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LOWER KIMMERIDGIAN LAYER WITH BORED AND ENCRUSTED HIATUS CONCRETIONS (UPPER JURASSIC, CENTRAL POLAND): IMPLICATIONS FOR STRATIGRAPHY AND BASIN EVOLUTION

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Abstract: The paper presents a comparative analysis of a Lower Kimmeridgian layer with bored and encrusted hiatus concretions collected in three study areas, located in Central Poland. These studies demonstrate distinct similarities between the hiatus concretions in terms of their origin, development and stratigraphic position. The layer with its characteristic concretions seems to represent an important marker horizon for the Lower Kimmeridgian successions in Central Poland. The identification of this marker horizon in drill cores and exposures could be important for definition of the stratigraphic position of the sediments, which otherwise lack appropriate biostratigraphic information. The matrix of the concretions is composed of pelagic calciturbidites, which reflect flooding of the early Kimmeridgian platform. These sediments were lithified early and formed a hardground. The origin of the hiatus concretions probably is related to erosion of the hardground, followed by redeposition and several phases of exhumation and erosion, preceding final burial. The characteristic ecological successions, observed in the concretions, document an evolution from soft to firm and hard marine substrates, typical of hardgrounds and evidenced by various burrows, borings (*Gastrochaenolites*, *Trypanites*), and epizoans. Calciturbidite sedimentation, hardground erosion and redeposition of the hiatus concretions, known from deposits of the Platynota Zone in Central Poland, were associated with synsedimentary activity of the Holy Cross Fault, on the NE margin of the extensive, tectonic Małopolska Block.

Key words: calciturbidites, hardground, synsedimentary tectonism, hiatus concretions, borings, encrustations, marker horizon, Upper Jurassic, Central Poland.

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INTRODUCTION

The Upper Jurassic sediments of the southwestern margin of the Holy Cross Mountains (HCM), in Central Poland (Fig. 1), include numerous discontinuity surfaces, already described in the older literature (see e.g., Kaźmierczak and Pszczółkowski, 1968; Roniewicz and Roniewicz, 1968). These surfaces separate sediments differing in facies development and represent various types of carbonate substrate. In the Polish literature, soft-, firm-, and hardgrounds already have been described from the HCM (see e.g., Kaźmierczak and Pszczółkowski, 1968; Gruszczyński, 1986). Particular discontinuity surfaces, known from the HCM area, reveal specific faunal and morphological features (see, e.g., Kaźmierczak and Pszczółkowski, 1968; Goldring and Kaźmierczak, 1974; Palmer and Fürsich, 1974; Gruszczyński, 1979, 1986). Soft bottoms are identified by the presence of an ichnofabric and sediment dwellers. Inorganic hard bottoms are defined as consolidated surfaces, which could be bored and encrusted by organisms, but were resistant to normal submarine erosion. Hard bottoms are represented by firm- and hardgrounds. Hardgrounds are surfaces, lithified *in situ* and formed by submarine cementation, usually of carbonate sediments (e.g., Wilson and Palmer, 1992; Taylor and Wilson, 2003; Flügel, 2004; Palmer and Wilson, 2004). Firmground usually is an initial phase of hardground and can be inhabited by both boring and burrowing organisms (e.g., Gruszczyński, 1979, 1986; Chudzikiewicz and Wieczorek, 1985; Taylor and Wilson, 2003; Flügel, 2004). Moreover, hardgrounds are identified by the occurrence of encrusting marine organisms (particularly oysters, bryozoans and serpulids), boring organisms, early marine cements and/or extensive surface mineralization with iron oxides (Palmer, 1982; Flügel, 2004).

Conditions in the Jurassic low-Mg calcite sea facilitated the rapid and widespread formation of hardgrounds under

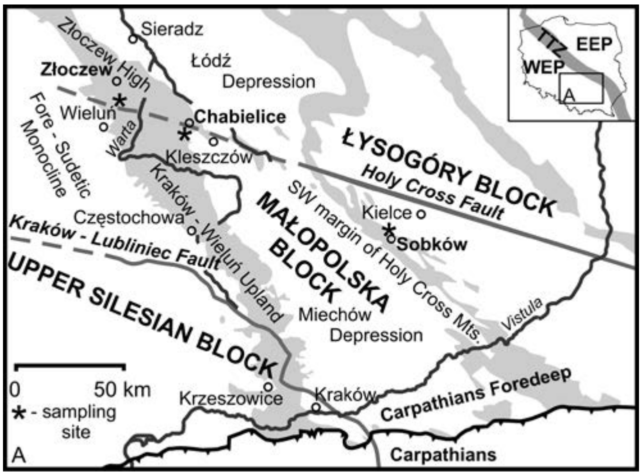


Fig. 1. Location map of the study areas with Upper Jurassic outcrops and sub-Cenozoic Upper Jurassic subcrops (grey) in southern and Central Poland (after Pożaryski *et al*., 1979; modified and simplified). Names in italics indicate location of main tectonic structures in the Palaeozoic basement (after Buła and Habryn, 2011; Żelaźniewicz *et al*., 2011). TTZ – Teisseyre-Tornquist Zone, EEP – East European Platform, WEP – West European Platform.

conditions of precipitation of low-Mg calcite and dissolution of skeletal aragonite (e.g., Wilson and Palmer, 1992). The Jurassic hardgrounds in places could be dissolved, cracked or eroded, forming, submarine cryptic cavities, commonly settled by cryptic, encrusting and cavity-dwelling faunas of serpulids, bryozoans, oysters and sponges (Palmer and Fürsich, 1974). In the Jurassic, borings were so frequent that hard substrates often were rapidly destroyed (Chudzikiewicz and Wieczorek, 1985; Gruszczyński, 1986; Taylor and Wilson, 2003).

Hardgrounds commonly are utilized as marker horizons and as distinctive indicators of sedimentary hiatuses and flooding events (Fürsich *et al*., 1981, 1992; Pope and Read, 1997; Flügel, 2004). The marker horizons are defined as isochronous stratigraphic units, observed in various regions, but characterized by identical, lithological and faunal features and with both origin and age undoubtedly in common. Such marker horizons may facilitate stratigraphic correlation. Hesselbo and Palmer (1992) demonstrated that regional discontinuities in the Lower Jurassic marine mudstones were marked by the bored and encrusted hiatus concretion layers. The regional stratigraphic gaps formed as a result of rises or falls in sea level, and the reduction of deposition or decreasing supply of material to the basin. Like condensed horizons, hardgrounds and the reworked hiatus concretions left after their erosion play a crucial role in the reconstruction of the evolution and dynamics of sedimentary basins (e.g., Taylor and Wilson, 2003; Zatoń *et al*., 2011). In Poland, hiatus concretions (HCs; HC in the singular – bored and encrusted clasts after Chudzikiewicz and Wieczorek, 1985) are known from Jurassic deposits at only a few localities and rarely were described in detail (e.g., Kaźmierczak, 1974; Chudzikiewicz and Wieczorek, 1985; Hoffmann and Krobicki, 1989; Zatoń *et al*., 2011). Similar bored and encrusted clasts also were described in brief from the Upper Kimmeridgian (Acanthicum Zone) sedimentary sequence (Radwański, 2003).

In Poland, the best-known Jurassic hardgrounds occur in Upper Callovian sediments of the Kraków-Wieluń Upland (Fig. 1; e.g., Giżejewska and Wieczorek, 1977) and in the Kimmeridgian strata of the Holy Cross Mountains (HCM; see e.g., Kaźmierczak and Pszczółkowski, 1968; Roniewicz and Roniewicz, 1968; Gruszczyński, 1979). The surfaces in the HCM show the features of lateral transition from soft- to hardgrounds (Kaźmierczak and Pszczółkowski, 1968) and there are redeposited HCs resulting from the erosion of hardgrounds (Kaźmierczak and Pszczółkowski, 1968; Kaźmierczak, 1974; Chudzikiewicz and Wieczorek, 1985). At such surfaces, several phases in the evolution of hiatus concretions were noticed, from soft- through firm- to hardgrounds, accompanied by corresponding ecological successions (e.g., Goldring and Kaźmierczak, 1974; Gruszczyński, 1979, 1986; Chudzikiewicz and Wieczorek, 1985). In the HCM, Upper Jurassic deposits particularly rich in discontinuity surfaces were dated as Lower Kimmeridgian (ammonite Platynota and Hypselocyclum zones; Kutek, 1968; Matyja, 2011). The sedimentary successions, in which these discontinuities were found, include a number of characteristic lithostratigraphic horizons, for example, the Lowermost Marly Horizon, with common submarine slumps, the Underlying Pelitic Limestones, and the Lower Oolithic Horizon (e.g., Kutek, 1969; Matyja *et al*., 2006). Some discontinuities separating these lithostratigraphic horizons are observed over vast areas of the HCM and are utilized in stratigraphic correlation (Kaźmierczak and Pszczółkowski, 1968).

In the vicinity of Sobków (Fig. 1), within the Lowermost Marly Horizon, a layer was found, some tens of centimetres thick, in which numerous bored and encrusted finely laminated HCs were encountered, originating from the erosion of hardground-type discontinuity surfaces. Matyja (2011) also mentioned a 28-cm-thick, finely laminated layer of marly and pelitic limestones, resting on the Lowermost Marly Horizon. On the upper surface of this thin layer, a hardground was identified (Matyja, 2011). The evolution of HCs from substrate erosion to final burial, documented by burrows, borings and encrustations, were described in detail by Chudzikiewicz and Wieczorek (1985). In recent years, numerous boreholes have been completed in the Upper Jurassic sediments of the Łódź Depression and S of the Złoczew High (Fig. 1; e.g., Szewczyk and Barwicz-Piskorz, 1997; Borowicz *et al*., 2007). In some drill cores, characteristic HCs were found, similar to those described by Chudzikiewicz and Wieczorek (1985) from the Sobków area, on the SW margin of the HCM.

The aim of this paper is to compare the sedimentary successions where layers with bored and encrusted HCs occur and to demonstrate the similarity and mutual relationships of HCs from the three adjacent study areas: (i) the SW margin of the HCM, (ii) the Łódź Depression and (iii) the S margin of the Złoczew High (Fig. 1).

MATERIALS AND METHODS

The samples were collected in the three areas mentioned above. The SW margin of the HCM is represented by the outcrop in the Sobków Quarry (Figs 1, 2), described in detail

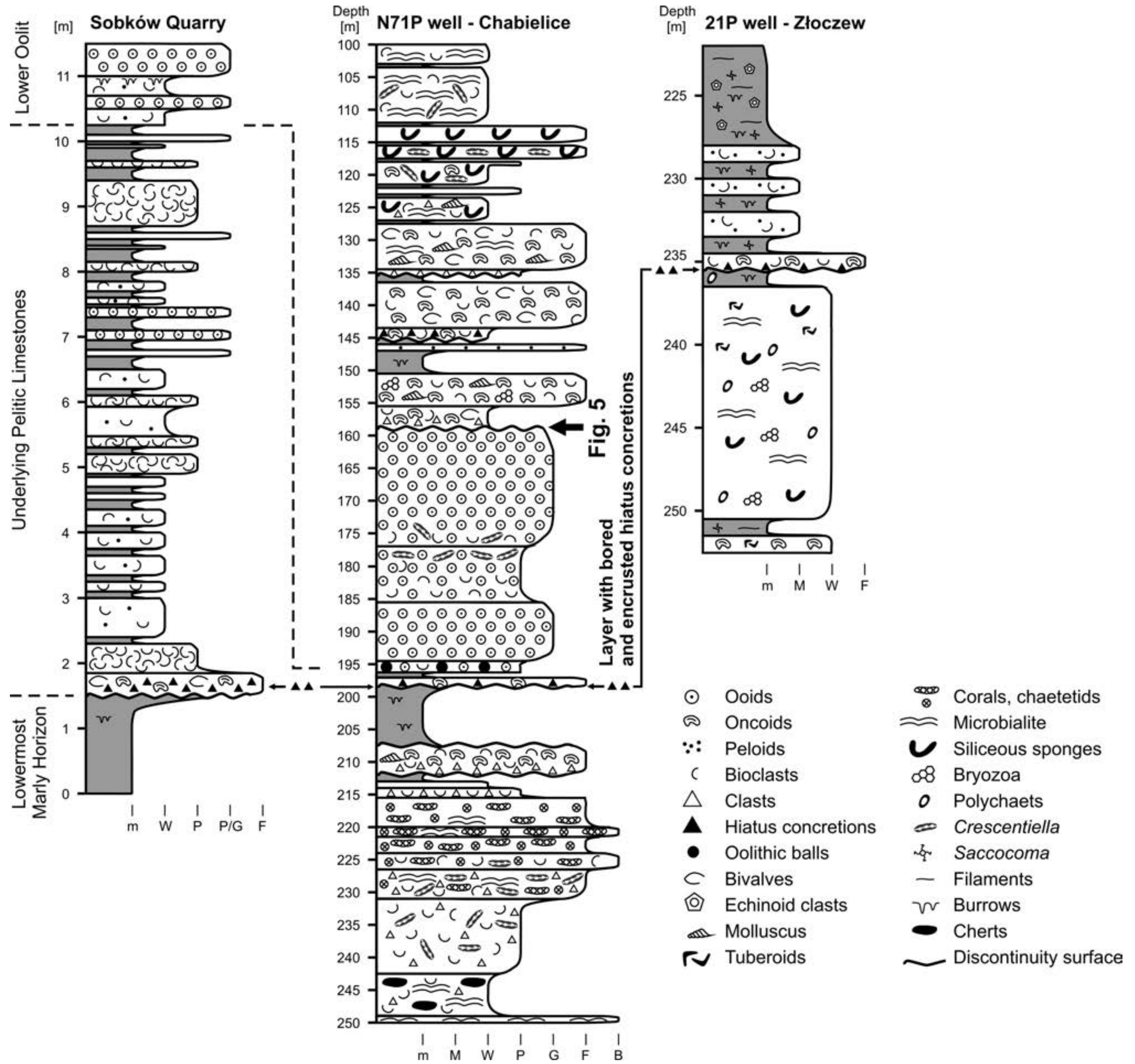


Fig. 2. Examples of lithological columns from the study areas, with positions of the layer with bored and encrusted HCs marked. In the N71P well column, the position of other regional hardgrounds (see Fig. 5; cf. Kaźmierczak and Pszczółkowski, 1968) is marked between the Oolithic and the Oncolithic Limestones horizons. Sobków Quarry – SW margin of the Holy-Cross Mts (after Chudzikiewicz and Wieczorek, 1985; modified), N71P well – Łódź Depression, 21P well – Złoczew High; m – marl, M – mudstone, W – wackestone, F – floatstone, P – packstone, G – grainstone.

by Chudzikiewicz and Wieczorek (1985). The HCs collected are stored at the Institute of Geological Sciences of the Polish Academy of Sciences, in Kraków. The authors had the opportunity to analyze this archival material (samples of the rocks, polished slabs and thin sections), by courtesy of L. Chudzikiewicz, who also kindly reprinted the archival photographs of the concretions. Unfortunately, the layer with HCs, described by Chudzikiewicz and Wieczorek (1985) from the Sobków Quarry, is unavailable for examination.

The Łódź Depression is represented by drill core from the N71P well, located in the vicinity of Chabielice village (Figs 1, 2). The sedimentary succession found in this well is representative for this area. The area close to the Złoczew High is represented by a drill core from the 21P well, located about 5 km SE of the town of Złoczew, in the Złoczew Graben (Figs 1, 2; Deczkowski and Gajewska, 1983; Borowicz *et al*., 2007). From samples collected in drill cores from the N71P and 21P wells, both polished slabs and thin sections were made, and became the basis for sedimentological studies. The principal study method was a comparative analysis of the sedimentary sequences with HCs, the HCs themselves and the matrix, in which the concretions are embedded.

The polished slabs, originally described by Chudzikiewicz and Wieczorek (1985), are presented in Figure 3. A part of sedimentary sequence penetrated by the N71P well is presented in Figures 4 and 5. HCs from all study areas are shown in Figures 6, 7, 8, and 9, they are grouped to facilitate comparison of their modes of occurrence.

The sedimentological studies were supplemented with geochemical analyses of stable carbon and oxygen isotopes (Table 1; Fig. 10) and scanning electron microscopy (SEM-EDS; Table 2). The stable isotope analyses were carried out for both the HCs and the matrix from the layer studied as well as for the underlying marls, all collected from the drill core from the N71P well. Powder samples were collected from polished slab, using a bit with $\Phi = 2.5$ mm. Calcitic grains and bioclasts were omitted as much as possible during the sampling. Carbonate powders were reacted with phosphoric acid at 70°C, using a Gasbench II device, connected to a ThermoFinnigan Five Plus mass spectrometer (GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg). Altogether, nine analyses of stable carbon and oxygen isotopes were completed. All measured values were reported in δ-notation, relative to the VPDB standard, by assigning $\delta^{13}C$ and $\delta^{18}O$ values of: +1.95‰ and –2.20‰ to the NBS19, and –26.7‰ to the LSVEC, respectively. Reproducibility and accuracy were monitored by replicate analysis of laboratory standards, calibrated to the NBS19 and the LSVEC. The measurement precision was higher than ±0.1‰ for both the carbon and oxygen isotopes.

The SEM observations were carried out with a FEI Quanta 200 FEG instrument in order to determine the chemical composition of HCs and the matrix in microareas. Of special interest was the silica content, which indicates the degree of silicification. Samples of HCs and matrix were collected at four selected points in the N71P drill core. In all, 13 SEM-EDS analyses were completed (AGH University of Science and Technology, Laboratory of the Faculty of Geology, Geophysics and Environmental Protection).

RESULTS

The southwestern margin of the Holy Cross Mts – the Sobków Quarry

The Sobków Quarry is located at the SW margin of the HCM (Fig. 1), in sediments including the Lowermost Marly Horizon, which represents Lower Kimmeridgian Platynota Zone (Fig. 2; Kutek 1968; Chudzikiewicz and Wieczorek, 1985). The lithology of this horizon includes micritic limestones, bioclastic limestones, oolithic limestones, intraformational conglomerate with bored and encrusted HCs, and marls (Fig. 2). Higher in the sequence, the sediments are succeeded by the Lower Oolithic Limestones (Kutek, 1968, 1969; Matyja *et al*., 2006) and the interface between them is a hardground (Fig. 2). The thickness of the succession studied by Chudzikiewicz and Wieczorek (1985) attains about 11 m. The layer with bored and encrusted HCs makes contact with the underlying marls along a sharp, irregular, erosional surface.

A detailed and illustrated description of the layer with the HCs, together with an interpretation of its origin, was published by Chudzikiewicz and Wieczorek (1985). The authors' observations and conclusions are consistent with those, presented in that paper. However, the present authors did not duplicate the detailed characterization of burrows, borings and incrustations, but presented only a general description of them. The layer with the HCs, about 30–40 cm thick, is located in the bottom part of the sequence (Fig. 2). The concretions usually lie at low angles, in relation to the general stratification of the sediment (Fig. 3A, B; see also Fig. 6A). The matrix of the layer is composed mainly of bioturbated bioclastic wackestone-floatstone (Fig. 3B, C).

The main component of the HCs is partly silicified, finely laminated, light to dark-grey microbioclastic peloidal calcisiltite (cf. Flügel, 2004, p. 682), represented by pyritized, fine-grained packstone, wackestone and mudstone with peloids, echinoderms, small bioclasts, filaments and rare, poorly preserved remains of *Saccocoma* (Figs 8A, B, 9A, C–F). In the concretions, grading and small-scale cross-lamination can be observed (Figs 3D, 8A, B).

In the HCs, several generations of borings were identified. Less common are encrustations of serpulids and oysters or, rarely, bryozoans and crinoids (Figs 3A, D, 6A, 8A, B). The density of the borings varies from low to very high. The diameters of HCs change from several millimetres to 20 cm and their thickness is up to 8 cm. The shapes are angular, irregular or discoidal (Fig. 3A, B). Biogenic structures typical of soft, firm or hard substrates are common (Figs 3D, 8A, B; cf. Gruszczyński, 1986). In some concretions, the authors observed undefined, elliptical or irregular burrows, filled with sediment identical to the enclosing matrix (Figs 3D, 8A, B). There are also irregular cavities and fractures, filled with internal sediments that originated from bivalve borings (Fig. 8A). The boring, *Gastrochaeonlites*, similar to that produced by the bivalve *Lithophaga* (Chudzikiewicz and Wieczorek, 1985), are from a few to 40 mm long and from a few to a dozen millimetres in diameter. Some borings still host bivalve shells, occasionally several generations of them (Figs 3A–D, 8A), the boring, *Trypanites*, produced probably by polychaetes, and encrusting serpulids. The borings show different degrees of abrasion (Figs 3A, 8B). *Trypanites* is a tunnel, ranging from a few millimetres to 4 cm long and up to several millimetres in diameter. It is filled with micrite.

A characteristic feature of the concretions studied is the presence of epizoans, mostly serpulids: *Cycloserpula* and the less common *Tetraserpula* and *Dorsoserpula*. *Cycloserpula* specimens vary in size from 0.5 to 3 mm in diameter. Serpulids are attached to the HC surfaces or to the walls of cavities (Figs 3A, D, 8A, B). Other observed epizoans are oysters (*Exogyra* and *Liostrea*), bryozoans, crinoids (*Apiocrinus*) and thin microstromatolites, the last of which overgrow the serpulid tubes in cavities (Chudzikiewicz and Wieczorek, 1985).

The Łódź Depression – the N71P well

The N71P well is located in the SW margin of the Łódź Depression, in the vicinity of Chabielice village (Fig. 1). The sedimentary succession found in this well is consistent with that described by Kutek (1968) from the SW part of the HCM (Fig. 2). It includes a characteristic facies of microbial-sponge, coral and chaetetid limestones, and bioclastic limestones with crinoids and bivalves, overlain by a marly complex, corresponding to the regional correlation horizon,

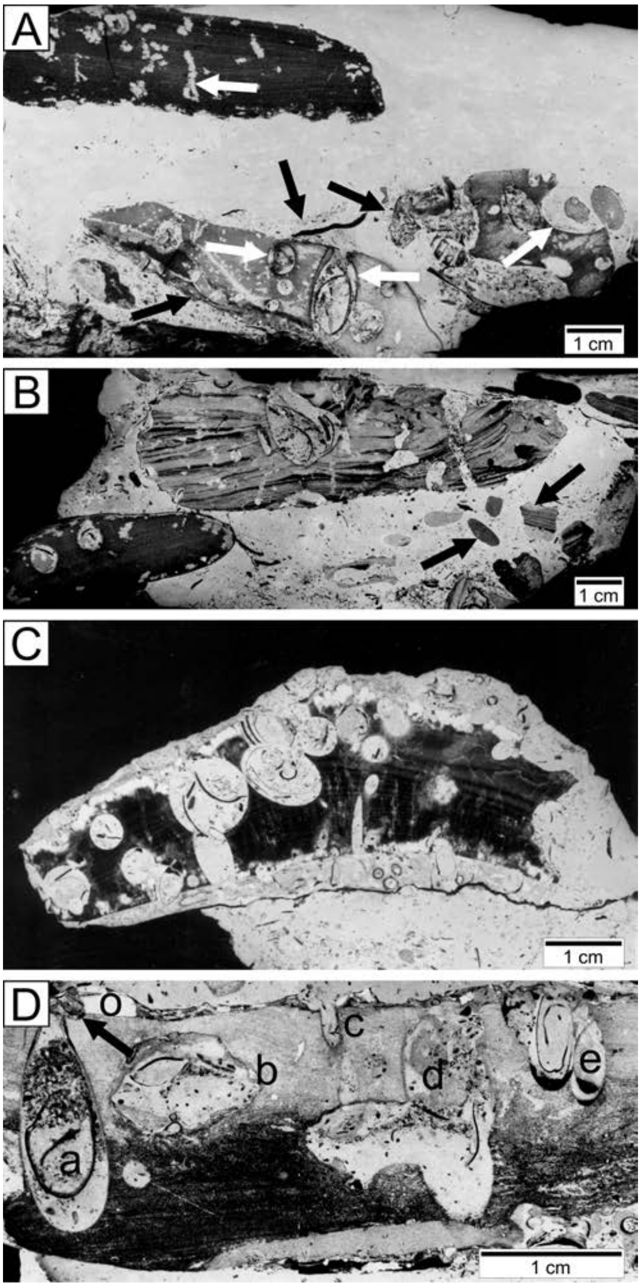


Fig. 3. Bored and encrusted HCs from the Sobków Quarry (polished slabs, new reprints of the archival material from Chudzikiewicz and Wieczorek, 1985). **A.** Upper part: HC showing dark, fine lamination; lower part: two HCs with biogenic layer composed of oysters and serpulids (black arrows). In the HCs, numerous borings *Trypanites* and *Gastrochaenolites* are visible. Some of the borings are strongly truncated (white arrows). Reprint of plate I/2. **B.** Bored HCs showing differences in lamination; on the right, numerous, small, angular HCs are seen (arrows). Matrix of the layer consists of small HCs, bioclasts, oysters and oncoids). Reprint of plate II/1. **C.** *Trichites* shell with biogenic layer on the upper part, some of the borings cut through the biogenic layer, white patches on the shell represent silicified areas; reprint of plate VII/6. **D.** Enlarged fragment of the HC: (a) bivalve boring *Gastrochaenolites* with fine-detrital internal sediment and bivalve shell, (o) encrusting oyster bored by bivalve (black arrow), (b) *Gastrochaenolites* with lower parts encrusted by serpulids (c) *Trypanites*, (d) cavity formed by a few generations of the bivalve boring *Gastrochaenolites*, (e) a few generations of *Gastrochaenolites* with geopetal infillings; reprint of plate II/3.

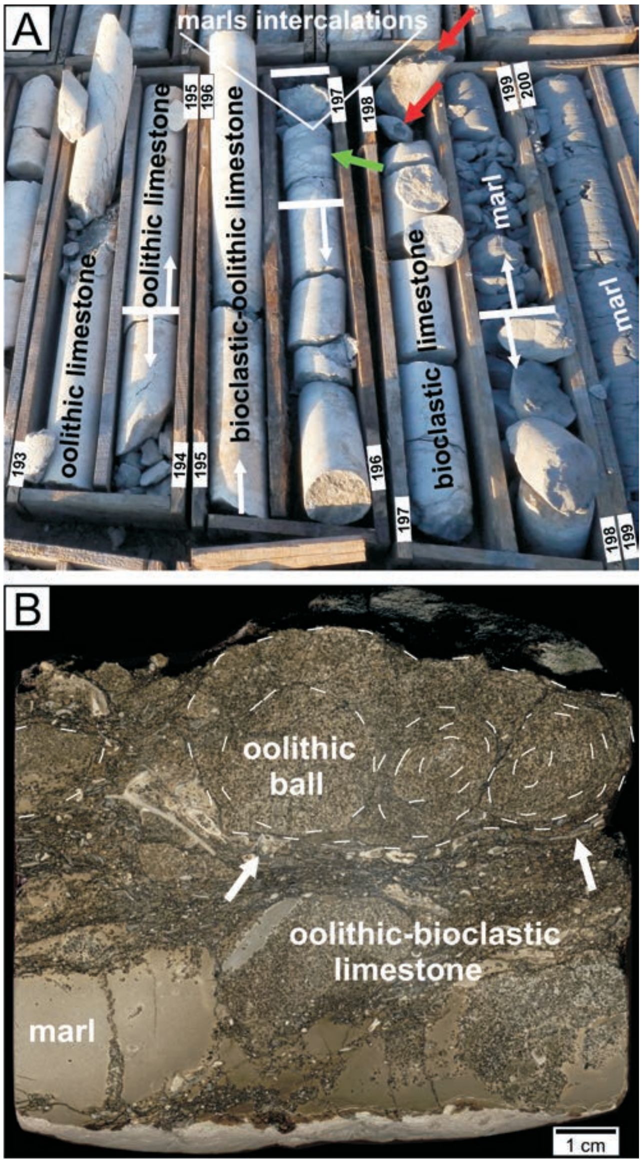


Fig. 4. Sedimentary sequence of the N71P well with localization of the HCs and oolithic balls. **A.** Fragment of drill core from N71P well (Łódź Depression) with marked lithological horizons presented in Fig. 2 and depth intervals. Red arrows point to position of bored and encrusted HCs within sedimentary sequence; green arrow indicates position of oolithic balls. **B.** Polished slab; in the lower part marls, in the upper part oolithic balls (see Radwański, 1960), white arrows indicate encrustations on the balls. This succession documents the beginning of the development of the Lower Kimmeridgian oolithic shallow platform in the Łódź Depression.

the so-called Lowermost Marly Horizon, known from the HCM (Kutek, 1968; Matyja *et al*., 2006). The marls are covered by a complex of pelitic limestones, interbedded with bioclastic and oolithic limestones with their characteristic, so-called spiral balls (Fig. 4A, B; see Radwański, 1960), followed by almost 40-m-thick complex of oolithic limestones (Fig. 2), separated from the overlying oncolithic limestones by a hardground (Fig. 5). The position of this discontinuity surface in the sedimentary sequence and in the stratigraphic subdivision corresponds to the hardground of regional correlation status, distinguished in the top part of the

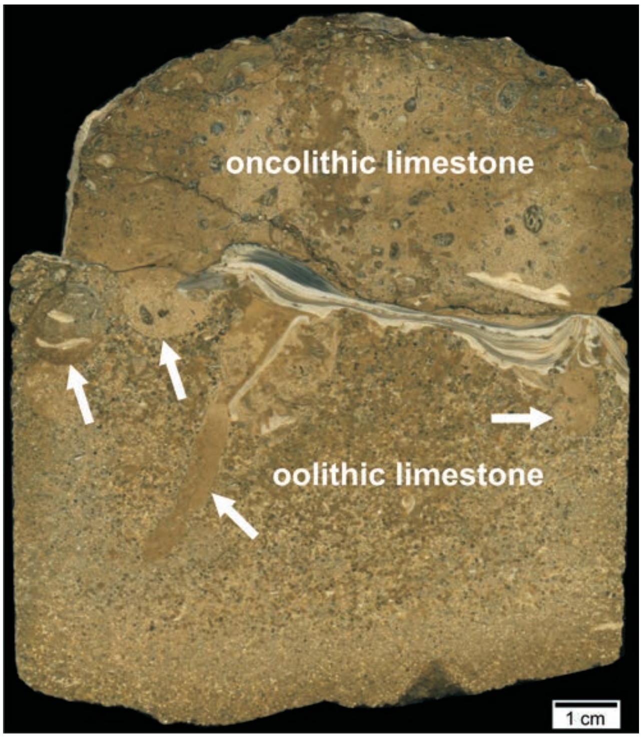


Fig. 5. Fragment of drill core from N71P well. Hardground perfectly visible between the Oolithic and Oncolithic Limestones horizons represents regional discontinuity surface, described and interpreted by Kaźmierczak and Pszczółkowski (1968). On the erosional surface, shell of encrusting pelecypod and numerous burrows and borings (arrows) are visible. Position of hardground is marked in Fig. 2.

Upper Oolithic Limestones, at the contact with the Oncolithic Horizon (Kaźmierczak and Pszczółkowski, 1968; Kutek, 1968). This discontinuity surface has been described from outcrops, scattered along 57 km. A similar lithological succession of Lower Kimmeridgian sediments in the HCM and in the N71P well, together with the presence of the regional correlation horizon – the Lowermost Marly Horizon and the hardground at the contact of the Oolithic Limestone and the Oncolithic Limestone horizons – enabled the authors to position the succession studied in the N71P well as being in the Lower Kimmeridgian Platynota Zone.

The marl complex, in which the layer with bored and encrusted HCs occurs, was found in the N71P well at the depth interval 197.8–207.8 m (Fig. 4A). These are grey marls, with rare intercalations of marly limestones. Burrows with single bioclasts are common.

Table 1

Carbon and oxygen isotopic composition of hiatus concretion, matrix of layer and underlying marls from N71P well

Layer with bored and encrusted hiatus concretions	Sample	Isotopic data	
		$\delta^{13}C$ [‰ VPDB]	$\delta^{13}O$ [‰ VPDB]
Hiatus concretion	Is 1	0.65	–2.84
	Is 2	–1.62	–3.15
	Is 3	–1.31	–2.81
	Is 4	–1.45	–2.67
	Is 5	–1.48	–4.04
Matrix of the layer	Is 6	2.24	–2.80
	Is 7	2.28	–2.43
Underlying marls	Is 8	2.06	–2.93
	Is 9	2.00	–1.84

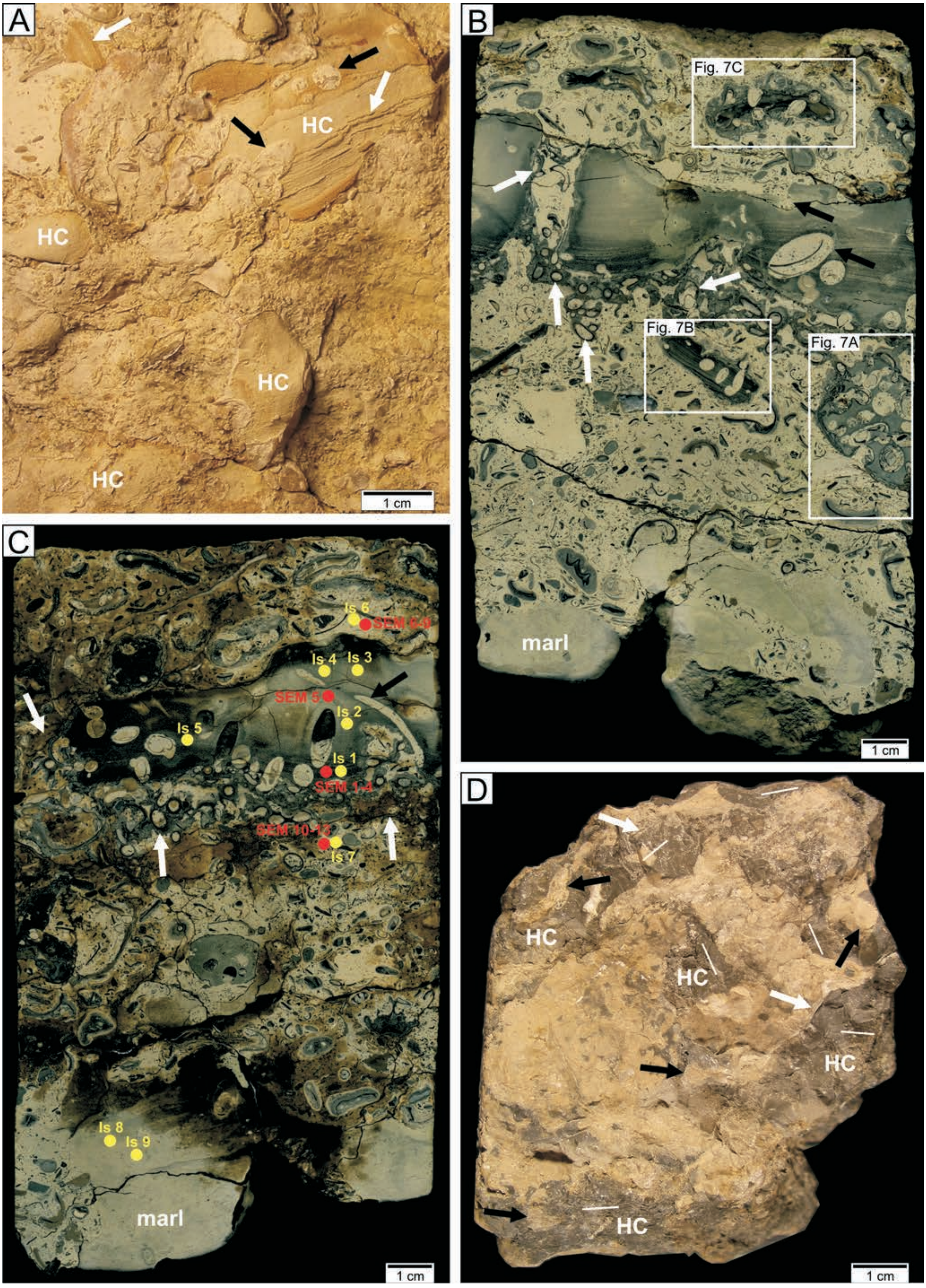
Table 2

SiO_2 content (SEM-EDS chemical analyses) in hiatus concretion and matrix of layer from N71P well

Layer with bored and encrusted hiatus concretions	Sample	SiO_2 [%]
Hiatus concretion	SEM 1	12.02
	SEM 2	15.61
	SEM 3	43.65
	SEM 4	12.92
	SEM 5	8.02
Matrix of the layer	SEM 6	1.56
	SEM 7	6.46
	SEM 8	1.33
	SEM 9	2.65
	SEM 10	2.99
	SEM 11	5.03
	SEM 12	1.43
	SEM 13	6.95

The layer with bored and encrusted HCs occurs in the depth interval 197.8–198.1 m (Fig. 4A). The larger HCs are usually parallel to or arranged at low angles to the general stratification of the sediment (Fig. 6B, C). The matrix consists of bioturbated wackestone with bivalve shells and oncoids (Figs 6B, C, 7). The oncoids are from a few millimetres to 2 cm in diameter (Figs 6B, 7C). Their shapes are highly diversified: from oval through elongated to irregular, with sharp or diffused boundaries. Most of the observed oncoids have bioclastic nuclei, which are usually bivalve shells

Fig. 6. Layer with bored and encrusted HCs from Sobków Quarry and N71P and 21P wells. **A.** Fragment of the eroded hardground with HCs; white arrows indicate lamination well visible in calciturbidites which constitute HCs; black arrows indicate borings; Sobków Quarry. **B.** Polished slab; in the central parts fine-laminated, bored and encrusted HCs with burrows and numerous borings *Trypanites* and *Gastrochaenolites* (black arrows) are visible. On the outer surfaces of the HCs a biogenic layer with serpulids colony (white arrows) is deposited. Matrix of the layer consists of bivalve and oyster shells, bioclasts and oncoids; in the lower part sharp contact with marls is visible. Details marked with rectangles are presented in Fig. 7; N71P well. **C.** Polished slab; in the central part strongly bored, silicified HCs with tunnels of *Trypanites* type (black arrow) and biogenic outer layer (white arrows) are seen, in the lower part bioturbated marls occur, red dots indicate samples collected for SEM-EDS analysis, yellow dots mark samples taken for stable $\delta^{13}C$ and $\delta^{18}O$ isotope analyses; N71P well. **D.** Fragment of drill core with a few bored and encrusted HCs, black arrows indicate borings, white arrows show biogenic layer with serpulids, oysters and microbial crusts, white lines mark orientation of individual HCs; 21P well.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and/or serpulids (Fig. 7). The oncoid shapes are strictly controlled by the shapes of the nuclei. The cortex lamination is micritic or, rarely, organism-bearing (Fig. 7C). Numerous oncoids show traces of bioerosion, particularly the borings *Gastrochaenolites* or *Trypanites*, similar to those observed in the HCs. Oncoids observed in the authors' samples roughly correspond to oncoid types, known from the Late Oxfordian facies described, for example, by Olivier *et al*. (2011).

The sizes of the HCs vary from several centimetres to more than the diameter of the drill core (Figs 6B, C, 7A, B, D). The HCs are angular, irregular, and with numerous fractures, usually arranged transversally to the lamination of the HCs. The fracture walls are encrusted and the filling material is the matrix of the layer (Fig. 6B. In hand specimen, the HCs are composed of light to dark-grey, finely-laminated pyritized microbioclastic peloidal calcisiltite (Figs 6B, C, 7, 8C, D; cf. Flügel, 2004, p. 682). Under the microscope, the authors observed grading from fine-grained bioclastic packstone and wackestone to mudstone (Fig. 8C, D, 9B, G, H). The SEM-EDS analyses proved that the silicification process had taken place. The SiO_2 content of the HCs varied from 8.02% to 43.65%, while in the enclosing sediment it is much lower, from 1.33% to 6.95% (Table 2; Fig. 6C). The packstones are composed of well-sorted peloids, small bivalves, echinoderms, rare calcified radiolarians, foraminifers and rare fragments of the poorly preserved remains of the planktonic crinoid, *Saccocoma* (Fig. 9G, H). In both the packstones and wackestones, horizontally distributed bioclasts are frequent. Higher up the sequence, the packstones grade into wackestones with filaments and also into mudstones (Figs 8C, D, 9G, H).

Biogenic structures, typical of soft, firm or hard substrates, are common: undefined, elliptical or irregular burrows, filled with sediment that is identical to the enclosing matrix (Figs 7, 8C, D). Irregular cavities and fractures within the HCs are presumably fragments of the burrow *Thalassinoides*. The sediment that fills the burrows contains numerous bivalves and the boring *Trypanites* (Figs 6B, 8C, D). The boring *Gastrochaenolites* is from a few to 20 mm long and from a few to a dozen millimetres in diameter (Figs 7A, B, D, 8C, D). In many borings, shells or several generations of bivalve shells are preserved (Fig. 7A) as well as the boring *Trypanites* (Fig. 6B, C) and encrusting serpulids (Fig. 8C). Some borings are partly abraded (Fig. 7). The borings are filled with micrite. In some HCs, the authors distinguished several generations of *Gastrochaenolites* and *Trypanites*, and encrustations made by serpulids or, less commonly, by bryozoans. The density of borings varies from low to very high.

The typical feature of the HCs studied is the presence of epizoans (Fig. 8C). These are mostly colonies of *Cycloserpula,* from 0.5 to 3 mm in diameter. Serpulids are attached to the surfaces of the HCs or to the walls of the cavities and fractures (Figs 6B, C, 8C). Other epizoans observed are oysters, bryozoans and thin microbialite crusts (Figs 7, 8C). The latter overgrow serpulid tubes in the cavities or are directly attached to the surfaces of the HCs (Fig. 8C).

In the HCs, $\delta^{13}C$ values range from –1.62‰ to 0.65‰ and $\delta^{18}O$ values vary from –4.04‰ to –2.67‰, whereas the matrix of the layer shows $\delta^{13}C$ values of 2.24‰ to 2.28‰ and $\delta^{18}O$ values between –2.80‰ and –2.43‰. The marls have $\delta^{13}C$ values of 2.00‰ to 2.06‰ and $\delta^{18}O$ values of –2.93‰ to –1.84‰ (Table 2; Figs 6C, 10).

The Złoczew High – the 21P well

The 21P well is located about 5 km SE of Złoczew town, close to the margin of the Fore-Sudetic Monocline, in the Złoczew Graben (Fig. 1). This is one of many wells completed in recent years, which penetrated the Upper Jurassic strata with a thickness of up to 120 m. The total thickness of the Upper Jurassic sequence of the Złoczew Graben is known from the wells (Biesiec 1, Biesiec 2) and reaches 200 m on the border and 270 m in the central part of the graben. The Upper Jurassic sediments in the Złoczew Graben are mostly Upper Oxfordian (Deczkowski and Gajewska, 1983) microbial-sponge, microbial-*Crescentiella* facies, commonly observed in the Kraków-Wieluń Upland (Matyszkiewicz, 1997; Krajewski, 2000, 2001; Matyszkiewicz *et al*., 2006, 2012; Olchowy, 2011), overlain by biostratigraphically dated Lower Kimmeridgian marly limestones and marls (Deczkowski and Gajewska, 1983). This stratigraphical position is confirmed by foraminifers, found in the 21P well (B. Olszewska, pers. comm., 2013). At a depth of 238.5 m as well as in the lower intervals *Paalzowella turbinella* and *Protomarssonella jurassica* were found; their stratigraphic distribution is limited to the Oxfordian (Olszewska *et al*., 2012). In the intervals related to the Lower Kimmeridgian, *Sievoides kocyigiti* was found, which is stratigraphically limited to the Kimmeridgian and Tithonian (Olszewska *et al*., 2012). The position of the layer with HCs in the sedimentary sequence, close to the contact between the Upper Oxfordian microbial-sponge facies and the Lower Kimmeridgian marly limestones and marls, indicates a Lower Kimmeridgian age. These marly limestones and marls were also described by Kowalski (1958) and Wierzbowski *et al*., (1983) from outcrops in the vicinity of Burzenin village, close to the study area. In the Mysłakowice and Brzyków areas, about 5 km NE of the 21P well, marly limestones and marls were described layer-by-layer in outcrops and dated at Lower Kimmeridgian, using the ammonite fauna (Kowalski, 1958).

The sediments found in the 21P well comprise three intervals differing in lithology (Fig. 2). The lowest interval includes microbial-sponge wackestones with cherts, which represent bedded facies, typical of the adjacent Kraków–Wieluń Upland (Wierzbowski *et al*., 1983; Krajewski, 2001; Matyszkiewicz *et al*., 2012; Kochman and Matyszkiewicz, 2013). These are overlain by characteristic, 6-m-thick limestone-marl alternations, composed of thin-bedded, pelitic, bioclastic limestones, marly limestones and marls in which several-centimetres-thick clay laminae occur. In these sediments, echinoids, foraminifers and burrows are common (Fig. 2). In the lower part of the succession, the authors observed the characteristic, bored and encrusted HCs with numerous *Trypanites*, which were the principal target of the research. The uppermost interval comprises grey marls with frequent echinoids, benthic crinoids, planktonic crinoids *Saccocoma* sp., and filaments.

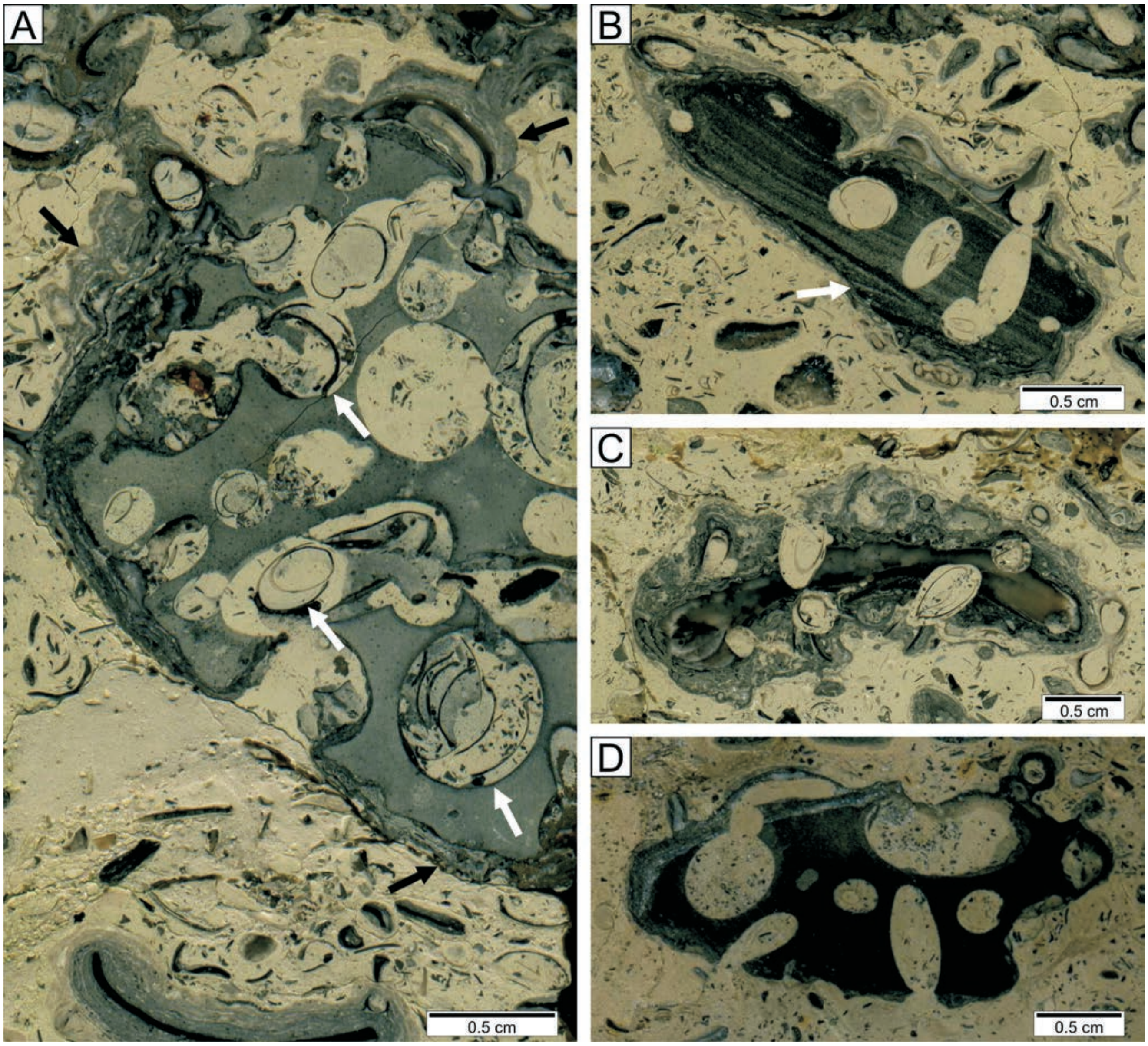

Fig. 7. Details of layer with bored and encrusted HCs from N71P well (for location of A–C see Fig. 6B). **A.** Silicified HC with numerous bivalve boring *Gastrochaenolites*; in borings shells are visible with a few generations of bivalves (white arrows); on the outer surfaces encrusters are seen: bivalves, serpulids and microbialites (black arrows). **B.** Small, angular, fine-laminated HC, in the lower right part of the HC cross-lamination is visible (white arrow), outer surfaces around the HC consist of well-developed, encrusting biogenic layer with bivalves, serpulids and microbialites, in the central part of the HC numerous *Gastrochaenolites* are seen. **C.** Expanded view of strongly bored oncoid, on bivalve nuclei the organism-bearing microbial envelope grows, truncated by the bivalve boring *Gastrochaenolites*. **D.** Small HC with *Gastrochaenolites Gastrochaenolites*. Some of the borings are strongly abraded; others are filled with micrite and bioclasts, composed of material identical to the enclosing sediment.

The layer with small, bored and encrusted pyritized carbonate HCs was found in the depth interval 236.1–236.3 m (Figs 2, 6D). The HCs, several centimetres in diameter, are irregular and angular (Fig. 6D). Most are arranged transversally to the sedimentary bedding. Under the microscope (Fig. 8E, F), the HCs are composed mostly of light- to dark-grey pyritized fine-bioclastic peloidal calcisiltite (Fig. 8E; cf. Flügel, 2004, p. 682) and exhibit grading, from fine-grained packstone-wackestone to mudstone with peloids, echinoderms, small bioclasts and rare, poorly preserved *Saccocoma* (Fig. 9I).

In the HCs, *Gastrochaenolites* and serpulid (*Cycloserpula*) encrustations were identified (Fig. 6D). The density of borings varies from low to very high. Common are biogenic structures, typical of firm or hard substrates (Fig. 8E, F). In some HCs, the authors found undefined, irregular burrows, filled with sediment identical to the enclosing matrix. The authors also observed irregular cavities and fractures, probably representing the burrows of *Thalassinoides* type. In the sediments filling the burrows, bivalve borings occurred. The borings, *Gastrochaenolites* and *Trypanites*, were identified (Fig. 8F). The bivalve boring, *Gastrochaenolites*, is

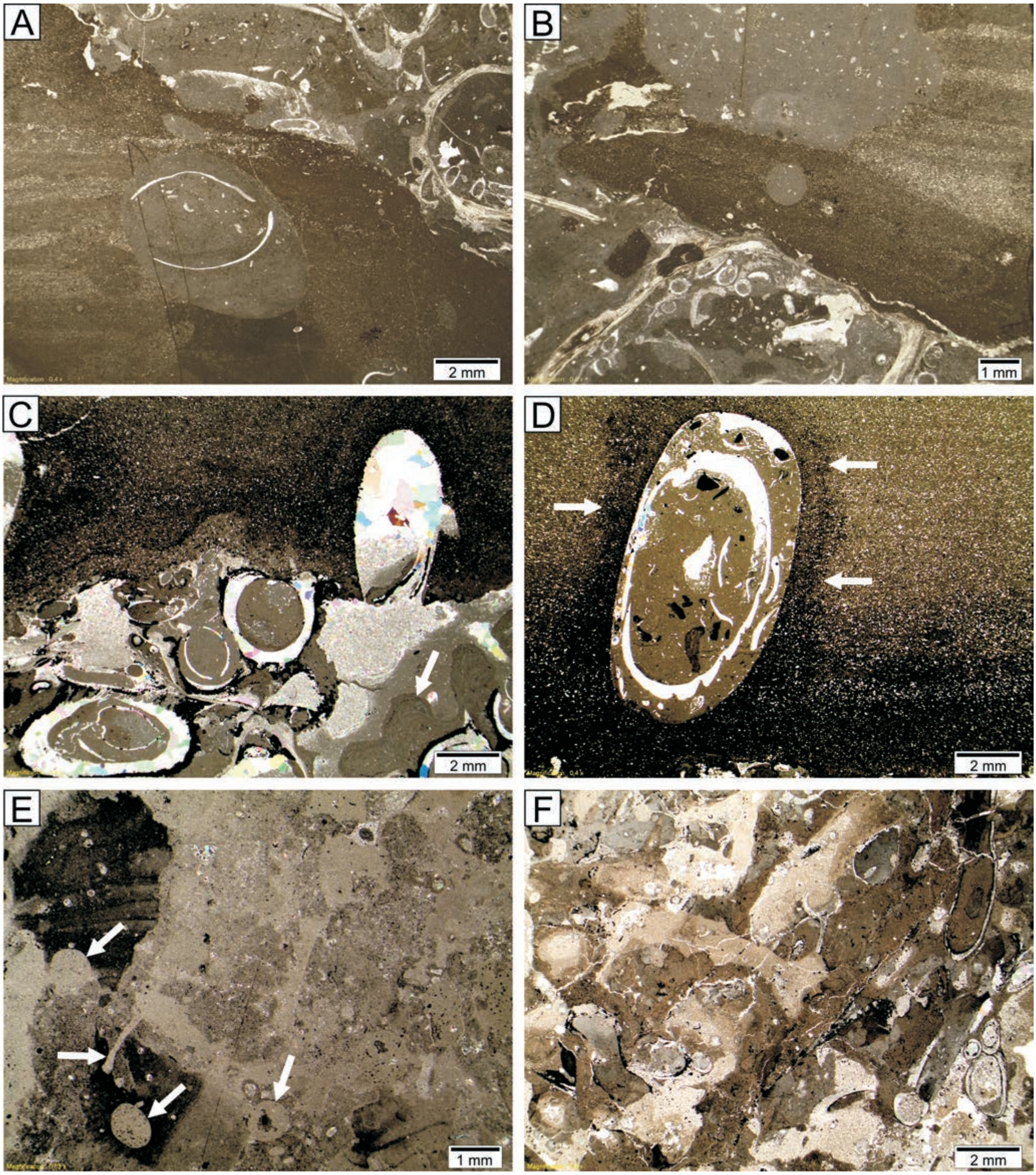

Fig. 8. Microfacies observed in layer with bored and encrusted HCs from Sobków Quarry and N71P and 21P wells. **A.** In the lower part of the photograph, pyritized HC is visible consist of bored thin-laminated microbioclastic-peloidal calcisiltite. In the upper part of the photograph, bioclastic wackestone with serpulids and bivalves is observed (Sobków Quarry). **B.** In the central part of the photograph, strongly abraded HC built of thin-laminated calcisiltite. In the lower part of the photograph, bioclastic wackestone with serpulids and bivalves, occurs (Sobków Quarry). **C.** In the lower part of the photograph, serpulid colony bored by bivalves is observed. Microbialites (arrow) are visible on the serpulids. In the upper part of the photograph, calcisiltite with bivalve boring is visible, around the boring aureole of pyritized sediments is present (N71P well). **D.** Bored HC built of thin-laminated packstone-wackestone with the bivalve boring *Gastrochaenolites*, in the boring shells are seen representing a few generations of bivalves, around the boring aureole of pyritized sediments is present (arrows) (N71P well). **E.** Strongly bioturbated wackestone, on the left small, abraded, angular, fine-laminated HCs are seen with *Trypanites* and *Gastrochaenolites* (arrows) (21P well). **F.** Fragment of strongly bioeroded HC with serpulids colony (21P well).

from a few to some tens of millimetres long and from a few to a dozen millimetres in diameter. In the borings, bivalve shells occurred. The probable polychaete boring, *Trypanites*, from a few millimetres to 4 cm long and up to a few millimetres in diameter, was filled with micrite.

A feature of the HCs studied is the presence of epizoans. These are mostly the colonies of *Cycloserpula*, from 0.5 to 3 mm in diameter, attached to the surfaces of HCs (Fig. 8F). Apart from serpulids, the authors also identified oysters, bryozoans and thin microbial crusts, the latter usually overgrowing the serpulid tubes.

DISCUSSION

The results of the studies by the authors clearly demonstrate the similarity of the bored and encrusted HCs, found in the three sedimentary sequences at the SW margin of the Holy Cross Mts., in the Łódź Depression and on the Złoczew High (Figs 1, 2). The most important similarities are: (i) their stratigraphic position in the Lower Kimmeridgian (Platynota Zone), (ii) the similar marly sequence enclosing the layers with HCs and (iii) the distinctly similar development of HCs, together with burrows, borings, and encrustations (Table 3). These features show that the layer studied was deposited, as a result of the same Early Kimmeridgian event. A characteristic feature of the concretions studied is silicification, indicated earlier by Chudzikiewicz and Wieczorek (1985) and confirmed in the authors' samples by SEM-EDS analyses (Table 2; Fig. 6C). The observations by the authors may contribute to more precise positioning of the layer with HCs in the lithostratigraphic sequence. Up to now, the layer was considered to be referable to the Lowermost Marly Horizon (Chudzikiewicz and Wieczorek, 1985). However, the sedimentary sequence, presented by Chudzikiewicz and Wieczorek (1985), assigned to the recent lithostratigraphic subdivision (Matyja *et al*., 2006), indicates rather that the layer belongs to the top part of the Lowermost Marly Horizon, at the contact with the Underlying Pelitic Limestones. Higher in the sequence,, these sediments grade into the Lower Oolithic Limestone (Kutek, 1968). Such a stratigraphic position is strongly supported by the sedimentary sequence, observed in the N71P well (Fig. 2), where the regional Lowermost Marly Horizon and hardground-type correlation surfaces (Figs 2, 5; Kaźmierczak and Pszczółkowski, 1968; Kutek, 1968; Matyja *et al*., 2006) were found. Up to now, the lateral distribution of this hardground was estimated as 57 km. The results obtained by the authors permit the extension of this range to about 110 km. In contrast to other discontinuity surfaces encountered in the southwestern margin of the HCM, the layer with the HCs, which are the relics of hard-bottom erosion, to date has not been regarded as correlation marker horizon. The discontinuity surfaces are related to changes in sedimentation. The vast, regional extent of the layer, indicates the action of a formative event on a regional scale. The results obtained for three study areas demonstrate the presence of the layer with HCs over a distance of at least 140 km.

Origin of matrix of hiatus concretions

The origin of the fine-laminated sediments, from which the HCs were formed, has not been satisfactorily explained, as yet (see Chudzikiewicz and Wieczorek, 1985). The sediments comprise silicified fine-grained pelagic packstones, wackestones and mudstones (Figs 8, 9), with peloids, small bioclasts, peloids, echinoderms and loose remains of *Saccocoma* of various shapes (cf. Keupp and Matyszkiewicz, 1997; Hess, 2002; Brodacki, 2006; Olszewska *et al*., 2012), showing normal grading (Figs 6B, C, 8A–E), rarely also cross-lamination (Fig. 7B). These sediments correspond very well to microbioclastic peloidal calcisiltites, representing SMF 2, according to Flügel (2004, p. 682). This microfacies type represents a deeper basin, open-marine shelf, deep-shelf, toe-of slope or outer-ramp setting (Flügel, 2004, p. 682). During the Jurassic, a remarkable sea-level rise took place during the Callovian–Kimmeridgian. One of transgression peaks is dated at the Platynota Zone (e.g., Hardenbol *et al*., 1998, Km1–Km2 sequences; see also Matyszkiewicz, 1997; Gutowski, 2006). The development of sediments, from which the HCs were formed, is very similar to that of the calcareous calciturbidites, described from the Lower Kimmeridgian (Platynota Zone) in the Kraków area (Matyszkiewicz, 1996) as well as from the Ukrainian part of the Carpathian Foredeep basement (Krajewski *et al*., 2011) and southern Germany (Keupp and Matyszkiewicz, 1997; Matyszkiewicz, 1997). Similar deposits, although with numerous and better preserved filamentous-*Saccocoma* microfacies (wackestones-packstones), were described from the Lower Kimmeridgian fine-grained pelagic facies of the Krížna Unit in the Tatra Mts. (Jach *et al*., 2012). The sedimentary features, both observed in the authors' samples (Figs 8, 9) and described in publications on the Kraków area (cf. Matyszkiewicz, 1996) correspond to typical calciturbidites (e.g., Flügel, 2004; Reijmer *et al*., 2012) in bimodality of grain composition, normal grading and secondary silicification (e.g., Eberli, 1987; Matyszkiewicz, 1996). The difference between the calciturbidites making up the HCs and the sediment hosting the HCs indicates different sedimentary conditions.

In addition to microfacies data (Figs 8, 9), such a difference is clearly indicated by isotopic data (Table 1; Fig. 10). The results of stable isotope studies demonstrate low $\delta^{13}C$ (average: –1.04‰) and low $\delta^{18}O$ (average: –3.10‰) values in the HC, by comparison with those measured in the matrix of the layer (average $\delta^{13}C$: 2.26‰ and average $\delta^{18}O$: –2.62‰) and in the marls (average $\delta^{13}C$: 2.03‰ and average $\delta^{18}O$: –2.38‰; Table 1; Fig. 10). The negative $\delta^{13}C$ and $\delta^{18}O$ values, recorded in sediment forming the HC, may suggest a deeper, pelagic sedimentary environment (Marshall, 1992) and low circulation of pore solutions within the sediment (e.g., Rasser and Fenninger, 2002). This interpretation is supported by the development of concretion-forming sediments as pelagic packstones, wackestones and mudstones (Figs 8, 9). On the other hand, the higher $\delta^{18}O$ and $\delta^{13}C$ values found in the matrix of the layer may indicate deposition in a shallower environment of higher alkalinity (Elderfield *et al*., 1999) and higher content of nutrients (Ruf *et al*., 2005), dominated by oncolithic facies (Fig.

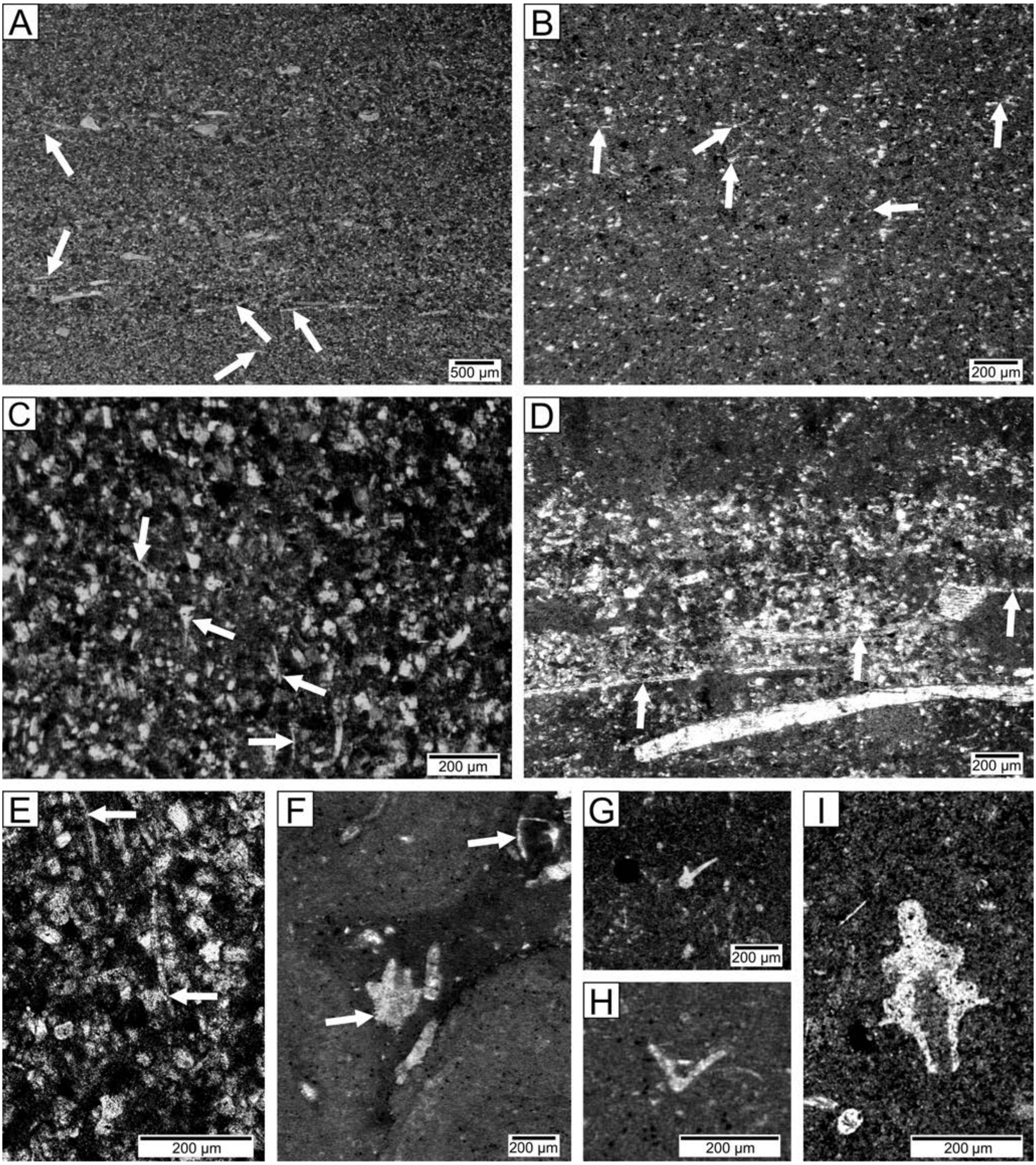

Fig. 9. Microfacies of HCs from Sobków Quarry and N71P and 21P wells. **A.** Microbioclastic peloidal fine laminated calcisiltite; fine–grained packstone–wackestone with peloids, filaments (arrows), echinoderms and bivalves; Sobków Quarry. **B.** Microbioclastic peloidal wackestone with rare *Saccocoma* remains (arrows); N71P well. **C.** Microbioclastic packstone–wackestone calcisiltite with filaments (arrows); Sobków quarry. **D.** Microbioclastic calcisiltite with filaments (arrows) and bivalve in the lower part which pass into bioclastic wackestone in the upper part; Sobków quarry. **E–I.** Remains of *Saccocoma* secundibranchials (E, F – Sobków Quarry; G, H – N71P well; I – 21P well.

6B, C) and affected by periodical supply of marly material. The high diversity of $\delta^{13}C$ and $\delta^{18}O$ values in the HCs and in the matrix of the layer suggests the possible impact of diagenetic processes on a stable isotope composition. According to Marshall (1992), a stable isotope composition is strongly influenced by cementation and replacement (including recrystallization). The microscopic observations of the authors revealed a low degree of recrystallization of both the HCs and the matrix of the layer. In the HCs, the SEM-EDS analyses indicated various degrees of silicification (from 8.02% to 43.65% SiO_2), whereas the isotopic values of $\delta^{13}C$ and $\delta^{18}O$ remained similar. This result demonstrates that replacement phenomena did not affect the isotopic composition. Similarly, in the matrix of the layer, the isotopic values are comparable, despite the silica contents (Table 1; Fig. 10).

The calciturbidites studied (the matrix of the HCs) may be related to the phase of basin deepening in the early Kimmeridgian (Platynota Zone), described from the SW margin of the HCM (e.g., Gutowski, 2006) and the SE part of the Kraków-Wieluń Upland (Matyszkiewicz, 1996), which resulted in a change of sedimentary environment into pelagic with deep-sea deposition. The appearance of silicification in calciturbidites is in agreement with the model, in which early diagenetic silicification is related to the enrichment of pore solutions in silica, due to the abrupt burial of the sediment (Bustillo and Ruiz-Ortiz, 1987). For example, silica may originate from the opaline skeletons of radiolarians (Bustillo and Ruiz-Ortiz, 1987; Matyszkiewicz, 1996) or from an external source (e.g., Migaszewski *et al*., 2006). It is suggested that the silicification of the calciturbidites might have been preceded by calcite cementation, which significantly limited both the porosity and permeability of the sediment (Hesse, 1987). Presumably, the early diagenetic silicification started when the permeability of the sediment already was strongly limited by progressing cementation (Matyszkiewicz, 1996; cf. Migaszewski *et al*., 2006). Moreover, the anaerobic bacterial oxidation of organic matter caused an increase in pH and, in consequence, facilitated calcium carbonate precipitation (e.g., Wetzel and Allia, 2000; Zatoń *et al*., 2011). Also the negative values of $\delta^{13}C$ in the HC indicate that their micritic material originated from bacterial anaerobic oxidation of organic matter within the sediment, in the sulphate reduction zone during a reduced sedimentation rate (e.g., Hesselbo and Palmer, 1992; Wetzel and Allia, 2000; Zatoń *et al*., 2011). However, in the concretions studied, most $\delta^{13}C$ values are negative (Fig. 10), but higher than the $\delta^{13}C$ values known from other HCs (Wetzel and Allia, 2000; Zatoń *et al*., 2011), which does not indicate the sulphate reduction zone (Irwin *et al*., 1977; Wetzel and Allia, 2000). As suggested by Zatoń *et al*. (2011), higher values of $\delta^{13}C$ may have been related to microenvironments, in which pyrite might have precipitated. Impregnations with pyrite, observed on the margins of many borings in the concretions studied (Fig. 8C, D) as well as on borings at other localities (see Wetzel and Allia, 2000, figs 4, 8) may be related to organic matter present in the borings. Deposition of calciturbidites was terminated by a break in sedimentation. Prior to the burial, these sediments were subjected to lithification, which must have been a long process, indicating a condensation horizon.

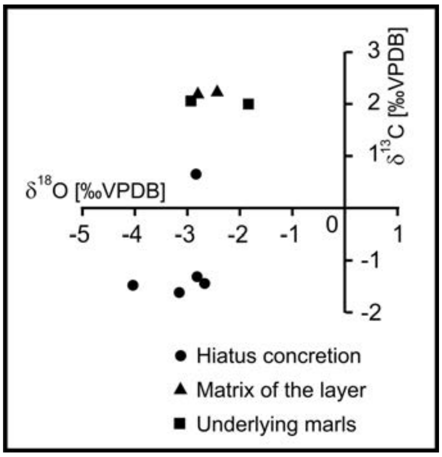

Fig. 10. Carbon and oxygen isotopic data for hiatus concretion, matrix of layer and underlying marls from N71P well.

Formation of hiatus concretions

The sedimentation break was succeeded by erosion and redeposition of the sediments, in which concretions were formed. Cementation of bored and encrusted HCs proceeded during very early diagenesis. The formation of the sediments producing the HCs was similar to the formation of the hardgrounds, which suggests that differences between the hardground and the HCs resulted from the more continuous nature of the hardground and the more advanced displacement processes affecting the concretions. The characteristic formation processes of hardgrounds, the levels of reworked HCs and the condensation horizons have been attributed to phases of rise in relative sea level (e.g., Fürsich *et al*., 1992) on both global and local scales.

The studies by the authors confirmed the interpretation and evolution phases of HCs proposed by Chudzikiewicz and Wieczorek (1985). In the HCs studied, a characteristic ecological succession can be found; it was described in detail from the HCM region (Gruszczyński, 1979, 1986). Also the phases in development of the concretions can be distinguished: from those of softgrounds and firmgrounds with burrows to hardgrounds with borings and encrustations. The authors support the opinion of Chudzikiewicz and Wieczorek (1985) that the phase of concretion formation was related to erosion of the hardgrounds (see Fig. 6A; cf. Anketell *et al*., 1970; Radwański, 2003). Before final burial, the HCs were subjected to many phases of development, including burial, submarine exhumation, redeposition (including rolling) and recolonization by boring and encrusting organisms (Chudzikiewicz and Wieczorek, 1985). The multi-phase history of the HCs studied indicates a long period of formation preceding final burial. According to Chudzikiewicz and Wieczorek (1985), the hardground from the Sobków Quarry developed over the local, adjacent highs and passed laterally into sediments of less advanced lithification, as noted earlier by Kaźmierczak and Pszczółkowski (1968). During the exhumation and boring phases, the layer was lithified to different degrees over the local highs and in depressions, which influenced its preservation within the sediment. In the areas, where consolidation was incomplete, the layer might have been destroyed, leaving only single, small concretions, or might have been totally removed. In the areas where the layer was more lithified, it was preserved together with numerous, larger concretions. The destruction of hardgrounds might have been facilitated by the

Table 3

Location and most important features of the layer with bored and encrusted HCs from Upper Jurassic sediments, in Central Poland

Features / Localization	Holy Cross Mts., Sobków Quarry	Łódź Depression, N71P well	Złoczew High, 21P well
stratigraphic position of the layer with HCs	Lower Kimmeridgian *Platynota* Zone	Lower Kimmeridgian *Platynota* Zone	Lower Kimmeridgian *Platynota* Zone
lithostratigraphic horizon	Lowermost Marly/Underlying Pelitic Limestone horizons (after Kutek, 1968)	marls/bioclastic limestones	marls/bioclastic limestones
contact with underlying marls	sharp, uneven erosional contact	sharp, uneven erosional contact	sharp, uneven erosional contact
thickness of the layer with HCs	30–40 cm (after Chudzikiewicz and Wieczorek, 1985)	30 cm	20 cm
composition of the HCs	light to dark grey fine-laminated calciturbidite	light to dark grey fine-laminated calciturbidite	light to dark grey fine-laminated calciturbidite
silicification of the HCs	present	present	present
size of the HCs	>milimetre to 20 cm in diameter up to 8 cm in high	>milimetre to more than core size in diameter, up to 6 cm in high	>millimetre to 5 cm in diameter up to 3 cm in high
matrix of the layer	bioturbated bioclastic-oncoid wackestone-floatstone	bioturbated bioclastic-oncoid wackestone-floatstone	bioturbated bioclastic-oncoid wackestone-floatstone
burrows	*Thalassinoides*-type and undefined burrows	*Thalassinoides*-type and undefined burrows	undefined burrows
borings	*Gastrochaenolites* and *Trypanites*	*Gastrochaenolites* and *Trypanites*	*Gastrochaenolites* and *Trypanites*
encrustations	serpulids, oysters, bryozoans, crinoids, microbial crusts	serpulids, oysters, bryozoans, crinoids, microbial crusts	serpulids, crinoids, microbial crusts

removal of part of the less consolidated marly sediments, deposited beneath the hardground (e.g., Fürsich *et al*., 1992), due to bioerosion or the action of currents, which produced cavities with a cryptic fauna (e.g., Palmer and Fürsich, 1974; Taylor and Wilson, 2003). During the exhumation and erosion phases that followed, these cavities might have caused brecciation of the layer, which facilitated the formation of the HCs. A similar explanation of the destruction of the hardground may be related to the model described by Anketell *et al*. (1970), applied to deformational structures in systems with reversed density gradients. This model assumed that in a sedimentary sequence, in which an upper layer is characterized by brittle behavior, the disturbance resulting from liquefaction of a soft lower layer, may lead to the fracturing, fragmentation and collapse of a hardground. This model was used by Radwański (2003) in description of the genesis of the bored and encrusted HCs from Upper Kimmeridgian of the SW margin of the HCM, but it was not discussed in detail.

Factors triggering redeposition process

The calciturbiditic genesis of the HC-forming sediments as well as the later redeposition of the concretions (including rolling) indicates the presence of a distinct sea-floor relief and the action of mechanisms, generating mechanical erosion and redeposition of the sediments. An important fact may be a link of the area where the layer with HCs was observed to the NW-SE-trending, Holy Cross Fault (Fig. 1), active in the Late Jurassic (Kutek, 1994; Gutowski and Koyi, 2007; Krajewski *et al*., 2011). This dislocation separates the basement blocks of the Małopolska Block and the Łysogóry Block, both of them interpreted as Palaeozoic terranes (Fig. 1; Buła and Habryn, 2011; Kosakowski *et al*., 2012). The Early Kimmeridgian synsedimentary tectonics might have influenced the development of submarine redeposition of sediments, known from the HCM region (e.g., Radwański, 1960; Kutek, 1968, 1994; Migaszewski *et al*., 2006). These redeposition processes along the Holy Cross Fault are documented in the form of calciturbidites (Krajewski *et al*., 2011; this paper), erosion and redepositions of the hardground, and the HCs (Pszczółkowski and Kaźmierczak, 1968; Chudzikiewicz and Wieczorek, 1985; this paper), as well as debrites (Kutek, 1968; Migaszewski *et al*., 2006) and oolithic balls (Radwański, 1960; this paper). The synsedimentary movements might have contributed to the formation of small fault scarps, resulting in abrupt, lateral variation in facies and thickness and to the occurrence of angular boulders (e.g., Radwański, 1960; Fürsich *et al*., 1992; Drzewiecki and Simó, 2002).

The same features were observed in the southern part of the Kraków-Wieluń Upland (Kutek, 1994; Matyszkiewicz *et al*., 2006, 2012), where the transcontinental Kraków–Lubliniec Fault, similar to the Holy Cross Fault, was identified in the basement (Fig. 1; Buła and Habryn, 2011). The Kraków–Lubliniec Fault, which separates the SW margin of the Małopolska Block from the Upper Silesian Block (e.g., Matyszkiewicz *et al*., 2006; Buła and Habryn, 2011), also was active during the Late Oxfordian–Early Kimmeridgian, resulting in the formation of grain flow, debris flow, neptunian dykes, calciturbidite sediments and stromatactis-like cavities, known from the southern part of the Kraków–Wieluń Upland (e.g., Matyszkiewicz, 1997; Krajewski, 2000; Olchowy, 2011; Matyszkiewicz *et al*., 2006, 2012).

CONCLUSIONS

The authors' results clearly indicate distinct similarities in both the development and stratigraphic position (lowermost Kimmeridgian, Platynota Zone) of bored and encrusted HCs in three areas of Central Poland. Thus, the layer with the HCs should be regarded as an important marker horizon for correlation in the Upper Jurassic sediments in Poland, similar to other hardgrounds located in the Lower Kimmeridgian (Hypselocyclum Zone) succession, at the contact of the Oolithic and the Oncolithic lithostratigraphic horizons. These marker horizons are particularly valuable, owing to their extensive occurrence over a significant part of the area, occupied by Jurassic strata in Central Poland. Identification of these marker horizons in characteristic sedimentary sequences, observed in drill cores and in outcrops in Central Poland, may be crucial for the stratigraphic positioning of the sediments, if biostratigraphic data are insufficient.

The HCs indicate stratigraphic condensation after the early Kimmeridgian flooding, documented by marls and pelagic sediments represented by calciturbidites, mainly composed of calcisiltite. After deposition, these sediments were subjected to early lithification. The authors observed characteristic stages from soft-, and firm- to hardground, reflected in numerous generations of the borings *Gastrochaenolites* and *Trypanites* as well as serpulid, oyster, bryozoan and microbial encrustations. The origin of the HCs was related to the erosion of the hardground, followed by burial, submarine exhumation and redeposition.

The development of calciturbidites, erosion of the hardground and redeposition of the HCs as well as debrites and balls, known from deposits in the Platynota Zone of Central Poland, were initiated by the synsedimentary activity of the Holy Cross Fault, at the NE margin of the Małopolska Block. However, the phenomena in the Platynota Zone can be observed also in the southern part of the Kraków–Wieluń Upland, in the vicinity of another fault that was active during sedimentation, namely the Kraków–Lubliniec Fault at the SW margin of the Małopolska Block. This, in turn, clearly indicates the presence of a regional event, related to tectonic movements of the Małopolska Block (Palaeozoic terrane) as well as intensive erosion and redeposition at the NE and SW margins of this extensive tectonic block.

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