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PALYNOLOGY OF CARBONIFEROUS DEPOSITS (ZARĘBY BEDS) FROM THE JABŁONNA IG 1 CORE AND THE KOWALA QUARRY (HOLY CROSS MOUNTAINS, POLAND)

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Abstract: Palynological samples from the Zaręby Beds (lower Carboniferous, Holy Cross Mountains) were investigated for palynostratigraphy and palynofacies. Samples, obtained from the Jabłonna IG 1 drill core (21 samples) and the Kowala Quarry (46 samples), allowed determinations of age, ranging from the HD (*Cristatisporites hibernicus–Claytonispora disticta*) miospore zones in the Kowala Quarry section, to the PC (*Spelaeotriletes pretiosus–Raistrickia clavata*) Miospore Zone in the Jabłonna section, which corresponds to middle and late Tournaisian. This confirmed the diachronism of these sediments. Land microflora and plant remains predominated over marine phytoplankton. The sections are diachronous; the palynofacies record is rather uniform at both sites, with a small difference in age between the investigated areas. The palynofacies study reveals the deposition close to the source area for the land material. Moreover, the presence of amorphous organic matter, obtained from black shales and cherts, suggests a relatively deep and anaerobic sea bottom conditions.

Key words: Lower Carboniferous, black shales, miospores, phytoplankton, palynofacies, depositional setting.

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INTRODUCTION

The Holy Cross Mountains (HCM) are located in a southern Poland (Fig. 1), showing a unique exposure of Palaeozoic rocks from the Cambrian to the Permian (e.g., Żakowa and Migaszewski, 1995). During the Paleozoic, this area was part of a shelf basin that extended along the south-eastern margin of the Laurussia continent, located in equatorial latitudes (e.g., Racki, 1993; Bełka *et al.*, 1996; Golonka and Gawęda, 2012). The HCM consists of two regions, separated by major tectonic dislocation, dividing it into two parts: the northern (Łysogóry) and the southern (Kielce; Fig. 1). These regions have different geological histories. This is clearly seen in the development of Middle Devonian and lower Carboniferous deposits (e.g., Szulczewski, 1995). Currently, Carboniferous rocks are exposed only in the Kielce Region (Fig. 2). The geological differences are clearly seen in the spatial distribution of the Zaręby Beds. They are diachronous and their age varies in different parts of the Kielce Region, ranging from early Tournaisian to Viséan (Fig. 2; see e.g., Filipiak, 2004).

The Zaręby Beds are characterized by a fauna-poor monotonous siliceous and shale succession, containing phosphorites and pyroclastic material. They were formed under complex environmental conditions. According to Żakowa and Migaszewski (1995), these sediments are sedimentary-volcanic hybrids with a hydrothermal imprint. The impact of volcanism on the environmental conditions was confirmed recently by Rakociński *et al.* (2021). Their faunal biostratigraphy is restricted and is based mainly on brachiopods, lamellibranchs, radiolarians and trilobites (Żakowa and Paszkowski, 1989). Owing to the lack of other recognizable fossils (especially conodonts), reliable dating of these sediments can only be carried out using palynology (see e.g., Szulczewski, 1995). Palynomorphs (miospores) are considered to be the best indicators for determining the age of the Zaręby Beds (e.g., Jachowicz, 1967; Filipiak, 2004). The thickness of the Zaręby Beds varies in the Kielce Region, ranging from ~25 m up to 250 m (Żakowa, 1981; Żakowa and Migaszewski, 1995). These clastic and siliceous

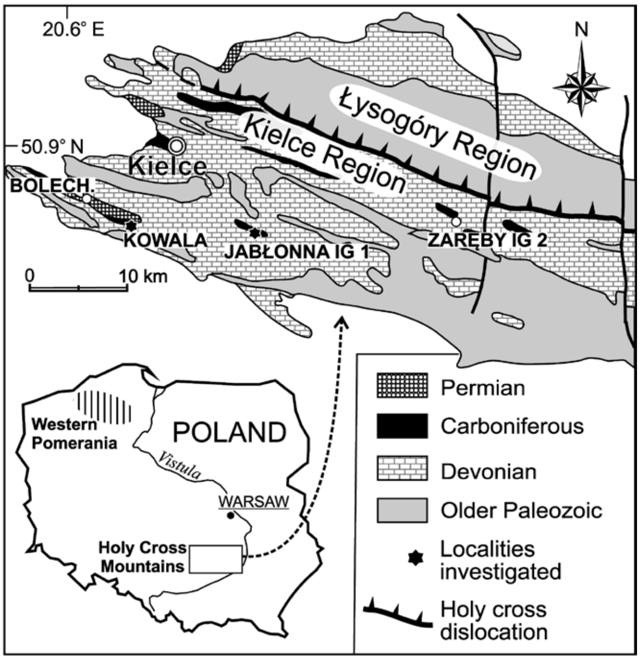

Fig. 1. Location of the Holy Cross Mountains and Western Pomerania with simplified geological map of the western and central parts of the HCM, with locations of the Jabłonna IG 1 borehole and Kowala Village (black stars); Bolech.: Bolechowice 1 borehole.

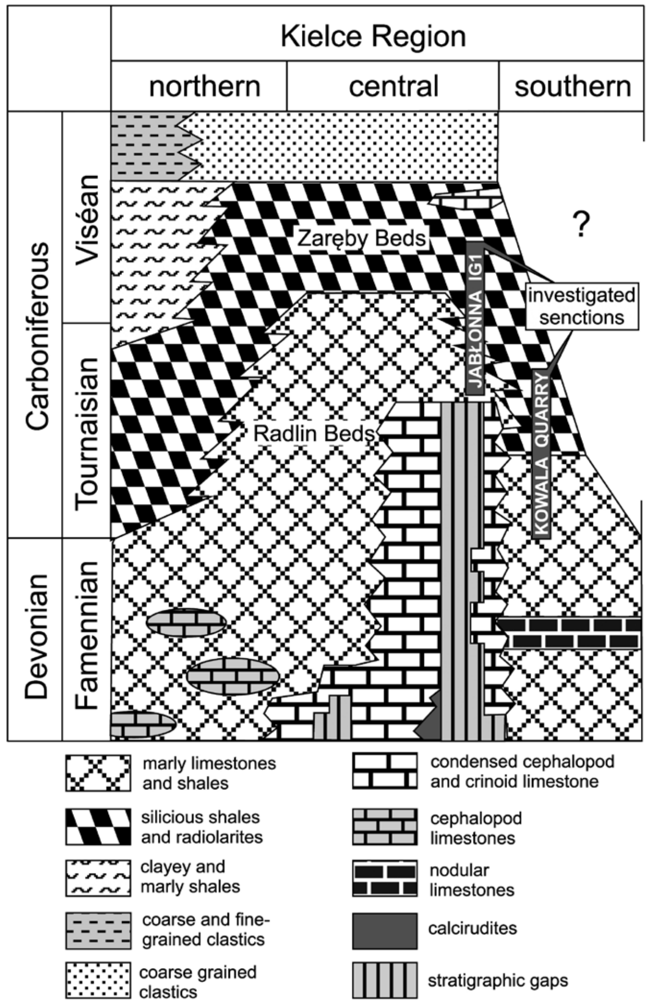

Fig. 2. Simplified diagrammatic cross-section through the Kielce Region of the Holy Cross Mountains from the Upper Devonian to the lower Carboniferous (after Szulczewski, 1995).

sediments are considered to be the Culm facies, which occurs commonly in the lower Carboniferous of Europe (see e.g., Gursky, 2023).

Palynological studies of the Zaręby Beds are scarce, compared to those of the other lithostratigraphic units of the HCM (e.g., Turnau, 1990; Filipiak, 2004, 2009, 2011; Filipiak and Racki, 2010; Fijałkowska-Mader and Malec, 2011; Filipiak *et al.*, 2022). Jachowicz (1962, 1967) was the first to study their palynostratigraphy. These studies revealed a broad Devonian–Carboniferous stratigraphic interval. Jachowicz and Żakowa (1969) determined the age of the youngest part of these deposits as Viséan, which was palynologically confirmed by Turnau (1979), Utting *et al.* (1989) and Kmiecik (1995). The latest refined palynological studies of these siliceous deposits were carried out by Filipiak (e.g., 2004, 2005; the boreholes: Bolechowice IG 1, Galęzice IG 3, Zaręby IG 2 and the Kowala Quarry section). As the result of these studies, the oldest part of the Zaręby Beds was recognised in the Zaręby IG 2 borehole and was dated as early and middle Tournaisian: VI (*Vallatisporites verrucosus–Retusotriletes incohatus*) and HD (*Cristatisporites hibernicus–Claytonispora distincta*) miospore zones; Higgs *et. al*., 1988). The HD Miospore Zone also was documented in the lowermost deposits within a trench, close to the Kowala Quarry (Filipiak, 2004). Recent, high-resolution studies of the Zaręby Beds in the Kowala Quarry (Filipiak, in Rakociński *et al.*, 2021) have confirmed the age of its basal part as the HD Miospore Zone, as was proposed previously (Filipiak, 2004). The age of the lower part of Zaręby Beds in the Bolechowice IG 1 borehole was identified as PC (*Spelaeotriletes pretiosus–Raistrickia clavata*) and CM (*Schopfites claviger–Auroraspora macra*) miospore zones, indicating a middle and late Tournaisian age (Filipiak, 2004). In turn, the uppermost intervals of these deposits were palynologically dated in the Gałęzice IG 3 borehole as TC (*Perotrilites tessellatus–Schulzospora campyloptera*) to NC (*Bellispores nitidus–Reticulatisporites carnosus*) miospore zones, indicating a Viséan age (for details see Filipiak, 2004).

Preliminary palynological age determination was also attempted in the Jabłonna IG 1 borehole. According to Żakowa *et al.* (1983, p. 73), the age of the siliceous deposits (42.3–54.2 m) in this borehole is "Tournaisian close to the D/C boundary". Filipiak (2000) presented palynostratigraphical results for only two samples from the Jabłonna IG 1 borehole, revealing the presence of the two Tournaisian microfloral zones, PC and CM (Fig. 4). Those results are revised in the present study.

In order to study the stratigraphy and environmental conditions of the Tournaisian deposits, sections from two locations of the Kielce Region were selected for the current analysis. At both locations, the lower parts of the sections are composed of marly limestones and shales (Radlin Beds), while in the upper parts of the sections, monotonous deposits of siliceous shales occur (Zaręby Beds; Fig. 2).

The main aims of this study are: (1) to revise the age of samples from the Jabłonna IG 1 borehole (Zaręby Beds) on the basis of numerous samples, using palynostratigraphy, and (2) to determine the palaeoenvironmental conditions of the studied succession, using palynofacies for the Jabłonna IG 1 and Kowala Quarry sections.

GEOLOGICAL SETTING OF KIELCE REGION

The carbonate platform, which started to form in the Middle Devonian, played an important role in the geology of the Kielce Region (for details see e.g., Szulczewski, 1995). In the Frasnian, in the central part of region, deposits were developed as shallow carbonate build-ups (Dyminy reef complex). During the Famennian, this complex was drowned and became a pelagic swell that persisted until the Tournaisian (Szulczewski, 1995; Bełka *et al.*, 1996; Szulczewski *et al.*, 1996). This process caused a contrast between the condensed limestone sequence and the basinal, mostly much thicker carbonate deposits, which were created in two deeper intra-shelf basins, surrounding the carbonate platform: from the south, the Chęciny-Zbrza Basin, and from the north, the Łysogóry Basin (Racki, 1993; Szulczewski, 1995; Racki *et al.*, 2002). The overall geology of the Kielce Region remains complex, owing to the swell that affected the regional facies pattern. The Famennian and lower Carboniferous successions evidence progressive and stepwise foundering of the carbonate platform (Szulczewski, 1995). The deepening, decreasing oxygenation and higher sedimentation rates are recorded as alternating limestones and shales (Radlin Beds; Fig. 2). Next, the younger deposits were unified and drowned in the early Viséan, when the siliceous-organic-rich shales and radiolarites (Zaręby Beds) were diachronously deposited (see Fig. 2). Consequently, the deposits located beyond the platform (northern and southern sides) are Tournaisian in age (e.g., Żakowa, 1981; Żakowa and Paszkowski, 1989; Filipiak, 2004) and the sediments occurring above the platform are Viséan (e.g., Bełka *et al.*, 1996; Szulczewski *et al.*, 1996; Skompski, 2006).

MATERIAL AND METHODS

The middle part (*sensu* Żakowa, 1981; 35.0–55.7 m) of the Jabłonna IG 1 borehole was selected for this study (Fig. 3). In total, 21 samples were palynologically processed, of which 13 contained palynomorphs. The first two samples from the Zaręby Beds (JA 14 and JA 16; Fig. 3) contained a poorly preserved, and poorly diversified miospore assemblage. All samples taken from the Radlin Beds were palynologically barren (Fig. 3). Forty-six samples were processed from the Kowala Quarry, of which 33 were positive, and 13 were barren (11 from the Radlin Beds and two from the Zaręby Beds; for details see Rakociński *et al.*, 2021).

All samples were treated with the standard combination of acids: HF-HCl-HF (e.g., Wood *et al.*, 1996; Riding, 2021). Two types of slides were prepared from the residuum obtained. The first type (unsieved) contained all the organic material, obtained after acid treatment. Owing to the very high concentration of amorphous organic matter (AOM), the inclusion of this component in the statistics was abandoned. The second type of slide additionally was treated with fuming nitric acid (HNO_3) in order to remove the substantial concentrations of AOM. The time required to remove the AOM varied from 24 up to 48 hours. In the final stage, an 18-µm mesh screen was used to concentrate the palynomorphs. All laboratory processes were performed in single-use vessels. Four standard palynological slides of the second type were prepared for each rock sample. Petropoxy 154 was used as a mounting agent and CELLOSIZE (hydroxyethyl cellulose) was used as an organic dispersing agent. Palynological investigations and taxa pictures were made, using a Nikon Eclipse 50*i* transmitted light microscope with an integrated DS-Fi2 digital camera. England-Finder coordinates were used to locate the specimens on the palynological slides.

All positive samples (excluding JA 14 and JA 16) yielded rich and well-preserved palynomorph assemblages, containing taxa of sufficient stratigraphic importance to enable assignment to specific biozones.

The palynofacies analysis was based on 300 specimens of 3 different categories: miospores, prasinophytes and phytoclasts. This classification allowed establishment of the relative percentage proportion of each component counted. In addition, the presence of palynomorphs of lower frequency was noted: acritarchs, scolecodonts and miospore tetrads.

Taxa with biostratigraphic importance and phytoplankton elements are shown in Figures 5, 6. The miospore, prasinophytes and acritarchs taxa, documented in this study, are listed separately in the Appendix.

Slides, macerates and sample remains are housed in the Institute of Earth Sciences (University of Silesia in Katowice, Poland) collections in Sosnowiec.

Lithological characteristics of the investigated sections

Jabłonna IG 1 drill core

The Jabłonna IG 1 borehole (Fig. 1) was drilled in 1973 within the Borków Syncline, located in the southwestern part of the HCM (Malec, 2014). The lowermost part of the section to a depth of 55.7 metres belongs to the Radlin Beds that are represented by green to gray claystone, with thin intercalations of pyroclastic rocks, marls and limestone (Żakowa *et al.*, 1983; Malec, 2014; Fig. 2). The upper deposits (55.7 m and upwards; Fig. 3) composed of black siliceous claystone with radiolarians and phosphates, are considered to be the Zaręby Beds. According to Żakowa *et al.* (1983), the contact between the Devonian and Carboniferous is sedimentary, with probable intervals of non-deposition (Fig. 2).

Kowala Quarry section

The analysed section is located in the active Kowala Quarry, on the southern flank of the Gałęzice Syncline (the Kielce Region of the HCM; Fig. 1). The lower Tournaisian

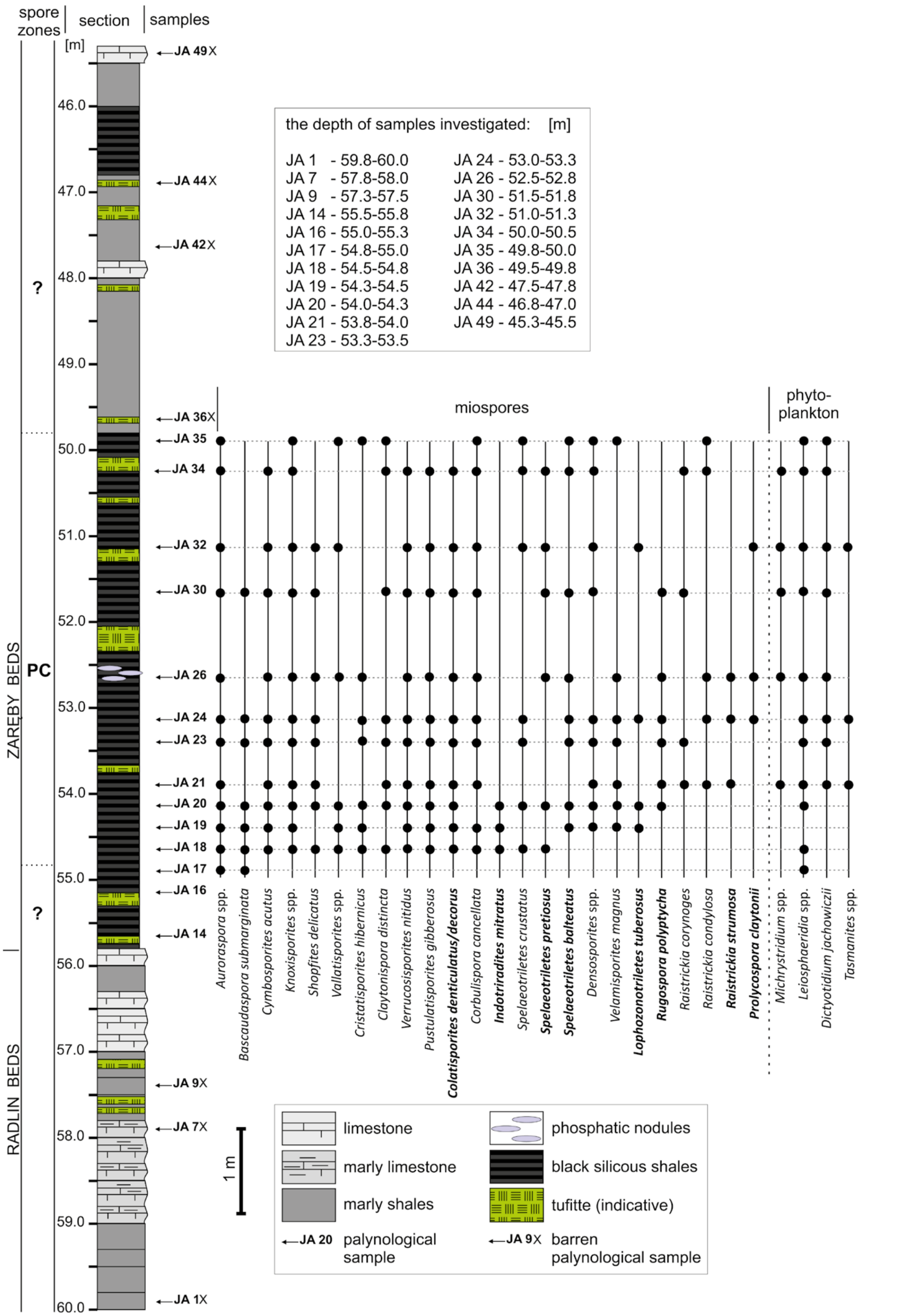

Fig. 3. Lithology of the Jabłonna IG 1 borehole (partly from Żakowa *et al.*, 1983) with lithostratigraphy, sample location, miospore zonation and stratigraphic range of selected miospore and phytoplankton taxa. Bold: important miospores for palynostratigraphy.

deposits, the Radlin Beds, are composed of bright green, yellow and red siltstone with gray carbonate nodules and thin intercalations of limestone and black shales, occurring in the lower part of the section. The overlying Zaręby Beds (mid-Tournaisian) are represented by siliceous shales and radiolarites that include tuffites and belong to the deposits of the intra-shelf Chęciny-Zbrza basin (e.g., Rakociński *et al.*, 2021). The lithological set E *sensu* Malec (1995, 2014) correlates with this interval.

RESULTS

Palynostratigraphy

Miospore schemes for the Lower Carboniferous of western Europe (Higgs *et al.*, 1988) and a local subdivision for the Western Pomerania (Turnau, in Matyja *et al.*, 2000) were used to determine the palynostratigraphy (Fig. 4).

Jabłonna IG 1

The first sample that contained microflora was JA 17 (54.8–55 m; Fig. 3). Miospores were limited in number and with long stratigraphical ranges (e.g., *Auroraspora* spp., *Bascaudaspora* sp., *Discernisporites micromanifestus, Lophozonotriletes* sp., *Verrucosisporites scurrus*), so establishing a precise stratigraphy was not possible (Fig. 3). In the remaining samples (JA 18–JA 35; Fig. 3), the recognised microflora assemblage was very diverse taxonomically and dominated by miospores of the genera *Auroraspora*, *Retusotriletes, Vallatisporites, Verrucosisporites* and *Cymbosporites*. Taking into account the composition of the miospores assemblage, one biozone was identified here. In the sample JA 18 (54.5–54.8 m) and younger samples, *Spelaeotriletes pretiosus* was recognised. It is the zonal index species and on the basis of its appearance, the PC (*Spelaeotriletes pretiosus–Raistrickia clavata*) Miospore Zone was determined (Higgs *et al*., 1988; Figs 3, 4). *Raistricka clavata*, the second eponymous taxon, was recognised in the JA 26 (52.5–52.8 m) sample, but its occurrence within the section is irregular. The assemblage also contained some other taxa, important for this biozone, such as *Prolycospora claytonii* and *Raistrickia strumosa*. *P. claytonii* is the index taxa of the Cl Local Miospore Zone of Western Pomerania (e.g., Turnau, in Matyja *et al.*, 2000; Stempień-Sałek, 2002; Fig. 1) with its lower boundary occurring close to the lower boundary of the PC Miospore Zone (see Fig. 4). The first appearance of *P. claytonii* was recorded in sample JA 24 (Fig. 3). However, it is worth noting that this taxon was recognised in only a few samples (Fig. 3), and in limited numbers. In turn, *R. strumosa* appears in the PD (*Spelaeotriletes pretiosus–Colatisporites decorus*) Miospore Zone of Western Gondwana (Melo and Loboziak, 2003; Playford *et al.*, 2012), which is the Gondwana equivalent of the PC Miospore Zone of Euroamerica. However, it is important to note that *R. strumosa* was previously recognised in the HD Miospore Zone (Filipiak in Rakociński *et al.*, 2021; Fig. 4) in the Kowala Quarry. According to Higgs *et al.* (1988), the presence of *Anaplanisporites centrosus*, *Colatisporites decorus, C. denticulatus* and *Indotriradites mitratus* is significant for recognition of the PC Miospore

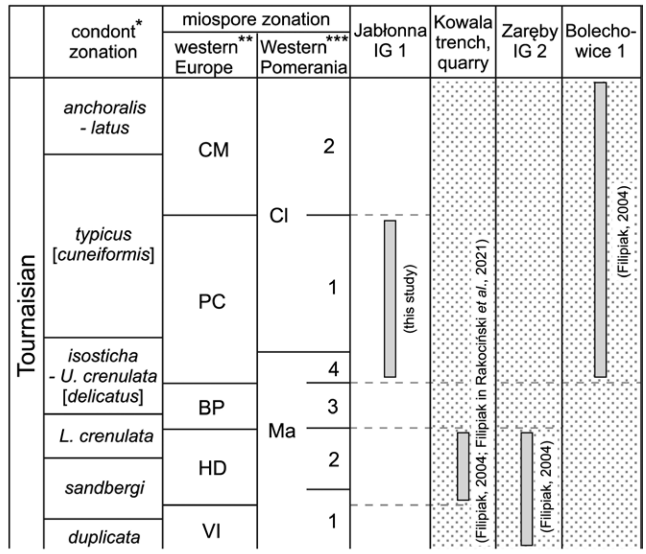

Fig. 4. Correlation of the miospore and conodont (* – Wendt *et al*., 2009) zonal schemes for the Early Carboniferous of western Europe (** – Higgs *et al*., 1988) and the Western Pomerania (*** – Turnau in Matyja *et al*., 2000) with stratigraphical range of samples from the Jabłonna IG 1 borehole and historical data (dotted area) of earlier investigated sections of Zaręby Beds, dated as Tournaisian.

Zone. All these taxa have their first appearance in the PC Miospore Zone (Fig. 4). Moreover, according to Higgs *at al.* (1988) the stratigraphic range of *I. mitriatus* is limited to this zone only. Significant for the recognition of this level was the absence of *Schopfites claviger*, a nominal miospore for the next Tournaisian CM (*Schopfites claviger–Auroraspora macra*) Miospore Zone (Higgs *et al.*, 1988; Fig. 4). The recognition of the PC Miospore Zone here is also strengthened by the fact that some of the recognized species are considered to make their last appearance at the top of PC Miospore Zone: e.g., *Lophozonotriletes tuberosus*, *Indotriradites mitratus* and *Tumulispora* spp. (see Higgs *et al.*, 1988; Avkhimovitch and Turnau, 1994). The most important miospore taxa are shown in Figure 5.

This study has shown that not all taxa, considered as important in Western Europe or Western Pomerania, occur regularly in the HCM area. This is especially true for the irregular presence of *Raistrickia clavata* as discussed above. It is also worth noting that *Spelaeotriletes* spp. appear as dispersed individuals within the whole section. Probably, for this reason, previous studies that involved a limited number of samples (Filipiak, 2000) did not show their presence in this time interval. Higgs *et al.* (1992) suggested that the low frequency of *S. pretiosus* is indicative of the lower part of the PC Miospore Zone. Therefore, the issue of *Spelaeotriletes* frequency in the HCM area requires further research. On the other hand, another noteworthy feature of the Jabłonna IG 1 microflora assemblage is the regular appearance of *Colatisporites* spp. These taxa were frequently observed within the PC Miospore Zone by Turnau (e.g., Avchimovitch and Turnau, 1994) in the area of Western Pomerania (Fig. 1). Thus, they may be considered as valuable for palynostratigraphy in the area of Poland.

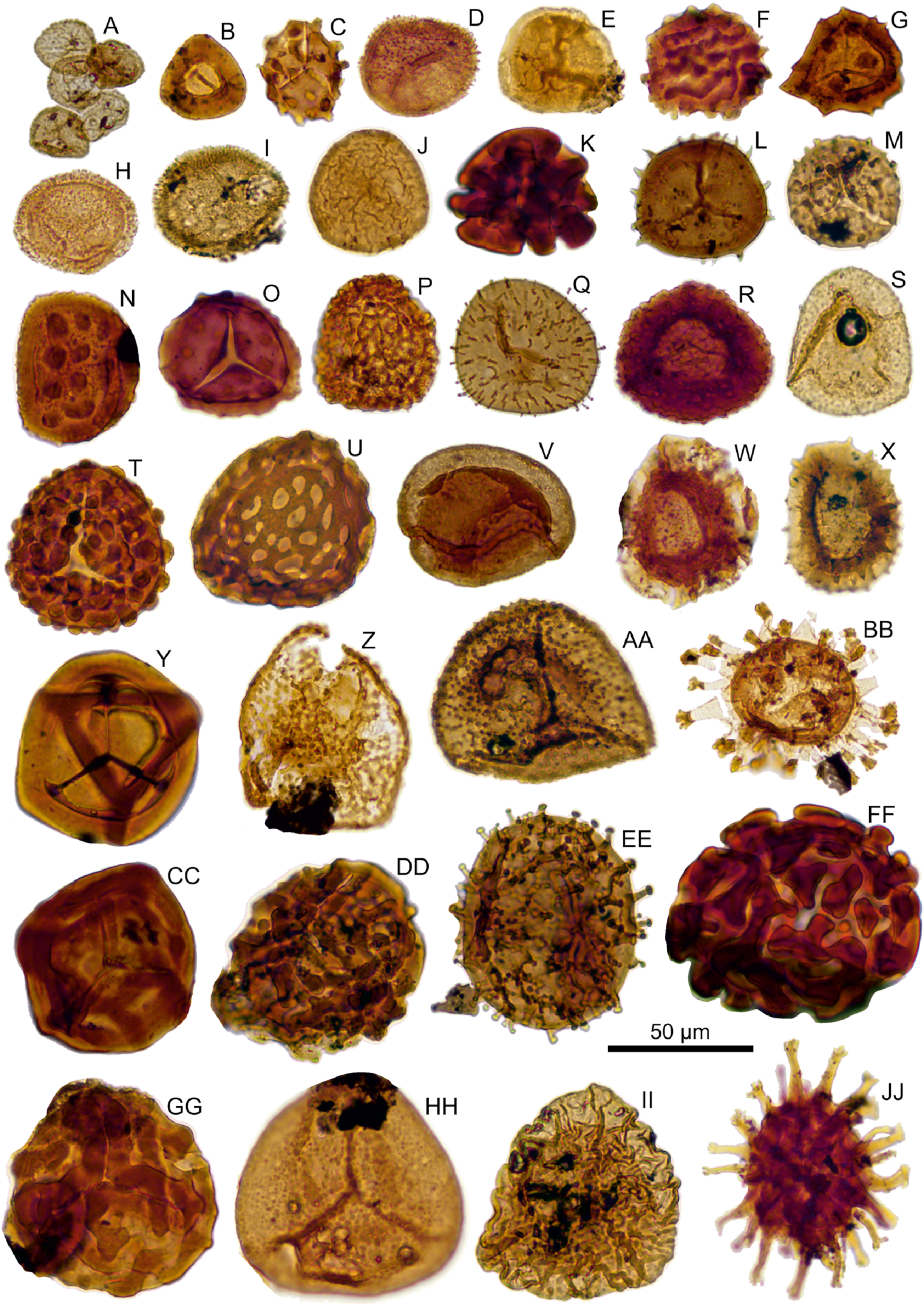

Fig. 5. Miospores from the Jabłonna IG 1 borehole. Same scale for all images.

The Tournaisian palynology of Western Pomerania (Fig. 1) was recognised in detail by Turnau (e.g., 1978). In a few subsequent papers, she clarified and detailed the order of local palynostratigraphic levels (see Turnau summary in Matyja *et al.*, 2000). According to this division, the lower part of the local Cl (*Prolycospora claytonii*) Miospore Zone is a partial equivalent of the standard PC Miospore Zone with *Prolycospora claytonii* being a key taxon for this zone (see Fig. 4). This species was documented in three samples from the middle part of Jabłonna IG 1 section (Fig. 3) and when one compares this to the Western Pomerania occurrences, it was limited in numbers (see Turnau, 1979). In this work, the first appearance of these miospores was recorded in sample JA 24 (53.0–53.3 m; Fig. 3). Some of the common taxa that Turnau considers important for the Cl Miospore Zone that were documented in HCM include: *Colatisporites denticulatus, Raistrickia clavata* and *Spelaeotriletes pretiosus* (see Turnau in Clayton and Turnau, 1990; Avchimovitch and Turnau, 1994). Moreover, Stempień-Sałek (in Matyja and Stempień-Sałek, 1994; Stempień-Sałek, 2002), who also modified the local miospore zonations of Western Pomerania, noticed that *S. pretiosus* appears earlier than *P. claytonii*. The same sequence was observed in the currently investigated Jabłonna IG 1 section (Fig. 3).

Referring to previous studies, only two positive samples from the Jabłonna IG 1 core (53.5 and 50.5 m) were examined palynologically by Filipiak (2000). This study was carried out on the same depth interval (50.0–55.0 m; see Fig. 3), but with a higher resolution, and confirmed the occurrence of the PC Miospore Zone and excluded the occurrence of the succeeding CM (*Schopfites claviger–Auroraspora macra*) Miospore Zone (Fig. 4). Additionally, the revision of historical slides from a depth of 50.5 m has not confirmed the presence of *Schopfites claviger*.

In addition to the miospores, the samples also contained organic-walled microplankton that had no palynostratigraphic value. They were mainly prasinophytes with a small number of acritarchs (the most characteristic specimens are shown in Fig. 6). Prasinophytes were represented by *Leiosphaeridia* spp*.*, *Hemiruptia* spp., *Tasmanites* spp. and *Dictyotidium jachowiczii*. A few acritarchs assignable to *Micrhystridium ampilatum, M. pentagonale, M. stellatum, Unellium piriforme* and *Veryhachium* spp. were documented, as well. Only the occurrence of *D. jachowiczii* can be considered as a characteristic taxon of the Early Carboniferous, as it was observed in the Tournaisian–Viséan interval from the HCM area (Poland; Jachowicz, 1967; Filipiak, 2005; Rakociński *et al.*, 2021) and Denmark (Bertelsen, 1972).

Kowala Quarry

Thirty-three positive samples were investigated from the 7-m-thick interval of the Zaręby Beds. The succession of recognised miospores indicated the presence of the HD Miospore Zone (*Cristatisporites hibernicus–Claytonispora disticta*; Higgs *et al.*, 1988; Fig. 4). For more palynostratigraphic details see Filipiak in Rakociński *et al.*, 2021.

Palynofacies

The classification of organic components was established according to the age of the material and the aim of the study (see also Tyson, 1995; Batten, 1996; Mendonça Filho *et al.*, 2011). The specific nature of the Zaręby Beds should be taken into account in the environmental evaluation, as well. The sediments were deposited in a complex environment (e.g., Żakowa and Migaszewski, 1995). The strong eutrophication of marine environments caused by frequent volcanism and hydrothermal waters may have played a significant role for the frequency of the analysed components (e.g., Rakociński *et al.*, 2021). Volcanism also could have played a negative role, especially in the terrestrial environment: wildfires, acid rains, environment pollution (Hg, CO_2, SO_2), mutations, etc. (Galloway and Lindström, 2023). Nevertheless, more general considerations of palynofacies can be made.

In the present analysis, the most common categories, such as miospores, phytoclasts and prasinophytes, observed in all microscopic slides, were selected for statistics. For a better understanding of the miospores and non-pollen palynomorphs assemblage composition, only slides macerated with HNO_3 were studied. The presence of AOM was noted,

Fig. 5. Miospores from the Jabłonna IG 1 borehole. Same scale for all images. **A.** *Prolycospora claytonii*, sample JA 24, 53.0–53.3 m, T31/3. **B.** *Densosporites annulatus*, sample JA 30, 51.5–51.8 m, K35. **C.** *Pustulatisporites gibberosus*, sample JA 30, 51.5–51.8 m, P47/3. **D.** *Schopfites delicatus*, sample JA 32, 51.0–51.3 m, U24/3. **E.** *Auroraspora asperella*, sample JA 18, 54.5–54.8 m, F18. **F.** *Lophozonotriletes tuberosus*, sample JA 19, 54.3–54.5 m, M17/4. **G.** *Densosporites* sp. A, sample JA 18, 54.5–54.8 m, R15. **H.** *Colatisporites decorus*, sample JA 26, 52.5–52.8 m, R21/3. **I.** *Colatisporites denticulatus*, sample JA 18, 54.5–54.8 m, M36/3. **J.** *Plicatispora scolecophora*, sample JA 24, 53.0–53.3 m, N33/3. **K.** *Secarisporites mauriceus*, sample JA 30, 51.5–51.8 m, N37. **L.** *Cymbosporites acutus*, sample JA 26, 52.5–52.8 m, J41/3. **M.** *Pustulatisporites dolbii*, sample JA 24, 53–53.3 m, Q37/3. **N.** *Tumulispora rarituberculata*, sample JA 26, 52.5–52.8 m, U16/3. **O.** *Tumulispora malevkensis*, sample JA 32, 51.0–51.3 m, L32. **P.** *Bascaudaspora submarginata*; sample JA 30, 51.5–51.8 m, F35/4. **Q.** *Claytonispora distincta*, sample JA 24, 53.0–53.3 m, F17/2. **R.** *Densosporites* sp., sample JA 32, 51.0–51.3 m, P39/4. **S.** *Spelaeotriletes obtusus*, sample JA 26, 52.5–52.8 m, E49. **T.** *Verrucosisporites nitidus*, sample JA 30, 51.5–51.8 m, E39/3. **U.** *Brochotriletes* sp.; sample JA 30, 51.5–51.8 m, Q29. **V.** *Auroraspora macra*, sample JA 24, 53.0–53.3 m, W43. **W.** *Cristatisporites hibernicus*, sample JA 26, 52.5–52.8 m, G21/3. **X.** *Indotriradites mitratus*, sample JA 19, 54.3–54.5 m, S46/2. **Y.** *Knoxisporites triangularis*, sample JA 30, 51.5–51.8 m, O10. **Z.** *Spelaeotriletes balteatus*, sample JA 20, 53.3–53.5 m, D33/1. **AA.** *Spelaeotriletes balteatus*, sample JA 34, 50.0–50,5 m, F22/4. **BB.** Unidentified miospore, sample JA 34, 50.0–50,5 m, C35/3. **CC.** *Knoxisporites literatus*, sample JA 24, 53–53.3 m, Q41/3). **DD.** *Corbulispora cancellata*, sample JA 24, 53.0–53.3 m, D30. **EE.** *Raistrickia strumosa*, sample JA 26, 52.5–52.8 m, U20. **FF.** *Convolutispora* cf. *circumvallata*, sample JA 30, 51.5–51.8 m, H38/3. **GG.** *Convolutispora major*, sample JA 26, 52.5–52.8 m, N6/2. **HH.** *Spelaeotriletes crustatus,* sample JA 34, 50.0–50.5 m, T38. **II.** *Rugospora polyptycha,* sample JA 24, 53.0–53.3 m, Y40/4. **JJ.** *Raistrickia corynoges,* sample JA 26, 53.8–54.0 m, U26/4.

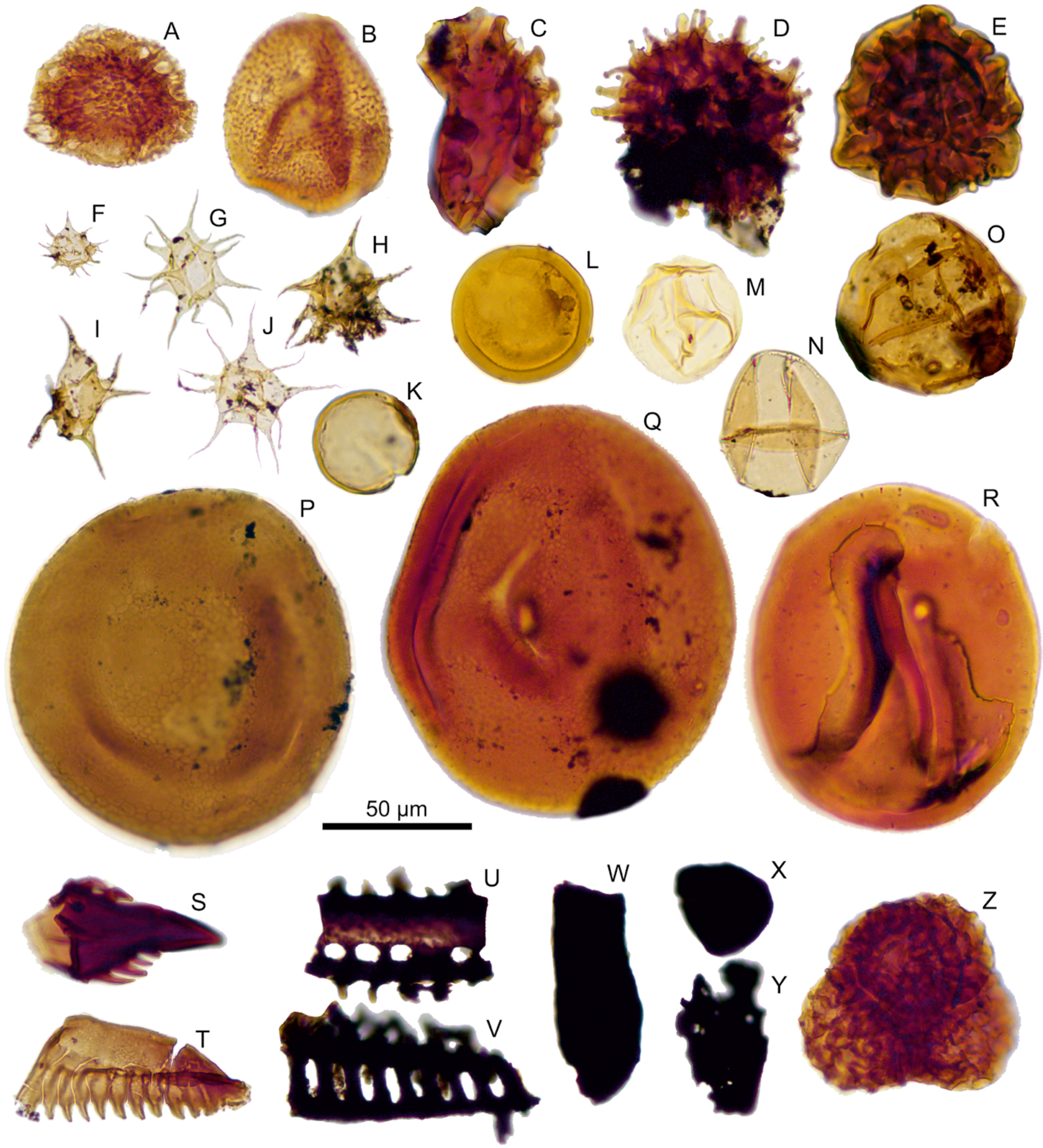

Fig. 6. Miospores, phytoplankton and other palynomorphs from the Jabłonna IG 1 borehole. Same scale for all images. **A.** *Vallatisporites* sp., sample JA 24, 53.0–53.3 m, P3. **B.** *Dictyotriletes membranireticulatus*, sample JA 26, 52.5–52.8 m, G11. **C.** *Raistrickia clavata*, sample JA 26, 52.5–52.8 m, O6. **D.** *Raistrickia condylosa*, sample JA 24, 53.0–53.3 m, R18/2. **E.** *Gorgonispora multiplicabilis*, sample JA 26, 52.5–52.8 m, E14/3. **F.** *Unellium piriforme*, sample JA 32, 51.0–51.3 m, W39/2. **G.** *Micrhystridium ampliatum*, sample JA 30, 51.5–51.8 m, W46. **H.** *Micrhystridium ampliatum*, sample JA 30, 51.5–51.8 m, R30/4. **I.** *Micrhystridium* cf. *ampliatum*, sample JA 30, 51.5–51.8 m, V33/1. **J.** *Micrhystridium pentagonale*, sample JA 32, 51.0–51.3 m, W25. **K.** *Hemiruptia* sp., sample JA 24, 53.0–53.3 m, P36/2. **L.** *Hemiruptia* sp., sample JA 18, 54.5–54.8 m, S37/2. **M.** *Leiospharidia* sp., sample JA 32, 51.0–51.3 m, H33/2. **N.** *Leiospharidia* sp., sample JA 24, 53.0–53.3 m, U21. **O.** *Leiospharidia* sp., sample JA 21, 53.8–54.0 m, M 31. **P.** *Dictyotidium jachowiczii*, sample JA 26, 52.5–52.8 m, R45/4. **Q.** *Dictyotidium jachowiczii*, sample JA 32, 51.0–51.3 m, W35. **R.** *Tasmanites* sp., sample JA 32, 51.0–51.3 m, G22/4. **S.** Scolecodont, sample JA 24, 53.0–53.3 m, J19/4. **T.** Scolecodont, sample JA 24, 53.0–53.3 m, H37. **U.** Tracheid, sample JA 26, 52.5–52.8 m, O36/4. **V.** Tracheid, sample JA 26, 52.5–52.8 m, L29/3. **W.** Opaque phytoclasts, sample JA 26, 52.5–52.8 m, 036/2. **X.** Opaque phytoclasts, sample JA 26, 52.5–52.8 m, 036/3. **Y.** Opaque phytoclasts, sample JA 26, 52.5–52.8 m, O36. **Z.** Miospore tetrad (*Bascaudaspora submarginata*), sample JA 24, 53.0–53.3 m, N21.

but not quantified (Figs 7, 8). Both miospores and phytoclasts are interpreted as components of terrestrial origin. The opaque phytoclasts are extremely resistant and they may have been transported for long distances (Tyson, 1995). The higher the frequency of opaque phytoclasts in relation to phytoclasts, the more distal the setting that it indicates. The inverse proportions indicate shallowing of the basin. Biostructured and opaque phytoclasts dominate the distal settings as well as the small fraction (Mendonça Filho *et al.*, 2011). Small and lath phytoclasts are concentrated in distal settings, while equant and larger phytoclasts are more common in proximal settings (Tyson, 1995).

Prasinophytes, on the other hand, may represent marine phytoplankton as well as freshwater organisms (Batten, 1996; Guy-Ohlson, 1996). Acritarchs and scolecodonts are considered to be unequivocally of marine origin. It is worth pointing out that acritarchs lost their statistical significance at the end of the Devonian period, owing to the crisis affecting this group (e.g., Falkowski *et al.*, 2004). This phenomenon is commonly observed and is defined as the “phytoplankton blackout” (see e.g., Riegel, 2008; Martin and Servais, 2019). Hence, in the Early Carboniferous, they are rare.

Jabłonna IG 1

Miospores are abundant, ranging from ~30% (sample JA 19) up to 50% (sample JA 34). The frequency of the phytoclasts is higher and varies from 42% in sample JA 34 to ~60% in JA 19 sample, with the opaque phytoclasts being mostly lath-like in shape (more than 70% of opaque phytoclasts). The least frequent are the prasinophytes, the frequency of which ranges between ~2–10% in samples JA 26 and JA 19, respectively. Other palynomorphs, such as acritarchs and scolecodonts are so limited in number that they are excluded from the statistics; the same is true for the miospore tetrads that occasionally occurred (Fig. 7). All samples contained abundant AOM.

The palynofacies are homogeneous. All major components (miospores, phytoclasts and prasinophytes) are present in all samples with some minor fluctuations, but terrestrial material predominates (Fig. 7). Prasinophytes (leiospheres, tasmanitids and *Dictyotidium* spp.) occur in low numbers in all samples, except for the JA 19 bottom sample, in which their most significant frequency was noted (10%). Prasinophytes may be considered as an indicator of high primary productivity and the presence of AOM indicates anaerobic conditions (Tyson, 1995; Batten, 1996).

In summary, this type of palynofacies can be interpreted as representing a proximal but deep shelf, with generally anaerobic sea-bottom conditions (Fig. 7).

Kowala Quarry

The frequency of miospores is between ~20% in the KQ 173F2 sample and 38% in the KQ 173O2 sample. The relative frequency of the phytoclasts ranges from 68% in the KQ 173G1 sample up to 48% in the KQ 173O2 sample. The opaque phytoclasts are represented by the remains of lath shapes and filamentous particles. The proportion of prasinophytes, on the other hand, ranges from 2 to 7% (see Fig. 8). The other components like acritarchs, scolecodonts and miospores tetrads occur sporadically (less than 1%). All samples contained abundant AOM.

The palynofacies generally show similar homogeneity as in Jabłonna IG 1. The assemblage is dominated by terrestrial components (Fig. 8). The presence of AOM suggests anaerobic conditions on the sea bottom and the occurrence of prasinophytes is the signal of high primary productivity.

In summary, this type of palynofacies can be interpreted as a proximal but deep shelf, with generally anaerobic sea-bottom conditions.

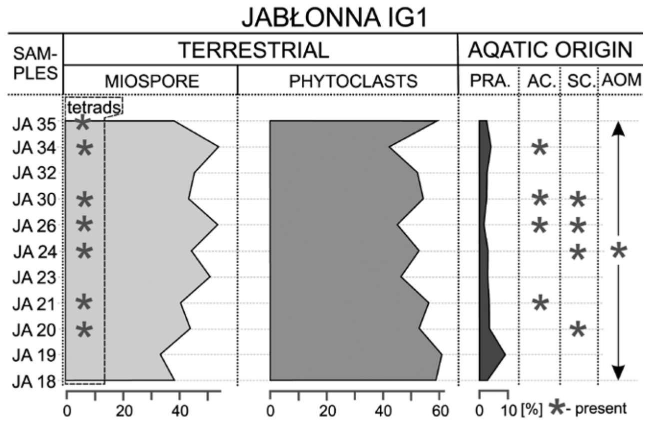

Fig. 7 Relative frequency of organic components in Jabłonna IG 1 borehole samples. Abbreviations used: PRA. – prasinophytes, AC. – acritarchs, SC. – scolecodonts.

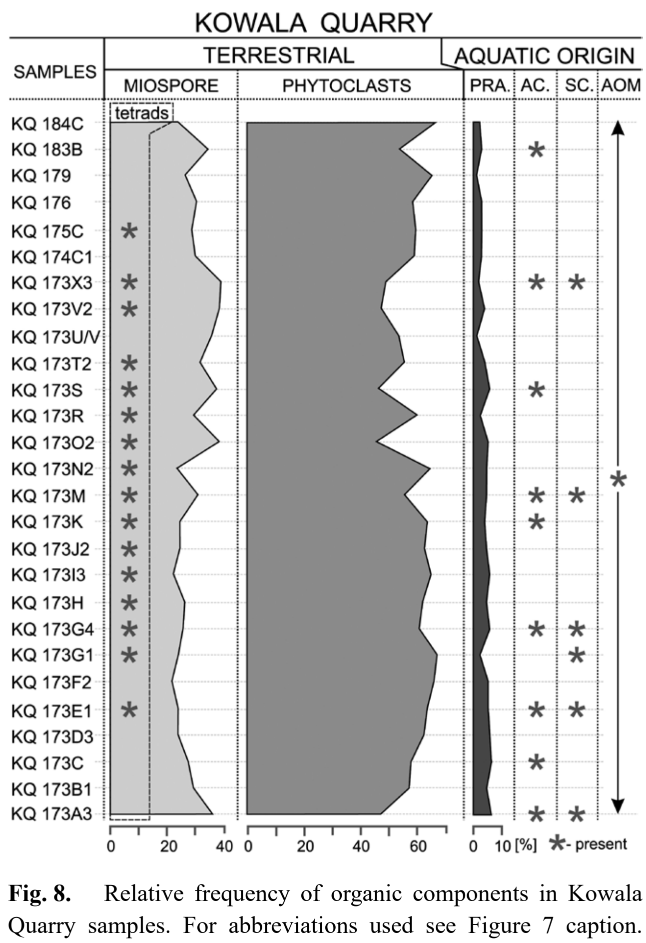

Fig. 8. Relative frequency of organic components in Kowala Quarry samples. For abbreviations used see Figure 7 caption. The thickness of the Zaręby Beds is approximately 7 m (for details see Rakociński *et al.*, 2021).

PALAEOENVIRONMENTAL DISCUSSION

According to Tyson (1995), the palynofacies parameters chosen for analysis may depend on the objectives of the study and palynomorphs classifications used, when one collected the data. Taking into account the result of the palynofacies analysis, it should be stated that both analysed sections have similar environmental characteristics, even the minor fluctuations. Despite the fact that both sections represent the Zaręby Beds, comparison of them is meaningless, because of their diachronicity.

Sedimentation may have occurred on a deepening shelf, with an intensive supply of land organic material. Proximal-distal variation is indicated by land-originated components (miospores, phytoclasts; see Tyson, 1993, 1995). The presence of tetrads is indicative of a more proximal setting, with their abundance increasing towards the land (Tyson, 1995). The graphs show the difference in the relative frequency of miospores and opaque phytoclasts in both sections (Figs 7, 8). Biostructured, opaque phytoclasts that dominated the studied sections are dominant in the more distal settings. They may decrease in size toward the distal basin because of breaking up into smaller particles during transportation (Tyson, 1995). Also, the opaque phytoclasts are more resistant to degradation than the brown ones (Mendonça Filho *et al.*, 2011). The phytoclasts assemblage can be interpreted according to their shape, as well. According to Whitaker *et al.* (1992), the more distal settings are enriched in lath particles. The lath-shaped opaque particles are extremely resistant and can be transported for long distances (Mendonça Filho *et al.*, 2011). In the classic approach, the phytoclast assemblage, similar to the currently documented one, indicates a more distal setting. This set of palynofacies features reflects the complex character of the Zaręby Beds. One needs to consider that depositional setting might have been influenced by the volcanic processes (e.g., Rakociński *et al.,* 2021), palaeogeographical configuration as well as the synsedimentary tectonic movements that could lead to the sinking and uplift of blocks, located close to the shore. This may explain the deep anaerobic setting, but with proximity to land. Tectonics was considered a particularly important factor for regional facies development, especially when one considers the role of syndepositional faults (Szulczewski, 1973, 1989; Żakowa and Migaszewski, 1995). In both sections, spores and phytoplankton show little evidence of fungal and bacterial degradation; also, tiny traces of pyrite corrosion are visible. This preservation mode indicates relatively rapid organic deposition and reducing conditions (Tyson, 1995). Moreover, substantial concentrations of AOM were documented; the abundance of AOM is correlated with environments of low oxygen content and with high preservation of planktonic organic matter or benthic microbial material (Tyson, 1995). This is in agreement with the geochemical data. Rakociński *et al.* (2021) interpreted the Radlin Beds as being deposited in oxygen-depleted conditions, with short episodes of seafloor oxygenation, and the organic-rich Zaręby Beds originated in a low-oxygen environment. The presence of radiolarian deposits may be a signal for high pelagic productivity in marginal basins and is related to the deepening of the basin (Jones and Murchey, 1986; Randon and Caridroit, 2008). The palynofacies confirm the organic-rich depositional conditions in a deepening basin. Increased eutrophication may have been the result of volcanism, the presence of which (tuffite layers), was frequently recorded in the sections investigated (e.g., Żakowa *et al.*, 1983; Skompski, 2006; Rakociński *et al.*, 2021).

The palynofacies studies from the analysed time interval are scarce. The significant transgression that accelerated during the deposition of the Lower Alum Shale (Tournaisian) was recorded in the Sauerland area (Germany; Bless *et al.,* 1993). In the currently investigated sections, there is a slight increase in land-derived components, but owing to the multitude of factors that influenced deposition of the Zaręby Beds, it is not clear if these sections represent the same environmental changes.

Quantitative visual assessment of the colour of the unoxidized palynomorphs, from both investigated sections, shows that they are thermally changed in a similar manner and display a dark yellow colour. This colouration indicates a thermal alteration scale (TAS) value of 3.5 (~0.5 R_o; e.g., fig. 1 in Batten, 1982; Traverse, 2008), roughly indicating a palaeotemperature of 60–90 °C. The previous research on conodont colour in this area showed 1.0–1.5 on the CAI scale (Bełka, 1990; Narkiewicz and Malec, 2005), which is consistent with the current findings, based on microflora.

CONCLUSIONS

On the basis of palynostratigraphic analyses, the age of the bottom part of the Zaręby Beds was determined as the PC Miospore Zone in the Jabłonna IG 1 borehole. In comparison, at the Kowala Quarry, the oldest part of these sediments was determined as the HD Miospore Zone (both Tournaisian in age). This confirmed the diachronous nature of these sediments in the HCM. The palynofacies composition of both analysed sections indicates the depositional environment as deep shelf with generally anaerobic sea-bottom conditions, but with high terrestrial input (a proximal setting). This general determination is caused by the complexity of the environmental factors that possibly could have affected deposition of the Zaręby Beds. It is likely that volcanism enhanced eutrophication, causing anoxia. Moreover, similar depositional settings were encountered at different times (Tournaisian and Viséan), owing to tectonic activity that generated deep marine areas close to land.

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Appendix

All palynomorph taxa recorded in the Jabłonna IG 1 borehole

Miospores

Auroraspora asperella (Kedo) Van der Zwan, 1980
Auroraspora macra Sullivan, 1968
Bascaudaspora submarginata (Playford) Higgs, Clayton and Keegan, 1988
Brochotriletes sp.
Claytonispora distincta (Clayton) Playford and Melo, 2012
Colatisporites decorus (Bharadwaj and Venkatachala) Williams in Neves *et al.*, 1973
Colatisporites denticulatus Neville, 1973
Convolutispora caliginosa Clayton and Keegan in Clayton *et al.*, 1982
Convolutispora cf. *circumvallata*
Convolutispora major (Kedo) Turnau, 1978
Corbulispora cancellata (Waltz) Bharadwaj and Venkatachala, 1961
Cristatisporites hibernicus (Higgs) Higgs, 1996
Cymbosporites acutus (Kedo) Byvscheva, 1985
Cyrtospora cristifera (Luber) Van der Zwan, 1979
Densosporites annulatus (Loose) Schopf, Wilson and Mentall, 1944
Dictyotriletes membranireticulatus Bertelsen, 1972
Discernisporites micromanifestus (Hacquebard) Sabry and Neves, 1971
Gorgonispora crassa (Winslow) Higgs, Clayton and Keegan, 1988
Gorgonispora multiplicabilis (Kedo) Turnau, 1978
Grandispora uncata (Hacquebard) Playford, 1971
Indotriradites mitratus (Higgs) Higgs, 1996
Knoxisporites literatus (Waltz) Playford, 1963
Knoxisporites triangularis Higgs, Clayton and Keegan, 1988
Knoxisporites triradiatus Hoffmeister, Staplin and Malloy, 1955
Lophozonotriletes tuberosus Sullivan, 1964
Murospora dubitata Higgs, 1975
Plicatispora scolecophora (Neves and Ioannides) Higgs, Clayton and Keegan, 1988
Prolycospora claytonii Turnau, 1978
Pustulatisporites dolbii Higgs, Clayton and Keegan, 1988
Pustulatisporites gibberosus (Hacquebard) Playford, 1964
Raistrickia clavata (Hacquebard) Playford, 1964
Raistrickia corynoges Sullivan, 1968
Raistrickia condylosa Higgs, 1975
Raistrickia minor (Kedo) Neves and Dolby, 1967
Raistrickia strumosa Playford, 1976
Raistrickia variabilis Dolby and Neves, 1970
Reticulatisporites sp.
Retusotriletes incohatus Sullivan, 1964
Rugospora polyptycha Nevs and Ioannides, 1974
Secarisporites mauriceus Higgs, 1996
Schopfites delicatus Higgs emend. Higgs, Clayton and Keegan, 1988
Spelaeotriletes balteatus (Playford) Higgs, 1996
Spelaeotriletes crustatus Higgs, 1975
Spelaeotriletes obtusus Higgs, 1975
Tumulispora malevkensis (Kedo) Turnau, 1978
Tumulispora rarituberculata (Luber) Playford, 1991
Vallatisporites vallatus Hacquebard, 1957
Vallatisporites verrucous Hacquebard, 1957
Velamisporites caperatus (Higgs) Higgs, Clayton and Keegan, 1988
Velamisporites magnus (Huphes and Hayford) Playford, 1971
Verrucosisporites nitidus Playford, 1964

Phytoplankton

Acritarchs
Micrhystridium ampliatum Wicander and Playford, 1985
Micrhystridium pentagonale Stockmans and Willière, 1963
Michrystridium stellatum Deflandre, 1945
Michrystridium sp.
Unellium piriforme Rauscher, 1969

Prasinophyte algae
Leiosphaeridia sp.
Dictyotidium jachowiczii (Jachowicz) Filipiak, 2005
Hemiruptia sp.
Tasmanites sp.