Fig. 4A);

— micro-columnar phosphatic stromatolite may be present, forming a discontinuous polygonal bed (Fig. 7), lying directly on deposits developed in microfacies FCP/W or PhFW+QG;

— almost smooth phosphate stromatolite covers are present on the walls of some burrows (Figs. 8 and 9); these covers developed directly on the limestone developed in microfacies FCW/P;

— burrows can be impregnated by authigenic glauconite; three generations of burrows are visible, of which the first two are phosphatized (Fig. 10);

— burrows and borings, as well as spaces between the stromatolite columns, may be filled by a foraminiferal-inoceramid packstone with admixture of quartz and glauconite (Fig. 11, microfacies FIP+QG); in some cases deposits of this microfacies lie directly on the limestones developed as microfacies FCW/P; microfacies FIP+QG is not phosphatized and belongs to the Coniacian (description below).

SANDY-GLAUCONITE DETRITAL LIMESTONE — UPPER LOWER CONIACIAN

Coniacian deposits are developed as the foraminiferal-inoceramid wackestone microfacies (FIP+QG) with a considerable admixture of quartz and glauconite (Fig. 12). Particles noted in much smaller quantities include calcispheres, echinoid fragments and sporadical phosphatic pellets, as well as crushed fragments of phosphatic stromatolites. Due to the large admixture of quartz and glauconite, point counting of the thin sections was carried out, as it was uncertain whether the analysed rock should be classified as limestone. The content of the grain framework was plotted on the diagram of Zuffa (1980). In this, most of points cluster in the carbonate

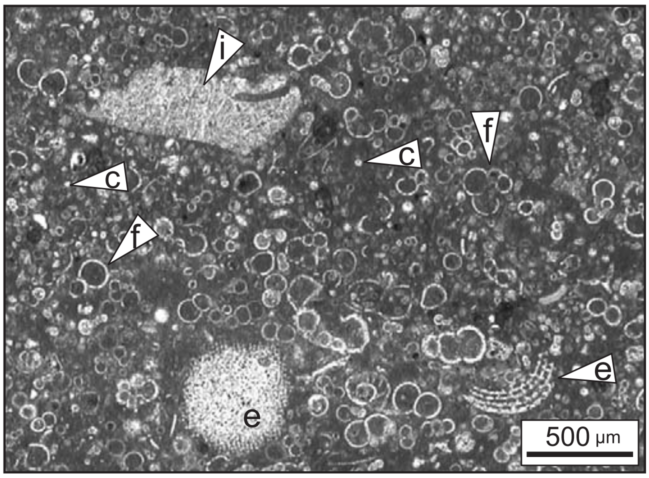

Fig. 6. Foraminiferal-calcisphere wackestone/packstone microfacies of the pelitic limestone, upper Turonian

f — foraminifers, c — calcispheres, e — echinoderms, i — inoceramid debris

intrarenite field (calcarenite according to Folk, 1959), and only some are located in the hybrid arenite field. Therefore, the rock can be classified as a calcarenite with a considerable content of quartz and glauconite (Fig. 13). Cross-sections through glauconite grains are rather regular. The grains are neither deformed nor crushed. The presence of small contractional fractures, sharp but not very deep, within the grains points to the authigenic origin of the glauconite (Amorosi, 1997).

RECONSTRUCTION OF THE HARDGROUND DEVELOPMENT

Three distinct stages, with a composite middle stage, can be distinguished in the development of the hardground at the Turonian/Coniacian boundary in Wielkanoc (Fig. 14).

FIRST STAGE — *INOCERAMUS COSTELLATUS* CHRON — EARLY LATE TURONIAN (FIG. 14A)

In the terminal part of the early late Turonian, slow pelagic sedimentation took place, dominated by a planktonic fauna, such as planktonic foraminifers and calcispheres, together with carbonate mud. The abundance of the planktonic fauna indicates an increase of organic productivity in sub-surface waters, what is one of the features of a drowning carbonate platform (Wilmsen, 2000). In the case of Wielkanoc, the Cracow Swell in this area underwent slight subsidence, resulting in a depth increase and, as a consequence, eutrophication of sub-surface waters took place. This is a soft-ground stage. Bioturbation which developed during this stage was overprinted by subsequent processes.

SECOND STAGE — LATEST TURONIAN–EARLIEST CONIACIAN (FIG. 14B–G)

During the late Turonian, the drowning of the Cracow Swell in the vicinity of Wielkanoc ceased due to the activity of Sub-Hercynian phases and/or as the result of a regression

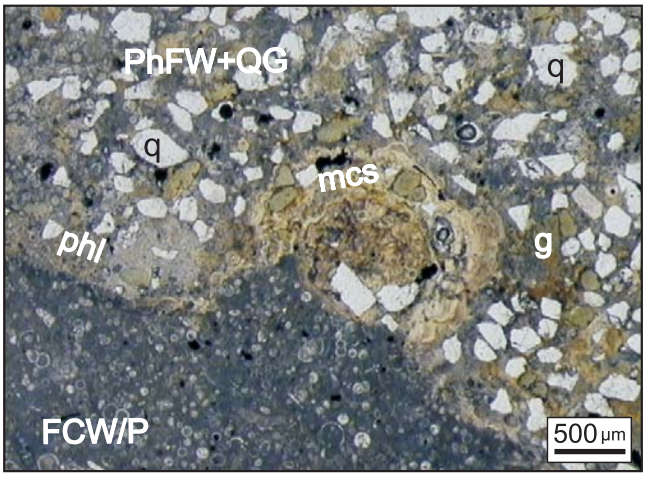

Fig. 7. Microfacies of the hardground zone. Phosphatized layer (phl) with micro-columnar phosphatic stromatolite (mcs) overlying the foraminiferal-calcisphere wackestone/packstone (FCW/P); PhFW + QG — phosphatized foraminiferal microfacies with admixture of quartz and glauconite; q — quartz, g — glauconite

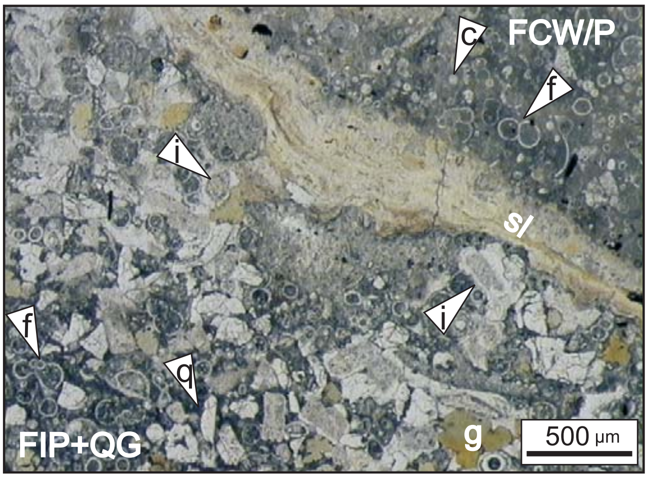

Fig. 8. Microfacies of the hardground zone. Almost smooth phosphatic stromatolite layer (sl) developed on upper wall of a burrow; FIP + QG — foraminiferal-inoceramid packstone with admixture of quartz and glauconite, upper lower Coniacian; other explanations as on Figures 6 and 7

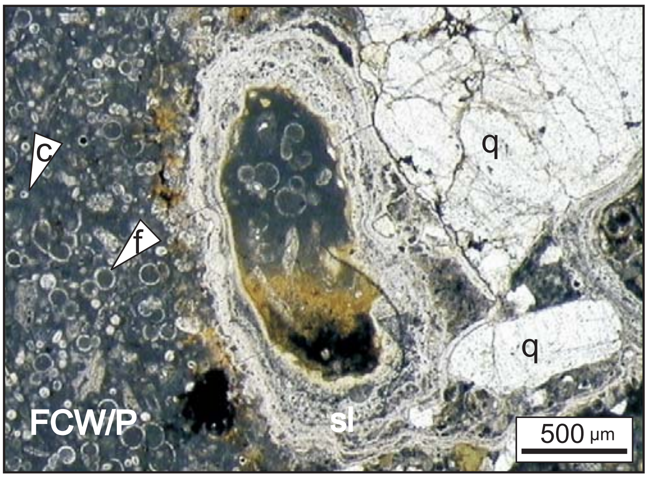

Fig. 9. Another example of the stromatolite layer (sl) coating the burrow and oncoid-like clast, oncoid-like form probably is the result of intersection of the uneven hardground surface; other explanations as on Figures 6 and 7

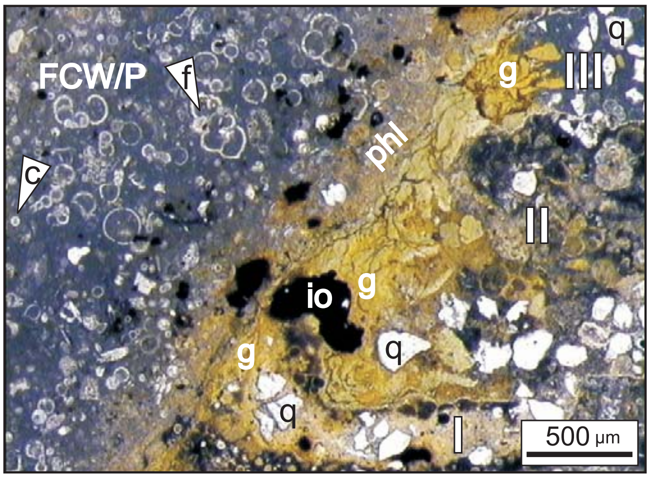

Fig. 10. Generations of burrows, glauconitization and phosphatization in the hardground zone; I–II — first and second generation of burrows with glauconitization and phosphatization; III — third rejuvenating generation of burrows, infilled with non-phosphatized deposit; g — authigenic glauconite; io — mineralisation by iron-oxides; other explanations as on Figures 6 and 7

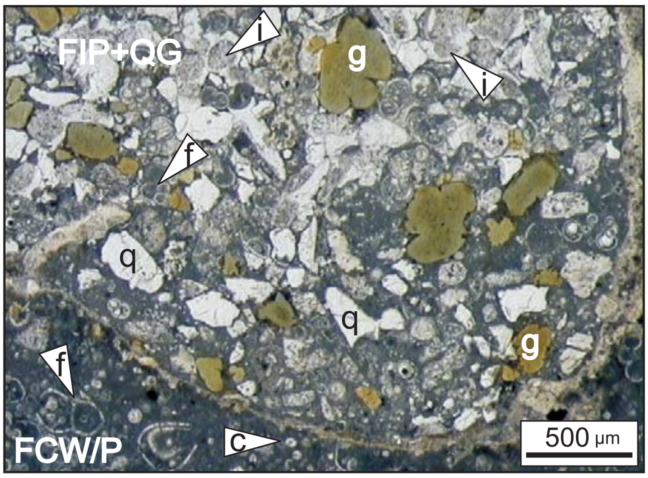

Fig. 11. Foraminiferal-inoceramid packstone with admixture of quartz and glauconite, upper lower Coniacian, infilling borings in the foraminiferal-calcisphere wackstone/packstone, upper Turonian; other explanations as on Figures 6–8

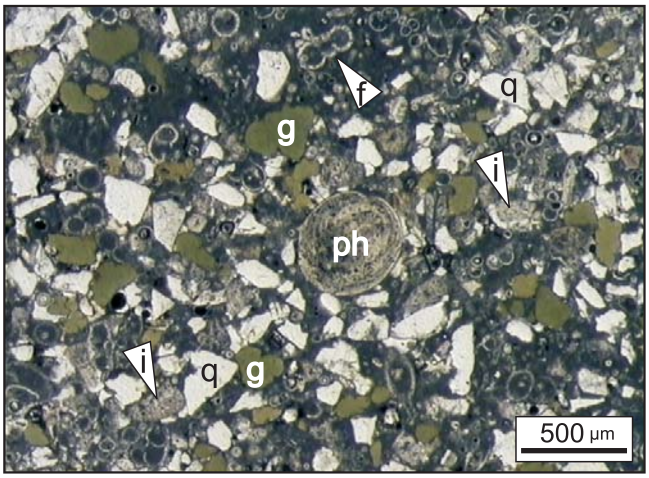

Fig. 12. Foraminiferal-inoceramid packstone with admixture of quartz and glauconite, microfacies of sandy-glauconitic limestone, upper lower Coniacian; ph — phosphate pellet; other explanations as on Figures 6 and 7

pulse, which led to a termination of carbonate sedimentation in this area. As a result, a firmground developed. The consolidated deposit was penetrated by organisms producing *Thalassinoides* traces. *Thalassinoides* is commonly linked with consolidated sediments (Bromley, 1968, 1975, 1990; Goldring and Kaźmierczak, 1974; Fürsich, 1979; Gruszczyński, 1979, 1986). An omission surface with a burrow system was formed. Burrow walls were most probably cemented faster by their dwellers (Fig. 14B). The non-cemented deposit was partly removed, and as a result an uneven sea floor was exposed (Fig. 14C). The parts of the deposit near the burrows, which were most quicky cemented, after removal of the loose material became small elevations (*cf.* Bromley, 1975, fig. 18.1). Later on, lithification of a sediment started and a hardground with a borings system developed. The big, oval borings belong to *Gastrochaenolites* ichnogenera (*cf.* Wilson and Palmer, 1988; Wilson and Taylor, 2001; Taylor and Wilson, 2003). Microbial mats of irregular shapes could develop within the burrows and borings (Fig. 14C). The mats grew downwards from the top of the burrow/boring (*cf.* also Figs. 4 and 8). The mats could also possibly grow on the hardground surface, but they were removed by erosion processes on the sea floor. Stromatolites characterized by the largest thickness of up to 1 cm are found only within the burrows or borings. During this stage, glauconitisation at the water/sediment boundary may also have taken place.

In the next stage, carbonate sedimentation recommenced, with an admixture of quartz (Fig. 14D). These deposits filled both burrows and borings. The sedimentation was very slow and/or intermittent, as shown by authigenic glauconite forming mineralised linings in some burrows (Fig. 10). The freshly deposited carbonate deposit with quartz was then colonised by burrowing organisms (Fig. 14E), as several generations of deposit penetration can be observed (*cf.* Fig. 10). Burrows/borings were emptied and then filled once again by the carbonate deposits with quartz.

The next distinct termination of sedimentation allowed colonization of the sea floor by microbial mats (Fig. 14F). It is worth noting that the mats colonized a rather variable surface. A common feature is the overgrowths of relatively high microbial domes above the burrow outlets, which were positive elements already during the firmground stage (Fig. 14C). Much lower microbial domes appear directly above the carbonate deposit with quartz. Later, phosphate was introduced into the microbial mat structure, resulting in the formation of thin layers of phosphatic stromatolite. Such accretion of phosphates within the microbial mat structure was described by Krajewski *et al.* (2000) from Turonian stromatolites of the Polish Jura Chain from areas in the vicinity of Wielkanoc. Phosphatization affected also the carbonate deposit with quartz. Although the stromatolite layer is lacking locally, phosphate penetrates the sediment giving grey-brownish zones of phosphatized rock (*cf.* Figs. 4 and 10).

The next episode included the destruction and truncation of higher stromatolite domes (Fig. 14G), whereas the lower ones were preserved (comp. Fig. 5). Truncation of stromatolite domes exhumed the previously produced burrows. These burrows were either partly empty or filled with post-hardground sediment, therefore they were once again used by burrowing

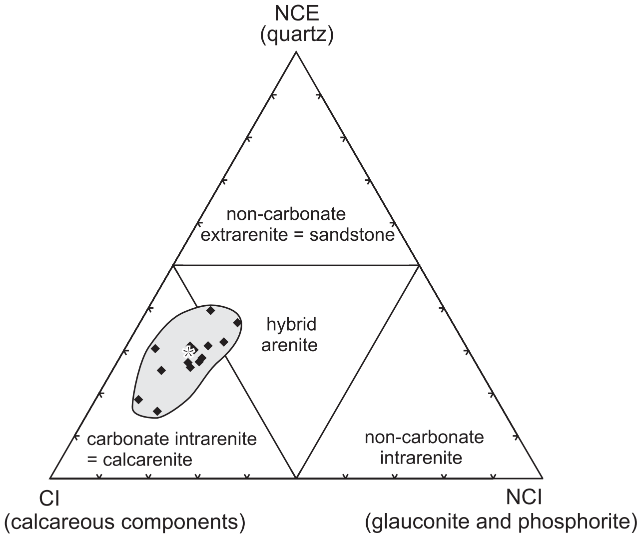

Fig. 13. Framework components of the sandy-glauconitic Coniacian limestone in the arenite classification by Zuffa (1980)

CI — carbonate intrarenite, NCI — non-carbonate intrarenite, NCE — non-carbonate extrarenite ; n = 14; * mean value

organisms (comp. Fig. 10, III generation of burrows), giving a post-omission suite of traces (Bromley, 1975).

THIRD STAGE — *CREMNOCERAMUS CRASSUS* CHRON — LATE EARLY CONIACIAN (FIG. 14H)

At the end of the early Coniacian, carbonate sedimentation recommenced with the supply of quartz in the sand fraction. Among carbonate grains, crushed fragments of inoceramids and planktonic foraminifers predominate. The non-carbonate grains, besides quartz, include authigenic glauconite in considerable quantities. These sediments fill the exhumed burrows, even down to several centimetres below the hardground surface, and are not phosphatized. The presence of authigenic glauconite indicates the slow accumulation of deposits in the *Cremnoceramus crassus* Chron.

DISCUSSION

COMPARISON WITH OTHER CRETACEOUS HARDGROUNDS

Features of the Wielkanoc hardground, such as the lack of epifauna, a lack of dwellers within the borings, the irregular and convolute surface of the hardground surface, the presence of glauconite and phosphatic mineralisation, the small content or lack of sparite cements, commonly appear in other Cretaceous hardgrounds of Europe e.g. (Pożaryski, 1960; Bathurst, 1971; Bromley, 1975; Kennedy and Garrison, 1975; Gruszczyński *et al.*, 2002). However, those are typically developed on a different type of a sediment, that is, in this case, on chalk. The Wielkanoc hardground, in turn, is associated with facies of biogenic limestones and limestones with a quartz admixture. A new feature in comparison to the cited hardgrounds from epicontinental Europe is the presence of phosphatic stromatolites, which commonly occur in Turonian deposits of the Polish Jura Chain (Golonka and

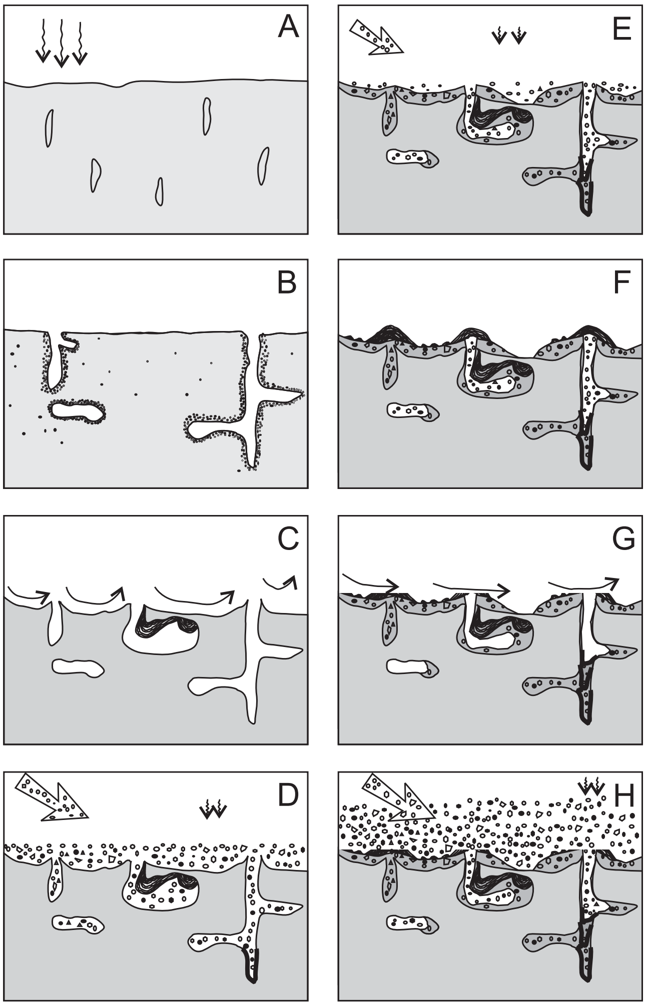

Fig. 14. Reconstruction of the composite hardground development at the Turonian/Coniacian boundary in the Wielkanoc region; detailed description in text

A — pelagic deposition; B — termination of sedimentation and formation of omission surface — firmground with *Thalassinoides* burrows, faster cementation of burrow walls by their dwellers; C — fast lithification of the consolidated deposit and removal of sub-surface loose layer of the soft sediment, formation of uneven sea floor; some cemented channel outlets form elevations on the sea-bottom, colonization by boring organisms, ?formation of microbial mats within borings and ?on the sea floor, beginning of glauconitization; D — recommencement of carbonate-clastic sedimentation, filling of burrows and borings by detrital quartz (open circles), faunal detritus (inoceramid remains and planktonic foraminifers) and carbonate mud, again termination of sedimentation, fast cementation of the deposit, glauconitization (thick black line) at the water/deposit boundary and glauconitization of pellets (black circles), ?phosphatization of micrite and microbial mats, leading to the formation of phosphatic stromatolites; E — removal of non-lithified deposit from the surface and re-colonization by boring or burrowing organisms, utilization and rejuvenation of older burrows, glauconitization (thick black line and black circles), ?phosphatization (the darker grey); F — development of polygonal microbial mats on the surface of the 2-generation hardground, rather high stromatolite domes above outlets of earlier channels, hardground covered by small stromatolite domes, fast accretion of phosphates in microbial mats and micrite, possibly only at this stage complete phosphatization of mats and micrite in one phosphatization process (the darker gray); G — destruction of upper, cemented hardground surface, truncation of higher stromatolite domes, preservation of lower domes, re-colonization by boring or burrowing organisms, rejuvenated older channels, glauconitization (thick black line); H — recommencement of carbonate-clastic sedimentation (inoceramid debris, planktonic foraminifers and carbonate mud as well as detrital quartz), filling of borings and burrows and covering of the entire hardground surface, peloid glauconitization (black circles), lack of phosphatization processes, only clasts of phosphatic stromatolites from destruction of domes and rare phosphatic peloids

Rajchel, 1972; Marcinowski and Szulczewski, 1972; Krajewski *et al*., 2000), and are also known from the Tethyan Cretaceous, where their development is always associated with a hiatus in marine sedimentation (Krajewski, 1981, 1984; Pomoni-Papaioannou, 1994).

Gruszczyński *et al*. (2002) observed a similar succession leading to formation of a composite hardground, but without episodes of microbial mat growth, for some late Turonian–Coniacian hardgrounds in Mangyshlak, western Kazakhstan. A very similar scenario of events leading to a hardground formation was outlined by Krajewski (1981) for Albian hardgrounds of the Tatra Mts. where a similar succession of a composite hardground formation and the presence of phosphatic bacterial stromatolites was associated with conditions transitional between the littoral and open oceanic zone (Krajewski, 1981). Drowning of the Cracow Swell resulted in a development of similar conditions. In the case of the Wielkanoc region, renewal of the carbonate-clastic sedimentation did not conserve the original morphology of the stromatolite layer, as in other Cretaceous stromatolites of the Polish Jura Cain (Golonka and Rajchel, 1972; Marcinowski and Szulczewski, 1972; Marcinowski, 1974; Krajewski *et al*., 2000), where the original morphology of the polygonal structures is very well preserved, and not erosionally truncated as in Wielkanoc.

MAIN FACTORS CONTROLLING THE DEVELOPMENT OF THE HARDGROUND

The development of the Turonian/Coniacian hardground boundary in the Cracow Swell corresponds to two late Turonian events: 1. early Subhercynian tectonism and 2. a brief regression within the generally transgressive Cretaceous succession.

The early late Turonian–early Coniacian Subhercynian movements, described as the early Ilsede tectonic pulse, are evidenced in northern Germany and in the Anglo-Paris Basin by angular discordances, sedimentary hiati and hardgrounds, change of facies, slumps, submarine slides and turbidites, and pull-apart nodular beds (Mortimore *et al*., 1998). The initiation of this phase corresponds approximately to the early second stage of the hardground formation in the Cracow Swell. During this phase local uplift of the Cracow Swell was possible (see also Walaszczyk, 1992).

The second important factor controlling the formation of the studied hardground could have been the late Turonian sea level fall (Haq *et al*., 1988). This global regressive event is widely documented in various places, e.g. in western Europe (Hancock, 1975,1990), western Kazakhstan (Marcinowski *et al*., 1996), and USA (Hancock and Walaszczyk, 2004). The late Turonian regressive pulse was distinguished in Central Poland by Leszczyński (2002) and it was correlated with the start of panregional tectonic cycle K4 with a regressive trend in other areas of the Polish Lowlands (Leszczyński, 1997). In the latest Turonian a sea level started to rise again in Western Europe, Kazakhstan and USA (Hancock, 1990; Marcinowski *et al*., 1996; Hancock and Walaszczyk, 2004). This transgressive event is also recorded in the Polish Lowlands (Leszczyński, 1997, 2002). The latest Turonian transgressive deposits are not documented in the Wielkanoc section. There is a stratigraphic gap in the hardground zone at Wielkanoc comprising the uppermost Turonian and lowermost Coniacian. However, it is highly probable that it was during this latest Turonian transgression that the studied thin composite hardground was formed. The next transgressive event during the *Cremnoceramus crassus* Chron (late early Coniacian) is recorded just above the hardground.

Thus, it seems that the main reason for the development of the hardground and the uppermost Turonian/lowermost Coniacian hiatus at the Wielkanoc section was some early phase of the Subhercynian tectonic movements and a local uplift in the studied area. Such interpretation is in agreement with the conclusion by Walaszczyk (1992) who claimed that Subhercynian movements were the main factor controlling Cretaceous evolution of a southwestern part of the Polish Basin. The global late Turonian sea level fall was probably only of secondary importance in a development of the studied hardground. The "crisis" of carbonate deposition was a local phenomenon developed on the submarine Cracow Swell while in the adjacent Danish-Polish Trough and Opole Trough areas the continuous opoka/marly facies were deposited (Walaszczyk, 1992).

CONCLUSIONS

North-westwards from Cracow, along the boundary between the Polish Jura Chain and the Miechów Trough, the Wielkanoc quarry is the first exposure of Coniacian deposits determined on the basis of inoceramids (Walaszczyk, 1992). During Turonian and Coniacian time, the present-day Polish Jura Chain area was a positive palaeotopographic element belonging to the Cracow Swell. The Cracow Swell separated the deeper basins of the Opole Trough in the SW from the Danish-Polish Trough to the NE (Fig. 1B). The Cracow Swell was divided into several tectonic blocks (Marcinowski, 1974; Walaszczyk, 1992). Turonian to Santonian deposits are preserved only sporadically and include many stratigraphic hiati and numerous unconformities (Walaszczyk, 1992). The hardground at the Turonian/Coniacian boundary from Wielkanoc, described in this paper for the first time, is one of the most spectacular unconformities. The stratigraphical gap connected with that harground zone comprises the latest Turonian and the earliest Coniacian.

The hardground indicates a shallowing event in the area of the Cracow Swell, however, without emergence in the section studied. The main factor governing the shallowing seems to have been a local uplift of the Cracow Swell during the early Subhercynian tectonic phase. The long-term marine non-depositional conditions resulted in the formation of the hardground surface. The eustatic fall of a sea level (regressive pulse) seems to have been a secondary factor which may have led to the shallowing in the area studied.

Three main stages can be distinguished in the development of the hardground at Wielkanoc. In the first stage during the early late Turonian, a gradual drowning of the carbonate Cracow Swell took place followed by eutrophication of the environment. The second stage, from the latest Turonian to the earliest Coniacian, was connected with a crisis in a carbonate sedimentation and its cessation. A firmground with *Thalassinoides* traces was formed, and then a hardground with *Gastrochaenolites* and *?Trypanites* borings. Carbonate-clastic sedimentation recommenced at least twice (with quartz arenites), followed by rejuvenation of burrows and/or borings, lithification of the sediment, glauconitization and phosphatization, as well as the accretion of microbial mats undergoing early phosphatization. As a consequence, a composite hardground was formed. The third stage took place in the late early Coniacian, beginning with a carbonate-clastic sedimentation. Carbonate arenites, with quartz and glauconite admixtures, filled in the last generation of the rejuvenated burrows and finally covered and buried the hardground. Phosphatization was not recorded at that stage. The time interval since the latest Turonian to the earliest Coniacian was long enough for formation of the composite hardground. The final drowning of the Cracow Swell took place in the late Santonian (Walaszczyk, 1992).

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REFERENCES

ALEXANDROWICZ S. (1954) — Turonian of the southern part of the Cracow Upland. Acta Geol. Pol., **4** (3): 361–390.

AMOROSI A. (1997) — Detecting compositional, spatial, and temporal attributes of glaucony: a tool for provenance research. Sed. Geol., **109** (1–2): 135–153.

BARCZYK W. (1956) — On the Upper Cretaceous deposits on Bonarka near Cracow. Studia Soc. Sc. Torunensis, Sectio C (Geographia-Geologia), **3** (2): 1–23.

BATHURST R. G. C. (1971) — Carbonate sediments and their diagenesis. Developments in Sedimentology, **12**. Elsevier. Amsterdam, London, New York.

BROMLEY R. G. (1968) — Burrows and boring in hardgrounds. Medd. Dansk Geol. Foren. København., **18** (2): 247–250.

BROMLEY R. G. (1975) — Trace fossils at omission surfaces. In: The study of trace fossils (ed. R. W. Frey): 399–428.SpringerVerlag. New York.

BROMLEY R. G. (1990) — Trace fossils: biology and taphonomy. Unwin Hyman. London.

BUKOWY S. (1956) — Geology of the area between Cracow and Korzkwia (in Polish with English summary). Biul. Inst. Geol., **108**: 17–82.

FOLK R. L. (1959) — Practical petrographic classification of limestones. Am. Ass. Petroleum Geologists Bull., **43** (1): 1–38.

FÜRSICH F. T. (1979) — Genesis, environments, and ecology of Jurassic hardgrounds. N. Jb. Geol. Paläont. Abh., **158** (1): 1–63.

GOLDRING R. and KAŹMIERCZAK J. (1974) — Ecological succession in intraformational hardground formation. Palaeontology, **17** (4): 949–962.

GOLONKA J. and RAJCHEL J. (1972) — Upper Cretaceous stromatolites in the vicinity of Cracow (in Polish with English summary). Kwart. Geol., **16** (3): 652–667.

GRUSZCZYŃSKI M. (1979) — Ecological succession in Upper Jurasic hardgrounds from Central Poland. Acta Palaeont. Pol. **24** (4): 429–450.

GRUSZCZYŃSKI M. (1986) — Hardgrounds and ecological succession in the light of early diagenesis (Jurasic, Holy Cross Mts., Poland). Acta Palaeont. Pol. **31** (3–4): 163–212.

GRUSZCZYŃSKI M., COLEMAN M. L., MARCINOWSKI R., WALASZCZYK I. and ISAACS M. C. P. (2002) — Palaeoenvironmental conditions of hardgrounds formations in the Late Turonian-Coniacian of Mangyshlak Mountains, Western Kazakhstan. Acta Geol. Pol. **52** (4): 423–435.

HANCOCK J. M. (1975) — The sequence of facies in the Upper Cretaceous of the Northern Europe compared with that in the western interior. In: The Cretaceous system in the Western Interior of North America (ed. W. G. E. Caldwell). Spec. Pap. Geol. Ass. Canada, **13**: 83–118.

HANCOCK J. M. (1990) — Sea-level changes in the British region during the Late Cretaceous. Proc. Geol. Ass. **100** (4): 565–594.

HANCOCK J. M. and WALASZCZYK I. (2004) — Mid-Turonian to Coniacian changes of sea-level around Dallas, Texas. Cretaceous Res. (in press).

HAQ B. W., HARDENBOL J. and VAIL P. R. (1988) — Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level changes. In: Sea-level changes: an integrated approach. (eds. C. K. Wilgus, B. S. Hastings, H. Posamentier, J. Van Wagoner, C. A. Ross and G. S. C. Kendall). Soc. Econ. Paleont. Mineral., Spec. Publ., **42**: 71–108.

JASKOWIAK-SCHOENEICHOWA M. and KRASSOWSKA A. (1988) — Palaeothickness, lithofacies and palaeotectonics of the epicontinental Upper Cretaceous in Poland (in Polish with English summary). Kwart. Geol., **32** (1):177–198.

KAZIUK H. (1978) — Mapa geologiczna Polski. B — Mapa bez utworów czwartorzędowych. Arkusz Kraków. 1: 200 000. Wyd. Geol.

KENNEDY W. J. and GARRISON R. E. (1975) — Morphology and genesis of nodular chalk and hardgrounds in the Upper Cretaceous of southern England. Sedimentology, **22** (3): 311–386.

KOWALSKI W. C. (1948) — Geological outline of Cretaceous deposits in the environs of Solca (in Polish with English summary). Biul. Inst. Geol., **51**: 5–52.

KRAJEWSKI K. P. (1981) — Pelagic stromatolites from the High-Tatric Albian limestones in the Tatra Mts. (in Polish with English summary). Kwart. Geol., **25** (4): 731–759.

KRAJEWSKI K. P. (1984) — Early diagenetic phosphate cements in the Albian condensed glauconitic limestone of the Tatra Mountains, Western Carpathians. Sedimentology, **31**(4): 443–470.

KRAJEWSKI K. P., LEŚNIAK P. M., ŁĄCKA B. and ZAWIDZKI P. (2000) — Origin of phosphatic stromatolites in the Upper Cretaceous condensed sequence of the Polish Jura Chain. Sediment. Geol., **136**(1–2): 89–112.

KUDREWICZ R. and OLSZEWSKA-NEJBERT D. (1997) — Upper Cretaceous “Echinoidlagerstätten” in the Kraków area. Ann. Soc. Geol. Pol., **67**(1): 1–12.

LESZCZYŃSKI K. (1997) — The Upper Cretaceous carbonate-dominated sequences of the Polish Lowlands. Geol. Quart., **41** (4): 521–532.

LESZCZYŃSKI K. (2002) — The Cretaceous evolution of the Ponętów-Wartkowice Zone. Pr. Państw. Inst. Geol., **176**.

MARCINOWSKI R. (1974) — The transgressive Cretaceous (Upper Albian through Turonian) deposits of the Polish Jura Chain. Acta Geol. Pol., **24**(1): 117–217.

MARCINOWSKI R. and RADWAŃSKI A. (1983) — The Mid-Cretaceous transgression onto the Central Polish Uplands (marginal part of the Central European Basin). Zitteliana, **10**: 65–95.

MARCINOWSKI R. and RADWAŃSKI A. (1989) — A biostratigraphic approach to the mid-Cretaceous transgressive sequence of the Central Polish Uplands. Cretaceous Res., **10** (2): 153–172.

MARCINOWSKI R. and SZULCZEWSKI M. (1972) — Condensed Cretaceous sequence with stromatolites in the Polish Jura Chain. Acta Geol. Pol., **22** (3): 515–538.

MARCINOWSKI R., WALASZCZYK I. and OLSZEWSKA-NEJBERT D. (1996) — Stratigraphy and regional development of the mid-Cretaceous (Upper Albian through Coniacian) of the Mangyshlak Mountains, Western Kazakhstan. Acta Geol. Pol., **46** (1–2): 1–60.

MORTIMORE R., WOOD C., POMEROL B. and ERNST G. (1998) — Dating the phases of the Subhercynian tectonic epoch: Late Cretaceous tectonics and eustatics in the Cretaceous basin of northern Germany compared with the Anglo-Paris Basin. Zbl. Geol. Palaont. **1** (11–12): 1349–1401.

OLSZEWSKA-NEJBERT D. (in prep.) — Development of the Turonian *Conulus* Lagerstätte in the Wielkanoc Quarry (southern Poland). Ann. Soc. Geol. Pol.

PANOW E. (1934) — Sur la stratigraphie du Crétacé des environs de Cracovie — note préliminaire. Ann. Soc. Geol. Pol, **10**: 577–585.

POMONI-PAPAIOANNOU F. (1994) — Palaeoenvironmental reconstruction of a condensed hardground-type depositional sequence at the Cretaceous-Tertiary contact in the Parnassus-Ghiona zone, central Greece. Sediment. Geol., **93** (1–2): 7–24.

POŻARYSKI W. (1960) — Phenomenon of hard ground in the Cretaceous section of Mielnik on the Bug river (eastern Poland) (in Polish with English summary). Kwart. Geol., **4** (1): 105–112.

RUTKOWSKI J. (1965) — Senonian in the area of Miechów, southern Poland (in Polish with English summary). Rocz. Pol. Tow. Geol., **35** (1): 3–53.

SMOLEŃSKI J. (1906) — Dolny senon na Bonarce, I Głowonogi i inoceramy. Rozprawy Wydziału Matematyczno-Przyrodniczego Akad. Um. Ser. **B**, **46**.

SUJKOWSKI Z. (1926) — Sur le Jurassique, le Crétacé et le Quaternaire des environs de Wolbrom (in Polish with French summary). Spraw. Państw. Inst. Geol., **3** (3–4): 382–434.

SUJKOWSKI Z. (1934) — Roches crétacées entre les villes Pilica et Szczekociny (in Polish with French summary). Spraw. Państw. Inst. Geol., **8** (1): 39–75.

TAYLOR P. D. and WILSON M. A. (2003) — Palaeoecology and evolution of marine hard substrate communities. Earth-Science Rev., **62**: 1–103.

WALASZCZYK I. (1992) — Turonian through Santonian deposits of the Central Polish Uplands; their facies development, inoceramid paleontology and stratigraphy. Acta Geol. Pol., **42** (1–2): 1–122.

WALASZCZYK I. and WOOD C. J. (1998) — Inoceramid and biostratigraphy at the Turonian/Coniacian boundary; based on the Salzgitter-Salder Quarry, Lower Saxony, Germany, and the Słupia Nadbrzeżna section, Central Poland. Acta Geol. Pol., **48** (4): 395–434.

WILMSEN M. (2000) — Evolution and demise of a mid-Cretaceous carbonate shelf: the Altamira Limestone (Cenomanian) of northern Cantabria (Spain). Sediment. Geol., **133** (3–4): 195–226.

WILSON M. A. and PALMER T. J. (1998) — The earliest Gastrochaenolites (early Pennsylvanian, Arkansas, USA): an Upper Paleozoic bivalve boring? J. Palaeontology, **72** (4): 769–772.

WILSON M. A. and TAYLOR P. D. (2001) — Palaeoecology of hard substrate faunas from the Cretaceous Quahlah Formation of the Oman Mountains. Palaeontology, **44** (1): 21–41.

ZARĘCZNY S. (1878) — O średnich warstwach kredowych w Krakowskim okręgu. Spraw. Kom. Fizjograf. Akademii Umiejętności, **12**: 176–246.

ZUFFA G. G. (1980) — Hybrid arenites; their composition and classification. J. Sediment. Petrol., **50** (1): 21–29.