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 Jurassic 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 Jurassic 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 rejuvenation 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.

INTRODUCTION

Turonian strata from the vicinity of Wolbrom were described in the 19th century (Zaręczny, 1878) and were often discussed in later papers (Sukowski, 1926, 1934; Kowalski, 1948; Marcinowski, 1974; Walaszczyzk, 1992; Olszewska-Nejbert, in prep.). Coniacian deposits from this area were documented for the first time by Walaszczyzk (1992) based on inoceramid faunas. From the Wielkanoc quarry, Walaszczyzk (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 (Walaszczyzk and Wood, 1998). Walaszczyzk (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-
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-glaucconitic 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-glaucconitic 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-glaucconitic calcarenite (Fig. 4D) and phosphatic stromatolites at the boundary between the pelitic limestone and the sandy-glaucconitic calcarenite (Figs. 4 and 3). 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 Szulczezki, 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 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
as FCW/P. Additionally, fragments of echinoids and inoce-
ramids occur in subordinate quantities, and bryozoan frag-
ments 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,
inoeceramid and echinoid fragments, are infrequent.

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

PELLITIC 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 fol-
lowing 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
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 FCWP;
— 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 foraminal-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 FCWP; 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 foraminal-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 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 + OG — 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 \textit{Thalassinoidea} traces. \textit{Thalassinoidea} is commonly linked with consolidated sediments (Bromley, 1968, 1975, 1990; Goldring and Kaźmierczak, 1974; Förtsch, 1979; Gruszczynski, 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 quickly 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 \textit{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 5). 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 colonisation 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 organisms (comp. Fig. 10, III generation of burrows), giving a post-omission suite of traces (Bromley, 1975).

**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. (Pożarski, 1960; Bathurst, 1971; Bromley, 1975; Kennedy and Garrison, 1975; Gruszczynski 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
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 hiatus 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 Leszczynski (2002) and it was correlated with the start of panregional tectonic cycle K4 with a regressive trend in other areas of the Polish Lowlands (Leszczynski, 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 Cretaceous-Palaeogene that the studied thin composite hardground was highly probable that it was during this latest Turonian transgression that the studied thin composite hardground was formed. The next transgressive event during the 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 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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