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SEDIMENTARY HISTORY AND BIOTA OF THE ZECHSTEIN LIMESTONE (PERMIAN, WUCHIAPINGIAN) OF THE JABŁONNA REEF IN WESTERN POLAND

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Abstract: The Jabłonna Reef, one of the reefs formed in Wuchiapingian time in the western part of the Wolsztyn palaeo-High (SW Poland), is characterized by quite irregular outlines and consists of three separate reef bodies (ca. 0.5–1.5 km^2 each; the thickness of the reef complex is usually >60 m). It is penetrated by four boreholes, which show two distinct phases of bryozoan reef development during deposition of the the Zechstein Limestone. The first one occurred early in the depositional history and botryoidal aragonitic cementation played a very important role in reef formation. This phase of bryozoan reef development terminated suddenly; one possible reason was that a relative change of sea level – first a fall and then a rise – disturbed the upwelling circulation. Consequently, bioclastic deposition predominated for a relatively long time until the second phase of bryozoan reef development occurred, but the latter was not accompanied by dubious early cementation. During this second phase, reticular fenestellid bryozoans were predominant. Subsequently, microbial reefs developed and abound in the upper part of the Zechstein Limestone sections. The general shallowing-upward nature of deposition in the Jabłonna Reef area resulted in reef-flat conditions with ubiquitous, microbial deposits, in the central part of the Jabłonna Reef. Then, the reef-flat started to prograde and eventually the entire Jabłonna Reef area became the site of very shallow, subaqueous deposition.

Five biofacies are distinguished in the Jabłonna Reef sections: the Acanthocladia biofacies at the base, then mollusc-crinoid, brachiopod-bryozoan, Rectifenestella and at the top, stromatolite biofacies. They represent a shallowing-upward cycle, possibly with some important fluctuation recorded as the distinctive lithofacies boundary, corresponding to the Acanthocladia/mollusc-crinoid biofacies boundary. The δ^{13}C curves of the Jabłonna 2 and Jabłonna 4 boreholes permit correlation of the trends in the middle parts of both sections and confirm the strong diachroneity of the biofacies boundaries, with the exception of the roughly isochronous Acanthocladia/mollusc-crinoid biofacies boundary. The presence of echinoderms and strophomenid brachiopods indicates that until deposition of the lower part of the Rectifenestella biofacies, conditions were clearly stenohaline. The subsequent elimination of stenohaline organisms and progressively poorer taxonomic differentiation of the faunal assemblage are characteristic for a slight, gradual rise in salinity. The taxonomic composition of organisms forming the Jabłonna Reef shows a similarity to reefs described from England and Germany, as well as the marginal carbonate platform of SW Poland. Filled fissures were recorded in the lower part of the Jabłonna Reef. The aragonite cementation recorded in some fissure fillings implies that they originated in rocks exposed on the sea floor and are neptunian dykes.

Key words: Wuchiapingian, reefs, Zechstein, bryozoans, stromatolites, aragonite cementation, neptunian dykes, carbon and oxygen isotopes.

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INTRODUCTION

Stromatolite and bryozoan reefs have been described from the marginal platforms of the Zechstein Limestone (Ca1) in various parts of the Southern Permian Basin of Europe (Paul, 2010, with references therein) including Poland (e.g., Lorenc, 1975; Peryt, 1978; Peryt *et al.*, 1978; Dyjaczyński, 2000). In western Poland, in addition to reefs occurring at the shelf-edge, isolated reefs have been recorded in the basinal facies of the Wolsztyn palaeo-Ridge area (Dyjaczynski *et al.*, 2001, with references therein). Previous studies of such reefs indicated that the main part of reef is made up of fragmented bryozoan zoaria (Dyjaczynski *et al.*, 2001; Kiersnowski *et al.*, 2010; Peryt *et al.*, 2012a). The colonization of the substrate began very early after the transgression, as indicated by the interbedding of breccia and bioclastic carbonates in some reef sections in the lowermost part of the Zechstein Limestone (D. Peryt *et al.*, 2012).

The Zechstein Limestone reefs of the Southern Permian Basin in Europe are characterized by an abundant fauna (see Kerkmann, 1969, and Hollingworth and Pettigrew, 1988); the most common taxa are bryozoans and thus Zechstein reefs are sometimes designated as bryozoan reefs (e.g., Smith, 1981a, b), although as pointed out by Paul (2010), the reefs are mostly microbial in origin. The base of each reef consists of wackestones and floatstones, composed of crinoids, bryozoans, brachiopods, bivalves and coated grains, and they are followed by bindstones formed by irregularly layered, microbial mats. Bryozoans, brachiopods and other fauna then progressively decline upwards and at the top, microbial communities appear and form extensive reef-flats. A second generation formed on top of the earlier reef-flat, owing to a new transgression that brought back a normal, marine, stenohaline fauna, such as bryozoans and brachiopods. This younger reef generation shows an evolution pattern, similar to that of the older reefs (Paul, 2010).

In this paper, the authors describe the sedimentary history and biota of one Zechstein Limestone reef, the Jabłonna Reef, recorded in the western part of the Wolsztyn palaeo-High area (SW Poland) (Fig. 1). It is characterized by distinctly elongated, quite irregular outlines and consists of three separate reef bodies, as established by a 3-D seismic study (Górski *et al.*, 2000; Dyjaczynski *et al.*, 2001), yet their lithofacies and biofacies sequences are very similar, as indicated by the initial survey by the present authors. The aim of this paper is to consider the possible controls on this similarity in facies.

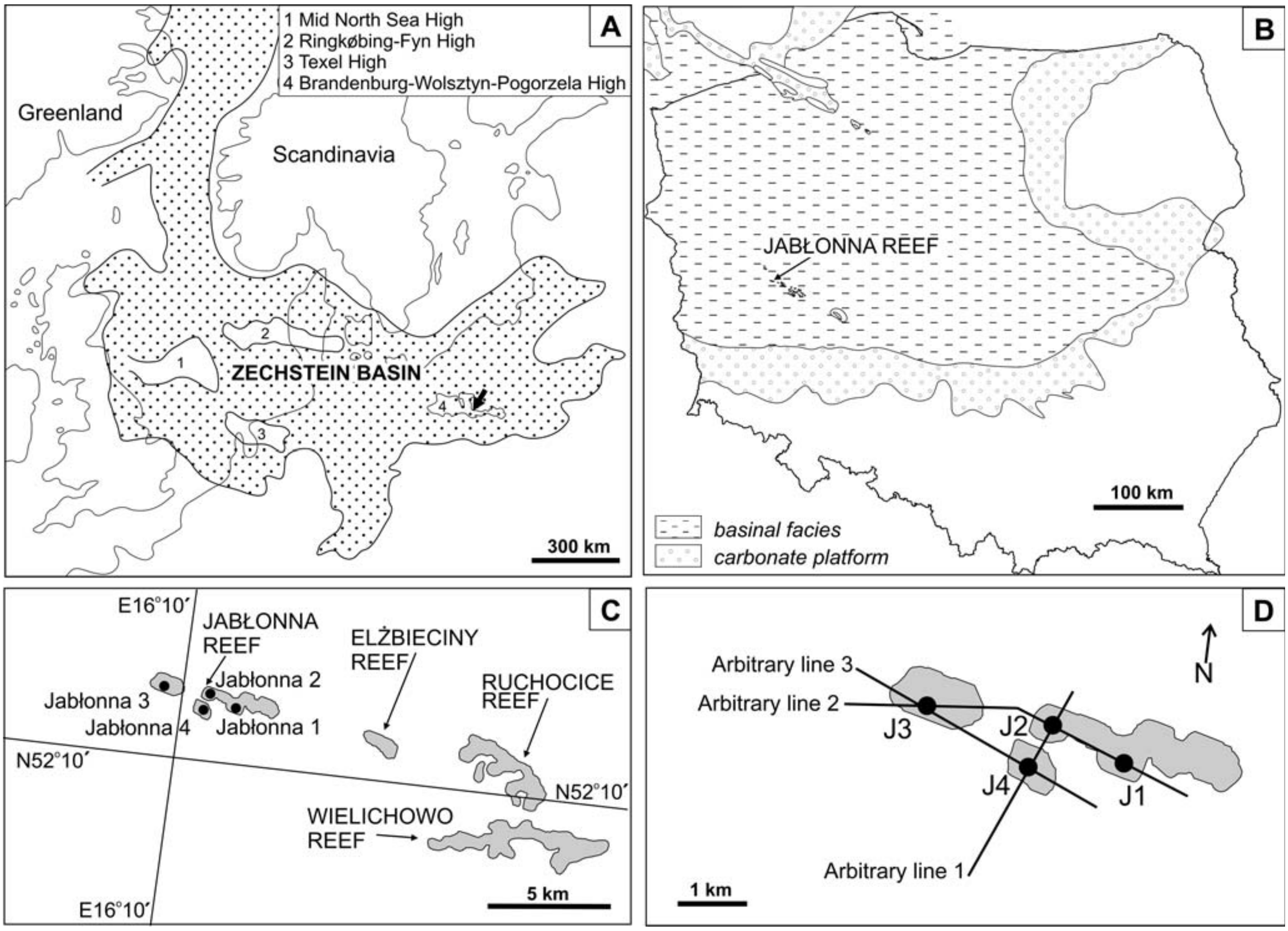

Fig. 1. Location map. **A.** Zechstein basin, showing the position of the Brandenburg-Wolsztyn-Pogorzela palaeo-High; arrow shows the position of the Jabłonna Reef. **B.** Basin facies of the Zechstein Limestone in Poland, showing the occurrence of isolated reefs related to the Brandenburg-Wolsztyn-Pogorzela palaeo-High. **C.** Outlines of the reefs delimited by seismic data and the occurrence of boreholes studied. **D.** Location of seismic sections shown in Figure 2.

GEOLOGICAL FRAMEWORK

Zechstein deposition in the Southern Permian Basin in Europe, which came into existence in the Late Carboniferous, commenced with flooding of the Rotliegend basin ca. 258 Ma ago (see Peryt *et al.*, 2012b, with discussion therein). This could have occurred later, as recently was concluded by Szurlies (2013) on the basis of a combination of magnetic polarity records, indicating that the basal Zechstein is most probably equivalent to the uppermost lower–upper Wuchiapingian (cf. Kozur, 1989, 1994; Denison and Peryt, 2009).

The oldest Zechstein sediments are those of the Kupferschiefer, which are not present on the elevated parts of the Brandenburg-Wolsztyn-Pogorzela High, where subsequently reefs were developed and the coeval transgressive systems tract (TST) deposits are the breccia (unit 1), occurring at the base of the Zechstein Limestone (D. Peryt *et al.*, 2012). The major part of the Zechstein Limestone deposits is a highstand systems tract. In the deeper parts of the basin, the Zechstein Limestone is developed in thin (<2 m thick), basinal facies (Peryt *et al.*, 2015, with references therein). The Zechstein Limestone is overlain by the Z1 (Werra) evaporites.

The central part of the Brandenburg-Wolsztyn-Pogorzela High, i.e. the Wolsztyn High, is characterized by the occurrence of reefs; those carbonate buildups originated and grew on the topmost edges of tilted blocks and/or on top of uplifted horsts (Kiersnowski *et al.*, 2010). These reefs are usually about one kilometre wide and a few are more than ten kilometres long (Mamczur and Czekański, 2000; Dyjaczynski *et al.*, 2001).

The Jabłonna reef is a typical example of such a pattern. The reef was penetrated by four boreholes: Jabłonna 1, 2, 3, and 4. In two of them (Jabłonna 2 and 3), the Zechstein Limestone deposits were cored completely, while in the Jabłonna 1 borehole the core recovery was almost complete; in Jabłonna 4, the coring was initiated some 2.5 m below the Zechstein Limestone top and in addition there is a minor gap in the core in the upper part of the Zechstein Limestone section of that borehole. The thickness of the Zechstein Limestone is >60 m in three boreholes (Jabłonna 1, 63.9 m; Jabłonna 3, 66 m; Jabłonna 4, 73.6 m) and only in Jabłonna 2 it is slightly less than 50 m. The analysis of 3-D seismic sections (Fig. 2) indicates that the Jabłonna Reef is composed of three parts: two smaller mounds, roughly elliptical, elongated WNW-ESE (penetrated by boreholes Jabłonna 3, situated clearly to the south of the reef centre, and Jabłonna 4, located approximately in the centre) and one elongated, larger mound (penetrated by boreholes Jabłonna 1, situated clearly to the south of the reef centre, and Jabłonna 2, located at its western end; Fig. 1C, D). During deposition of the basal Zechstein, presumably already during sedimentation of the Zechstein Limestone, active faulting (e.g., Jabłonna 3, Jabłonna 4) or flexural deflection (Jabłonna 1, Jabłonna 2) controlled the general facies pattern of the carbonate and evaporite facies. Above the elevations of the Zechstein substrate, composed of the Carboniferous sandstones (Jabłonna 1) and Rotliegend ignimbrites (Jabłonna 2, 3, 4) in the Jabłonna area, the Zechstein Limestone reefs are typically followed by anhydrite of the PZ1 cycle; the thickness of anhydrites in the Jabłonna boreholes is 59.2–66.0 m (Kiersnowski *et al.*, 2010, Table 1). The depressions between and outside the reefs are characterized by fill, consisting of very thin (a few metres at the most) Zechstein Limestone, underlain by the Kupferschiefer and thick anhydrite, and elsewhere in the western part of the Wolsztyn palaeo-High, thin Zechstein Limestone deposits and also halite deposits occur in addition to anhydrite (see Dyjaczyński and Peryt, 2014).

The Lower Anhydrite deposits in the region, in particular in the area of reef occurrence, show common pseudomorphs after selenitic gypsum (Hryniv and Peryt, 2010; Peryt *et al.*, 2010b; Dyjaczyński and Peryt, 2014). Ancient selenite facies occurred in a wide range of settings (Ortí, 2010); recent occurrences of modern, marine selenite facies include coastal salt works (i.e., evaporative salinas, e.g., Ortí Cabo *et al.,* 1984) and some natural, coastal lakes (e.g., Warren, 1982). A geological–geophysical correlation showed that there are two complexes of Lower Anhydrite occurring throughout the reef and basinal zones, showing a deepening-upward (transgressive) trend (Dyjaczyński and Peryt, 2014). The Oldest Halite sedimentation in the deepest parts of basins began shortly after deposition of the upper Lower Anhydrite complex, while in the reef area sulphate deposition lasted for a long time. The deposition of halite in the basin could have led to the elimination of the pre-existing relief, as precipitation of salts tends to level out any pre-existing topography, but subsequent early dehydration of thicker gypsum above and adjacent to the reefs created the accommodation space, making possible the deposition of the upper Oldest Halite. Accordingly, syndepositional subsidence, induced either by the dehydration of gypsum deposits or by reactivated former faults that in particular controlled the deposition of the lower Oldest Halite, was an additional, important factor controlling the development of the basal strata, but the prime control was inherited relief (see Dyjaczyński and Peryt, 2014).

The area underwent the main acceleration of burial during the Late Permian–Late Triassic, with additional burial events during the Jurassic and Late Cretaceous. The model implies higher heat flow in late Permian–Triassic, which would decrease subsequently during the Early Jurassic to Late Cretaceous uplift (see Kotarba *et al.*, 2006). At present, the top of the Jabłonna Reef occurs at a depth of ca. 2340 m.

MATERIAL AND METHODS

Four borehole sections (256.3 m of core in total) were measured. Macroscopic observations were controlled by the study of thin sections; altogether 211 thin sections were examined including 157 thin sections belonging to the Polish Oil and Gas Company (POGC).

The Jabłonna 2 and Jabłonna 4 borehole sections were sampled for carbon and oxygen isotopic studies; altogether 34 and 50 hand-picked samples of limestone were studied, respectively. In addition, six and eight samples from the fissure fillings of the Jabłonna 2 and Jabłonna 4 boreholes, respectively, were analysed. A 1.5-mm-diameter stainless

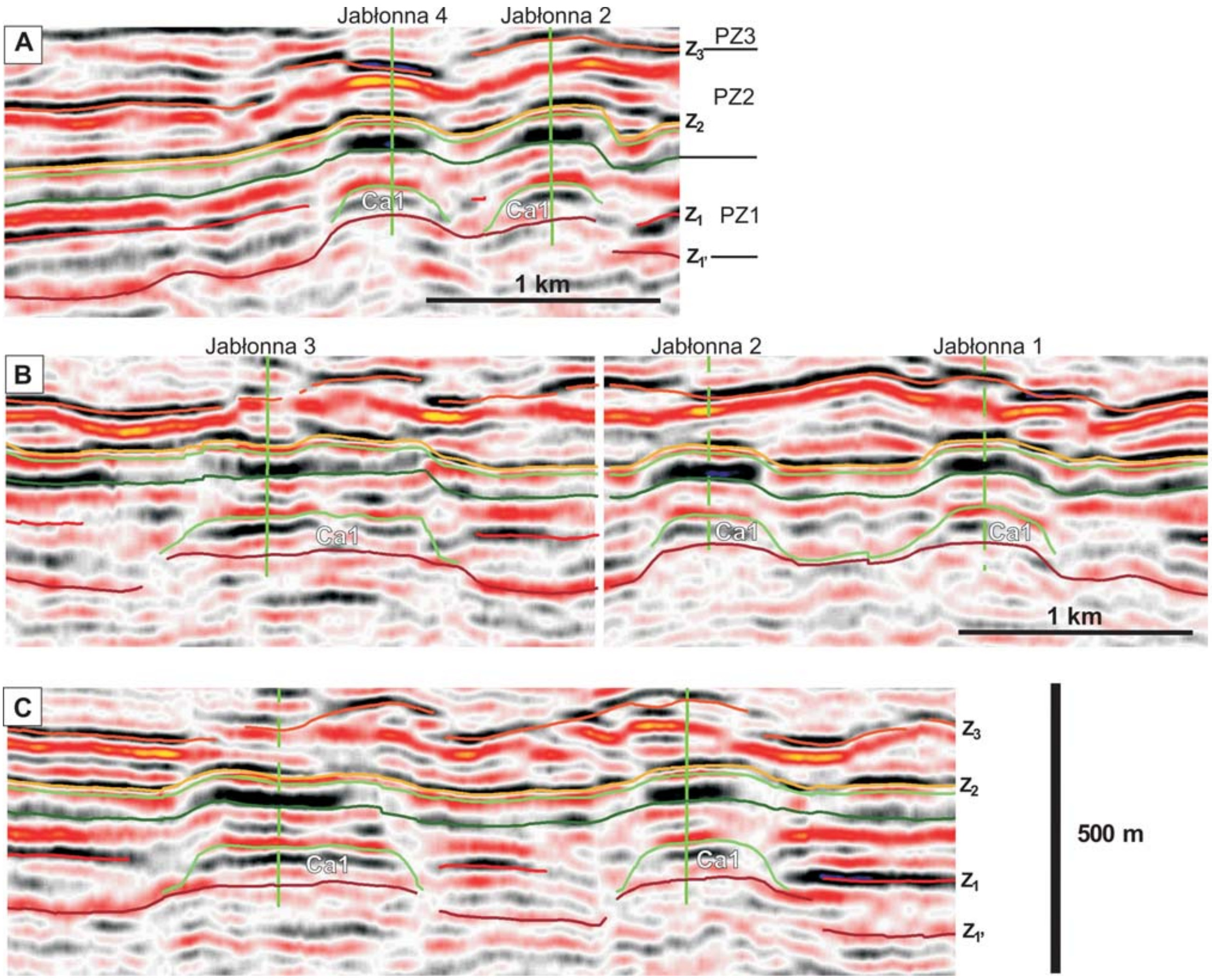

Fig. 2. 3-D seismic sections, comprising the depth intervals of 2,000–2,500 m; their location is shown in Figure 1D. **A.** Arbitrary line 1. **B.** Arbitrary line 2. **C.** Arbitrary line 3. Correlation of reflectors related to the boundaries of rocks with high acoustic impendence and rocks with lower acoustic impendence (Z_3 – bottom of Na3/top of A3; Z_2 – bottom of Na2/top of A2; Z_1 – bottom of Na1/top of A1d; $Z_{1'}$ – bottom of A1d or bottom of Ca1/top of T1 or of the Zechstein substrate) followed approach discussed by Antonowicz and Knieszner (1984) and Górski *et al.* (2000) (see Dyjaczyński and Peryt, 2014) and their relation to the Zechstein cycles PZ1–PZ3.

steel drill was used for the extraction of material from the surfaces of the samples. The samples were reacted with 100% phosphoric acid at 75°C, using a *KIEL IV* online automatic carbonate preparation line connected to a *Finnigan Mat delta plus* mass-spectrometer at the Light Stable Isotopes Laboratory of the Institute of Geological Sciences, Polish Academy of Sciences, Warszawa. All isotopic data were reported in per mil relative to VPDB, related to NBS 19. The precision (reproducibility of replicate analyses) of both carbon and oxygen isotope analyses was usually better than ±0.2‰.

The strontium isotope compositions in eight samples from the Jabłonna 2 and 4 boreholes were analysed at the Isotope Geochemistry Laboratory, Kraków Research Centre of Institute of Geological Sciences, Polish Academy of Sciences (see Peryt *et al.*, 2010c, for the analytical details). The material for the analyses was extracted from the surface of the fissure fills by a 1.5-mm-diameter stainless steel drill with tungsten carbide coating and then analysed by MC ICPMS Neptune in 2% HNO_3. Analyses were carried out in a static mode and performance of the instrument was monitored by frequent analyses of the SRM987 standard. Isotopic ratios were corrected for instrumental mass bias by normalising to $^{86}Sr/^{88}Sr = 0.1194$ using the exponential law. Reproducibility of the SRM987 over the period of analyses was $^{87}Sr/^{86}Sr = 0.710261 \pm 11$ (2SD error, n = 4), which is almost identical to reproducibility for 216 analyses of the same standard ($^{87}Sr/^{86}Sr = 0.710262 \pm 13$). The results obtained were normalized to the recommended SRM987 value $^{87}Sr/^{86}Sr = 0.710248$. The precision of individual $^{87}Sr/^{86}Sr$ ratios in Table 1 refers to the last significant digits and is at the 2SE level. The total procedure blank was below 50 pg. Howarth and McArthur (1997) compiled $^{87}Sr/^{86}Sr$ data and fitted to them a nonparametric LOWESS statistical regression function to convert quickly and easily from $^{87}Sr/^{86}Sr$ to numerical age; the present authors applied their LOWESS Version 4: 08/04 (McArthur *et al.*, 2001).

RESULTS

Lithology

The mineralogical composition of the Zechstein Limestone of the Jabłonna Reef shows some variation (Fig. 3), although limestone is the main rock type in all boreholes. Dolomite is rare; it occurs in the topmost part of the Zechstein Limestone in the Jabłonna 1 borehole and in the middle part of the Jabłonna 1 and Jabłonna 4 cores (Fig. 3), above the distinctive lithofacies and biofacies boundary (Figs 4, 5A). In addition, in the lower part of the unit of the Jabłonna 2 borehole, four intercalations (each a few tens of centimetres thick) of dolomite occur and a 1-m-thick bed occurs in the lower part of the Jabłonna 4 borehole, associated with calcareous dolomite. Calcareous dolomites also were recorded in the topmost part of the Jabłonna 2 and Jabłonna 3 boreholes and in the middle part of the Jabłonna 1 borehole (Fig. 3). In addition, thicker complexes of dolomitic limestones occur in the lower and middle parts of the Jabłonna 3 borehole and thinner complexes occur in the Jabłonna 2 and 4 boreholes (Fig. 3). The dolomite content in dolomitic limestones is frequently *ca*. 10% although in the lower part of the Jabłonna 3 borehole it is close to 50%. Even in limestones dolomite was encountered as forming grains and cements (in particular in the middle part of the Jabłonna 1 borehole, upper part of Jabłonna 3 borehole and middle and lower parts of the Jabłonna 4 borehole (Fig. 3). Similarly, in dolomite strata (such as in dolomite occurring in the lower part of the Jabłonna 1 borehole), irregular lenses (up to 20 cm or so thick) and millimetres-thick (or smaller) streaks of limestone occur.

A common constituent of the Zechstein Limestone rocks is anhydrite, usually occurring in the form of nodules. Its increased concentration (up to 40%) is mostly associated with intervals of dolomite-bearing strata and adjacent to them. Celestite, fluorite and barite are rare and where they occur, their content in thin section is a small fraction of 1%.

Most of the Zechstein Limestone sections of the Jabłonna Reef are composed of bioclastic (mostly bryozoan) grainstones (Figs 6, 7A, B, 8, 9B–D) that are accompanied by packstones and more rarely wackestones, except for in the uppermost part of the sections, and of bryozoan and microbial boundstones (Fig. 3). The uppermost part consists of breccias (Fig. 3) that are not considered in detail in this paper. In the Jabłonna 1 borehole, stromatolitic-pisolitic carbonates, typical of unit 5 of Dyjaczyński *et al.* (2001; Kiersnowski *et al.*, 2010), are common within the breccia unit (3.2 m thick). In the Jabłonna 2 borehole, the breccias (1.4 m thick) consist of clasts of limestones (mostly bryozoan grainstone and stromatolite) in the dolomite matrix and in some instances dolomicrite with quartz silt and micas (of aeolian origin?) was recorded. In the Jabłonna 3 borehole, similar breccias are thicker (4.8 m) and in their lower part the matrix is calcitic. In the Jabłonna 4 borehole, breccias are absent, but the topmost *ca*. 2.5-m-thick interval of the Zechstein Limestone was not cored.

The bryozoan grainstones contain intercalations (several tens of centimetres thick) of bivalve coquinas that are particularly common in the Jabłonna 2 borehole (Fig. 6D). In addition, the units of bioclastic (mostly bryozoan) grainstones, as shown in Figure 3, contain rare intercalations of rocks with a greater amount of matrix (of packstone and wackestone textures). In the Jabłonna 1 and 3 boreholes, in the upper part of the Zechstein Limestone, there are intervals, in which the depositional textures cannot be recognized (Fig. 3). However, in at least some parts of these recrystallized strata stromatolites occur (Figs 3, 10C), in addition to other steep-dipping, laminated encrustations (Fig. 3) that in some instances were thicker than the core diameter (10 cm). Both stromatolites and the laminated encrustations occur also in the adjacent strata (Figs 3, 6A, 7A, B, 10, 11A, B) and hence it seems that the primary, depositional textures of these recrystallized strata did not differ much in the range of wackestone to packstone (in the Jabłonna 1 borehole) and packstone to grainstone (in the Jabłonna 3 borehole). The encrustations were recorded in the upper part of the Jabłonna 2, Jabłonna 3 and Jabłonna 4 boreholes; in the Jabłonna 2 borehole they occur almost throughout the entire section, above the lithofacies and biofacies boundary (Fig. 3). In the Jabłonna 4 borehole, the encrustations occur also below the boundary (Fig. 3). Because the encrustations are steep-dipping, it is highly probable that in fact they are actually more common in vertical section than is shown in Figure 3, because the core could pass between the succeeding generations of encrustations (see Fig. 7A).

Stromatolites of the Jabłonna Reef commonly are crudely laminated and show a variety of forms (Fig. 10). They occur as planar millimetric–centimetric stromatolites, passing in some cases into domal forms, as observed both on polished slabs (Fig. 7A, B) and under the microscope (Fig. 10D, E), and into columnar stromatolites (Figs 10A, B, 11A, B). The columns are usually 2–6 cm high, and occasionally they evolved into planar forms (Fig. 10A). Usually, columns are inclined (Fig. 10A, B), with the deviation from the vertical direction varying during stromatolite growth by up to 70°.

In the lower part of the Zechstein Limestone, within bryozoan grainstone/boundstone, a distinct lithofacies and biofacies boundary was observed (Figs 4, 5A). It is arrowed in Figure 3. There, above dark limestone with abundant, botryoidal cement, very dark to black in colour, showing in some cases branching down (or up) of cement concentrations into several parts and then diffusing (Fig. 5E), beige dolomite (Jabłonna 1 and 4) or dolomitic limestone (Jabłonna 2 and 3) occur and at the same time a change in microfacies type was noted (Fig. 4). Rare, black cement concentrations were also recorded in the middle part of the Zechstein Limestone in the Jabłonna 4 borehole (Fig. 3).

The thickness of strata located below the boundary shows great variation (from 8 m in the Jabłonna 2 borehole to 28.5 m in the Jabłonna 4 borehole). In turn, the thickness of the upper unit, above the boundary to the base of breccia unit, is remarkably similar (from ca. 38 m in the Jabłonna 3 borehole to 45 m in the Jabłonna 4 borehole).

It should be mentioned that in the Jabłonna 3 and Jabłonna 4 boreholes, dolomitic limestone–dolomite appear earlier in the Zechstein Limestone section, but these occurrences are not accompanied by a microfacies change.

The bryozoan grainstones in the Jabłonna 2 and 4 boreholes are cut by subvertical to vertical fissures (Figs 6A–C, 8).

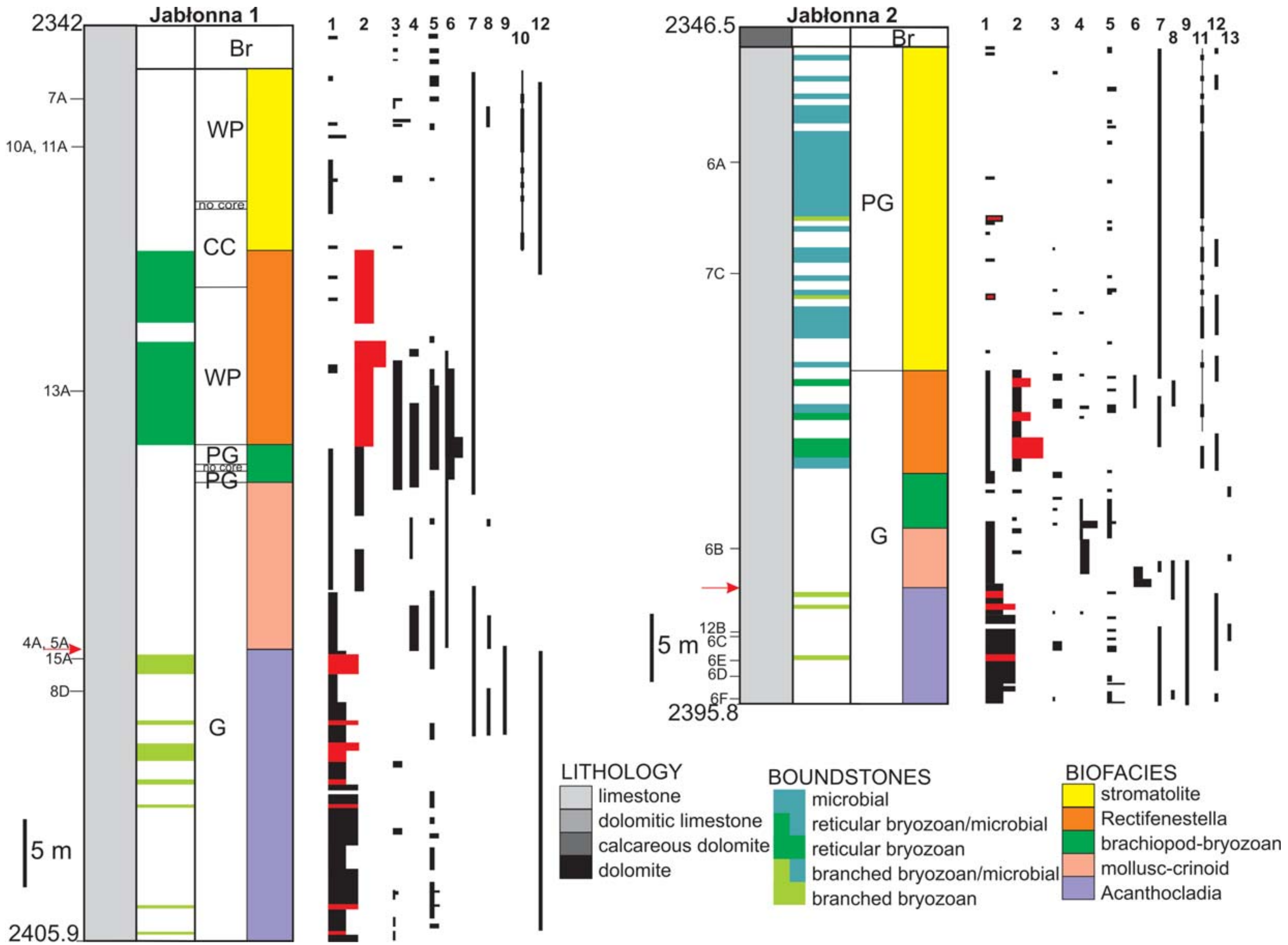

Fig. 3. Major lithologies, textural types, and biofacies in the Jabłonna 1, 2, 3 and 4 boreholes, showing – left of the lithology column – location of some photos in the borehole sections. Lithology column (outer left part of the column) shows the predominant carbonate rock; red arrow indicates the characteristic lithofacies-biofacies boundary discussed in the text and illustrated in Fig. 4. The central columns show the major occurrence of boundstones (yellow green – branched bryozoan; green – reticular bryozoan; marine – microbial) – left central column; and the predominant depositional texture (CC – recrystallized carbonate; G – grainstone; P – packstone; PG – packstone to grainstone; WP – wackestone to packstone) right central column.

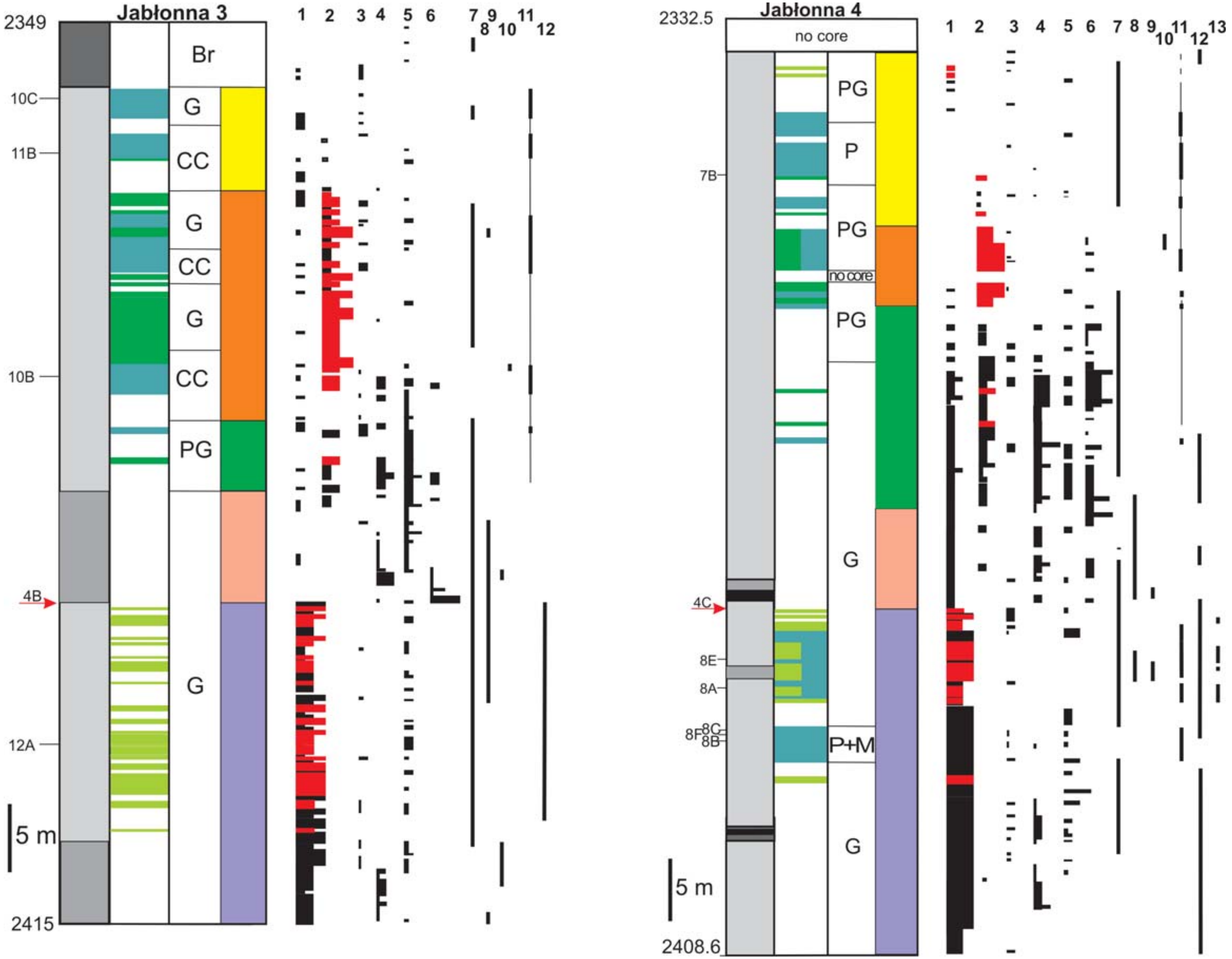

Fig. 3 continued. The outer right column shows the biofacies distinguished. Right of the columns, relative frequency of macrofauna (the thicker the column, the more abundant faunal group) and recorded occurrence of microfauna, microbial encrustations (including stromatolites), pseudomorphs after (mostly) botryoidal aragonite and neptunian dykes are shown. A1 – PZ1 Anhydrite; Br – breccia unit; 1 – branched bryozoans (red: in life position); 2 – reticular bryozoans (red: in life position); 3 – terebratulid brachiopods; 4 – strophomenid brachiopods; 5 – molluscs (gastropods and bivalves); 6 – crinoids; 7 – encrusting foraminifers, 8 – spiral foraminifers; 9 – uniserial foraminifers; 10 – domal stromatolites; 11 – microbial encrustations, mostly steep; 12 – primarily aragonite cementation; 13 – neptunian dykes.

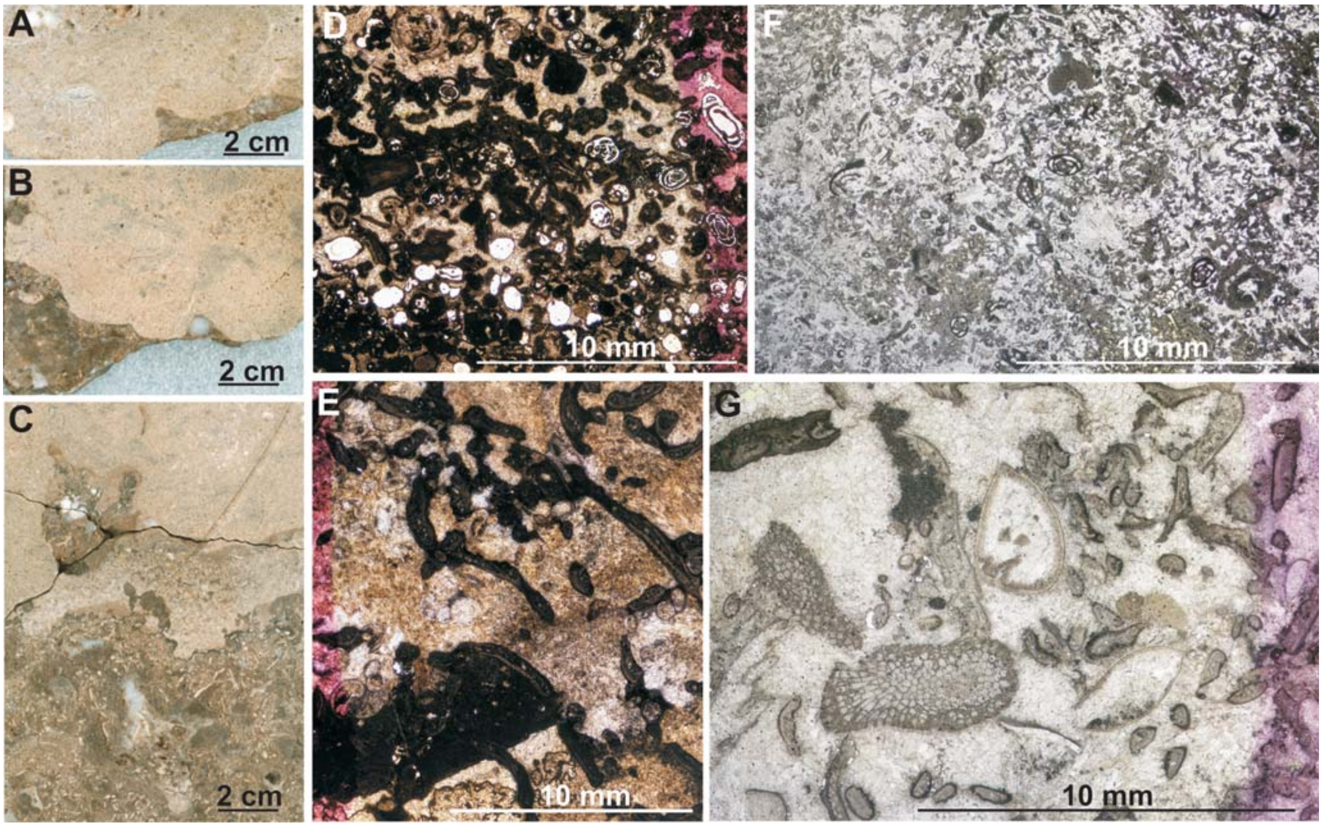

Fig. 4. A characteristic correlation surface in the Zechstein Limestone of the Jabłonna Reef. **A.** Jabłonna 1, 2385.3 m. **B.** Jabłonna 3, 2391.75 m. **C.** Jabłonna 4, 2380.2 m. Bioclastic grainstone (calcareous dolomite in Jabłonna 1 and dolomite in Jabłonna 4) occurring above it: **D.** Jabłonna 1and **F.** Jabłonna 4. Bryozoan bafflestone/grainstone (limestone) with abundant originally aragonitic botryoidal cement below it: **E**. Jabłonna 1, **G.** Jabłonna 4.

These fissures occur below the lithofacies and biofacies boundary (Jabłonna 2 and Jabłonna 4) and above it (Jabłonna 2). They are characterized by usually planar boundaries (Figs 6B, 8). The fissures broaden towards the bottom and show several generations of fill, as indicated by the different colours of micritic limestone occupying the fissures. In one case (Fig. 8A), it was observed that the fissure shows the U-shaped trace fossil *Diplocraterion* made by suspension-feeders (Schlirf, 2011), indicating that the fissure was used by burrowing organisms and thus supporting the very early-penedepositional origin of the fissures and their fillings.

Petrology

The Zechstein Limestone rocks suffered diagenetic changes. However, except for the upper part of the Jabłonna 1 borehole section, where recrystallized limestone occurs (Fig. 3), these did not obliterate sedimentary structures and textures to such an extent as to make it impossible to decipher the original textures. One exception is the steep-dipping encrustations that suffered pervasive recrystallization, destroying all primary, microscopic features. Diagenetic alteration is variable in its intensity and spatial distribution. Dolomitisation, both fabric-preserving and fabric-destructive (cf. Jasionowski *et al.*, 2014), plays the most important role; other significant, diagenetic processes include calcite cementation of synsedimentary, meteoric and burial origins, and dolomite and anhydrite cementation and recrystallisation. When calcite and dolomite co-occur in dolomitic limestones, they show rarely (as in the lower part of the Jabłonna 3 borehole and in the middle part of the Jabłonna 4) a textural control, with the grains being calcitic and the matrix dolomitic (Fig. 9C, D); in most cases, there is no such regularity and in fact, there is no pattern.

Extraclasts are rare. They were recorded only in the Jabłonna 4 borehole. Just above the Rotliegend ignimbrites, the clasts derive from the immediate neighbourhood. In addition, they occur at *ca*. 16.5 and 17.8 m above the base of the Zechstein Limestone in the borehole and consist of clasts of grey siltstones that are usually millimetres in size.

In addition to ubiquitous bryozoan bioclasts, other fauna also occur: brachiopods, bivalves, gastropods, ostracods, crinoids, echinoids, and foraminifers (Figs 3, 5, 6, 8, 9, 11–20).

Bioclastic sediments are synsedimentary cemented with fibrous calcite rims and fans, showing two main growth morphologies: crusts and botryoids (Figs 9, 14, 15, 16A, B). The fans are usually black or dark in colour. Although the fans presently are composed of calcite, their form and acicular growth forms and blocky to square terminations of calcite crystals as well as an interlocking mosaic of equant calcite, commonly were produced during aragonite inversion to calcite (Sandberg, 1985; Wilkinson *et al.*, 1985), indicating that the original composition of the fans was aragonite (e.g., Loucks and Folk, 1976; Assereto and Folk, 1980;

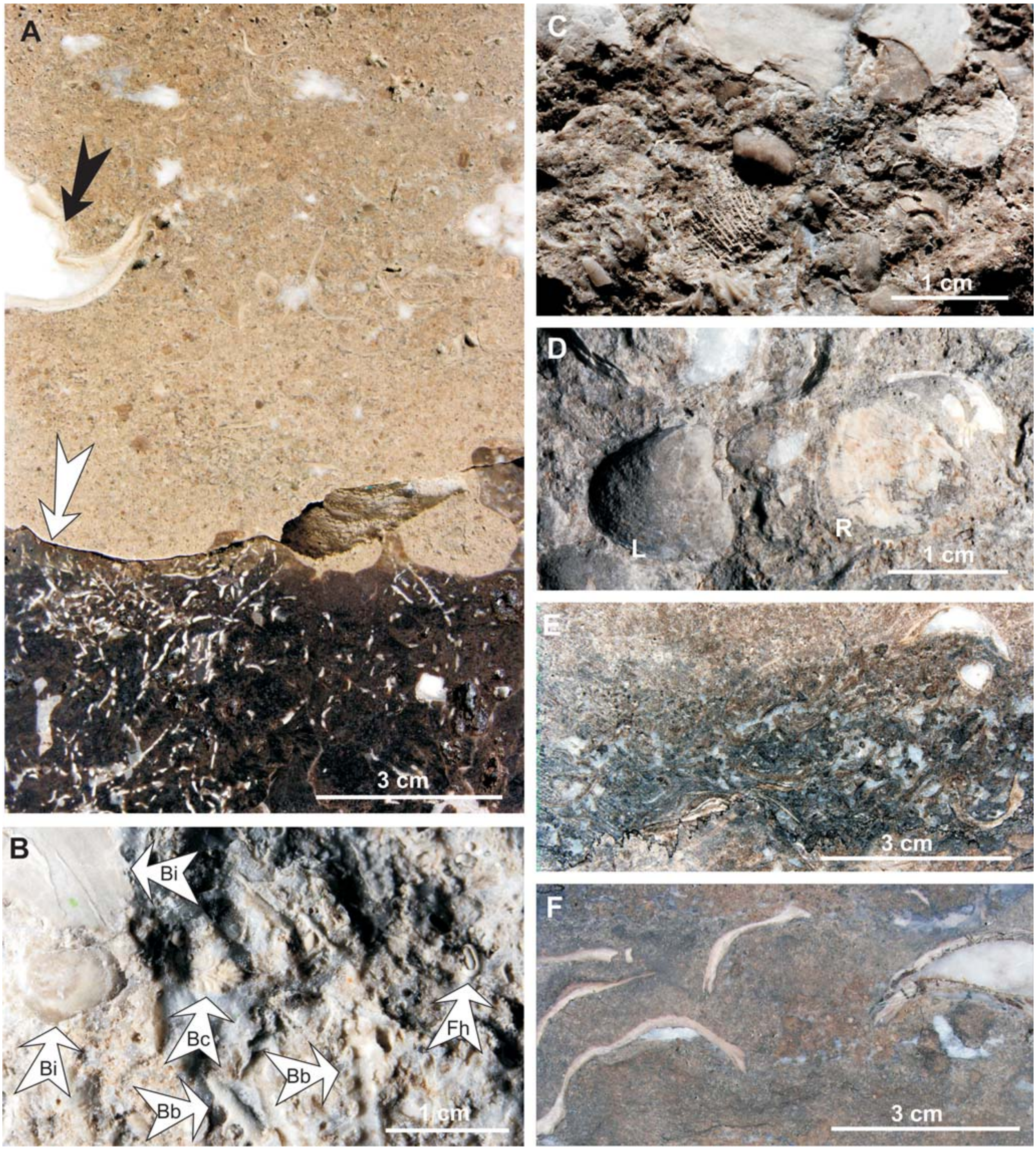

Fig. 5. Mollusc-crinoid biofacies. **A.** Boundary (white arrow) between bryozoan bafflestone of Acanthocladia biofacies (limestone, below) and bioclastic grainstone of mollusc-crinoid biofacies (dolomitic limestone of dolomite content of *ca*. 10%; cf. Fig. 4A). Black arrow - *Horridonia horrida* (Sowerby) shell in mollusc-crinoid-bryozoan grainstone. Jabłonna 1, 2382.4 m. **B.** Bivalve (Bi) shells, branched (Bb) and columnar (Bc) bryozoan zoaria, hemigordiopsid foraminifers (Fh). Jabłonna 4, 2377.15 m. **C.** Debris of bivalve and brachiopod shells, fenestral and branched bryozoan zoaria. Jabłonna 2, 2382.45 m. **D.** Bivalve coquina. Jabłonna 3, 2386.65 m. **E.** Internal mold of left valve (L) and right valve (R) of *Pseudomonotis speluncaria* (Schlotheim). Jabłonna 4 2373.9 m. **F.** Disarticulated, strophomenid brachiopod shells, lower part of biofacies. Jabłonna 3, 2390.25 m

Mazzullo, 1980; Sandberg, 1985; James and Choquette, 1990; Peryt *et al.*, 1990; Sumner and Grotzinger, 2000). There are common, dark inclusions, showing a parallel orientation in the fans, and growth banding occurs, marked by irregular, indented surfaces between crusts common dark inclusions showing a parallel orientation. Botryoids exhibit no preferential growth direction, as can be seen in Figure 10, where botryoids grew out into pores from the floors,

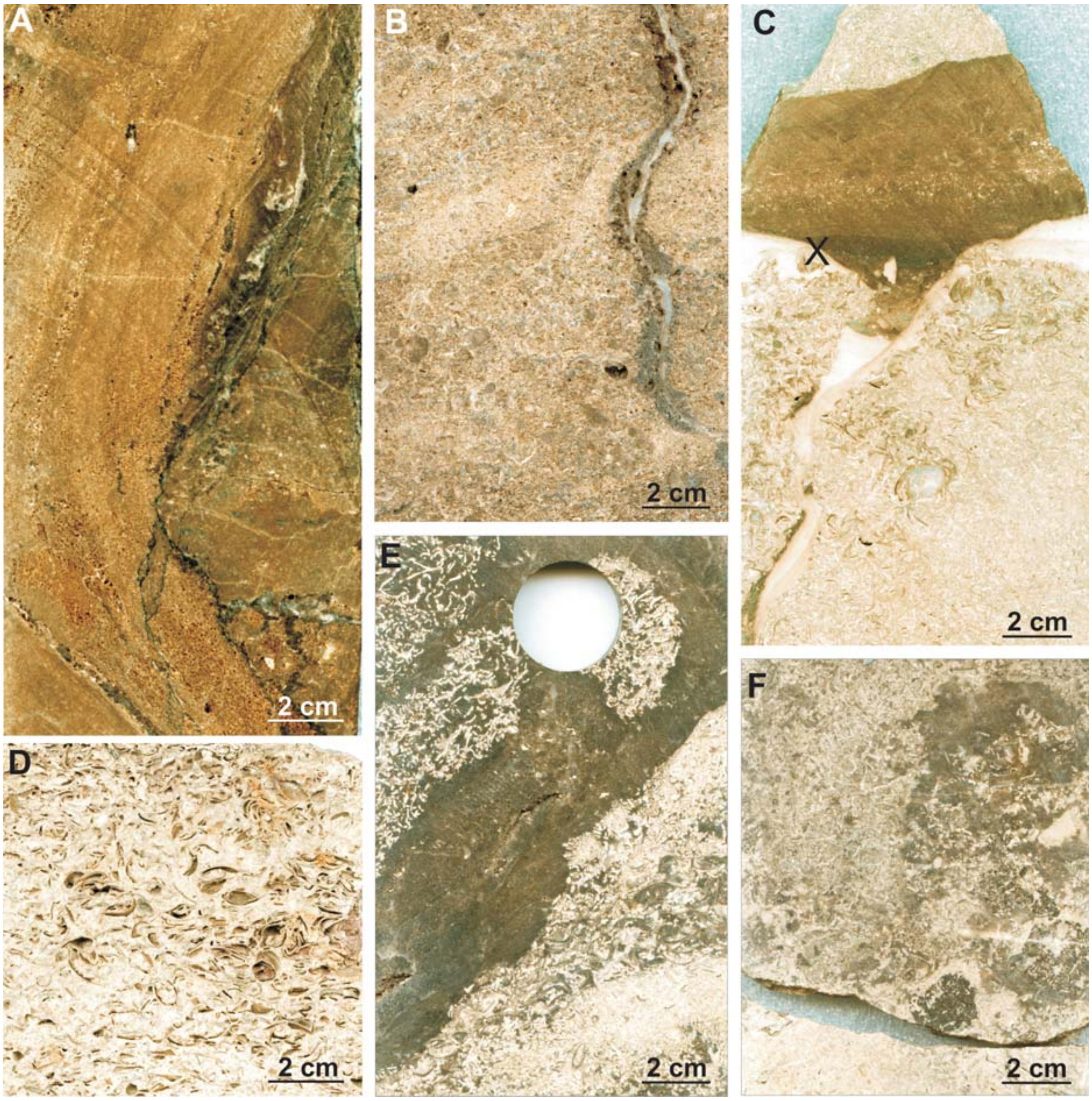

Fig. 6. Photos of core slabs from the Jabłonna 2 borehole (see Fig. 3 for their location). **A.** Steep laminar encrustations composed of sparite, showing post-aragonitic fabric in places. **B.** Recrystallized granular limestone with a neptunian dyke, shown in Figure 16C. **C.** Recrystallized grainstone with an oblique fissure, filled by laminated fine peloidal deposit (microbial?), in the upper part peloidal deposit with large bioclasts covered by dark sparite (X shows location of thin section shown in Figure 15B). **D.** Bivalve grainstone. **E.** Dark fissure-like occurrence of post-aragonitic calcite cement within bioclastic (mostly bryozoans) grainstone. **F.** Bryozoan grainstone with sparitic cement overlying ignimbrites.

walls, or ceilings of the cavities, formed by the bryozoan framework. Such no-preferential-growth of botryoids is characteristic for the slopes of the Bahamas and Belize (Grammer *et al.*, 1993).

Often sparite, forming crusts other than steep-dipping encrustations, composed of botryoidal fans (as shown in Figs 15A, B, 16A), is related to changes in the rock texture. For example, Figure 15A shows a bryozoan grainstone, occurring ca. 1.3 m below the lithological boundary in the Jabłonna 1 borehole, covered by bioclastic (mostly ostracod) wackestone, passing into ostracod packstone (the lower, light part of the core slab; Fig. 15D), overlain by sparite (primarily aragonite hemispheroids; Fig. 15B). The sparite contains isolated ostracods with thick foraminiferal encrustations (such as those occurring in the packstone shown in Fig. 15C), followed by bryozoan grainstone (the uppermost part of the core slab). In the Jabłonna 2 borehole, ca. 3 m below the lithological boundary, sparite crusts overlie a peloidal deposit with bioclasts (bryozoans, rare gastropods, shells, foraminifers, ostracods) (Fig. 16A). However, sparite crusts often overlie bioclastic grainstones, as well (Figs 9B, 16B).

The fill of most fissures is mainly micritic, faintly laminated and occasionally peloidal (Figs 8, 17, 20A, B). A cross-section of some fissure fills shows consecutively a vaguely laminated part, a sparite part, and then a thin micritic part (Fig. 17C, F); the lamination follows the inclination (mostly

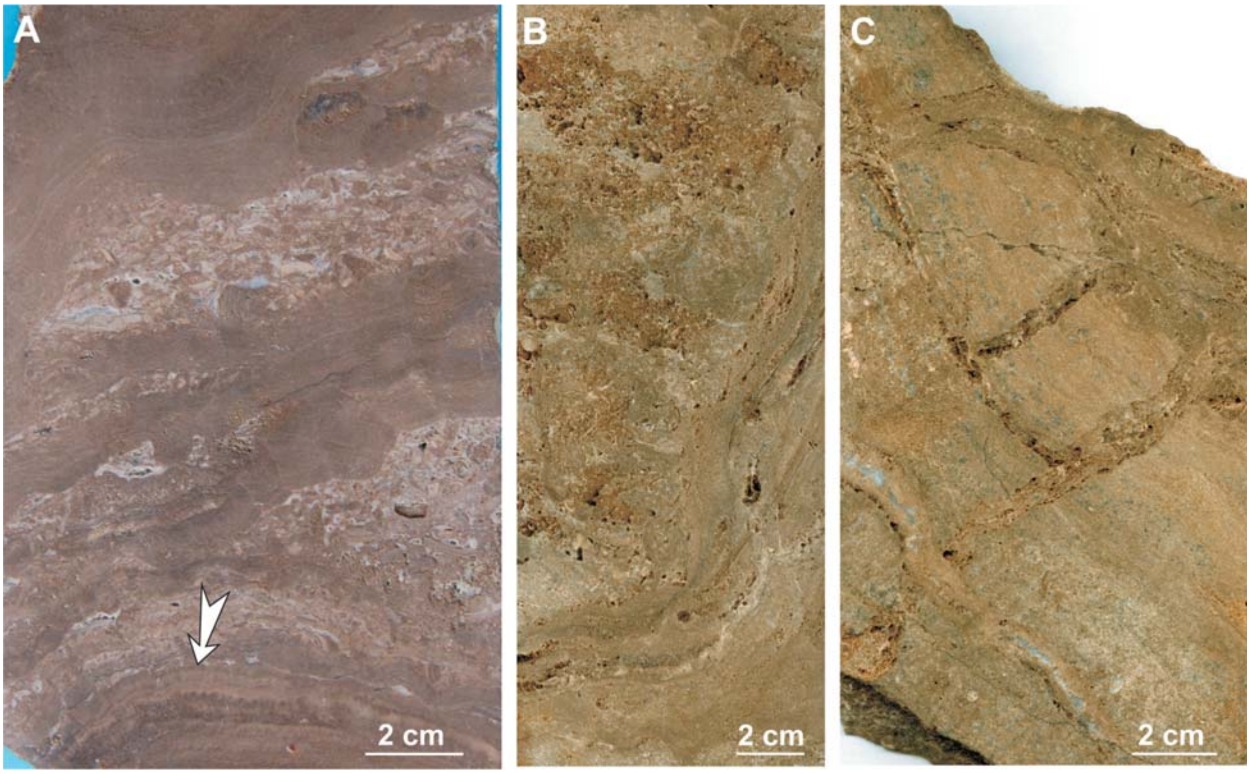

Fig. 7. Microbial encrustations. **A.** Approximately horizontal microbial encrustations of grainstone; notice microcolumnar fabrics (arrowed, lower part; Jabłonna 1). **B, C.** Steep to subvertical encrustations (cracked in C) of grainstone (B – Jabłonna 4; C – Jabłonna 2).

close to vertical; see Fig. 8) of former fissures. Other fissure fills are composed of peloidal and sparitic parts (Fig.17G) or of laminated micrite, in places peloidal, with rare quartz grains of the silt fraction occurring in micrite (Fig. 17B, H). There sparite cement occurs, characterized by the ubiquitous nature of aragonite pseudomorphs in some fissure fillings (Fig. 16C). In a few cases, it was noted that the sparite fill of the fissure, showing clear botryoids, was overlying horizontally laminated, peloidal deposits. Figure 8E shows a 7-cm-thick fissure fill, consisting mostly of sparite and anhydrite that in other fissure fills on occasions forms their thin, axial component. However, an outer part of this fissure fill, shown in Figure 17D, contains a horizontally laminated, peloidal deposit (Fig. 20A, B) that is arranged perpendicular to the laminated deposit, forming the bulk of the fill (Fig. 8E). Both the micrite and sparite components of fissure fills are calcite; no dolomite was recorded.

Biota

Foraminifers. Encrusting foraminifers are very common throughout the entire section of the Zechstein Limestone, except for in its lowest part (Figs 3, 9A, D, 14, 17–20). Only in the Jabłonna 2 borehole they were recorded in its lowest part, but it may be that this interval corresponds to slightly higher levels in other boreholes, as discussed below. In contrast, the distribution of uniserial and spiral foraminifers is rather sparse. Both groups occur in the lower part of the Zechstein Limestone, both below and above the distinctive lithofacies and biofacies boundary. In addition, spiral foraminifers are rarely recorded in the middle and upper parts of the Zechstein Limestone (Fig. 3).

Encrusting foraminifers mostly are related to bryozoan clasts and the entire bryozoan colonies (Figs 9A, 14A, 18K, M), but they also are found on bivalve shells (Fig. 14B–D), crinoid fragments (Fig. 9C) and gastropod shells (Fig. 9C). In addition, they are common in the recrystallized limestones of supposedly microbial origin and the arrangement of foraminifers indicates that they formed coatings on stromatolites. This in turn indicates calcification at the surface (see Flügel, 2010, with references).

Vachard *et al.* (2010) concluded that all Miliolata in the Permian were represented by undivided, tubular chambers with diverse types of coiling. Tubular foraminifers were accompanied by variable, encrusting microorganisms and are referred to by the name *Palaeonubecularia* (e.g., Kabanov, 2003, pl. 42, fig. 3).

Bryozoans. Bryozoans are the main, biotic component in the Jabłonna Reef. Their skeletons form the packstones, grainstones and boundstones of the lower part of the section and in addition are abundant in other parts of it (Figs 3, 5A–C, 11D, 12A–B, F, 13A–D). The most common are representatives of the family Acanthocladiidae (mostly *Acanthocladia*, more rarely *Thamniscus*, *Synocladia*, *Penniretepora* and *Kalvariella*), with pinnate, branched or massive, reticular (*Synocladia*) zoaria. Their complete or crushed skeletons, mostly belonging to various species of *Acanthocladia*, are the main constituents of the lower part of the section, but in addition they also occur, in variable quantities in other parts of the section (Fig. 3). In the lower part of the

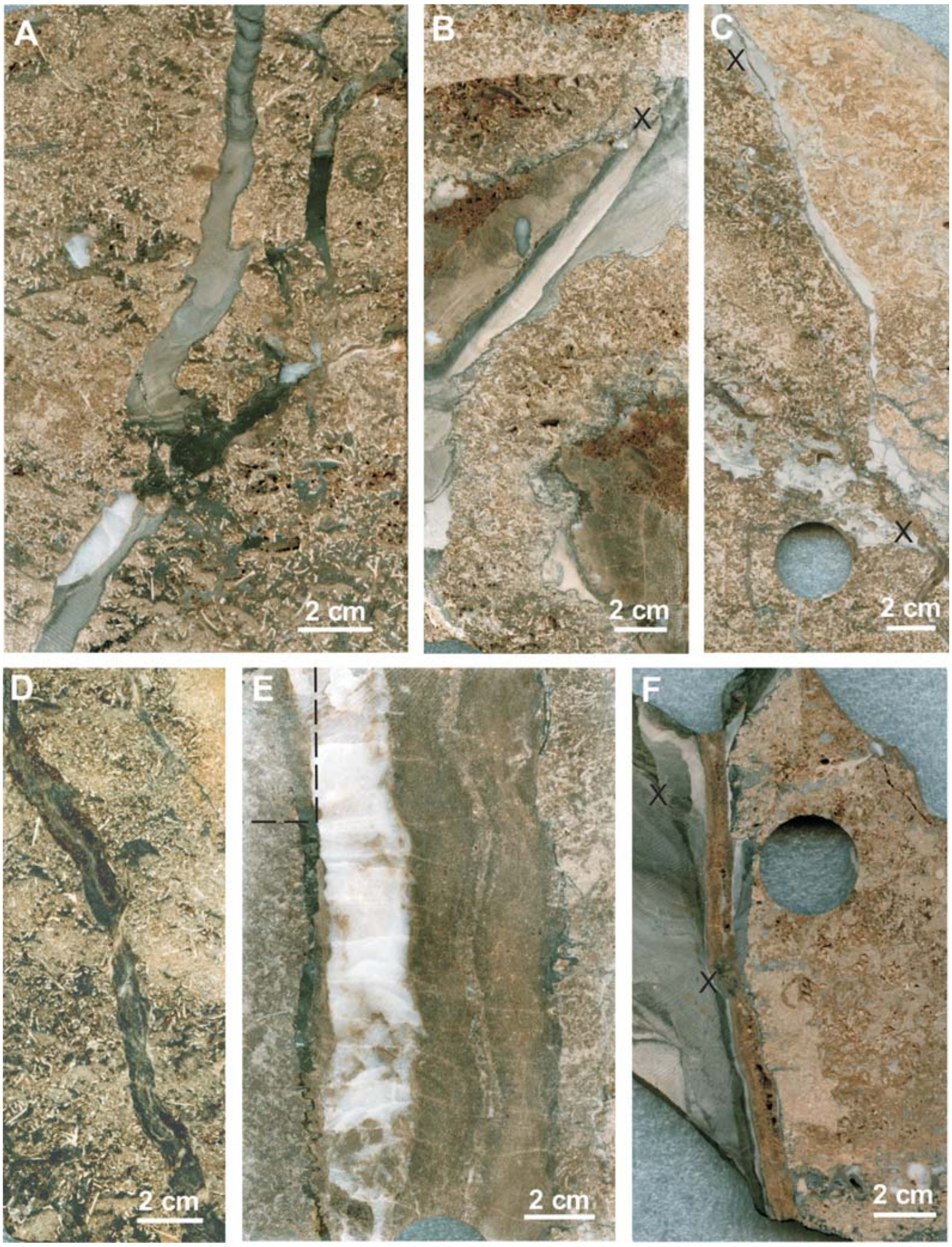

Fig. 8. Examples of fissure fillings in the Jabłonna 4 (A–C, E–F) and Jabłonna 1 (D) boreholes, with X showing the location of thin section illustrated in Figure 17. **A.** Fissure filled by micrite showing burrows. **B.** Micritic, multi-phase filling of fissure, locally peloidal (in particular close to the fissure borders); detail shown in Fig. 17A. **C.** Micritic fill of the fissure cutting recrystallized bryozoan grainstone with post-aragonitic cement; details shown in Fig. 17B, H, I. **D.** Fissure filled by sparite. **E.** Fissure filling consisting of post-aragonitic sparite and anhydrite; the upper left corner of the sample is shown in Fig. 17D. **F.** Complex fill of fissure including polyphase micritic, peloidal, and sparitic parts; details shown in Fig. 17C.

section, representatives of the family Dyscritellidae (*Dyscritella*) also occur with massive (Fig. 9A) or incrusting (Fig. 12E) zoaria. Representatives of family Fenestellidae (*Rectifenestella*, *Spinofenestella*) are common, occurring mostly in the lower part of the upper interval of the Zechstein Limestone (Fig. 3) and characterized by delicate, reticular zoaria. As opposed to other bryozoans, they did not require a solid substrate and the vertical orientation of colonies was achieved owing to lateral spines. Rare representatives of the family Reteporinidae (*Kingopora*) occur mostly in the middle part of the section, having more massive reticular zoaria than fenestellids.

These stationary, epifaunal suspension feeders are very good palaeoenvironmental indicators, in particular for energy conditions. They can be evaluated by zoaria shape: delicate fenestrate (fenestellids) in low energy and more and more massive and less ramified (acanthocladids) up to massive (dyscritellids) with increasing energy.

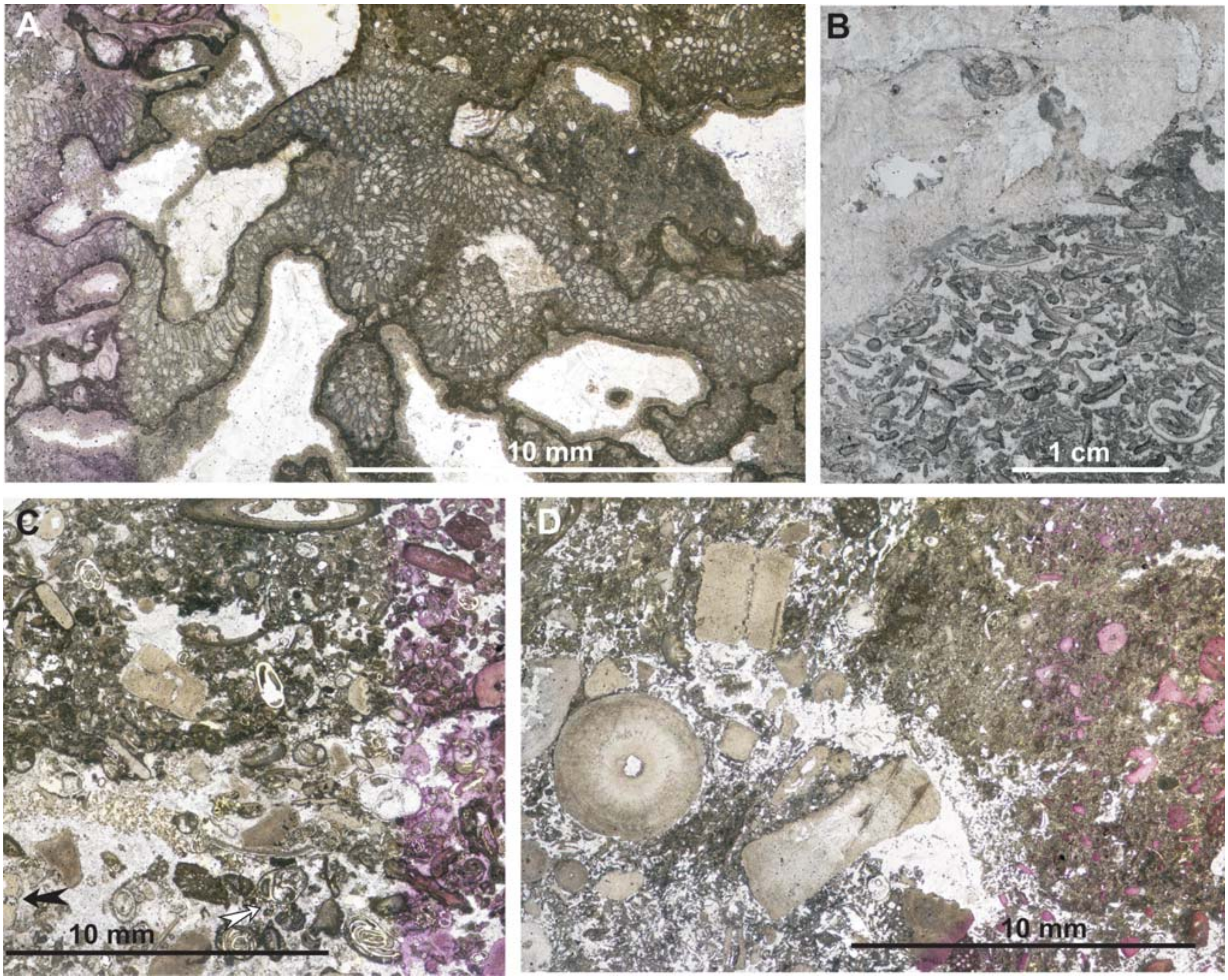

Fig. 9. Microfacies of Acanthocladia biofacies (A, B), mollusc-crinoid biofacies (C) and crinoid-rich type of brachiopod-bryozoan biofacies (D). **A.** Bryozoan bafflestone/cementstone; bryozoans encrusted by sessile foraminifers are then coated by marine isopachous cements. Caverns (white) are filled by anhydrite and blocky calcite (Jabłonna 4, 2387.85 m). **B.** Bryozoan grainstone with abundant ostracods covered by sparite (primarily aragonite cement) with hosts of original biodetrital deposit; the oblique sparite concentration disappears upwards (Jabłonna 1, 2389.0 m). **C, D.** Bioclastic grainstone containing fragments of bryozoans, crinoids, brachiopods, foraminifers and other fauna. In C, hemigordiopsid foraminifers abound; in C and D, encrusting foraminifers occur (among others, on crinoid fragments – black arrow, and gastropod shells – white arrow) (C – Jabłonna 4, 2376.2 m, D – Jabłonna 4, 2373.05 m).

Brachiopods. The brachiopod assemblage is diversified. The most common are terebratulids (*Dielasma*, Fig. 12D), occurring in small numbers in the entire section and only in its upper part locally forming thin coquina intercalations (Fig. 11C). Rare strophomenids (*Horridonia, Streptorhynchus, Strophalosia*) occur in the lower parts of the sections (*Horridonia*, in particular in Jabłonna 3) and in their middle part (Fig. 5A, F; all named strophomenids); *Streptorhynchus* (Fig. 13E, F) is an indicator for the interval characterized by brachiopod-bryozoan biofacies (see below; cf. Fig. 3), and sporadically spiriferids (*Pterospirifer*, *Spiriferellina*) and rhynchonellids (*Stenoscisma*) can be observed in the same interval. All brachiopods are epifaunal suspension feeders. Accumulations of brachiopod shells provided an excellent substrate for bryozoan colonies. In particular, this refers to strophomenids lacking a pedicle (*Horridonia* and *Strophalosia*) and attaching to the substrate (*Streptorhynchus*). In the area devoid of a solid substrate, the accumulation of coquinas may have provided suitable conditions for bottom colonization by reef-forming bryozoans. As the Jabłonna Reef could develop on a solid rocky substrate, the significance of coquinas for reef initiation was only auxiliary. This is best seen in the Jabłonna 3 and 4 sections, where the substrates were *Horridonia* shells (Fig. 12E). In the lithologic sections of two other boreholes, bryozoans started to colonize the rocky bottom, eventually using the shells of bivalves or terebratulids.

Articulata occurring in the Jabłonna Reef were controlled by stenohalinity that is poorest in terebratulids; supposedly this is why in the upper part of the section, brachiopods other than *Dielasma* are absent.

Bivalves. Because of a relatively wide spectrum of adaptional ability of bivalves, they occur throughout the entire section (Fig. 3). The most common genera are *Bakevellia*

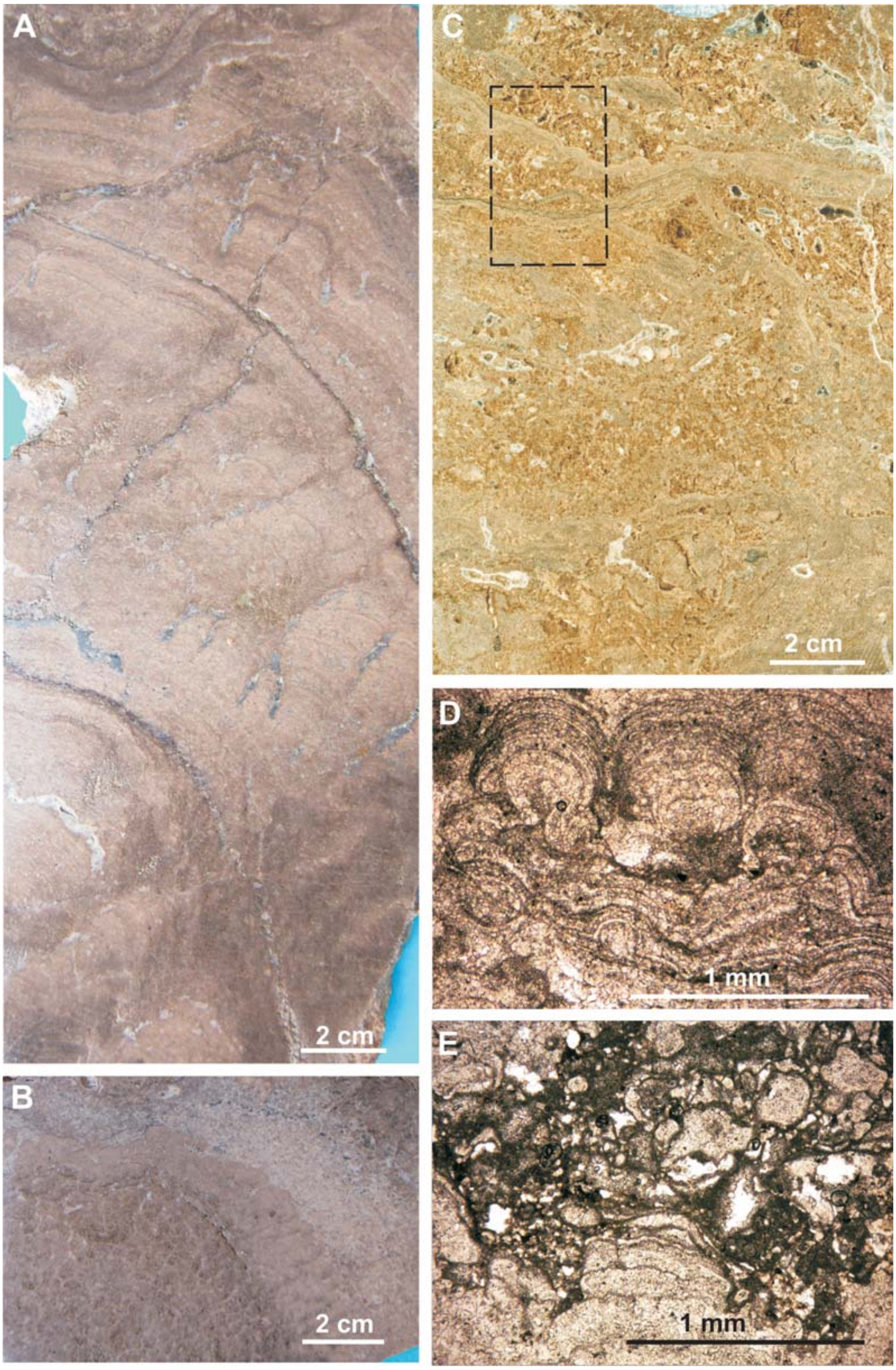

Fig. 10. Stromatolites. **A, B.** Columnar stromatolites of variable inclination of columns, eventually passing into planar forms (A – Jabłonna 1; B – Jabłonna 3). **C, E.** Recrystallized, granular deposit with common subhorizontal microbial planar encrustations (Jabłonna 3). The dotted quadrangle in C shows the place of thin section, parts of which are shown in **D** (thinly-laminated microdomes and mats) and E (more vaguely laminated stromatolite).

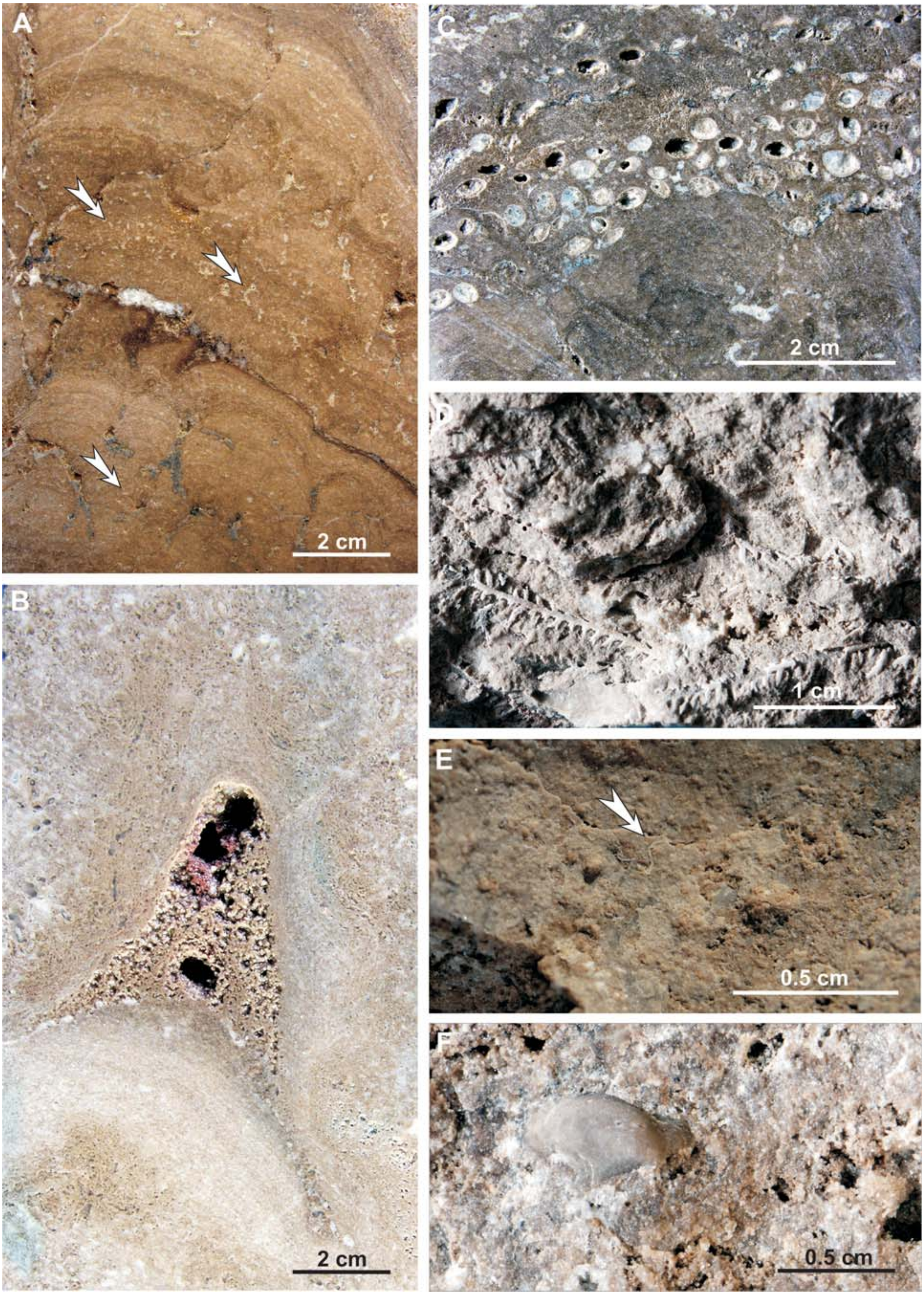

Fig. 11. Stromatolite biofacies. **A.** Columnar stromatolite with abundant bryozoans (arrows); upper part of sample shown in Figure 10A. **B.** Columnar stromatolite, its central part porous, strongly recrystallized. **C.** Terebratulid brachiopod coquina (*Dielasma elongatum*). Jabłonna 1, 2348.8 m. **D.** *Acanthocladia anceps* (Schlotheim) within microbialite. Jabłonna 2, 2365.1 m. **E.** Sessile foraminifer (arrow) on bivalve *Schizodus* shell cast. Jabłonna 2, 2352.8 m. **F.** *Bakevellia* sp. (Bivalvia). Jabłonna 2, 2363.99 m.

Fig. 12. Acanthocladia biofacies. **A.** Debris of *Acanthocladia* zoaria. Black arrow – bivalve shell with geopetal infilling. The middle part of the biofacies interval of Jabłonna 3 borehole. **B.** *Acanthocladia* in life position with primarily aragonitic cement (dark) preserving the original shape of zoaria. Upper part of the biofacies interval of Jabłonna 2 borehole. **C.** Bivalve *Pseudobakevellia* shells with sessile foraminifers (arrow). Jabłonna 3, 2400.7 m. **D.** The interior of the brachiopod *Dielasma elongatum* (Schlotheim) with brachidium. Jabłonna 4, 2408.6 m. **E.** Cross-section of the brachiopod shell *Horridonia horrida* (Sowerby) in life position. Black arrows – spines stabilizing the shell position in sediment, white arrow – incrusting bryozoan zoarium. Lower part of the biofacies interval of Jabłonna 3 borehole, 2412.3 m. **F.** Well preserved *Acanthocladia* zoarium. Upper part of the biofacies interval of Jabłonna 3 borehole, 2402.02 m.

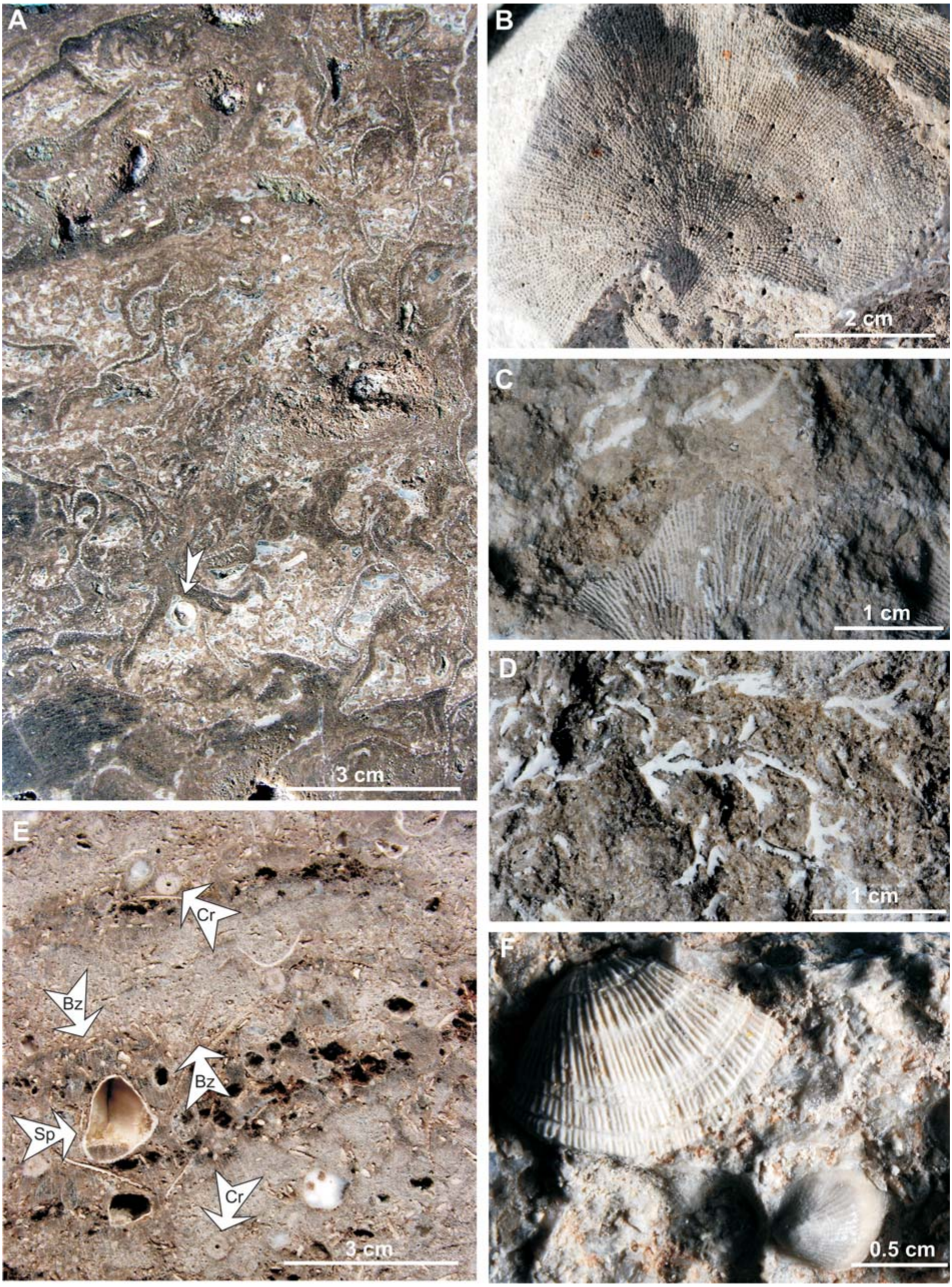

Fig. 13. Rectifenestella (A–D) and brachiopod-bryozoan biofacies (E–F). **A.** Many *Rectifenestella* zoaria in microbial limestone. Arrow – *Dielasma elongatum*. Jabłonna 1, 2366.45 m. **B.** *Rectifenestella retiformis* (Schlotheim) in life position. Jabłonna 2, 2371.2 m. **C.** Fenestral (bottom) and columnar (top) bryozoan zoaria. Jabłonna 3, 2367.99 m. **D.** Fenestellid bryozoan *Thamniscus* (anhydritized zoaria). Jabłonna 3, 2378.05 m. **E.** *Streptorhynchus pelargonatus* (Schlotheim) with geopetal infilling (Sp), fragments of bryozoan zoaria (Bz), crinoids ossicles (stems, Cr). Jabłonna 4, 2370.3 m. **F.** Brachiopod *Streptorhynchus pelargonatus* (left top) and bivalve *Pseudomonotis seluncaria* (bottom right). Jabłonna 4, 2370.95 m.

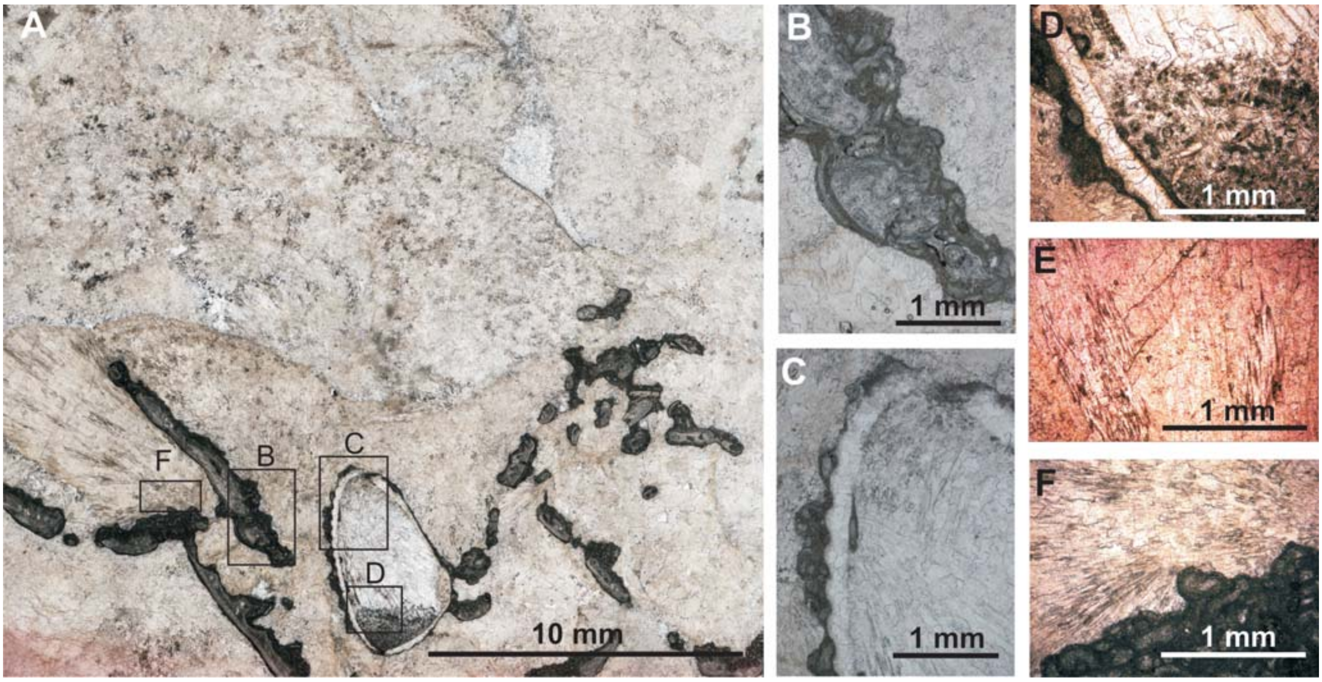

Fig. 14. Sparite with many botryoidal fans (A, C–F) and bryozoan zoaria (A, B, F) and bivalve shell (A, C, D) heavily encrusted by foraminifers. Note that also the inner part of bivalve shell is encrusted by foraminifers and that in the lower part of the shell bioclastic (ostracod) packstone occurs (D). Jabłonna 1, depth of sample: 2386.00–2386.05 m.

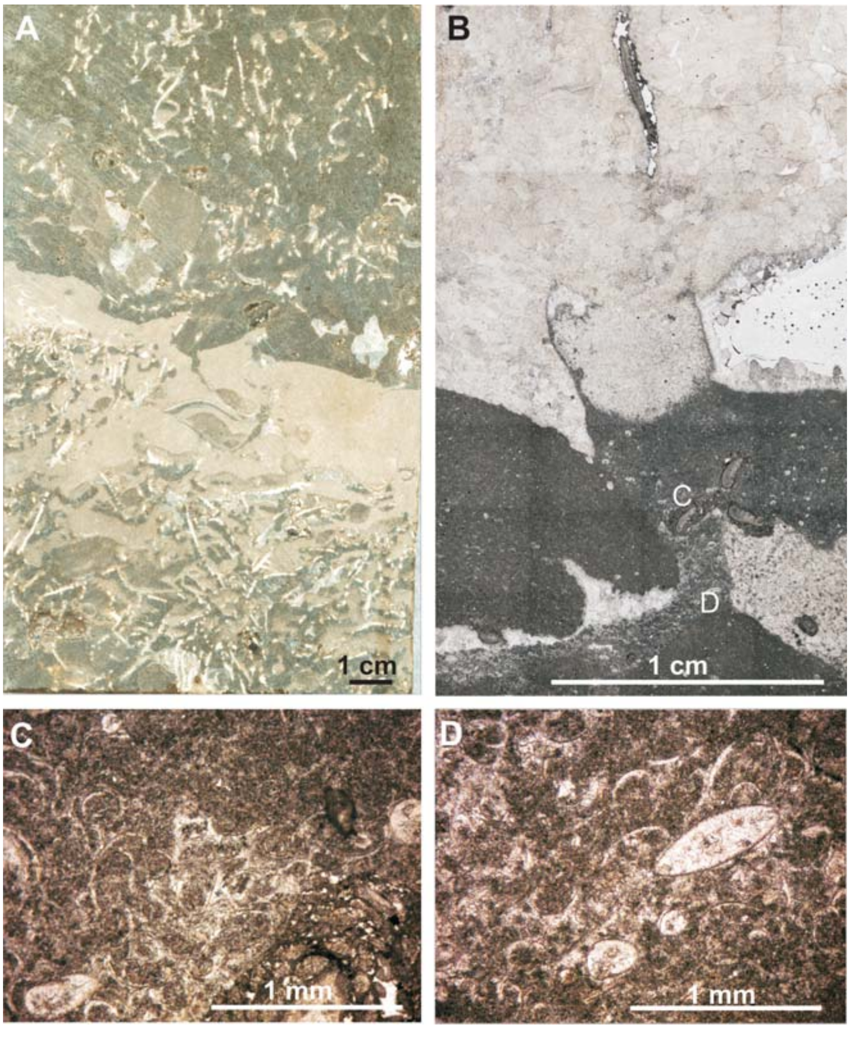

Fig. 15. Rocks from the lower part of the Zechstein Limestone, below the characteristic correlation surface in the Jabłonna 1 borehole (sample K). **A.** Bryozoan grainstone covered by bioclastic (mostly ostracod) wackestone, passing upward into ostracod packstone (lower light part of the core slab) overlain by sparite (primarily aragonite hemispheroids) containing isolated ostracods with thick foraminiferal encrustations; sparite is followed by bryozoan grainstone (the uppermost part of the core slab), depth of sample: 2386.55– 2386.75 m. **B.** Thin section showing the contact of ostracod packstone (dark) and sparite (white) in the sample shown in photo A, showing the location of photos C and D. **C, D.** Microphotographs of ostracod packstone (in C, left upper corner, with foraminiferal encrustations) shown in photo B.

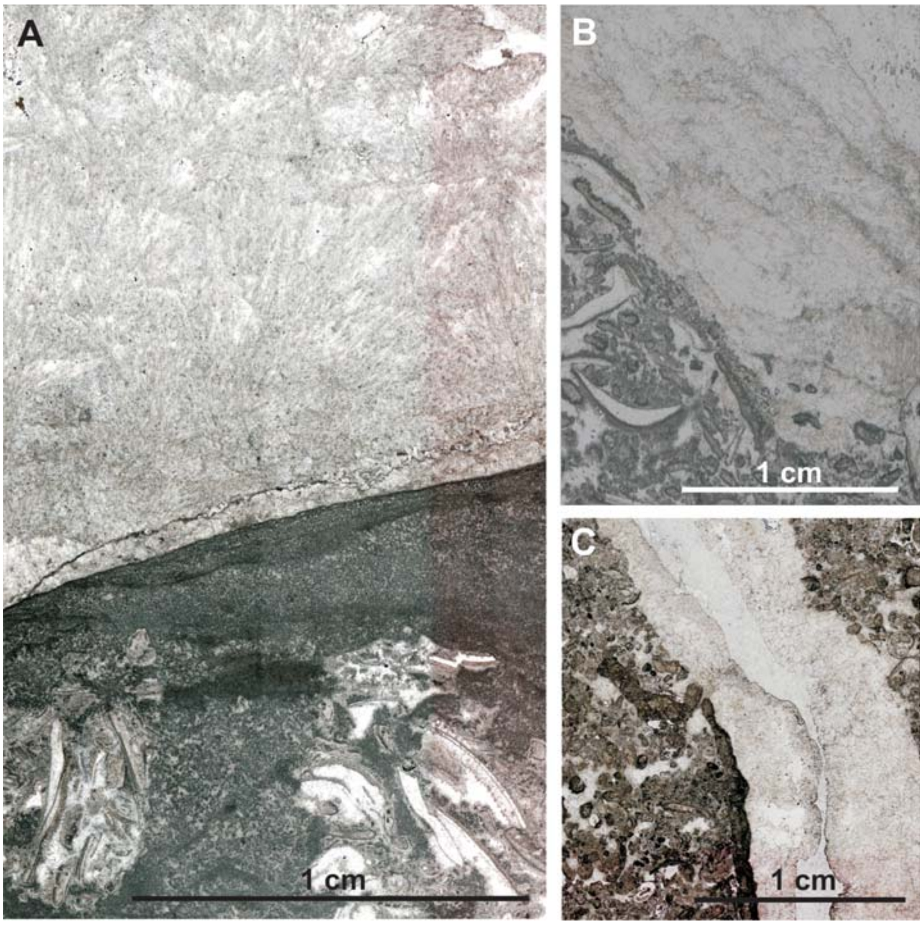

Fig. 16. Microfacies of the Zechstein Limestone of the Jabłonna 2 borehole (A – depth of sample: 2391.2 m, B – 2393.1 m, C – sample 2385.3 m). **A, B.** Sparite crusts overlying peloidal deposit with bioclasts (bryozoans, rare gastropods, shells, foraminifers, ostracods) (A) and bioclastic, mostly bryozoan grainstone (B) from the lower part of the section; sparite crust consist of botryoidal fans with presumable discontinuity horizons representing episodic interruptions in the growth of the cement. **C.** Fissure in recrystallized grainstone shown in Figure 6B filled by sparite with common fans of original aragonite cement and by anhydrite in the fissure centre.

(Fig. 11F, 12C), *Permophorus*, *Liebea* (in the entire section; their shells are the main constituents of coquinas occurring in the lowermost and uppermost parts of the section) *Parallelodon* (mostly in the lower half of the section), *Pseudomonotis* and *Schizodus* (in its upper part, Fig. 11E). The recorded taxa are mostly epifaunal or infaunal suspension feeders. Only rarely do they occur in the life position and usually were seen as disarticulated shells. The taxa attached to the substrate or partly buried (*Bakevellia*, *Permophorus*, *Liebea*) were living in higher-energy conditions in bigger concentrations that periodically were subject to destruction (Fig. 5E). Those taxa (most often partly infaunal *Bakevellia*) and *Schizodus* could also live scattered, in quiet-water conditions (the upper part of the section), partly buried and therefore their shells may be preserved in the life position. *Parallelodon* preferred depressions in gravel deposits and hence it occurs most commonly among the strongly crushed *Acanthocladia* and in the deposits overlying the characteristic lithofacies boundary. *Pseudomonotis* (Fig. 5D) lived on a sea bottom characterized by low-energy conditions (lower part of the upper interval of the Zechstein Limestone); its asymmetric shell was used to stabilize on the sea bottom.

Gastropods. Gastropods are common, although because of their minute size, they are most commonly identified in thin section. Most of the recorded gastropods are algal grazers and thus their common occurrence is in association with stromatolites and microbial encrustations in the upper part of the Zechstein Limestone section (Fig. 3). However, their presence in the lower and middle part of the Zechstein Limestone implies the frequent occurrence of algae and cyanobacteria in the entire reef.

Crinoids. In some parts of the section, large accumulations of crinoid ossicles occur and in places form crinoidal limestone (Fig. 9D). Most commonly, the detritus of columnals occurs with smaller admixtures of brachials and rare cup plates (Fig. 13E). The earlier studies on Late Permian echinoderms (e.g., Donovan *et al.*, 1986; Reich, 2007) indicated that the only crinoid species in the Zechstein basin is *Cyathocrinites ramosus* (Schlotheim) and all of the specimens determined belong to this species. As a rheophilic suspension feeder, it lived in the reef zone, characterized by moderate to considerable water activity, and occurs in the middle parts of the section. Crinoid ossicles often formed the basis for the settlement of bryozoan larvae and the beginning of the formation of new colonies (in particular *Dyscritella* and *Kingopora*).

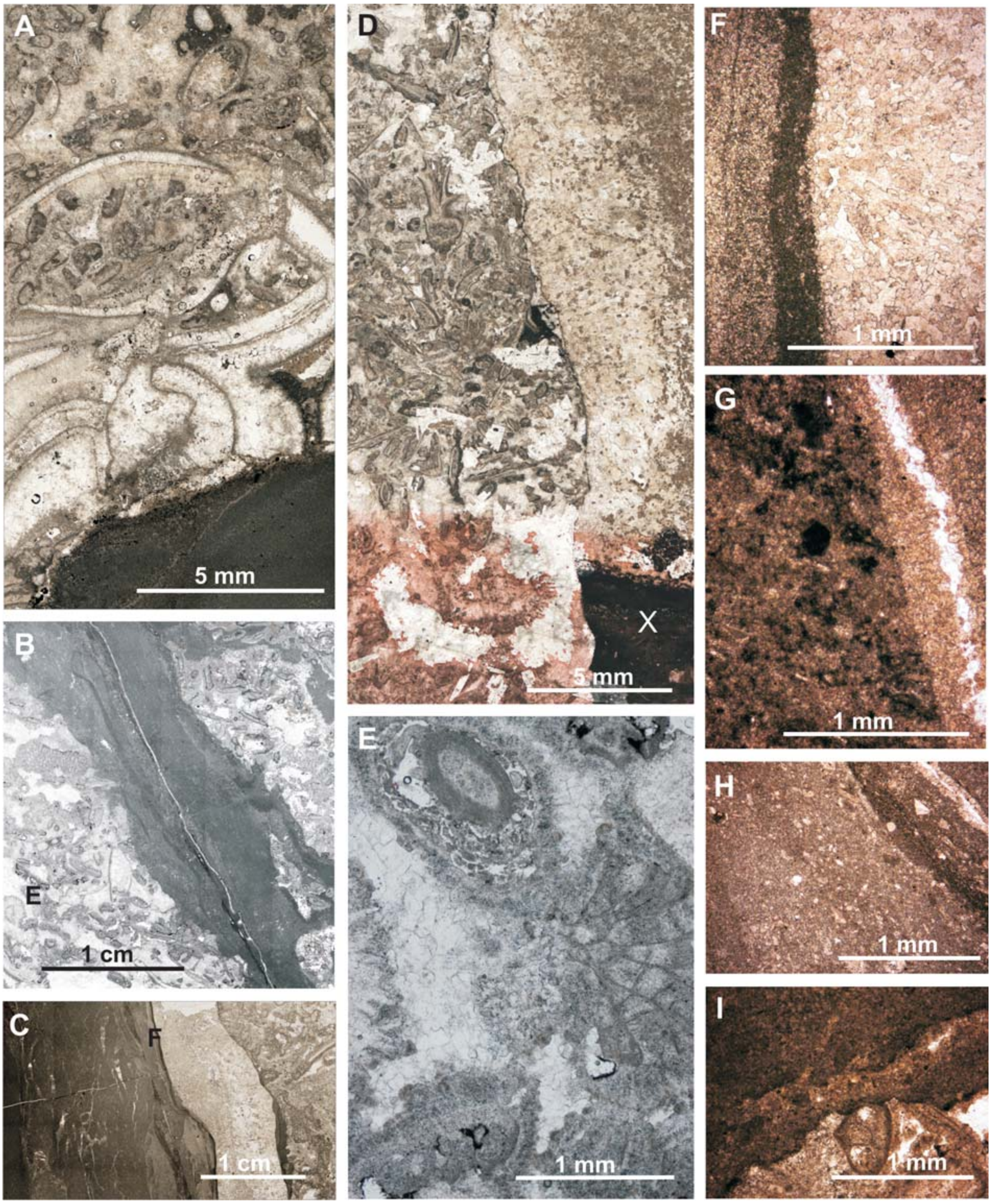

Fig. 17. Microfacies of the Zechstein Limestone of the Jabłonna 4 borehole. **A.** Coarse bioclastic grainstone, in the lowermost part micritic fill of the fissure (location of thin sections shown is marked by X on the sample shown in Fig. 8B). **B.** Micritic fill of the fissure cutting recrystallized bryozoan grainstone with post-aragonitic cement (X in the upper part of photo shown in Fig. 8C); in the micrite rare quartz grains of silt fraction occur, E shows location of the corresponding photo. **C.** Fissure filling in the sample shown in Fig. 8F (X in the middle of the sample) showing vaguely laminated part (left), sparite part (right centre), then thin micritic part and the bryozoan grainstone as the host rock (right), F shows the location of object shown under magnification in photo F. **D.** Fissure filling (to the right) in the bryozoan grainstone host rock, the fissure filling is mostly post-aragonitic sparite except of the lowest part formed by layered peloidal rock shown in Figure 20A (thin section comes from the upper right corner of the sample shown in Figure 8E). **E.** Bryozoan grainstone (some bryozoans such as that in the upper left corner of the photo are heavily encrusted by foraminifers) with sparite cement containing post-aragonitic sparite fans (left side of the photo). **F.** Contact of laminated and sparitic parts of the fissure shown in the photo C. **G.** Contact of peloidal and sparitic parts of the fissure, location of the figure is shown in Figure 8F, upper X. **H.** Laminated micritic, in places peloidal part of the fissure shown in the photo B. **I.** The lower contact of the fissure shown in Fig. 8C (place indicated by lower X) with the host rock (recrystallized bryozoan grainstone).

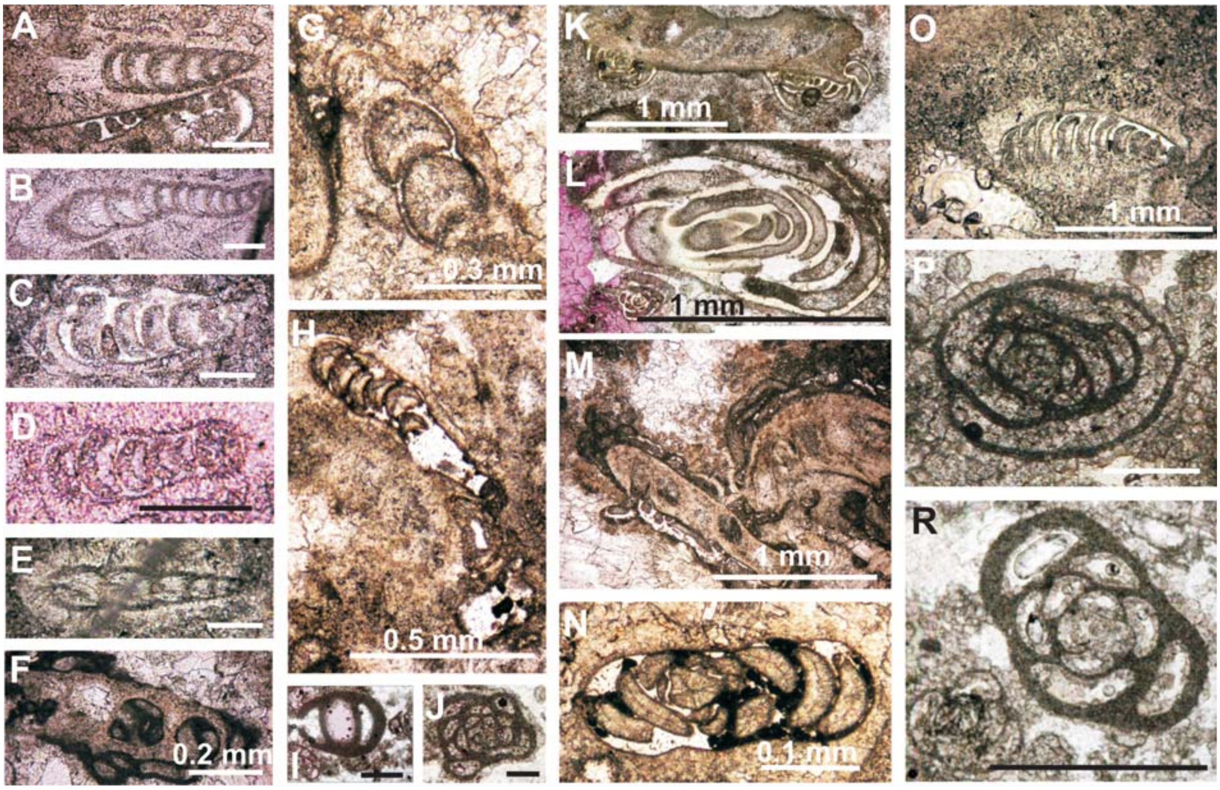

Fig. 18. Foraminifers from the Jabłonna Reef (A–E, M, O – Jabłonna 2; F, I–L, P, R – Jabłonna 4; G–H, N – Jabłonna 1; O – Jabłonna 2). Scale bars: A–E = 0.1 mm; I, J = 0.5 mm. **A.** *Geinitzina*?, *Calcivertella*. **B.** *Nodosinelloides*?. **C.** *Geinitzina*?. **D.** *Nodosaria.* **E.** *Nodosaria*. **F.** *Calcivertellinae.* **G.** *Nodosaria.* **H.** *Hemigordiopsida*. **I.** gen. et sp. indet. **J.** *Pseudoglomospira.* **K.** *Calcivertella.* **L.** *Agathammina*. **M.** Foraminiferal encrustations on bryozoan fragments. **N.** *Hemigordius.* **O.** *Geinitzina.* **P.** *Glomospira* sp. **R.** *Hemigordius.*

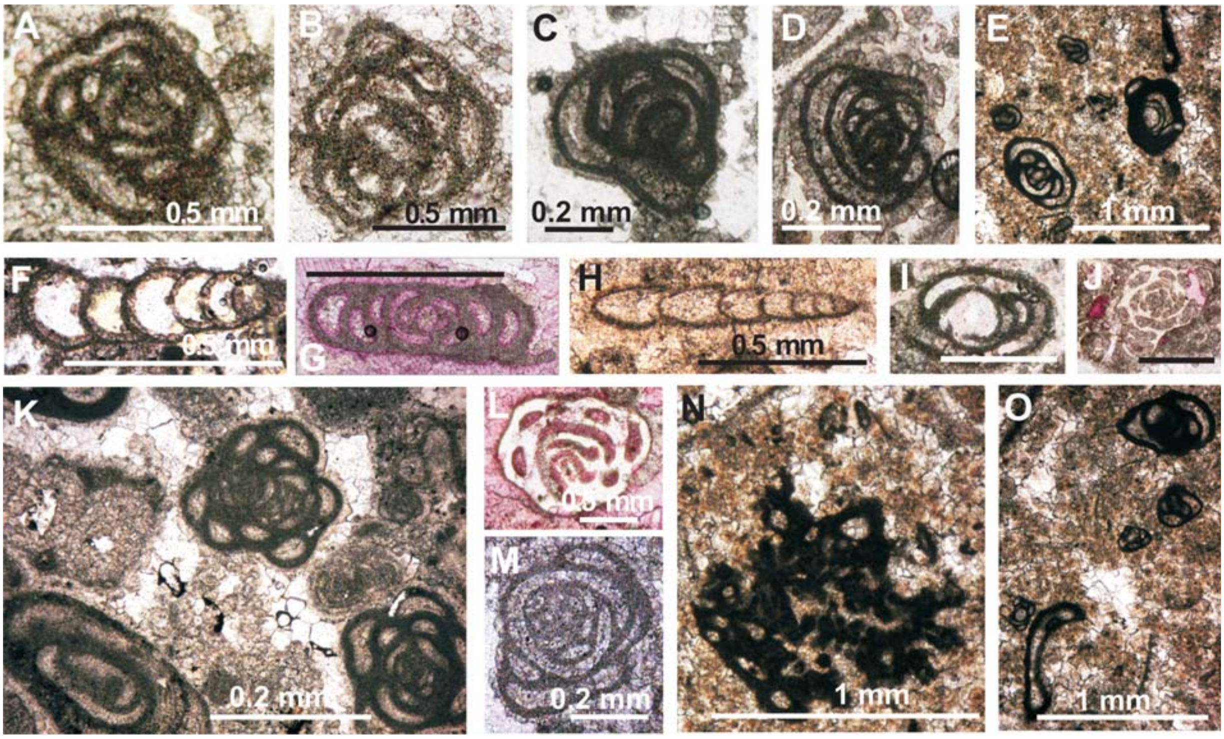

Fig. 19. Foraminifers from the Jabłonna Reef (A–E, G, I, J, L, N, O – Jabłonna 4; F, M – Jabłonna 3; H, K – Jabłonnna 1). Scale bars: G, I, J = 0.5 mm., **A–D.** *Glomospira* spp. **E.** Hemigordiopsida, *Glomospira*. **F.** *Nodosaria*. **G.** *Hemigordius.* **H.** *Nodosaria*. **I.** *Hemigordius*. **J, L.** *Pseudoglomospira*. **K.** *Glomospira* spp., *Agathammina*. **M.** *Pseudoglomospira*. **N.** Encrusting or framework-building tubes of problematic origin (possibly encrusting foraminifers). **O.** Hemigordiopsida (photos are from the upper right corner of sample shown in Figure 8B).

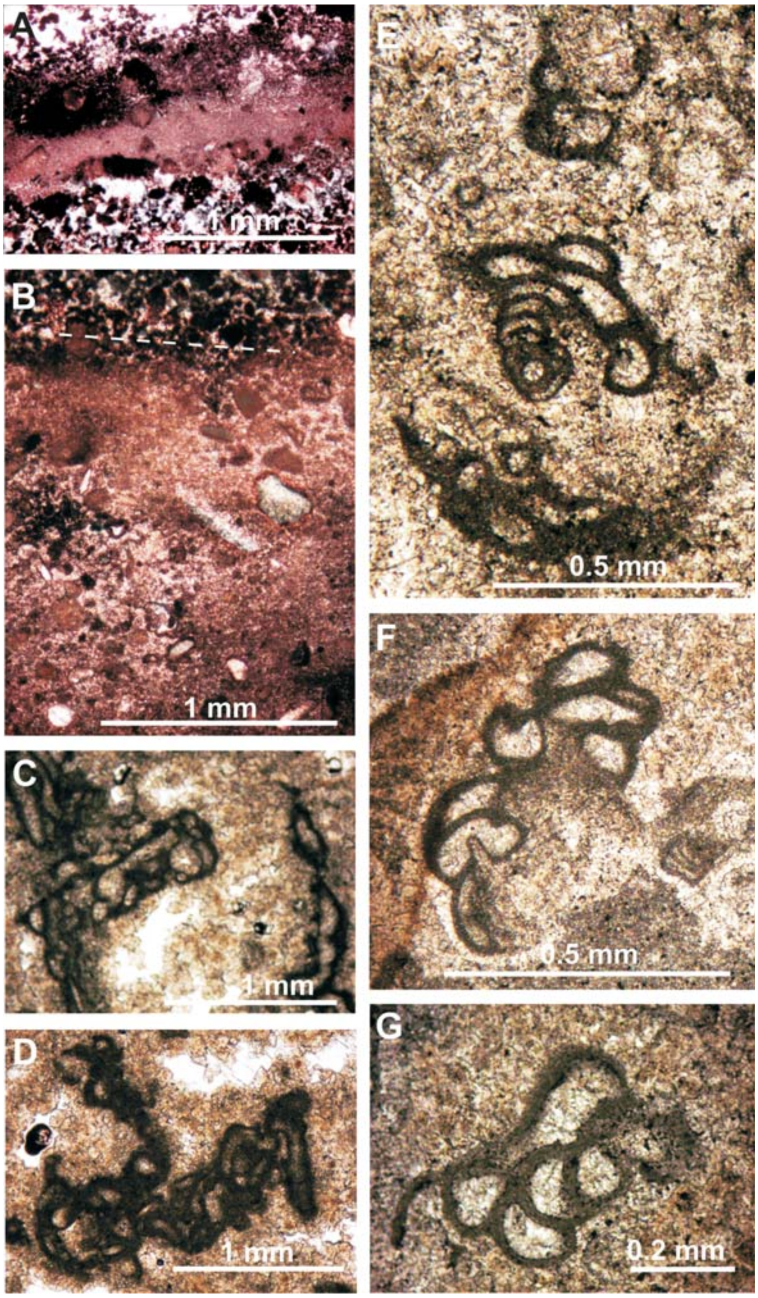

Fig. 20. Peloidal filling of the fissure and sessile foraminifers. **A, B**. Peloidal filling of the fissure in Jabłonna 4 (photos come from the place marked by X in Fig. 13D); the dotted line in B corresponds to the scale bar line in A. **C, D.** *Palaeonubecularia* sp. (Jabłonna 3 well). **E.** *Calcitornella.* **F, G**. Calcivertellinae (E–G – Jabłonna 4 well).

Other fauna. In addition to the faunal groups discussed above that comprise the bulk of skeletal organisms recorded in the Jabłonna Reef, ostracods are common (Fig. 15D). They occur in particular in the lower part of the section, in the deposits enriched in micrite, for example, in spaces between the branches of a bryozoan colony. They are mainly disarticulated, which implies higher energy. Echinoids (*Miocidaris*) are rare, and the occurrence of sponges is problematic. So far, sponges were recorded by one of the authors (PR) in the Zechstein Limestone deposits of the North-Sudetic Trough as well as in the reefs of Lithuania.

Isotope geochemistry

The results of isotopic studies are shown in Tables 1 and 2 and Figures 21 and 22.

$\delta^{13}C$ values of samples obtained from the Jabłonna 2 and Jabłonna 4 boreholes range from 0.8 to 5.0‰ and from –0.3 to 6.4‰, respectively; the means are 3.2±1.1‰ and 2.4±1.6‰, respectively. $\delta^{18}O$ values range from –9.5 to –2.4‰ and from –9.9 to –0.8‰, respectively; the means are –6.3±1.3‰ and –7.0±2.0‰, respectively (Table 1). The fissure fillings show a range of $\delta^{13}C$ values from 0.6 to 6.4‰ and a mean of 3.4±1.7‰; $\delta^{18}O$ values range from –9.9 to –0.8‰, with a mean of –5.8±2.7‰.

In the Jabłonna 2 borehole, the $\delta^{13}C$ curve above the characteristic lithofacies and biofacies boundary shows first an increase and then a gradual decrease, although with some positive excursions, and in the upper part the $\delta^{13}C$ values increase just below the breccia deposits (Fig. 21). The same general trend is observed in the Jabłonna 4 borehole (Fig. 21). In the part of the section located below the lithofacies and biofacies boundary in the Jabłonna 4 borehole, the $\delta^{13}C$ values show first a decrease (from *ca.* +3 to 0‰), then a gradual increase to +5‰ and next a decrease to ca. +1% about 21 m above the Zechstein Limestone base (Fig. 21). The interval above, up to the lithological boundary, is characterized by increased values (in this part of the section the highest $\delta^{13}C$ values were recorded) and a large spread of data. In the Jabłonna 2 borehole, a distinct trend to increased and then decreased $\delta^{13}C$ values was observed in the part of the section located below the lithofacies and biofacies boundary (Fig. 21).

The trends of change in $\delta^{18}O$ values in both boreholes are very similar to those characteristic for the $\delta^{13}C$ values (Fig. 21).

The strontium isotopic ratios of eight samples have values ranging from 0.707358 to 0.708537 (Table 2; Fig. 22).

INTERPRETATION AND DISCUSSION

Biofacies

The combined sedimentological and palaeoecological analyses indicated that in the Jabłonna area during the Zechstein Limestone there was continuous deposition of carbonates in subtidal environments until the onset of deposition of the uppermost, stromatolitic-pisolitic unit (unit 5 of Dyjaczyński *et al.*, 2001; cf. Kiersnowski *et al.*, 2010). However, there was some variation in water depth, as can be deduced from the analysis of the occurrence of faunal elements

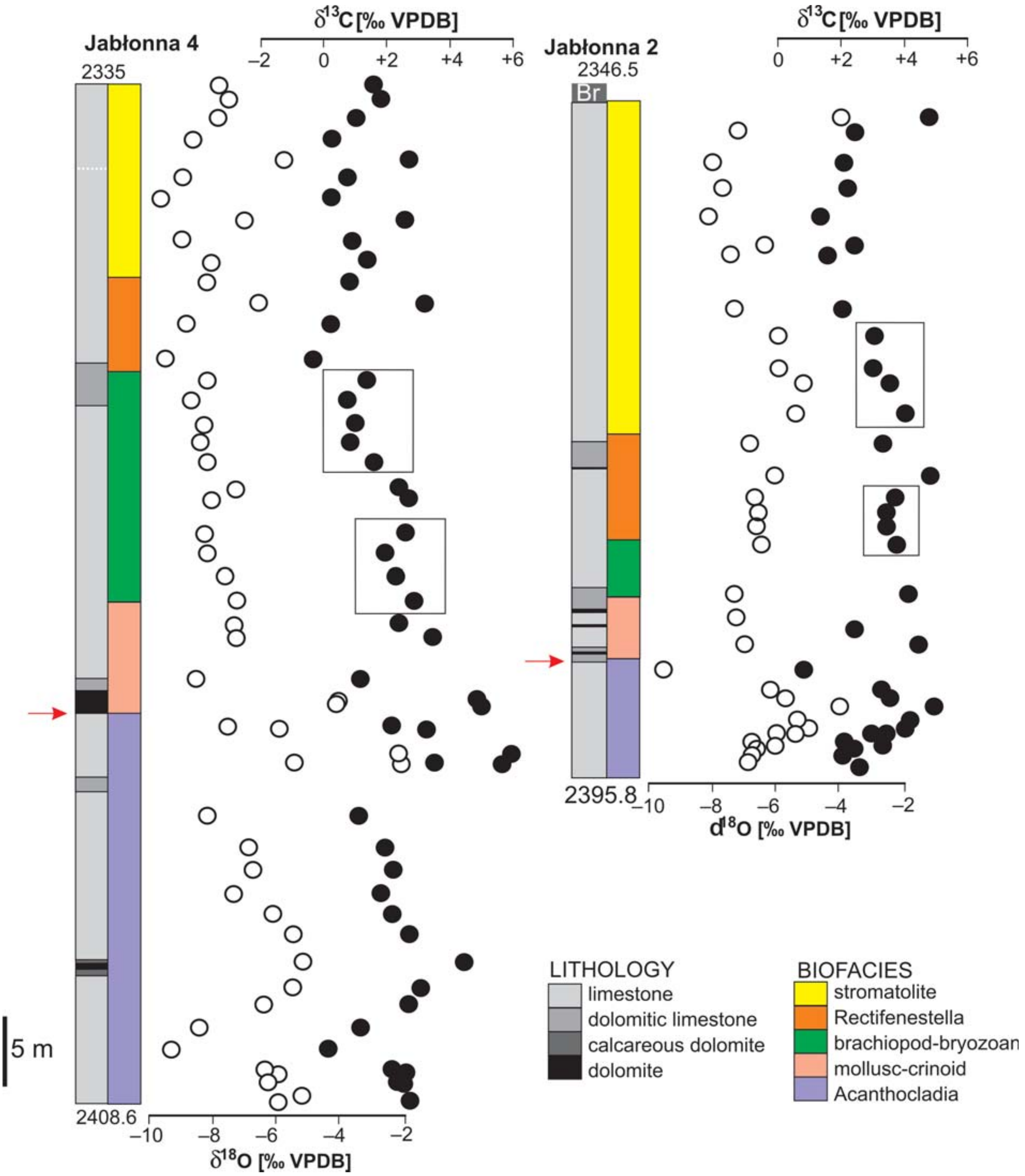

Fig. 21. Carbon (solid circles) and oxygen (open circles) isotope values of the Jabłonna 2 and 4 boreholes. The polygons show the results that are of correlation potential (see discussion in the text). Red arrow indicates the characteristic lithofacies-biofacies boundary discussed in the text and illustrated in Fig. 4. Note the lack of core in the uppermost part of the Zechstein Limestone of the Jabłonna 4 borehole (2332.5–2335.0 m).

(in-growth position *versus* fragmented) and their preferred environments. The variable frequency of faunal groups and stromatolites (including microbial encrustations) made it possible to distinguish the following biofacies in the sections studied: Acanthocladia, mollusc-crinoid, brachiopod-bryozoan, Rectifenestella, and stromatolite (Fig. 3; Table 3). The top boundary of the Acanthocladia biofacies is identical with the lithofacies boundary (Figs 4, 5A). The boundary between the mollusc-crinoid and brachiopod-bryozoan biofacies was placed at the first occurrence of the brachiopod *Streptorhynchus pelargonatus*. The lower boundary of the Rectifenestella biofacies was placed at the emergence of fenestellid bryozoans in the life position, and the upper boundary at the disappearance of fenestellids (Fig. 3).

The lower part of the Zechstein Limestone, corresponding to the Acanthocladia biofacies, contains mostly the frag-

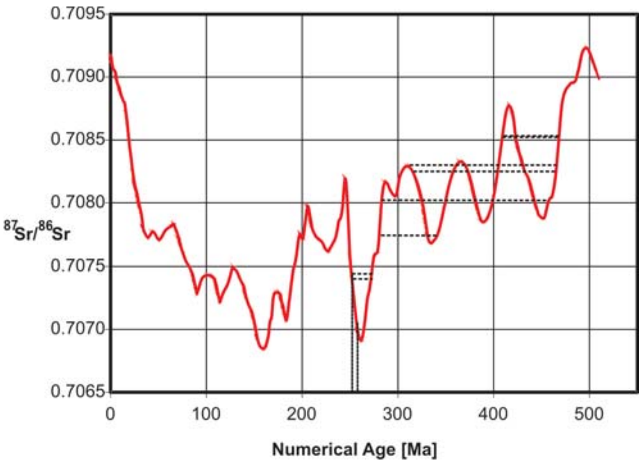

Fig. 22. 7Sr/^{86}Sr values for the calcite in the neptunian dykes of the Jabłonna Reef (horizontal dotted lines) *versus* the supposed lower and upper age limits of the Zechstein (vertical dotted lines).

Table 1

Statistical data on the stable isotopic composition in the boreholes studied

Borehole and isotope measured	Number of analyses	Minimum ‰	Maximum ‰	Mean ‰	Standard deviation ‰
Jabłonna 2 – C	40	0.84	4.96	3.16	1.06
Jabłonna 2 – O	40	–9.52	–2.40	–6.28	1.32
Jabłonna 4 – C	58	–0.3	6.43	2.36	1.55
Jabłonna 4 – O	58	–9.87	–0.81	–6.96	2.01
Earlier data[1] – C	126	–2.16	8.26	4.37	1.63
Earlier data[1] – O	126	–12.97	3.20	–4.79	2.65

[1] Peryt *et al.* (2015): Brońsko 1, Kokorzyn 1, Kościan 9, Kościan 10, Paproć 21, and Paproć 29 boreholes

mented zoaria of bryozoans that colonized the rocky bottom and the shells of *Horridonia* and bivalves, but underwent common crushing, owing to the location of the bottom above the storm wave-base. Higher up in the sections, intervals with *in situ* bryozoans occur, and these indicate slightly deeper, sedimentary environments below the storm wave-base. The intervals with *in situ* bryozoans are intercalated with intervals containing crushed bryozoans, indicating that the storm wave-base was undergoing some fluctuation. Irrespective of this, a slightly deepening-upwards trend within the Acanthocladia biofacies is evident, except perhaps in its uppermost part, where again crushed zoaria predominate.

The boundary between the Acanthocladia biofacies and the overlying mollusc-crinoid biofacies is sharp (Figs 4, 5A). Just above the boundary, bioclastic grainstones with common, spiral foraminifers occur, with more rounded, skeletal fragments (including *Acanthocladia*) than elsewhere in the biofacies, possibly from some reworking of the underlying strata. These factors strongly indicate increased energy and/or decreased water depth at the initial phase of formation of the the biofacies. However, soon the deeper-water bioclastic sediments started to accumulate, composed of strongly fragmented, branched bryozoans, but with high proportions of crinoids, rare *Horridonia* and even complete, fenestral bryozoans, *Synocladia* (characterized by coarser skeletons than fenestellids that are common in the later stages of deposition), indicating quiet-water conditions. The location of the mollusc-crinoid biofacies in the sequence as well as its taxonomic composition indicate that it is a back-reef deposit, originating from the destruction of a reef edge, but deposited on a relatively calm sea bottom. Accordingly, after the shallowing at the onset of the mollusc-crinoid biofacies, rapid deepening occurred and then deposits that accumulated below the storm wave-base were followed by material that originated below (mostly) and above (temporarily) the storm wave-base. The relative rise of sea level led to the origin of the brachiopod-bryozoan biofacies, where *Rectifenestella* and *Acanthocladia* are the dominating taxa. Then, however, the depth started to decrease and the lagoonal deposits of the biofacies were replaced by shallow-water (≤5 m deep), lagoonal and reef-flat deposits of Rectifenestella and followed by stromatolite biofacies; the latter originated in the reef-flat zone (Table 3).

The thickness of intervals characterized by particular biofacies varies from one borehole to another (Fig. 3). The thickness of intervals, characterized by the Acanthocladia and mollusc-crinoid biofacies, show the greatest variation, from 8 m and 4.5 m, respectively, in Jabłonna 2 borehole to

Table 2

Results of isotopic study of fissure fillings

Sample number	Sample depth [m]	^{87}Sr/^{86}Sr	2SE	δ^{13}C ‰	δ^{18}O ‰	Microfacies
J412 G2	2384.45	0.707440	0.000009	5.98	–2.40	sparite after aragonite
J412 G	2384.45	0.707358	0.000012	6.43	–0.81	sparite after aragonite
J411	2386.8	0.708253	0.000009	2.42	–7.90	micrite
J410B	2391.7	0.708537	0.000009	1.22	–9.34	micrite
J410A	2391.8	0.708526	0.000010	0.59	–9.87	laminated micrite
J2V	2348.35	0.708027	0.000009	1.49	–8.21	micrite
J2H	2385.32	0.708304	0.000010	2.43	–7.40	micrite
J2F	2391.2	0.707743	0.000008	3.83	–4.29	laminated micrite

Table 3

Biofacies characteristics of the Jabłonna Reef

Biofacies	Fossil groups	Fossil taxa	Environment energy	Water depth	Position in the reef	Remarks
stromatolite	stromatolites 5 (0–5) bryozoans 3 (0–5) brachiopods 1 (0–5) molluscs (bivalves and gastropods) 1 (1–3)	*Thamniscus* *Acanthocladia* *Dielasma* *Bakevellia*	low (occasionally high)	shallow to very shallow (decreasing)	reef flat	Low energy is indicated by in situ, or almost complete overthrown, zoaria, and occasional high energy is indicated by intercalations of coquinas
Rectifenestella	bryozoans 4 (3–5) stromatolites 5 (4–5) crinoids 2 (0–3) molluscs (bivalves and gastropods) 1 (1–3)	***Rectifenestella*** *Thamniscus* *Dyscritella* *Acanthocladia*	low	shallow (slowly decreasing)	lagoon – reef flat	
brachiopod-bryozoan	brachiopods 4 (2–4) bryozoans 4 (2–5) crinoids 3 (1–3) molluscs 2 (1–3) foraminifers 3 (2–3)	*Horridonia* ***Rectifenestella*** *Kingopora* *Synocladia* ***Acanthocladia*** *Thamniscus,* *Dyscritella* *Pseudomonotis* *Bakevellia* gastropods hemigordiopsid encrusting and uniserial foraminifers	low-medium	moderate/deep to shallow (decreasing)	lagoon	
mollusc-crinoid	bivalves 2 (0–2) crinoids 2 (0–5) bryozoans 3 (1–4) brachiopods 1 (0–2) foraminifers 3 (1–4)	*Permophorus* *Liebea* *Bakevellia* ***Acanthocladia*** *Rectifenestella* *Synocladia* *Horridonia* *Dielasma* hemigordiopsid encrusting and uniserial foraminifers	very high-medium	deep to moderate (decreasing)	back reef	Usually the backreef is protected against storm events and the environment shows medium or low energy, but due to small reef size the back-reef zone was subject to common storms and the lagoonal zone was non-existing in practice
Acanthocladia	branched bryozoans 5 (3–5) columnar bryozoans 1 (0–1) bivalves 2 (0–4) terebratulid brachiopods 2 (0–3) strophomenid brachiopods 1 (0–2)	***Acanthocladia*** *Dyscritella* *Liebea* *Permophorus* *Dielasma* *Horridonia* encrusting foraminifers	high-medium	moderate to deep and then to moderate (increasing and then decreasing)	reef core	High energy refers to bryozoan detritus deposited below the storm wave-base; the detritus was delivered from a shallow zone but due to a differentiated morphology it was a short transportation distance

The relative average (and, in brackets, range) of frequency of fauna groups and stromatolites (including less regular microbial encrustations), where 0 means the lack, 1 – very rare (single), 2 – rare (few), 3 – common, 4 – abundant, 5 – very common (en mass). The taxa listed in bold font indicate that they are principal biofacies indicator.

28.5 m and 8 m, respectively, in the Jabłonna 4 borehole. The thickness of intervals, characterized by brachiopod-bryozoan biofacies, is greater in Jabłonna 4 (16.5 m) than in the three other boreholes (Jabłonna 1, 2.5 m; Jabłonna 2, 4 m; Jabłonna 4, 5 m). In turn, the interval, characterized by Rectifenestella biofacies, is 14 m thick in Jabłonna 1 and 17 m thick in Jabłonna 3, and clearly thinner in the other boreholes (7.5 m in Jabłonna 2 and 5.5 m in Jabłonna 4). The thickness of the interval, characterized by stromatolite biofacies, is much thicker in centrally-positioned boreholes (Jabłonna 2: 23 m; Jabłonna 4: 15 m) than in Jabłonna 1 (9 m) and Jabłonna 3 (6.5 m). Various thicknesses of particular biofacies intervals clearly are an expression of lateral facies variation that finds support in the carbon isotope trends, as discussed below.

Dolomitization

The complex limestone–dolomite distribution pattern observed in the Jabłonna Reef (Fig. 3) as well as in other reefs of the Wolsztyn area (Jasionowski *et al.*, 2014; Fheed *et al.*, 2015), resulted from multiple reflux events, both in time and space and was controlled by the proximity to the brine source, zones of relatively higher porosity, and permeability contrasts (e.g., Garcia-Fresca *et al.*, 2012). As concluded by Jasionowski *et al.* (2014), the timing of dolomitisation is difficult to ascertain, but petrographical and geochemical data considered together indicate that the reef carbonates of the Wolsztyn palaeo-High were dolomitized shortly after deposition in a near-surface sabkha/seepage-reflux and then in burial systems. These multiple reflux events were related to sea-level fall during the deposition of the uppermost part of the Zechstein Limestone and thereafter. There is no convincing proof of sea-level fall and subsequent dolomitization (and eventual dedolomitization) during bioherm growth, as was described from the marginal carbonate platform (e.g., Peryt, 1984; Paul, 1991). There is increased abundance of dolomitized sediments above the lithological boundary (Fig. 3), but it is interpreted as being due to higher porosity and permeability above the boundary, compared to the bryozoan grainstones and/or boundstones, showing pervasive, aragonitic cementation below it and thus blocking the downward percolation of dolomitizing fluids.

Aragonitic cementation

Volumetrically, aragonite cement was the main precipitate during deposition of the Jabłonna Reef. Botryoidal aragonite cements were formed already during the first stages of deposition of the the Zechstein Limestone, as recorded in the Jabłonna 1 and Jabłonna 4 boreholes. This was noted in the lowest part of the Jabłonna 2 section, but as discussed below, the deposition of the Zechstein Limestone began there later than in other sections. Previously, D. Peryt *et al.* (2012) reported the common occurrence of aragonite cements in the basal Zechstein deposits in the southernmost part of the Brońsko Reef and thus this new finding strongly supports the earlier pattern of limited, areal distribution of aragonitic cementation at the onset of Zechstein Limestone deposition (D. Peryt *et al.*, 2012, their Fig. 3A); in the Brońsko Reef and also in the Jabłonna Reef, aragonitic cementation was first limited to the southernmost part. Subsequently, aragonitic cementation occurred throughout the entire area (cf. Fig. 3).

Aragonitic precipitation reached its peak prior to the lithological boundary. Above it, evidence of former aragonitic cementation is scarcer (Fig. 3), and when it occurs, it is less important volumetrically than during the early stages of Zechstein Limestone deposition.

Botryoidal aragonite cements have been reported from modern Caribbean marginal slope environments (e.g., Ginsburg and James, 1976; Land and Moore, 1980; Grammer *et al.*, 1993) and the Great Barrier Reef (e.g., Marshall and Davies, 1981) and have been interpreted from various slope deposits throughout the Phanerozoic (e.g., Davies, 1977). In particular, they are commonly recorded in the Permian reefs (e.g., Mazzullo and Cys, 1977; Given and Lohmann, 1985; Payne *et al.*, 2006), including the Zechstein reefs (e.g., Peryt, 1984; Hollingworth and Tucker, 1987; Weidlich, 2002; D. Peryt *et al.*, 2012; Peryt *et al.*, 2012a). However, the case of the Jabłonna Reef is important, because as noted by Grotzinger and Knoll (1995), the extensive dolomitization of the Zechstein deposits elsewhere and in particular in the Magnesian Limestone Reef of NE England (except locally in the Tunstall Hills; Hollingworth and Tucker, 1987), resulted in uncertainty as to whether the marine precipitates were restricted to the pores of a bryozoan framework, or actively formed part of the framework itself. In the Tunstall Hills, the reef-base coquina, consisting entirely of bioclasts, accumulated on a topographic high in a high-energy shallow-water location and was pervasively cemented on the sea-floor (Hollingworth and Tucker, 1987). The reef core facies of the Tunstall Reef, in spite of the dolomitization, shows evidence of extensive seafloor cementation (Hollingworth and Tucker, 1987).

Permian reefs are commonly cement-rich and high percentages of marine-phreatic cements may indicate that the reef communities lived under contrasting hydrophysical regimes (Weidlich, 2002, with references therein). Grotzinger and Knoll (1995) suggested that massive precipitation of Late Permian sea-floor encrusting aragonite and calcite deposits occurred during the upwelling of relatively warm, hypersaline, anoxic and mildly alkaline bottom waters that would have mixed with calcium-bearing surface waters. Such an interpretation was accepted by Weidlich (2002) and Peryt *et al.* (2012a). It is remarkable that pervasive aragonite cementation occurred at approximately the same position in the Jabłonna sections, below the lithological boundary that can be traced in separate parts of the Jabłonna reef complex (arrowed in Fig. 3), and thus it seems that the upwelling of bottom waters is a plausible triggering factor for widespread aragonite cementation at what geologically was a virtually instantaneous event (cf. Grammer *et al.*, 1993). The presence of botryoidal fans of original aragonitic composition was recorded previously in the shoals of the basinal facies of the Zechstein Limestone (Peryt, 1981).

Microbial encrustations

Steep-dipping encrustations very common in the Jabłonna 2, 3 and 4 boreholes are regarded as being of microbial origin. They are analogous to those described from coeval carbonates in Germany and England that suffered pervasive dolomitization and thus no direct evidence of their microbial origin has been preserved (Paul, 1995). The framework of the Magnesian Limestone reef in NE England contains a significant amount of problematic structures, described by Smith (1981b, 1994) as profuse encrustations resembling *Stromaria* (Smith, 1994, 1995), which were noted in Zechstein reefs of Germany (Peryt, 1986a, with reference therein). In addition, within the thickly encrusted bryozoan boundstones in NE England, steeply dipping, laminated limestone sheets occur; some of the sheets coat the walls of former fissures (Smith, 1981b; Aplin, 1985). They are interpreted as partly bilateral fissure-fills (interpreted by Smith, 1994, 1995 as tension gashes that probably resulted from unequal stresses around the sharp reef-crest) and partly primary reef-surface encrustations (Smith, 1981a, 1994, 1995; Aplin, 1985). Aplin (1985) suggested that although the laminar limestone sheets were mainly early and of marine origin, some could be subaerial flowstones (speleothems). Grotzinger and Knoll (1995) interpreted these structures as being formed as a result of microbial mat calcification under marine conditions of elevated calcium carbonate precipitation. The tension gashes are parallel to the reef trend and extend downwards into the reef-core; they include fallen blocks, up to 30 cm long (Smith, 1994, Plate 15), as well as grains of coarse quartz and feldspar sand; they do not contain fissure-dwelling fossils (Hollingworth, 1987 in Smith, 1994).

Paul (1980, 1987) documented the well exposed, entirely dolomitized Westerstein reef in the Harz Mts. that is a unique example of a stromatolite reef. The reef occurs above a cliff or elevation of Devonian greywackes and it is supposed that the lower part of the Zechstein Limestone is missing. The reef itself is elongate, about 200 m long, 50 m broad and 15 m high, and is composed almost entirely of stromatolites of different forms (cyanobacterial mats, domes, columnar forms, oncoids, and thrombolites) that show a clear pattern, reflecting the level of wave-energy. Thus, as recognized by Paul (1980, 1987), undulating mats dominate in the lower parts of the reef, columnar stromatolites towards the east and west sides of the reef, domal stromatolites in the upper and especially in the northern part, oncoids on the reef top, and thrombolites at the reef-platform. Microbial mats dip radially away from the reef-core. Paul (1980, 1987) concluded that the northern side of the reef was the high-energy side because of the trade winds, as in Late Permian times central Europe was at the 25°N palaeolatitude position; thus the reef centre was shifting northward as a result of the favoured production of the microbes on the northern, windward side. As noticed by Harris and Kenter (2008), aspects of the cementation of late Palaeozoic microbial boundstone platform margins may be more of a windward than leeward margin type and remain poorly understood. The sparse boreholes in the Jabłonna Reef as well as their locations only in the centre and southern, leeward margin, do not allow for any conclusion on this matter. However, there is no doubt that microbial steep-dipping encrustations in the Jabłonna Reef did stabilize the otherwise mostly granular deposit and thus facilitated the vertical and horizontal growth of the buildup (see Fig. 7A). This occurred during most of Zechstein Limestone deposition, except for during its earliest phase. There is one exception in the lowest part of the Jabłonna 2 borehole, although it seems that the interval below the characteristic lithofacies and biofacies boundary in Jabłonna 2 corresponds to the higher part of the interval occurring in other boreholes, as is discussed later in this paper.

The most common are microbial steep-dipping encrustations in the Jabłonna 2 borehole, somewhat less common in the Jabłonna 3 and Jabłonna 4 boreholes; they are absent in the Jabłonna 1 borehole. Instead, columnar stromatolites are common in the upper part of the Zechstein Limestone of the Jabłonna 1 borehole (Figs 3, 10A). In addition, columnar stromatolites were recorded in the upper part of the Jabłonna 3 borehole (Figs 3, 10B). In addition to the approximately horizontal crusts, also inclined stromatolitic forms, mostly columns, occur (Fig. 10A, B). Their inclination indicates that the substrate of stromatolites was subject to a considerable deviation from an approximately horizontal dip and reflects the movement of particular blocks, metres in size, on which the stromatolites were growing. These blocks originated from the entire Wolsztyn palaeo-High area, possibly owing to synsedimentary tectonism (cf. Kiersnowski *et al.*, 2010; Peryt *et al.*, 2012a) and the changing inclination of columnar stromatolites as well as their rapid transition to almost horizontally-arranged forms (Fig. 10A) indicates growth on unstable boulders (tilting blocks?).

Neptunian dykes

One of the manifestations of synsedimentary tectonism was the fissuring of the Zechstein Limestone strata of the Jabłonna Reef. A hallmark of early lithified and brittle platform-margin facies of steep, reef-rimmed carbonate platforms is syndepositional fractures, common in many carbonate systems throughout the geologic record (Frost and Kerans, 2009, 2010; Budd *et al.*, 2013; and references therein). In the Jabłonna Reef, the filled fissures were recorded only in the lower part of the Zechstein Limestone (Fig. 3). The timing of the origin of the fissures is unclear in most cases, because the fissure fillings do not contain sediments and fossils that could shed light on the sedimentary history of the area. Most of the neptunian dykes occur below the characteristic lithofacies and biofacies boundary, in the portion of the section that was subject to very early, pervasive aragonite cementation, and this may account for the lack of carbonate clasts in the fissure fillings.

The burrowing in the fissure fill shown in Figure 8A indicates the syndepositional origin of the fissures. Similarly, the fissure shown in Figure 6C originated soon after cementation, when the fissure was in contact with seawater, as it was then covered by the cement crust (cf. Fig. 15B). Whether similar reasoning can be applied to the other neptunian dykes shown in Figure 8 remains an open question.

Both in recent reef niches (Reitner *et al.*, 2000) and ancient ones (e.g., Jasionowski *et al.*, 2012), marine microbialites are common structures in cavities and fractures and contribute to fracture filling. Therefore, it is possible that the muddy matrix, clotted peloidal fabrics and micritic laminae, filling the fractures in the Jabłonna Reef, are microbial structures (cf. Vennin, 2007). There is no other deposit recorded in the fissures, except for rare silt-size quartz grains.

Aragonite cementation recorded in some fissure fillings implies that they originated in rocks exposed on the sea floor and are neptunian dykes (Playford, 1984; Smart *et al.*, 1988). Like many of the neptunian dykes described in the literature (see Smart *et al.*, 1988, and references therein), there is little evidence of void development after the initial opening. The filling of fractures occurred as a combination of microbial growth and cementation. In typical neptunian dykes, sediments pouring in from above are also an important factor of fracture filling (Playford, 1984), but apart from silt-size quartz grains, no other grains were found.

There are various explanations for the formation of neptunian dykes. In the Capitan reef carbonate margin, the neptunian dykes are interpreted as having originated owing to the differential compaction induced by reef loading of foreslope sediments (Yurewicz, 1977; Melim and Scholle, 1991). Neptunian dykes, aligned parallel to the platform margin of the Capitan reef, have been interpreted by Stanton and Pray (2004) as having been formed by gravity settling and downwarping of lithified platform carbonates. In the Lower Permian reef complexes of the Russian platform, neptunian dykes are related to synsedimentary tectonism, rather than gravitational phenomena on the reef flank (Vennin, 2007), and a similar explanation was proposed by Peryt *et al.* (2012a) for the Wolsztyn reefs in general. In any case, the limitation of occurrence of neptunian dykes in the Jabłonna Reef to the lower part of the Zechstein Limestone (Fig. 3) is in agreement with such an interpretation.

Reef constructors

Although the early, massive, aragonitic cementation was of prime importance for construction of the buildup, encrusting foraminifers played an essential role prior to the cementation (Fig. 9A). In modern environments, encrusting foraminifers have been found attached to a variety of substrates, including bryozoan colonies (Zampi *et al.*, 1997). They occur in a variety of environments, including reef environments, and show a correlation of their morphology with microhabitat (Elliott *et al.*, 1996; Gischler and Ginsburg, 1996). For example, in Bermuda reefs, the encrusting foraminiferan *Homotrema rubrum* exhibits a knobby and globose test morphology in sheltered reef cavities; in turn, in exposed reef settings, hemispherical and encrusting morphologies occur. In the Red Sea, another species, *Acervulina inhaerens* exhibits columnar growth in contrast to flatter morphologies, characteristic of deeper-water environments (Dullo *et al.*, 1990).

Encrusting foraminifers occur also in cryptic habitats, where they play a much more important role than in environments with high light exposure (Logan *et al.*, 1984; Palmieri and Jell, 1985). In fossil reef environments, encrusting foraminifers also showed preferences for cryptic habitats, such as the undersides of corals (Hayward *et al.*, 1996). In the Jabłonna Reef, encrusting foraminifers are equally common in cryptic and light-exposed habitats (Fig. 9A).

In the Jabłonna Reef, bryozoans are the main reef-forming organisms (cf. Figs 3, 4, 12A, B, 15A). Their relative ecological flexibility, combined with a lack of essential competition from other organisms, such as sponges and corals, made it possible for them to dominate the environment. A propensity for rapid bioaccumulation, combined with the possibility of the quick restoration of colonies after catastrophic events, such as strong storms and rapid change of relative sea level, enabled them to control reef growth for a long time in varied, environmental conditions. Eventually, along with essential sea-level fall, combined with increasing salinity of water, bryozoans were replaced by stromatolites, which thus became the main reef-forming constituent.

There were two main phases of reef formation by bryozoans in the Jabłonna Reef (Fig. 3). In the lower part, there are rudstones/bafflestones, dominated by branched acanthocladid bryozoans, and in the upper part there are bafflestones/bindstones with microbial structures and reticular fenestellid bryozoans occur. In comparison to the reefs from NE England, in the lower part of the Jabłonna section, encrusting and columnar bryozoans (*Dyscritella*) as well as reticular forms are rare, possibly owing to a different strategy of calcium carbonate production by the organisms. In the English reefs, delicate fenestrate bryozoans were stabilized by incrusting *Dyscritella*. In the Jabłonna Reefs, more resistant to mechanical destruction, fast-growing, branched colonies had replaced fenestrate forms in the lower part of the section. At the same time, they did not need to become strengthened by slower-growing, incrusting forms, since their preservation in life position was controlled by copious aragonitic cementation. It seems that part of the colonies preserved as a whole inhabited internal voids (caverns) within the reef and were growing from the tops of such caverns toward their bottoms (e.g., Fig. 12B).

The second phase of bryozoan reef growth was characterized by common, fenestrate fenestellid bryozoans that were stabilized by microbial structures, often stromatolites.

Isotopes

Considering the drill diameter and the petrographic variability, shown by the rocks studied, the isotopic sampling must be regarded as for bulk samples; consequently, each isotopic measurement reflects both depositional and diagenetic fluids. They are roughly similar to, although distinctly lower than, the ranges and means of $\delta^{13}C$ and $\delta^{18}O$ values in other Zechstein Limestone reefs of the Wolsztyn palaeo-High that for calcite are –2.1 to 8.3‰, with the mean 4.4 ± 1.6‰, and –12.8 to 3.2‰, with the mean –4.6 ± 2.6‰, respectively (Peryt *et al.*, 2015, their table 2). Still lower $\delta^{13}C$ values are characteristic for the adjacent, basinal sections; this was explained by Peryt *et al.* (2015) as being due to a different contribution of organic carbon. However, the difference may reflect the temperature difference between ambient waters. As recently noticed by Blendinger *et al.* (2015), the fractionation of $\delta^{13}C$ as a function of temperature is not normally considered important in the analysis of marine carbonates, because a single homogeneous fluid is assumed for the depositional isotope signals. The Zechstein Limestone basin was characterized by thermally and density stratified waters (Weidlich, 2002; Peryt and Peryt, 2012; cf. Peryt *et al.*, 2015), and because a temperature difference of ca. 10 °C results in a ca. 1‰ shift in $\delta^{13}C$ (Bottinga, 1968), the warmer the ambient temperatures, the lighter the $\delta^{13}C$ values.

There is a difference in the trends of $\delta^{13}C$ and $\delta^{18}O$ curves exhibited by two Jabłonna sections studied and the basinal sections in the neighbourhood (Peryt *et al.*, 2015) and elsewhere (Peryt and Peryt, 2012) that show an increase of $\delta^{13}C$ and $\delta^{18}O$ values upsection as being an expression of a major change in ocean water chemistry (Peryt *et al.*, 2012b). The reason for this remains enigmatic, but it can be interpreted as an upward increasing influence of local sources of light $\delta^{13}C$ and $\delta^{18}O$ values, related to meteoric waters. There is no petrographic evidence for subaerial exposure, except for the uppermost part of the Zechstein Limestone sections at Jabłonna that is not discussed in this paper. However, another option is that the meteoric waters were artesian in origin (cf. Blendinger *et al.*, 2015), and as in the case described by Blendinger *et al.* (2015), this is corroborated by the Sr isotope data that are discussed below.

The comparison of $\delta^{13}C$ and $\delta^{18}O$ curves of the Jabłonna 2 and Jabłonna 4 boreholes strongly indicates that the interval below the characteristic lithofacies and biofacies boundary in the Jabłonna 2 borehole is equivalent of the lower part of the interval between the base of the Zechstein Limestone and the characteristic boundary (approximately one-fourth of this interval) in the Jabłonna 4 borehole (Fig. 21). On the other hand, the entire interval below the characteristic boundary in the Jabłonna 2 borehole can be isotopically compared to the upper part of the interval below the characteristic boundary in the Jabłonna 4 borehole (cf. Fig. 21), where $\delta^{13}C$ values first increase and then decrease as far as can be concluded from the sparse sampling. Definitely, more analyses are needed before a final conclusion is reached regarding the C-isotopic correlation of both boreholes. The tentative conclusion that the entire interval below the characteristic boundary in the Jabłonna 2 borehole corresponds to and is coeval with the upper part of the interval located below the characteristic boundary in the Jabłonna 4 borehole is in agreement with the pattern of faunal occurrence within the interval, characterized by the Acanthocladia biofacies (Fig. 3).

The $\delta^{13}C$ curves of the Jabłonna 2 and Jabłonna 4 boreholes made it possible to correlate the trends in the middle parts of both sections (Fig. 21); sampling that was too sparse for isotope study does not permit reliable detailed correlation of other parts of the sections. Anyway, the $\delta^{13}C$ curves confirm the strong diachroneity of the biofacies boundaries, with the exception of the Acanthocladia/mollusc-crinoid biofacies boundary, which is roughly isochronous.

If the maximum $\delta^{18}O$ values are considered to be the closest to the pristine, original ones and if a $\delta^{18}O_{water}$ value = 0 is assumed, then the calculated palaeotemperature (following the formula given by Epstein *et al.*, 1953) is 34 °C in the Jabłonna 2 borehole (24.5 °C for fissure fillings) and 24.9 °C in Jabłonna 4 (18.9 °C for fissure fillings). These values are close to the range of calculated palaeotemperature of seawater in the basinal facies during deposition of the Zechstein Limestone in northern Poland (23 to 33 °C – Peryt and Peryt, 2012) and north of the Jabłonna Reef (24 °C and 19 °C in the Czarna Wieś 4 and Paproć 28 boreholes, respectively), if the same assumptions are applied. In turn, if the minimum $\delta^{18}O$ values are used for palaeotemperature calculations, then the results are 69 °C and 70.5 °C (for the host rock) and 60°C and 71.4 °C (for the filling), respectively Those maximum $\delta^{18}O$ values correspond to the maximum $\delta^{13}C$ values (5.0–6.0‰ for the bulk rock and 6.0–6.4‰ for the fissure filling) that are otherwise characteristic for the Zechstein Limestone (see Peryt and Peryt, 2012).

$^{87}Sr/^{86}Sr$ values of the fissure fillings studied show a strong fluctuation (Table 2) and therefore contamination of the seawater by increased continental run-off cannot be the explanation, taking into account the palaeogeographical context. The values are generally much higher than the ratios of the contemporaneous seawater (McArthur *et al.*, 2001; Denison and Peryt, 2009, with references therein) and thus contamination by radiogenic strontium from siliciclastic components (Veizer, 1989) in the Zechstein Limestone substrate is assumed (cf. Blendinger *et al.*, 2015). Ascending fluids had a varying Sr isotopic composition, depending on the rocks, through which they travelled. Only two values from the Jabłonna 4 sample 12 (Fig. 18) are close to the latest Permian values (251.2–251.8 and 252.1–253.0 Ma according to McArthur *et al.*, 2001), but still those ages are clearly younger than the age of the Zechstein Limestone, even considering the existing controversies (see discussion in Peryt *et al.*, 2012b). During the Palaeozoic, the $^{87}Sr/^{86}Sr$ ratios show repeated lows and highs, although the general trend is toward the higher values with increasing age (McArthur *et al.*, 2001; Fig. 18) and thus on the basis of strontium isotopic composition, it is difficult to establish the age of rocks contributing to the radiogenic strontium supply, because every value recorded in the Jabłonna neptunian dykes may correspond to several different ages (see Fig. 22).

COMPARISONS AND IMPLICATIONS

Evolution of the Zechstein Limestone of the Jabłonna area had much in common with the shelf-edge reef of Cycle 1 of the English Zechstein (characterized by Smith, 1981a), as far as the first phases of reef development (foundation, colonization, diversification, and specialization; Smith, 1981a) and the final one (senescence; Smith, 1981a), related to reef flat development, are concerned. However, there are some major differences with regard to the part of the section contained between these early and late phases.

Smith (1981a) showed that the foundation of the reef in NE England was an elongate lens of coarse coquina that was colonized by stenohaline, frame-building and baffling fenestrate bryozoans. This initiated reef growth and created sub-environments, encouraging explosive diversification of the stenohaline fauna. Subsequently, with continuing, active reef growth, some stenohaline fauna declined, probably because of slightly enhanced salinity (?38–40‰), and more tolerant species, notably ramose bryozoa, bivalves, gastropods, and ostracods, became dominant, accompanied by abundant, submarine cements and laminar encrustations (Smith, 1981a). It is assumed that in NE England, differentiation into reef-top and fore-slope sub-environments and biotas and the continued growth of a talus apron on the lower fore-slope occurred at this stage of reef evolution and upward growth was equal to or exceeded the subsidence inferred (Smith, 1981a). When the top of the reef approached sea level, upward growth became limited and lateral expansion was favoured. At this stage, the reef flat and fore-slope (20°–35°) developed, each with distinctive biotas, bivalves and gastropods increased their dominance, and laminar encrustations became widespread and abundant, with the

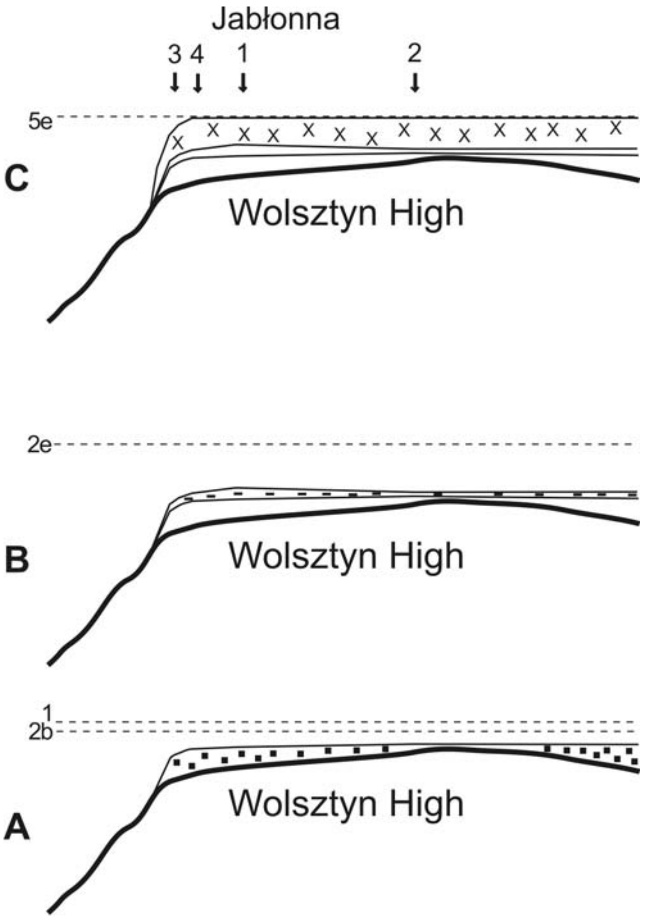

Fig. 23. The scheme showing the relative water-depth changes during the Jabłonna Reef evolution (in brackets, stages of reef evolution after Smith, 1980) and the thickness relationship between the Acanthocladia biofacies (A – squares), mollusk–crinoid biofacies (B – thick dotted line), and three other biofacies (C – crosses). 1–4: approximate locations of the Jabłonna boreholes. **A.** The end of deposition of the Acanthocladia biofacies (foundation and colonization); dotted line 1 – sea level at the end of the Acanthocladia biofacies deposition; dotted line 2b – sea level at the beginning of mollusc-crinoid biofacies. **B.** The end of deposition of the mollusc-crinoid biofacies (diversification and specialization); dotted line 2e – sea level at the end of mollusc-crinoid biofacies. **C.** The termination of deposition of the stromatolite biofacies (maturity and senescence); dotted line 5e – sea level at the end of stromatolite biofacies.

development of patches of stromatolites. When the reef flat was at or just below sea level, roughly bedded biolithite with a limited, specialised bivalve–gastropod fauna and small pedunculate brachiopods came into being and up to 90% of the reef-flat deposit was made up of diverse, laminar encrustations and algal-stromatolites (Smith, 1981a). Then, owing to a sharp fall in sea level, perhaps resulting from evaporative drawdown, most or all of the reef was subaerially exposed and initially dolomitized by refluxing lagoonal brines (Smith, 1981a). Hollingworth and Tucker (1987) provided data on the Tunstall Reef, showing relatively good preservation of primary features and concluded that the reef core facies consists of massive dolomite with fenestrate bryozoans and encrusting forms of *Dyscritella* in the life position, epibyssate bivalves (*Bakevellia* and *Liebea*) and brachiopods (*Dielasma*), the reef-flat facies is bedded dolomite with bioclastic debris (bivalve *Bakevellia* and gastropod *Anomphalus*) and stromatolites, and the reef crest palaeocommunity is dominated by *Acanthocladia* and *Dyscritella*, and in addition numerous epibyssate bivalves occur (Hollingworth and Tucker, 1987). The reef slope is dominated by crinoids, although ossicles may form crinoidal packstone lenses in the lower reef core (Hollingworth and Tucker, 1987).

In the Jabłonna Reef, the initiation of reef formation was related to the existence of a highly diversified relief covered by the Zechstein Sea, in contrast to the English reefs where coquina accumulations promoted reef development. In addition, the small size of the Jabłonna Reef (compared to the English reefs, located at the edge of a marginal carbonate platform; see Peryt *et al.*, 2010a) resulted in the Jabłonna Reef area being continually impacted by basin waters, both in respect to wave and storm energy as well as salinity and the amount of nutrients.

The presence of echinoderms and strophomenid brachiopods indicates that until the lower part of the Rectifenestella biofacies, conditions were clearly stenohaline. The subsequent elimination of stenohaline organisms and progressively poorer taxonomic differentiation of the faunal assemblage is characteristic for a slight, gradual rise of salinity.

As a whole, the taxonomic composition of organisms forming the Jabłonna Reef shows a similarity to the reefs described from England (e.g., Smith, 1981b; Hollingworth and Tucker, 1987), Germany (e.g., Kerkmann, 1969; Ernst, 2001) as well as the marginal carbonate platform of SW Poland (Hara *et al.*, 2013). The differences are noticed first of all in the quantitative proportions and the role of particular groups of organisms in the formation or binding of the deposit. In addition, it seems that the different palaeogeographical setting of the Jabłonna Reef compared to the platform-margin reefs of NE England meant that there was less opportunity to develop a distinct, horizontal pattern of reef zones in the Jabłonna area. However, there is a clear difference between the centrally-positioned boreholes (Jabłonna 2 and Jabłonna 4), where about a half of the interval located above the lithofacies/biofacies boundary is composed of grainstones (at the bottom), and other boreholes, where such grainstones occur before the first appearance of thicker packages of wackestones–packstones (Jabłonna 1) or packstones–grainstones (Jabłonna 3). In addition, the centrally-positioned boreholes show a much larger variation in thickness of intervals characterized by a particular biofacies than the other boreholes (Fig. 3).

In the lower part of the Acanthocladia biofacies, *Horridonia* appears (Fig. 3), but only one specimen was recorded *in situ*. Hence it is not possible to distinguish in the Jabłonna Reef the Horridonia biofacies, characteristic of many sections in the Wolsztyn alaeo-Ridge area (e.g., Raczyński, 2000; Peryt *et al.*, 2012a). As already mentioned, this difference is a reflection of the colonization of a solid, rocky substrate by bryozoans.

All Jabłonna borehole sections show the shallowing-upward cycle, comprising the part of the section contained between the lithological boundary and the breccia unit and resulting from upward growth exceeding inferred subsidence (Table 3). This cycle is characterized by a very sharp bottom and a radical, environmental change, interpreted as a rapid sea-level fall, compared to the situation characteristic for the time of deposition of the strata below the lithological boundary (cf. Fig. 23A); then there was a rapid return to a deeper environment (cf. Fig. 23B), although different characteristics and biota prevailed, by comparison with the time when the basal strata of the Zechstein Limestone were formed. The upward growth at this time was matching or exceeding the inferred subsidence and this may explain the supposed shallowing-upward trend during the formation of the upper part of the Acathocladia biofacies. In any case, the interval below the lithological boundary represents a different stage of deposition in the Zechstein Limestone basin.

This is in agreement with the reports of shallowing-upward cycles elsewhere in the marginal carbonate platform of the Zechstein Limestone and its equivalents (Peryt, 1986b, with references therein). For example, Füchtbauer (1980) described a stromatolitic-bryozoan bioherm north of Münster (Germany), located at the marginal carbonate platform-basin transition and showing two shallowing-upward cycles, with the percentage of stromatolites increasing upwards in each cycle; each cycle ended with subaerial exposure of the bioherm. The inference of an original composition of the bioherm, subject to several phases of dolomitization and dedolomitization, with the result that the sedimentary facies are poorly preserved, assumes that stromatolites contributed on average approximately 45% of the rock volume. Among fossils (15% of the rock volume), bryozoans were volumetrically twice as common as any other fauna. The matrix formed 25% and cement 15% of the sediment (Füchtbauer, 1980). The stromatolites show a high morphological diversity. Füchtbauer (1980) did not report (sub)vertical microbial encrustations, but he mentioned the occurrence of "vertical inorganic crusts" in the upper half of the Zechstein Limestone (Füchtbauer, 1980, p. 235); no details on them are available.

No indication of subaerial exposure was noticed in the Jabłonna Reef, except for the uppermost unit (as indicated, not discussed in this paper). The explanation is that sea-level fall (see Peryt, 1984, for discussion), leading to subaerial exposure of a marginal carbonate platform elsewhere during the Zechstein Limestone deposition, was smaller than the depth of the sea over the Jabłonna Reef. On the other hand, there is no doubt that the glacially-controlled fall of sea-level and then rapid sea-level rise (as assumed by Peryt, 1984) had to manifest itself even in areas not subject to this important, environmental change. Its record in the Jabłonna area is the distinctive lithofacies and biofacies boundary shown in Figure 4. It delimits the part of the section, formed by a combination of bryozoans, encrusting foraminifers, and copious amounts of botryoidal cement (Figs 4E, G, 9A, 12A, B) from the overlying strata characterized, near the boundary, by a lack of branched bryozoans in the life position, an abundant appearance of spiral foraminifers and a lack of botryoidal cement (Figs 3, 4). Soon afterwards, crinoids appeared in great abundance (Fig. 3), indicating deeper-water conditions.

The interpreted depth during deposition of the Zechstein Limestone in the Jabłonna area is shown in Table 3 and Fig. 23. These changes were the result of the combination of several different factors. (Glaci)eustatic sea-level fluctuations were responsible for the rapid termination of the Acathocladia biofacies (Fig. 4) and then rapid deepening, leading to the accumulation of crinoid-bearing deposits. There is also a possibility that a deepening phase occurred after the mollusc-crinoid biofacies, but that could have resulted from the block tectonics that caused the cessation of shallow-water carbonate deposition in some reef areas, which were then subject to condensed sedimentation (as already suggested by Dyjaczynski *et al.*, 2001).

Otherwise, after the formation of the lithofacies and biofacies boundary (Figs 3, 4, 5A) reflecting a major environmental change, the sequence was gradually shallowing-upward. During the deposition of this part of the Zechstein Limestone section, a distinct facies change occurred that manifested itself in different, predominant, textural types and biofacies (Fig. 3), and supposedly strong diachronism of biofacies in the centrally positioned boreholes (Jabłonna 4 and 2), which is tentatively supported by carbon isotope stratigraphy (Fig. 20).

The centrally positioned boreholes (Jabłonna 4 and 2) show a similar general sequence: grainstones followed by packstones with common, steep, microbial encrustations; in addition, in Jabłonna 2, the encrustations are common in grainstones, as well (Fig. 3). In contrast, the two reef sequences located in more basinward positions differ: above the grainstones mostly wackestones–packstones occur in Jabłonna 1 and mainly grainstones with encrustations in Jabłonna 3 (Fig. 3). In turn, the thickness of intervals characterized by particular biofacies is very similar in basinward locations (Fig. 3), although there is a distinct difference in the development of the stromatolite biofacies interval in the Jabłonna 1 and Jabłonna 3 boreholes. In the former, only columnar stromatolites occur, while in the latter there are only microbial encrustations that in addition abound in the Rectifenestella and brachiopod-bryozoan biofacies intervals in the Jabłonna 3 as well as in the Jabłonna 4 borehole; in the Jabłonna 2 borehole, microbial encrustations appear at the base of the Rectifenestella biofacies interval and continue to the top of stromatolite biofacies interval (Fig. 3).

The general shallowing-upward nature of deposition in the Jabłonna Reef area resulted in reef-flat conditions characterized, in the Jabłonna Reef as well as in other reefs of the Zechstein Limestone (e.g., Füchtbauer, 1980; Paul, 1980), by ubiquitous microbial deposits. First, they became characteristic for centrally located boreholes (and as indicated by C-isotope stratigraphy, much earlier in the Jabłonna 2 borehole than in the Jabłonna 4 borehole; Fig. 21). Then, the reef-flat started to prograde and eventually the entire Jabłonna Reef area became the site of very shallow, subaqueous deposition (cf. Fig. 23C) However, abundant, columnar stromatolites and aragonitic cementation in the Jabłonna 1 borehole indicate that in places slightly deeper (than very shallow water) conditions existed.

CONCLUSIONS

The Jabłonna Reef sections in western Poland show two distinct phases of bryozoan reef development during deposition of the Zechstein Limestone. The first one occurred early in the depositional history and can be termed the cement reef. Botryoidal aragonitic cementation played a very important role at that time, as it prevented the fragmentation of bafflestones. However, this phase of bryozoan reef development terminated suddenly. The reason remains enigmatic. One possibility is that a relative change of sea level – first a fall and then a rise – disturbed the upwelling circulation. Consequently, bioclastic deposition was predominant for a relatively long time until the second phase of bryozoan reef development occurred. The second phase of development was not accompanied by copious, early cementation. During this second phase, reticular fenestellids bryozoans were predominant. Subsequently, microbial reefs developed.

The lowermost breccia unit of the Zechstein Limestone that is characteristic for the lithologic sections in many boreholes of the Wolsztyn palaeo-High and is interpreted as a transgressive systems tract is lacking in the Jabłonna Reef. Except for the uppermost unit (that is, the breccia/stromatolite–pisolite unit, not discussed in this paper), all of the units present are highstand systems tract deposits. All Jabłonna borehole sections show a shallowing-upward cycle, comprising the part of the section contained between the lithofacies and biofacies boundary and the breccia unit and resulting from upward growth exceeding subsidence. This is in agreement with the reports of shallowing-upward cycles, recognized elsewhere in the marginal carbonate platform of the Zechstein Limestone and its equivalents.

Five biofacies are distinguished: Acanthocladia at the base, then mollusc-crinoid, brachiopod-bryozoan, Rectifenestella and at the top, stromatolite. They represent a shallowing-upward cycle, possibly with some important fluctuation recorded as the characteristic lithofacies boundary, corresponding to the Acanthocladia/mollusc-crinoid biofacies boundary, marking when possibly first shallowing and then deepening occurred. The presence of echinoderms and strophomenid brachiopods indicates that until deposition of the lower part of the Rectifenestella biofacies, conditions were clearly stenohaline. The subsequent elimination of stenohaline organisms and progressively poorer taxonomic differentiation of the faunal assemblage are characteristic for a slight, gradual rise in salinity. The taxonomic composition of organisms forming the Jabłonna Reef shows similarity to reefs, described from England and Germany, as well as the marginal carbonate platform of SW Poland. The differences are noticed first of all in the quantitative proportions and the role of particular groups of organisms in the formation or binding of the deposit.

The mean $\delta^{13}C$ values (Jabłonna 2: 3.2 ± 1.1‰, Jabłonna 4: 2.4±1.6‰) and $\delta^{18}O$ values (Jabłonna 2: –6.3±1.3‰, Jabłonna 4: –7.0 ± 2.0‰) of the Zechstein Limestone are roughly similar to, although distinctly lower than the ranges and means of $\delta^{13}C$ and $\delta^{18}O$ values in other Zechstein Limestone reefs of the Wolsztyn palaeo-High. The $\delta^{13}C$ curves of the Jabłonna 2 and Jabłonna 4 boreholes permit correlation of the lithologic trends in the middle parts of both sections and confirm the strong diachroneity of biofacies boundaries except for the roughly isochronous Acanthocladia/mollusc-crinoid biofacies boundary.

Filled fissures were recorded in the lower part of the Jabłonna Reef. The aragonite cementation recorded in some fissure fillings implies that they originated in rocks exposed on the sea floor and are neptunian dykes.

The general shallowing-upward nature of deposition in the Jabłonna Reef area resulted in reef-flat conditions with ubiquitous, microbial deposits in its central part. Then, the reef-flat started to prograde and eventually the entire Jabłonna Reef area became a site of very shallow, subaqueous deposition.

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