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Microphytoplankton from middle palaeolatitudes of the Southern Hemisphere – a record from climate change strata of Baltica's O/S boundary

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In the present study, data on the diversity of acritarch and prasinophyte microphytoplankton were collected from Ordovician–Silurian transitional strata at three different geological localities in Poland: southern part of the Holy Cross Mountains (Małopolska Block, southern Poland), East European Platform (Baltica), and Koszalin–Chojnice Zone (NW Poland). The material represents the *mucronata* (trilobite) to *vesiculosus* (graptolite) biozones. The Ordovician microphytoplankton assemblages are characterized by low frequency and low diversity: up to 110 specimens and 12 genera per slide, in contrast to Silurian ones that are more frequent and more diverse – >3000 specimens and 16 genera per slide (diversity at the species level is also higher). Throughout the Ordovician part of the succession, typical Ordovician genera occur, such as *Acanthodiacrodium, Ordovicidium*, *Orthosphaeridium* and large *Baltisphaeridium*, together with isolated occurrences of typical Silurian genera, especially in the upper part of the Hirnantian (e.g., *Diexallophasis*). The Silurian assemblages are typified by high frequency of prasinophytes followed by typical Silurian acritarchs: *Tylotopalla*, *Ammonidium*, *Domasia* and *Oppilatala*. The palynological material from Poland is compared with material known from other localities: the Rapla and Valga boreholes (Estonia) and Anticosti Island (Canada), as well as others placed in different palaeocontinents and different bathymetric zones. Palynological assemblages obtained from Polish material confirm that bathymetry played the key role in taxonomic diversification of the microphytoplankton assemblage. This supports the existing models of distribution: dominance of prasinophytes (leiospheres) and cryptospores is characteristic for shallow-water environments. In deeper water, dominance of acanthomorphs is observed. In the deepest-water zones – mixed assemblages occur. For the Holy Cross Mountains, microphytoplankton frequency is compared with a TOC curve in the same interval.

Key words: Poland, Ordovician/Silurian boundary, palynology, acritarch frequency, bathymetry, climate.

INTRODUCTION

One of the longest, most significant and sustained intervals of biotic diversification in the history of marine life on Earth occurred in the Ordovician Period (Miller and Mao, 1995; Miller, 1997; Servais et al., 2008). Evolutionary diversification during the Early and Middle Ordovician was interrupted in the latest Ordovician (Hirnantian) by one of most intense mass extinction events of the Paleozoic Era. The end-Ordovician mass extinction is associated with climate change and regression accompanied by a major glaciation on the Gondwana supercontinent (Beuf et al., 1971; Brenchley, 1988; Finney et al., 1997). Raup and Sepkoski (1982) calculated that ~22% of all marine families, 40% of marine genera (Sepkoski, 1996) and 85% of marine species (Jablonski, 1991) became extinct in the Late Ordovician.

During the Early Silurian, the global ecosystem gradually recovered from this mass extinction – during it, no major taxonomic groups disappeared – and biodiversity rose again during warmer palaeoclimatic conditions (Armstrong, 1996, 2007; Berry et al., 1996; Armstrong and Harper, 2014). The characteristics of microphytoplankton response to the Hirnantian biotic crisis and following the early Silurian recovery are still incompletely constrained. A general reduction in both diversity and frequency of acritarchs at the genera and species level during the Late Ordovician has been recorded in various localities worldwide (Paris et al., 2000; Servais et al., 2008; Stempień-Sałek, 2011). The Early Silurian (Llandovery) is characterized by a resurgence of amount and turnover: appearance of new taxa and expansion of taxa that appeared right at the end of the Ordovician (those of Silurian "affinity" *sensu* Le Hérissé in Paris et al., 2007:103).

The global and regional patterns of acritarch recovery after the Hirnantian mass extinction are relatively unknown, mainly due to the scarcity of detailed studies. A major problem affecting the analysis of acritarch distribution within stratal successions that span the Ordovician–Silurian boundary is the lithofacies control on the preservation of organic-walled microfossils (for example in Saudi Arabia – Le Hérissé, 2000; and Bohemia – Dufka and Fatka, 1993).

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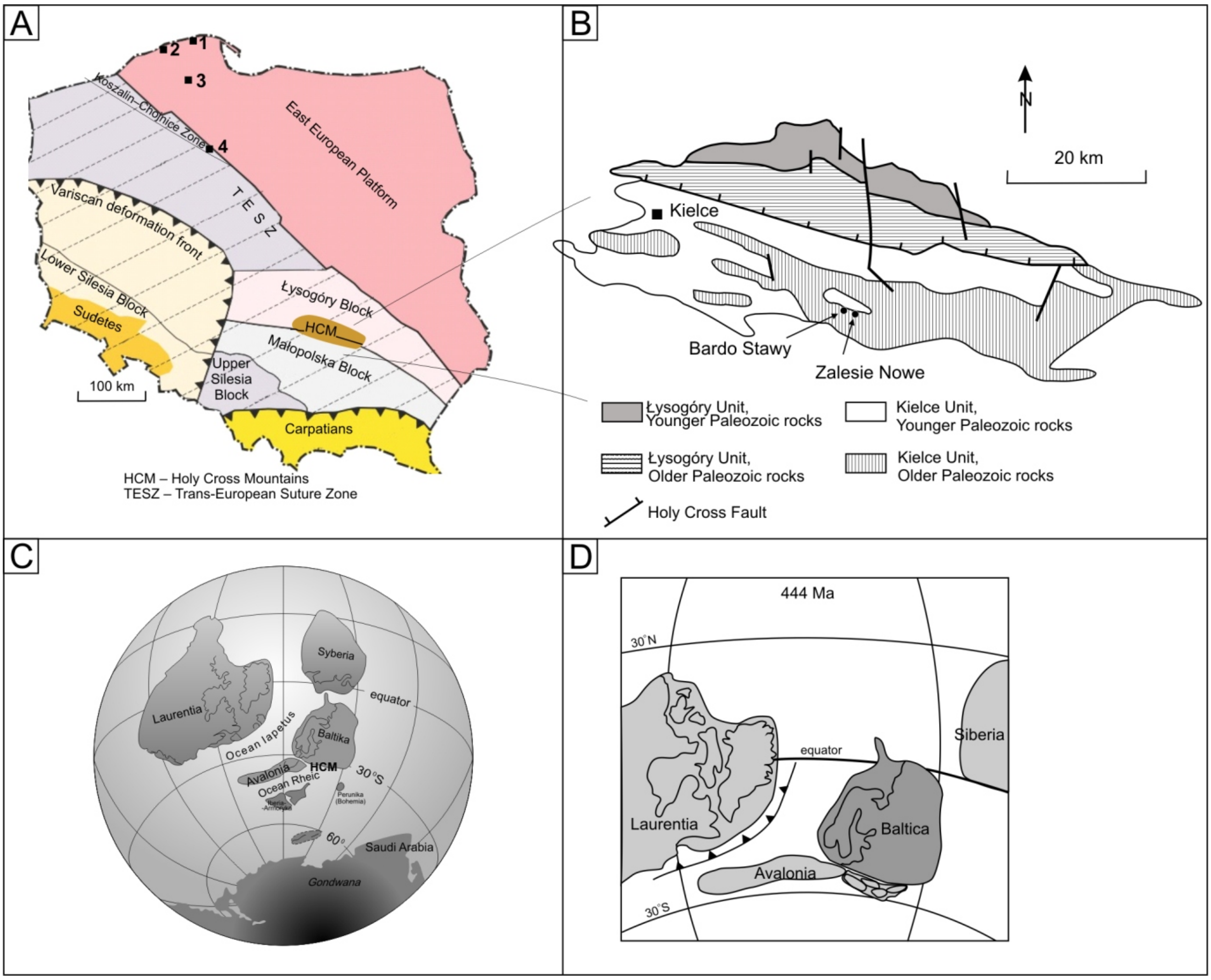

Fig. 1A – areas of investigation (a map after geoportal.pgi.gov.pl, supplemented): East European Platform, Baltic Depression: 1 – Białogóra 1 borehole, 2 – Łeba 8 borehole, 3 – Kościerzyna IG 1 borehole and Koszalin–Chojnice Zone; 4 – Toruń 1 borehole; B – Bardo Stawy and Zalesie Nowe sections in the Holy Cross Mountains, Kielce Region; palaeogeography: C – Late Ordovician (after Torsvik and Cocks, 2005, supplemented), D – Early Silurian (after Nawrocki et al., 2007, supplemented)

In the present study, acritarch diversity data were collected from Ordovician–Silurian transitional strata at three different main localities in Poland: Holy Cross Mts. (Małopolska Block), East European Platform: Pomerania (Baltica), and Western Pomerania (Koszalin–Chojnice Zone). All localities are shown in Figure 1.

The most complete record of microphytoplankton from O/S boundary strata comes from the Holy Cross Mts. (Małopolska Block) and poses a benchmark for assemblages from other Polish successions. In the the Bardo Stawy succession, strata demonstrate the response of acritarchs to palaeoenvironmental change through the latest Ordovician and earliest Silurian. The far-field effect of glaciation in Gondwana is evident in the latest Ordovician (Hirnantian), equated with a global climate cooling that may have been a major causal effect of mass extinction, including planktonic organisms such as graptolites, and impacting on reduced diversity within acritarch assemblages: this interval is also associated with the widespread appearance of the cool/ventilated-water *Hirnantia* fauna at lower latitudes (Rong et al., 2002). The global warming in the latest Ordovician and earliest Silurian is associated likely with oceanographic change (temperature, thermohaline circulation, etc.) that facilitated the recovery as an increase in frequency (numerical abundance and biodiversity) of acritarchs. Lithofacies studies confirm the regressive nature of Upper Ordovician deposits related to the growing ice sheet of the Southern Hemisphere. The maximum climate cooling and sea level regression took place during the early Hirnantian – *extraordinarius* graptolite Biozone using the British graptolite biozonation (Armstrong, 2007; Page et al., 2007). An equivalent of this zone in Poland is the *Mucrionaspis mucronata* trilobite Biozone due to the lack of graptolites (Kielan, 1956, 1959). In the uppermost Hirnantian (*persculptus* graptolite Biozone), represented by the deglaciation interval, the first signs of warming and eustatic change occurred with the deposition of beige claystones and shales containing silt- to sand-sized quartz grains, preceding the facies change to dark "graptolitic shales". Such a lithological succession indicates gradual stagnation and progressive oxygen deficiency of the depositional environment related to a deepening of the sea during the post-glacial sea level rise (Masiak et al., 2003). The results presented here are a further contribution to the understanding of the timing and causal mechanisms of early Silurian acritarch recovery after the Hirnantian mass extinction and its possible connection with the associated palaeoclimate and palaeoenvironmental change.

GEOLOGICAL SETTING

The palynological material analysed in this paper comes from both outcrops in central Poland and boreholes in northern Poland (Fig. 1A, B).

The study sections are located in three distinct palaeogeographic regions (*sensu* Torsvik and Cocks, 2005; Nawrocki and Poprawa, 2006; Nawrocki et al., 2007) – the Małopolska Block (Kielce Region), Baltica (Baltic depression) and Koszalin–Chojnice Zone (Fig. 1A, B). All localities, the Małopolska Block, Baltica and Koszalin–Chojnice Zone, occupied different palaeogeographic positions during Late Ordovician Hirnantian time, although the palaeolatitudes (~30°S) were similar (Lewandowski, 1993; Bednarczyk, 1999; Cocks, 2000; Cocks and Torsvik, 2005; Torsvik and Cocks, 2005). They were located in the same basin around western Baltica. The palaeogeographic positions are shown in Figure 1C, D.

MAŁOPOLSKA BLOCK

In the Early Ordovician the Małopolska Block was placed at ~60°S latitude (Lewandowski, 1993) and through the Ordovician it moved northward reaching ~30°S latitude in the Late Ordovician (Cocks and Torsvik, 2002; Torsvik and Cocks, 2005; Nawrocki et al., 2007). The geotectonic provenance of the Małopolska Block is still unclear, but some authors consider it as a Gondwana-derived terrain (Belka et al., 2000), others as a proximal terrain that detached from Baltica before the Ordovician (Dadlez et al., 1994; Narkiewicz, 2002). Southern part (Kielce Region) of the Holy Cross Mts. is considered a northern part of the Małopolska Block.

Ordovician/Silurian boundary deposits described in this paper come from the Bardo Stawy and Zalesie Nowe sections that are located in the Bardo Syncline (Fig. 1B). The Bardo Syncline is a small tectonic unit, ~16 km long and 2–5 km wide, oriented in a NW–SE direction. This Variscan structure is composed of Ordovician and Silurian deposits truncated and conformably overlain by Devonian sediments (Fig. 1B). These Paleozoic deposits are blanketed largely by a thick Quaternary cover. The outline of the Syncline is underlined by diabase intrusions that follow the boundary between Silurian graptolitic shales and greywackes.

The Ordovician/Silurian boundary interval of the Bardo Stawy section comprises a complete succession of deposits from the uppermost *mucronata*, ?*persculptus*, *ascensus–acuminatus* and *vesiculosus* biozones (Masiak et al., 2003 and Fig. 2) and exhibits a conformable and gradual transition from sandy through silty to clayey deposits, which is accompanied by a gradual change of colour of the rock from light to dark. This uppermost Ordovician–lowermost Silurian succession indicates a depositional environment that became oxygen-poor during the post-glacial sea level rise.

Deposits in the Zalesie Nowe section are divided into local formations (Bednarczyk, 1971, 1981). The topmost part of the Zalesie Formation (Fig. 3) is composed of marls and dark red and grey-greenish marly shales that grade consequently into dark grey shales interbeded by lydites – called the Bardo Beds. The lower stratigraphic unit (uppermost Zalesie Fm.) – the so called Dalmanitina Beds – is well-documented by the trilobite *Mucronaspis mucronata* as latest Ashgill (Kielan, 1956), pointing to a Hirnantian age. The latest investigation of graptolite fauna (Kremer, 2001) indicates a Late Ordovician (Ashgill) – Early Silurian age for the Bardo Beds at Zalesie Nowe.

A full lithological description of both sections (Bardo Stawy and Zalesie Nowe) is presented in Masiak et al. (2003) and Mustafa et al. (2015). The lithology and lithostratigraphy of the Lower Silurian deposits in the Bardo Stawy section was presented by Trela and Salwa (2007).

BALTICA (BALTIC DEPRESSION)

The Baltic Depression was developed in the southwestern part of the Baltica palaeocontinent (nowadays East European Platform) and was placed ~30°S latitude during the Late Ordovician (Cocks and Torsvik, 2002; Torsvik et al., 2002; Torsvik and Cocks, 2005; Nawrocki et al., 2007). Delabroye et al. (2011a) call this area the Livonian Basin after Kaljo et al. (2008; Livonian tongue of the central Baltoscandian Facies Belt). Baltica was geographically located at low southerly latitudes during the Early Ordovician and drifted slowly northward. In Late Ordovician/Early Silurian times, the East European Platform occupied subtropical and equatorial southern latitudes (Fig. 2).

The uppermost Ordovician and lowermost Silurian deposits in the Baltic Depression have been identified in numerous boreholes. In this region, all facies belts of the Baltic Basin are recognized – from the basinal facies in the west, through the slope, deep- and shallow-neritic, to the onshore facies in the east (see Podhalańska, 2009).

The material investigated in this study comes from boreholes situated in the Łeba area and corresponds to a deep neritic part of the sea, a southward extension of the Scanian confacies belt (see Podhalańska, 2009). The western border of the Baltic Depression is the TESZ and Koszalin–Chojnice Zone, which contain deep-water lithofacies.

The uppermost Ordovician strata in the Baltic Depression are generally developed as shaly-calcareous, calcareous and calcareous-dolomitic, and shaly glauconitic deposits, though the lithofacies differ between the western and eastern parts. The lithological descriptions of some borehole sections can be found, e.g., in Tomczyk (1962), Tomczykowa (1964), Bednarczyk (1968, 1971, 1996a, 1998, 1999), Podhalańska (1980, 1999, 2003a, b, 2009), Przybyłowicz (1980), Bednarczyk et al. (1996), Modliński and Szymański (1997, 2008), Podhalańska and Modliński (2006).

Sedimentation across the Ordovician/Silurian boundary in the bottom depressions took place probably without a break and the facies changes were gradual. Non-deposition, submarine erosion and minor hiatuses took place on bottom elevations and the transgressive unconformity surface (e.g. in the Kościerzyna IG 1 section) separates the partly eroded Hirnantian dark grey marls and sandstones containing the *Hirnantia* fauna from the laminated deeper marine Rhuddanian shales with graptolites of the *acuminatus* Biozone.

In the boundary beds, abundant marine faunas are well-documented: graptolites (Podhalańska and Modliński, 2006; Podhalańska, 2009), trilobites and inarticulate brachiopods (Bednarczyk, 1968; Modliński, 1988), ostracods, conodonts (Nehring, 1969; Bednarczyk, 1998), and the *Hirnantia* fauna (Podhalańska, 1980, 1999, 2003b, 2009).

The total thickness of the uppermost Ordovician (Ashgill Series) in the Baltic Depression varies from 3.5 to 70 m (Modliński and Szymański, 1997). A palaeothickness map of the Middle–Upper Ordovician deposits is shown in Modliński et al. (1999) and Modliński (2010). The total thickness of the lowermost Silurian (Llandovery) varies from 20 to 70 m (Modliński et al., 2006), and increases from east to west.

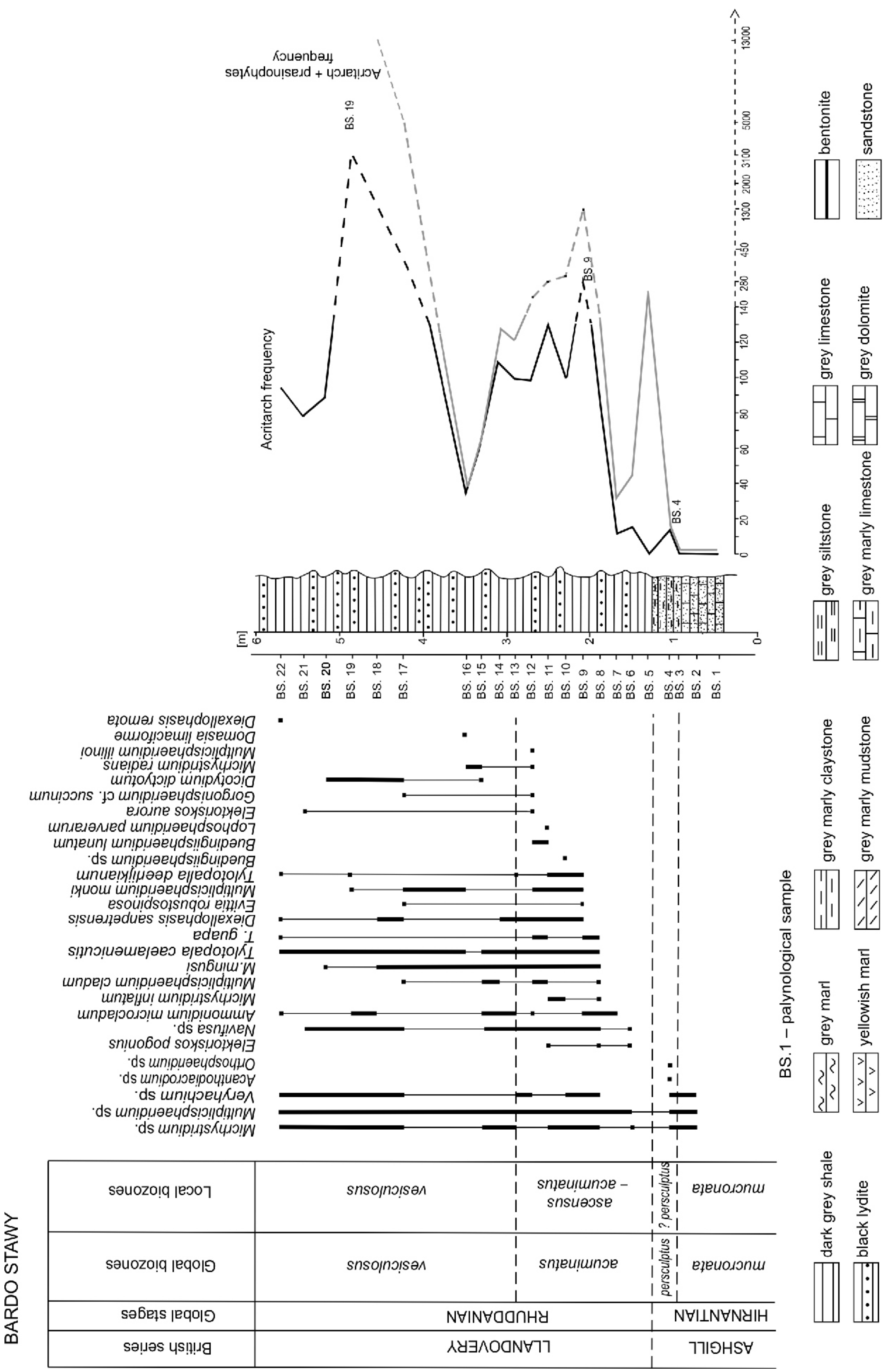

Fig. 2. Simplified lithology and acritarch range chart, and acritarch and prasinophyte + acritarch frequency in the Bardo Stawy outcrop

Explanations of lithology for Figures 2–8

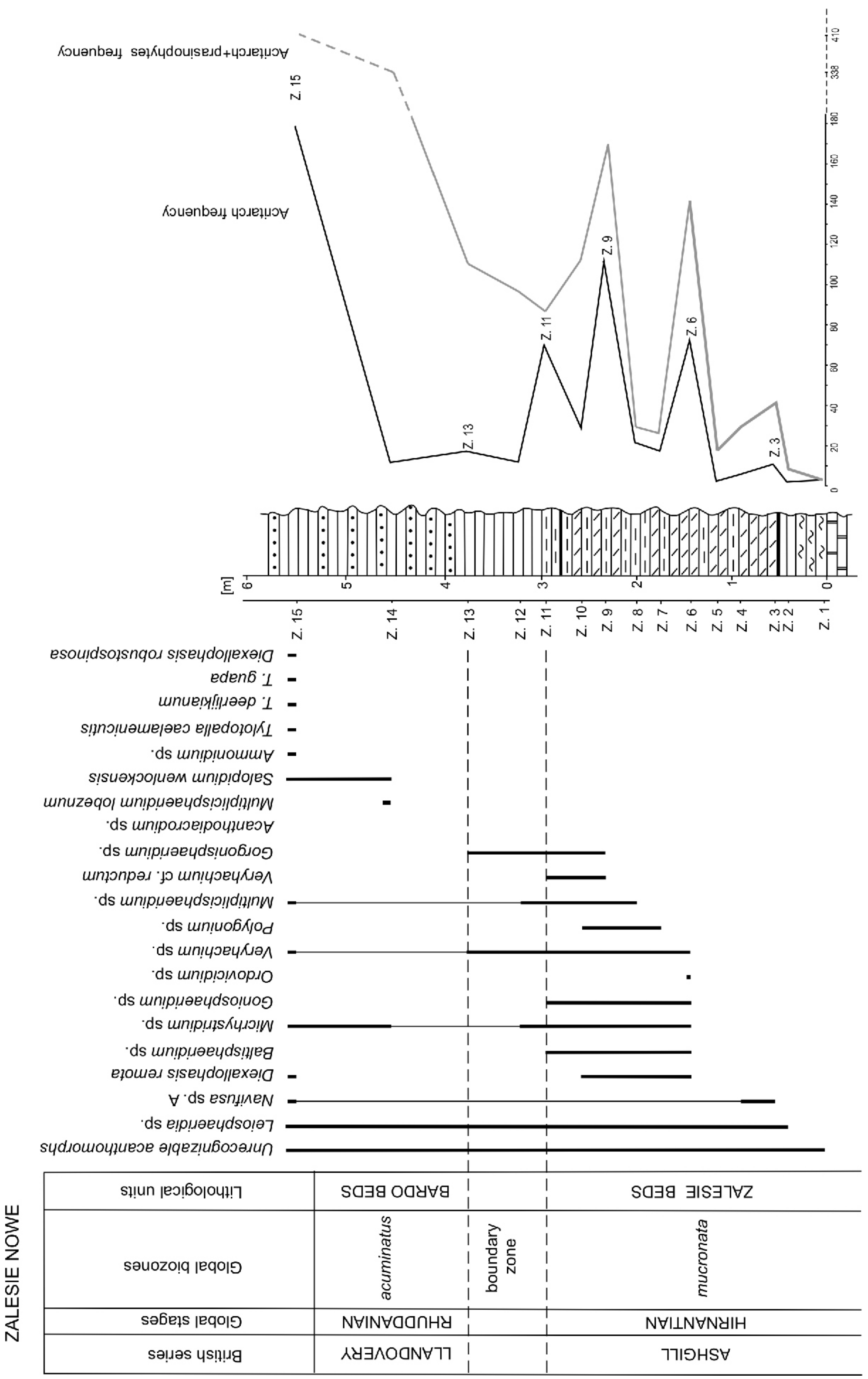

Fig. 3. Simplified lithology and acritarch range chart, and acritarch and prasinophyte + acritarch frequency in the Zalesie Nowe outcrop

For explanations see Figure 2; for the full list of the palynomorphs see Masiak et al. (2003)

KOSZALIN–CHOJNICE ZONE

The Koszalin–Chojnice Zone (Fig. 1A) is placed on an epi-Caledonian platform (Karnkowski, 2008: fig. 2 therein), on the border of the SW margin of the East European Platform and Avalonia (e.g., Belka et al., 2000; Poprawa, 2006; Podhalańska and Modliński, 2006). The Koszalin–Chojnice Zone is regarded as a Caledonian front of collision deformation (Żelaźniewicz et al., 2011: fig. 5).

The crystalline basement of the Ordovician strata in the Koszalin–Chojnice Zone is supposed to be an Early Paleozoic terrane derived from Gondwana, described as Eastern Avalonia (Tait et al., 1997; Pharaoh, 1999; Jaworowski, 2000; Wrona et al., 2001; Samuelsson et al., 2002). Early Paleozoic deposits of this zone contain biotic assemblages of both Baltic and Avalonian origin (Podhalańska and Modliński, 2006; Torsvik and Cocks, 2013).

During the movement of Avalonia towards Baltica, in Ordovician and Silurian times, the Koszalin–Chojnice Zone was the proximal part, whereas the Baltic Basin was the distal part of the same basin. The distance between them was relatively close, but they were immediately adjacent (Krzemiński and Poprawa, 2006).

The Paleozoic sedimentary cover of the Koszalin–Chojnice Zone includes Ordovician deposits identified in many boreholes that were drilled mainly in the 1960s and 1970s (Tomczyk, 1968; Modliński, 1968, 1978, 1987; Bednarczyk, 1974; Dadlez, 1978, 1982a, b, 1993, 2000).

The Middle–Upper Ordovician and Silurian deposits form the Older Paleozoic sequence. This sequence, composed mainly of shales (dark grey and grey clayey-muddy sediments with scarce sandy, dolomitic and sideritic intercalations – e.g., Krzemiński and Poprawa, 2006), is intensely folded and unconformably overlain by the younger Paleozoic sequence.

The strata above the Ordovician locally attain 4000 m in thickness. The Upper Ordovician in the Koszalin–Chojnice Zone is documented (Podhalańska and Modliński, 2006) by graptolites only for the Sandbian (Caradocian). Other groups of fossils, such chitinozoans, prasinophytes and various trace fossils, also fragments of brachiopods and trilobites, occur sporadically (Bednarczyk, 1974; Wrona et al., 2001; Podhalańska, 2007). Palynological data based on acritarchs indicates a Llanvirn–Caradoc age of the Ordovician deposits of the Pomeranian Caledonides (Szczepanik, 2000).

The latest stratigraphic division of the uppermost Ordovician is based on a correlation with the Polskie Łąki PIG 1 borehole and other boreholes. The overlying deposits are Sandbian in age, and are strongly deformed and faulted. A tentative stratigraphic subdivision is based on lithofacies studies (Podhalańska and Modliński, 2006).

Llandovery deposits are represented by deep-marine siliciclastic sediments most frequently containing sedimentary structures related to sea current activity (Teller and Korejwo, 1968; Teller, 1974; Podhalańska and Modliński, 2006). The strata documented in the Toruń 1 borehole are Silurian in age (lower Llandovery, Rhuddanian; Dadlez, 1982b; Tomczyk, 1987). Currently, it is not possible to define the detailed stratigraphy due to poor preservation of the rock and tectonic deformation. The original thickness of the strongly folded Llandovery deposits (Lutom 1 and Toruń 1 sections) is >400 m (Poprawa, 2006).

The macrofaunal assemblage found in the Llandovery deposits was dominated by graptolites and rare inarticulate brachiopods. The frequency of graptolites is low. Among microfossils, the presence of acritarchs, prasinophytes and chitinozoans was documented by Teller (1974), Jachowicz (2000), Wrona et al. (2001) and Podhalańska and Modliński (2006). Numerous tectonically deformed biserial graptolites were found in black shale in the Toruń 1 section at a depth of 5298.0 m (Podhalańska and Modliński, 2006). They indicate the presence of Rhuddanian deposits, which succeed the strongly folded Upper Ordovician rocks.

MATERIAL AND METHODS

MATERIAL

The palynological investigation presented in this paper includes data from 73 samples collected and studied over the past few years – palynological data, especially palynomorph frequency, were obtained as an additional result of studies on stratigraphy by the Institute of Geological Sciences PAS in Warsaw. Thus, only acritarchs were counted in some cases (Zalesie Nowe and Kościerzyna IG 1), but generally acritarchs and prasinophytes were counted for their frequency.

Thirty-seven samples from the Holy Cross Mountains (Fig. 1B) yield both well-preserved material – yellow to brown acritarchs and yellow prasinophytes in the Bardo Stawy samples – and less well-preserved dark brown to black palynomorphs in the Zalesie Nowe samples. Detailed description of samples is published in Masiak et al. (2003) and shown in Figures 2 and 3 in this paper.

The material from the East European Platform (Baltica palaeocontient, Baltic Depression) consists of samples from three boreholes: Białogóra 1, Kościerzyna IG 1 and Łeba 8 (Fig. 1A). Thirty-two samples from dark grey shales were taken, which span a stratigraphic interval equivalent to the uppermost Hirnantia beds of the *mucronata* trilobite Biozone, the *ascensus* graptolite Biozone (Early Silurian, Rhuddanian), and the lowermost part of the succeeding *acuminatus* graptolite Biozone (Silurian).

The material studied for palynology in the Koszalin–Chojnice Zone comprises four samples from the Toruń 1 borehole (Fig. 1A). All samples are from dark grey shale. This interval probably spans the uppermost part of the Hirnantia beds (*mucronata* trilobite Biozone) to the Llandovery (Rhuddanian) undivided.

The material from the East European Platform and the Koszalin–Chojnice Zone is poorly preserved, mostly incomplete and dark brown to black in colour.

Preservation in some samples is too poor to distinguish the acanthomorphic acritarchs with a short process from prasinophyte algae. In other samples, however, the sphaeromorphs are sufficiently well-preserved – especially the existence of thin-walled forms – to indicate that the lack of acritarchs is probably primary and not the result of preservation. Obviously, it cannot be excluded that some specimens were destroyed during post-sedimentation processes.

There are few samples from the Toruń 1 borehole because of long non-cored intervals. Generally, all palaeontological data from boreholes of the Koszalin–Chojnice Zone are scarce and poor, so the authors decided to publish even these modest data.

The position of individual samples taken from boreholes is measured directly from the core depth, not from well logs. All slides are housed at the Department of Stratigraphy and Palaeogeography, Institute of Geological Sciences, PAS (ING PAN) Warsaw, Poland.

PALYNOLOGICAL METHODS

All samples were subjected to a standard palynological laboratory treatment (Wood et al., 1996). The samples were used for quantitative analysis of assemblage similarity. In this analysis, the organic residues obtained after complete dissolution of 5 g of rock were supplemented to a volume of 4 ml with methyl alcohol. From each sample, three slides were made; and for each slide, 0.5 ml of well-mixed solution was analysed for palynomorphs. For each sample level, the arithmetic mean was calculated from three slides. The same method was used in Masiak et al. (2003).

RESULTS

MAŁOPOLSKA BLOCK

Palynological data from the sections and boreholes are different. The richest and most diverse assemblages are from the Early Silurian of the Bardo Stawy section (Fig. 2). This section is the best-documented according to palynological and graptolitic assemblages (Masiak et al., 2003) and in our investigation is treated as a benchmark for comparison with other sections.

The latest Ordovician palynological assemblage in the Bardo Stawy section includes only long-ranging acritarchs, mainly of simple morphology. The acritarch frequency is poor to moderate (samples BS. 1 to BS. 4) – from 0 to 20 specimens per sample. The Ordovician/Silurian boundary in the Bardo Stawy section (BS. 5) is marked by a considerable decrease of acritach frequency – the sample is barren. The frequency and diversity increase in the lower part of the *ascensus–acuminatus* graptolite Biozone of the Early Silurian (BS. 6–BS. 13): a significant peak in both diversity and frequency is observed in sample BS. 9 (up to 280 specimens per slide). In the Bardo Stawy section, the maximum acritarch frequency is attained in the lower part of the *vesiculosus* graptolite Biozone, although the genera and species diversity do not change (sample BS. 19). This change in acritarch assemblages does not appear to be related to lithology. For detailed descriptions of palynological assemblages see Masiak et al. (2003). Apart from acritarchs, there are many sphaeromorphs, such as *Leiosphaeridia* spp. regarded as prasinophytes (Le Hérissé, 1989), as well as prasinophytes from two genera: *Cymatiosphaera* and *Pterospermella* sp. (samples BS. 17–BS. 19).

The number of prasinophyte specimens was counted in samples BS. 1 to BS. 18. Samples BS. 1 to BS. 3 contain no specimens. From BS. 4 to BS. 5, the number of specimens increases to 260 specimens per slide. The next peak in the frequency is noted in sample BS. 9 (1300 specimens per slide) and then a decreasing trend is observed. A minimum is noted in BS. 16 (no specimens). Starting from sample BS. 17, the number of specimens rapidly increases and the maximum frequency is noted in sample BS. 18 – 13,000 specimens.

In the Zalesie Nowe section (Fig. 3), the trend in microphytoplankton diversification is similar, but the overall diversity is always lower than in the Bardo Stawy section, which could be connected with differences in lithology. The main difference here is the poorly defined O/S boundary because of lack of index graptolite.

A distinct drop in acritarch and prasinophyte frequency is evident in the O/S boundary zone in the Zalesie Nowe section within the interval of clayey shales (Z12–Z13). This change is similar to the decrease in frequency in the Bardo Stawy section (*?persculptus* – lowermost part of the *ascensus–acuminatus* biozones). This boundary zone involves most probably the ?*persculptus* graptolite Biozone and the lowermost part of the *ascensus–acuminatus* Biozone and is defined by the occurrence of a distinct drop in acritarch frequency, similar to that of the Bardo Stawy profile. Regarding the frequency and diversity of microphytoplankton, the peak observed in sample Z. 15 may be at the same level as that of sample BS. 9 in the Bardo Stawy section. Detailed description of the Zalesie Nowe section is published in Masiak et al. (2003) and Mustafa et al. (2015).

Microphytoplankton from the described sections of the HCM is generally well preserved, yellow to pale brown in colour.

BALTICA (BALTIC DEPRESSION)

Microphytoplankton assemblages of the Białogóra 1, Kościerzyna IG 1 and Łeba 8 boreholes are generally poor and poorly preserved, dark grey to black in colour, and surficially corroded (in contrast to those from the southern part of the Holy Cross Mts., which are much clearer), which is caused by different thermal maturity.

Range charts of the most important genera and species are shown in Figures 4–6.

BIAŁOGÓRA 1 BOREHOLE.

Detailed data from the Białogóra 1 borehole is shown in Figure 4.

The lowermost palynological sample from the uppermost Ordovician (Hirnantia beds) in the Białogóra 1 borehole (sample B1.8) is barren. The first change in diversity and frequency of microphytoplankton occurs in the upper part of the Hirnantian in sample B1.7. The assemblage is poorly diverse and comprises mainly long-ranging taxa, such as *Micrhystridium* sp., *Multiplicispaeridium* sp., *Veryhachium* sp. and importantly the Upper Ordovician index taxa of *Baltisphaeridium* sp., *Ordovicidium* sp. and *Orthosphaeridium* sp. The sample contains prasinophytes (*Leiosphaeridia* spp.) comparable in number to the acritarchs.

The slide for sample B1.6 comprises 46 specimens of acritarchs recognizable mainly at the generic level: *Baltisphaeridium* sp. (probably redeposited), *Diexallophasis* sp,. *Micrhystridium* sp., *Multiplicisphaeridum* sp. and *Oppilatala* sp. This sample contains a very large number of prasinophytes (*Leiosphaeridia* spp.) up to 200 specimens per slide.

The frequency in the next sample (B1.5) is decreasing with only nine leiosphaeres (Prasinphyceae) and two unrecognizable acanthomorphs. Sample B1.4 is more abundant – it contains 33 specimens per slide. Some new species appear: *Tylotopalla caelamenicutis*, *T. deerlijkianum, T. guapa* and *?Oppilatala* sp. The sample contains a huge number of prasinophytes (*Leiosphaeridia* spp.) – 880 specimens per slide.

In following two samples – B1.3 and B1.2 that represent the upper part of the *ascensus* Biozone, the abundance of acritarchs goes down to <20 specimens per slide (B1.3 – 17 specimens, B1.2 – 10), but the number of prasinophytes is decreasing to 230 specimens per slide.

The frequency and diversification of acritarchs in the sample from the lowermost part of the *acuminatus* Biozone (B1.1) increases to 43 specimens per slide, whilst the frequency of prasinophytes is still prominent – >500 specimens.

KOŚCIERZYNA IG 1 BOREHOLE

Detailed data from the Kościerzyna IG 1 borehole is shown in Figure 5. The palynological samples from the uppermost Ordovician (Hirnantia beds) in this borehole (samples K21–K15)

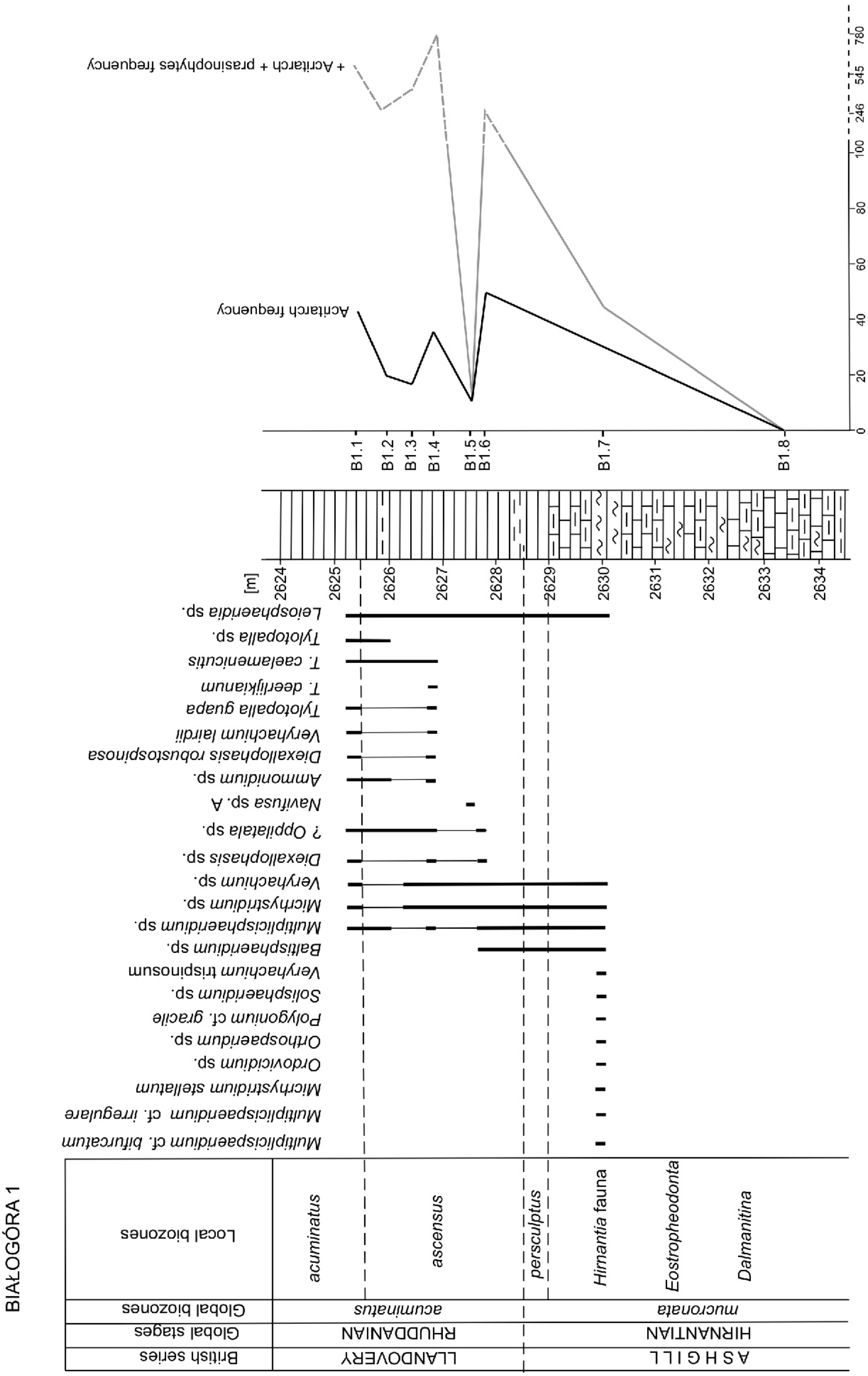

Fig. 4. Simplified lithology and acritarch range chart, and acritarch and prasinophyte + acritarch frequency in the Białogóra 1 borehole

For explanations see Figure 2

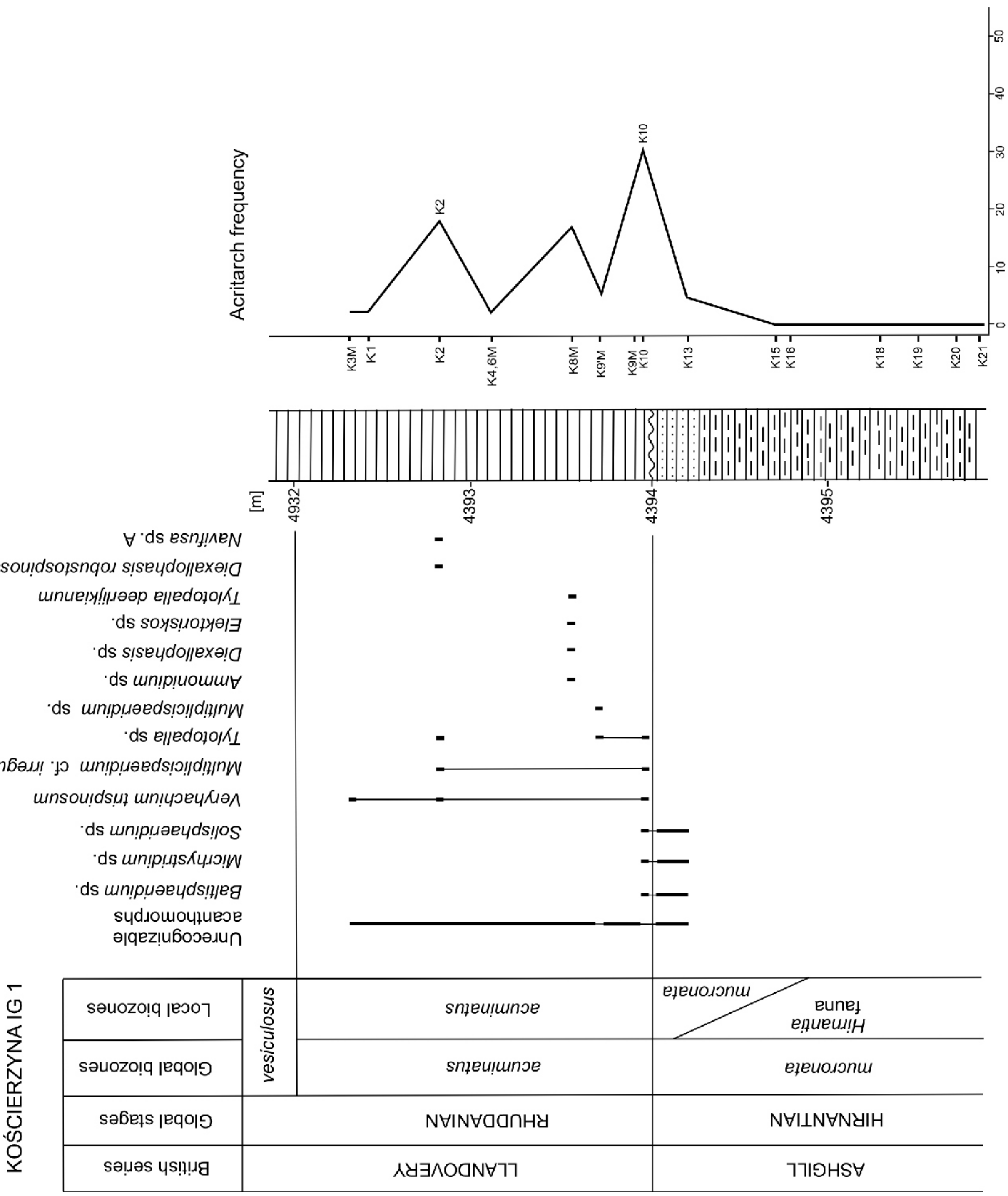

Fig. 5. Simplified lithology and acritarch range chart, and acritarch frequency in the Kościerzyna IG 1 borehole

For explanations see Figure 2

are barren. The first change in diversity and frequency of microphytoplankton occurs in the upper Hirnantian in sample K13. The assemblage is poorly diversified and comprises mainly long-ranging taxa, such as *Micrhystridium* sp. and *Solisphaeridium* sp., and the Upper Ordovician index taxon *Baltisphaeridium* sp.

The slide for sample K10, which is the first Silurian sample, comprises 30 specimens of acritarchs recognizable mainly at the generic level: *Baltisphaeridium* sp. (probably redeposited), *Micrhystridium* sp., *Multiplicisphaeridum* cf. *irregulare, Veryhachium trispinosum, Tylotopalla* sp. and *Solisphaeridium* sp.

The frequency in the next sample (K9'M) is decreasing, only a few leiospheres and two acanthomorphs occur (*Multiplicisphaeridium* sp. and *Tylotopalla* sp.). The assemblages in sample K8M are more abundant – comprising 17 specimens per slide. Some new species appear: *Ammonidium* sp.*, Diexallophasis* sp.*, Elektoriskos* sp. and *Tylotopalla deerlijkianum.*

In the following sample – K4,6M, the abundance of microphytoplankton decreases. The frequency in the next sample K2 increases to 18 specimens per slide. The assemblage is poorly diversified and contains only long-ranging taxa: *Veryhachium trispinosum*, *Multiplicisphaeridium* sp. and *Tylotopalla* sp.

In the two last samples K1 and K3M, the frequency dramatically decreases (2 specimens per slide). In K1, two new taxa appear: *Diexallophasis robustospinosa* and *Navifusa* sp.

Prasinophytes were not counted (see explanations in chapter Material and methods).

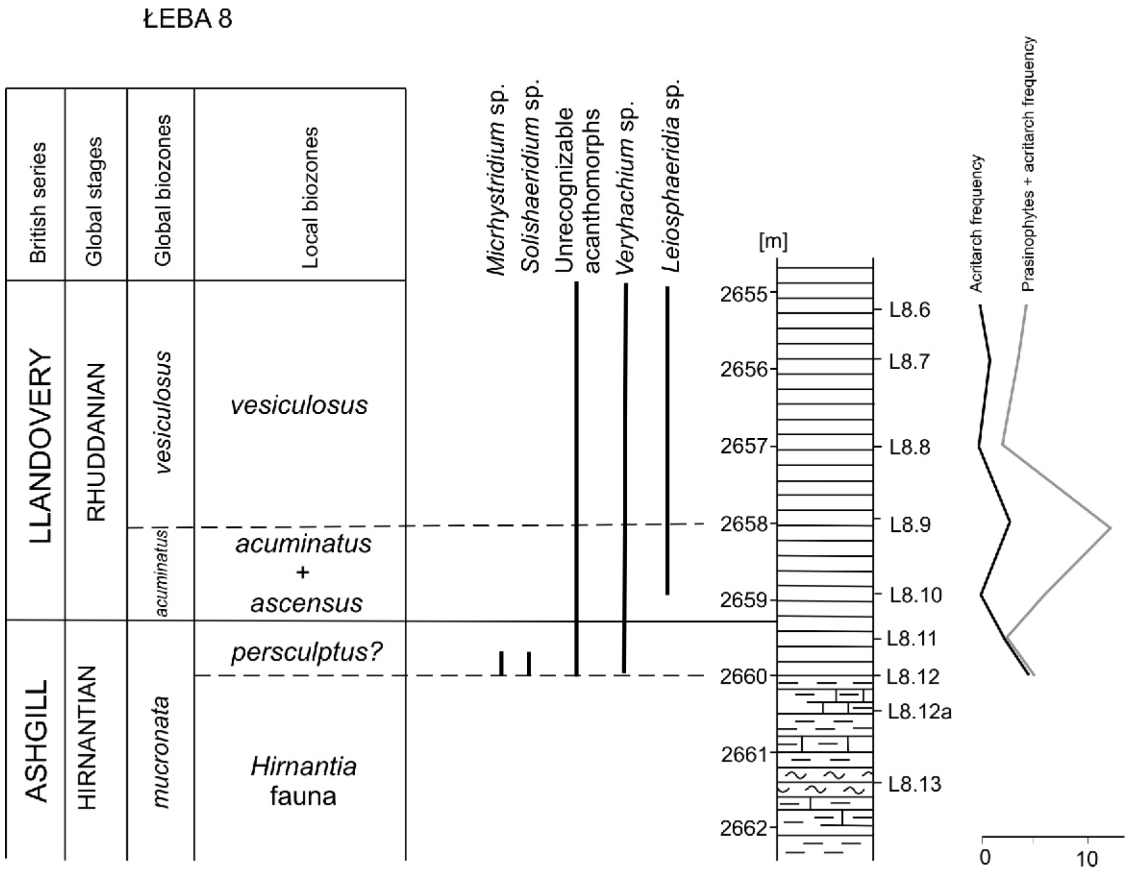

Fig. 6. Simplified lithology and acritarch range chart, and acritarch and prasinophyte + acritarch frequency in the Łeba 8 borehole

For explanations see Figure 2

ŁEBA 8 BOREHOLE

Detailed data from the Łeba 8 borehole is shown in Figure 6.

Microphytoplankton is very poorly preserved (dark brown and black) in the borehole. Only three recogniszable taxa occur. Most acanthomorphs are indeterminate even to the generic level, and there are also some *Leiosphaeridia*. The most productive sample in terms of acritarch taxa recognizability is L8.12 (*persculptus?* graptolite Biozone), while sample L8.9 (probably the uppermost part of the *ascensus* + *acuminatus* graptolite Biozone) is richer in both acritarchs and prasinophytes – with 12 specimens per slide.

KOSZALIN–CHOJNICE ZONE – TORUŃ 1 BOREHOLE

Detailed data from the Toruń 1 borehole is shown in Figure 7.

The palynological assemblage in the samples from the Uppermost Ordovician (Hirnantia beds) of the Toruń 1 borehole (samples T.1.5 and T.1.4) is diverse and moderately abundant (up to 18 specimens per slide). It comprises mainly long-ranging taxa. Almost all the above-listed, except *Deunffia* sp. and *Pterospermella* sp., occur in sample T.1.3 (lowermost Silurian). The abundance dramatically decreases through the investigated interval to three specimens per slide in T.1.3, and to two specimens in sample T.1.2.

COMPARISON OF DATA FROM POLAND WITH OTHER REGIONS

A major problem affecting the analysis of acritarch distribution across the Ordovician–Silurian boundary is the lithofacies control on preservation of organic-walled microfossils. Palynomorphs, such as acritrachs and prasinopytes, prefer specific, characteristic facies of environments with prevalence of fine-clastic sedimentation. Based on this fact, in the other world localities of the O/S boundary, the possibility of following the trend of frequency and diversity of acritarch assemblages is straitened because of lack of relevant facies and continuity of deposits (Fig. 8).

The Bardo Stawy, Zalesie Nowe, Białogóra and Łeba sections are unique because of sedimentary continuity and palynological yields across the O/S boundary, as well as good independent stratigraphic control provided by graptolites.

In the following section, we compare the present results with previously published similar studies, as conducted in a different palaeogeographic position, regarding also the bathymetry and dependence of acritarchs and prasinophytes on sea depth (Al-Ameri, 1983).

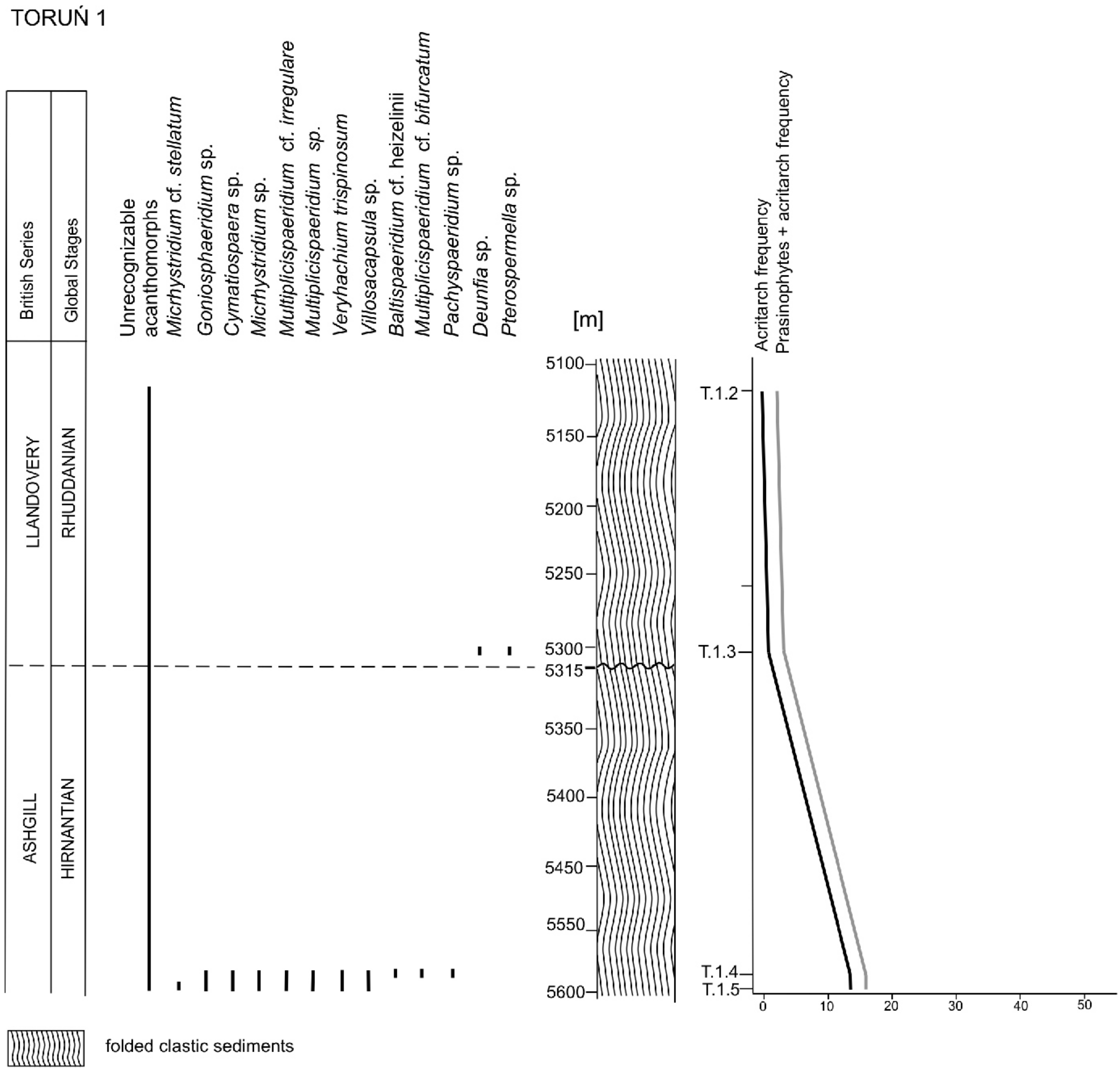

Fig. 7. Simplified lithology and acritarch range chart, and acritarch and prasinophyte + acritarch frequency in the Toruń 1 borehole

For other explanations see Figure 2

LOW TO MIDDLE LATITUDES OF THE SOUTHERN HEMISPHERE

Considering the palaeogeographical position of the main landmasses in Late Ordovician times (Fig. 1C, D), Baltica occupied subtropical latitudes between an equator and 30°S-latitude (Torsvik and Cocks, 2004). This continent was separated from Gondwana (on the South Pole) by the Rheic Ocean. Smaller blocks, such as Avalonia, the Bohemian Massif and Małopolska Block, occupied ~30°S-latitude in the Late Ordovician (Cocks, 2000; Torsvik and Cocks, 2005). All these localities were placed more or less in the same climatic zone. Differences within the microphytoplankton content of deposits may results from environmental depositional conditions, such as bathymetry, influence of oceanic currents, etc.

BALTICA

Apart from the Polish localities described above, other palynological data comes from Estonia – from the Rapla borehole in northern Estonia and the Valga 10 borehole in southern Estonia.

At Rapla, where the problem of facies control on preservation of organic-walled microfossils is evident in sections spanning the O/S boundary (Uutela and Tynni, 1991), shallow-water carbonate platforms developed during the Late Ordovician. The presence of discontinuity surfaces within the boundary interval and lack of precise stratigraphic control are additional problems for this section. In the uppermost Ashgill (Hirnantian) of the Rapla borehole (Uutela and Tynni, 1991), 40 acritarch and prasinophyte species were recorded, of which 29 cross the O/S

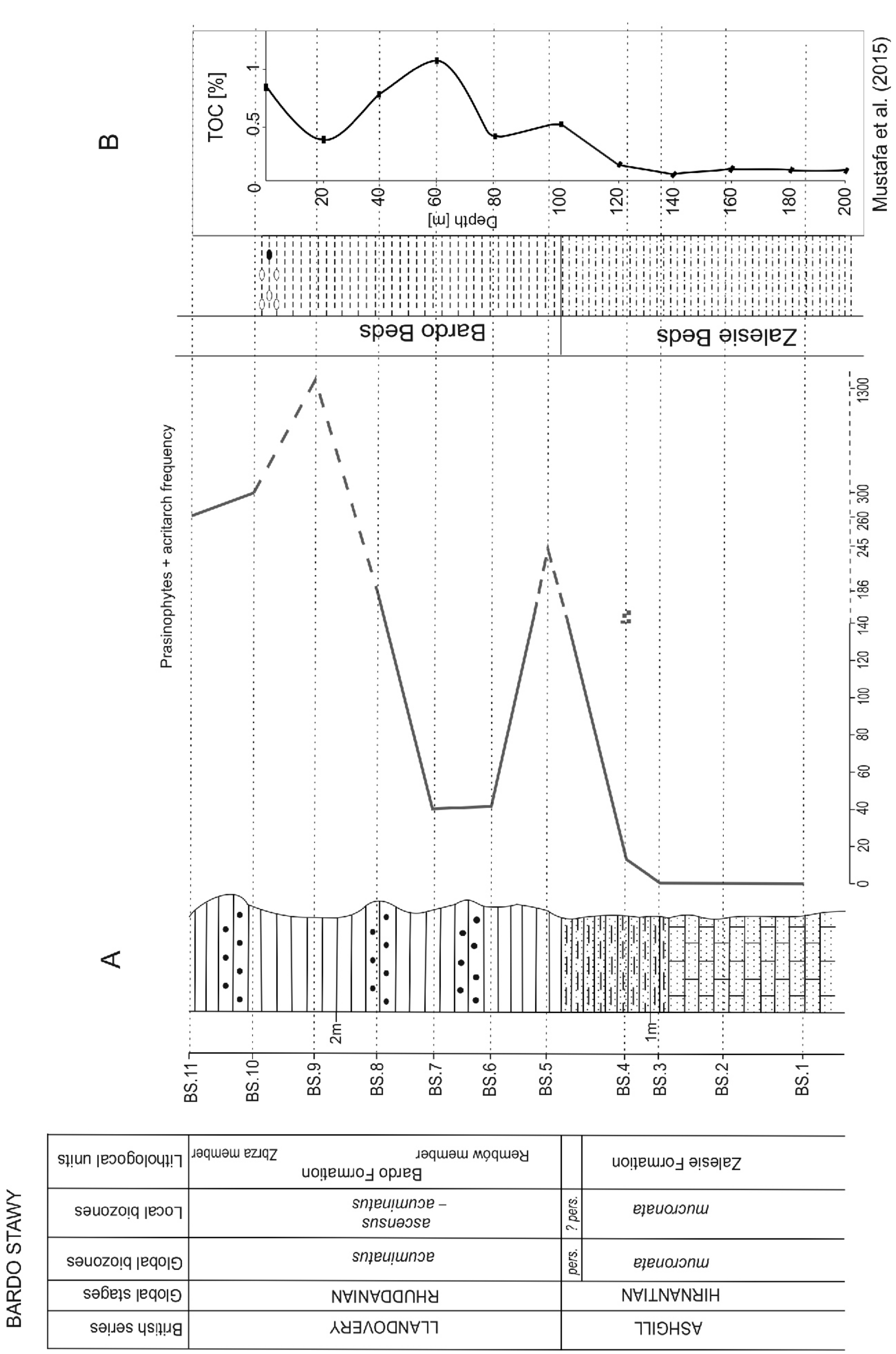

Fig. 8. Comparison of TOC and palynomorph frequency curves in the Bardo Stawy section

A – prasinophyte and acritarch frequency; **B** – stratigraphical trends of TOC percentage across the Ordovician/Silurian transition boundary (after Mustafa et al., 2015) boundary. Assemblages from the Lower Silurian strata are impoverished, with only four acritarch species recorded.

In terms of the abundance, *Micrhystridium* sp. and *Lophosphaeridium* sp. are the dominant taxa. Other taxa, such as *Baltisphaeridium* sp, *Gorgonisphaeridium* sp, Leiosphaeridia spp., *Stellechinatum* sp., *Multiplicisphaeridium* sp., *Tasmanites* sp., *Cymatiosphaera* sp., *Pulvinosphaeridium* sp. and *Estiastra* sp. are rare.

Generally, the trend in the frequency of genera and species is decreasing from the uppermost Ashgill (middle Pirgu, Regional Stage) to the lowermost Silurian (lowermost Juurgu, Regional Stage; Kaljo et al., 1996: table 1 and fig. 3).The O/S boundary in the Rapla borehole is characterized by a minor discontinuity surface. In the Porkuni Regional Stage (uppermost Ashgill), acritarchs are generally absent due to both secondary dolomitization and the occurrence of high-energy sediments of reef facies (Kaljo et al., 1996).

Following the trend in the increasing/decreasing number of genera and species, it is possible to compare data from the Rapla borehole with the Polish data.

In general, the uppermost Ordovician assemblages from Poland are less numerous than those in Rapla, but the lowermost Silurian ones are more. In the Polish profiles, there are no typical shallow-water carbonate platform genera, such as *Estiastra*, *Pulvinosphaeridium* and *Schismatosphaeridium*.

More information comes from detailed studies on palynological investigations from the Valga 10 drill core (Delabroye et al., 2011a). The latest Ordovician/earliest Silurian deposits from this borehole of southern Estonia represent transitional environments of the Livonian Basin – a transitional basin between north Estonian carbonate shelves and deeper-water sediments of the Scandinavian Basin.

Palynological material from the Valga 10 drill core represents shallower-water deposits than those from the Baltic Depression and the southern part of the Holy Cross Mts. The investigated profile of the Valga 10 borehole involves a longer time interval – the latest Katian and Hirnantian (Ordovician) and the earliest Silurian (Delabroye et al., 2011a). The correlations with other profiles are hindered: chitinozoan biozones have not been identified; probably some redeposited assemblages occur (Delabroye et al., 2011a and references therein).

Deposits of the O/S boundary from Gotland are known from the Nar borehole. They occur at similar depths to those from the Valga 10. Stratigraphy of this interval in the Nar borehole during acritarch and prasinophyte investigation was incomplete and showed the existence of a hiatus at the O/S boundary, which included the *acuminatus* Zone (Le Hérissé, 1989).

It is difficult to compare quantitative data; however, table 2 in Le Hérissé (1989) shows the existence of a taxonomically diverse (14 taxa) assemblage.

The latest Katian and Hirnantian palynological assemblages were studied both in the Baltic Depression (Stempień-Sałek, 2011) and the Holy Cross Mts. (Trela and Szczepanik, 2009). In the Szumsko Kolonia borehole, drilled in the Bardo Syncline, the upper Hirnantian acritarch assemblages are similar to those from Zalesie and Bardo Stawy, although, the diversity and frequency are higher. Particularly interesting is the occurrence of taxa from the peri-Gondwanan acritarch palaeoprovince (Trela and Szczepanik, 2009).

The sample from upper Hirnantian deposits of the Szumsko Kolonia borehole contains frequent and diversified assemblages dominated by the *Veryhachium* taxa (70%). This sample comes from older deposits than those described in the Bardo Stawy and Zalesie Nowe sections, and the palynological assemblages are comparable to the coeval ones from the Valga 10 borehole, although the composition is different (dominance of *Veryhachachium versus* cryptospores). For a full list of microphytoplankton assemblages see Delabroye et al. (2011a) and Trela and Szczepanik (2009).

The uppermost Hirnantian acritarch assemblages in the Bardo Stawy and Zalesie Nowe sections are similar to those from the Szumsko Kolonia and Valga 1 boreholes, although they are poorer.

Comparison of the earliest Silurian acritarchs is difficult because there is only one productive Rhuddanian sample from the Valga 10 drill core. This sample (Valga 10) from the lowermost Silurian contains a small and poorly diversified assemblage dominated by one morphotype of Leiosphaeridia. Such an assemblage is similar to those from the Bardo Stawy section (Fig. 2). The same peak in the frequency of Leiosphaeridia (whereas acritarchs are rare) is observed in sample BS. 5, just above the O/S boundary. A similar situation is observed in sample Z. 14 in the Zalesie Nowe section (Fig. 3). Other (younger) Silurian samples from the southern part of HCM (BS. 6–BS. 20) show a diversification trend in the palynological assemblage.

Such a diversification of acritarch assemblage disagrees with a general statement in Delabroye et al. (2011a: 33) that extremely low diversity seems to be a general feature of phytoplanktonic assemblages of the beginning of the Silurian, dominated mainly by sphaeromorphs and environmentally tolerant acritarchs. More diverse acritarch associations developed at the Rhuddanian/Aeronian transition (Duffield and Legault, 1981; Martin, 1989; Le Hérissé, 2000; Vecoli, 2008).

In our opinion, this is probably true for acritarch assemblages from deposits representing rather shallower facies, similar to those in southern Estonia (Valga 10), as well as deep basin facies, e.g. from northern Poland (Baltic Depression): Białogóra 1 and Łeba 8.

Acritarchs in the Bardo Stawy (S-HCM) section come from deposits considered (probably) deep-water sediments, but not so deep as in northern Poland. In the Bardo Stawy section, diversification of the acritarch assemblage starts in deposits of the *acuminatus–ascensus* Biozone. Additionally, deposits from the O/S interval of the Zalesie Nowe section come from shallower environments (Bednarczyk, 1996b; Trela, 2005, 2006; Trela and Szczepanik, 2009).

While studying the distribution of palynomorphs taxa, a clear dependence on bathymetry is observed. The dominance of prasinophytes (leiosphaeres) and crypyospores is characteristic for shallower depths. In deeper water, acanthomorphs are more abundant; they dominate in the assemblage. In the deepest environments, the dominance of leiosphaeres returns, although acantomorphs are numerous, but not as abundant as in shallower ones. Additionally, giganteus acritarchs occur in carbonate deposits (Le Hérissé, 1989). Such a pattern is generally compatible with a bathymetric model by Dorning (1981) and Al-Ameri (1983).

LAURENTIA

At the Ordovician/Silurian transition, Anticosti Island (Québec, eastern Canada) was located at low to intermediate palaeolatitudes (15–30°S) on the eastern margin of Laurentia (Torsvik and Cocks, 2005; Nawrocki et al., 2007).

The uppermost Ordovician–lowermost Silurian deposits of Anticosti Island, Québec, are represented by a carbonate sequence of calcareous shales and interbedded fossiliferous limestones, shales and bioherms that were deposited in shallow to deep subtidal environments. In different sections of Anticosti Island, the O/S boundary is drawn within different types of sediments (Barnes, 1988).

Very interesting palynological data on Hirnantian acritarchs from Anticosti were published by Delabroye et al. (2011b). These authors observed a post-crisis, low diversity acritarch assemblage dominated by large forms typical of carbonate platforms, as well as long-ranging taxa and cryptospores (land-derived), while typical Ordovician taxa (*Ordovicidium* spp., *Baltisphaeridium* spp., *Peteinosphaeridium* spp.) were not recorded.

At Anticosti, the O/S boundary sections are characterized by scant biostratigraphic control (lack of graptolite fauna) and the presence of palynologically barren strata (e.g., bioherm beds above the systemic boundary; Martin, 1988). This hinders the analysis of microphytoplankton diversity trends.

CHINESE BLOCK

In the Zhejiang Province of South China, continuous Ordovician–Silurian transitional strata are characterized by low diversity and unfavourable preservation of palynomorphs. There is no clear change in the acritarch palynoflora across the Ordovician/Silurian boundary. The presence of abundant cryptospores may suggest a near-shore marine environment during latest Ordovician–earliest Silurian times. Acritarchs become abundant and well preserved 400 m above the accepted Ordovician/Silurian boundary. The insufficiency of detailed investigation of microphytoplankton at the O/S boundary, due to sparse sampling along the thick section, is the major obstacle of this section (Yin and He, 2000).

HIGH PALAEOLATITUDES OF THE SOUTHERN HEMISPHERE

BOHEMIAN MASSIF (PERUNICA)

The high-latitude palaeogeograpic position of the Bohemian Massif at the O/S transition, shown by Delabroye et al. (2011a), is accepted herein (Fig. 1C). According to that paper, the Bohemian Massif is classified as a terrain adjacent to Northern Gondwana.

The Ordovician–Silurian boundary in the Prague Basin is identified in two continuous sections (Dufka and Fatka, 1993). Both sections are well-dated by means of graptolites (Štroch, 1986). The O/S boundary interval is characterized there by a transition from flysch-type deposits into black graptolitic shales. The dark shales with graptolites appear already below the base of the *ascensus* Biozone and they correspond probably to the uppermost part of the *persculptus* Biozone (similar situation to the southern part of the Holy Cross Mts.). The weakness of this section for palynological investigations is the absence of acritarchs and prasinophytes from the base of the Llandovery. Acritarchs were recorded only from the green-grey claystone of the upper part of the *acuminatus* graptolite Biozone – ~1.2 m above the boundary (Dufka and Fatka, 1993).

GONDWANA

In Saudi Arabia, well-established chitinozoan zones could be correlated with the graptolite zonation of the British Standard. The systemic interval – *persculptus* and the lower part of the *acuminatus* graptolite biozones – is characterized by low diversity of microphytoplankton. The organic-rich black shales ("Hot Shales") from the middle and upper part of the *acuminatus* graptolite Biozone are particularly unfavourable for acritarchs and prasinophytes. Only some cryptospores were found (Spina, 2015). However, it is important to note that this zone is not sufficiently investigated. For full understanding of the recovery pattern of microphytoplankton, it is important to study the silty intercalation and clays within the black graptolitic shales (Le Hérissé, 2000).

Some interesting data come from the Tt1 borehole – Ghadamis Basin, southern Tunisia (Vecoli et al., 2009). "There is no evidence of the major discontinuity at the Ordovician/Silurian boundary even the sequence is condensed", as stated by Vecoli et al. (2009), and the Silurian begins from the *vesiculosus* Biozone. The *ascensus–acuminatus* Biozone is not present there.

In NE Algerian Sahara (borehole Nl-2) the profile is not continuous across the O/S boundary and is characterized by an important gap comprising most of the upper part of the Ordovician and the whole Llandovery. This hiatus caused the Wenlock black shales to overlie directly the Hirnantian sediments (Paris et al., 2000). Other localities (Chad) from northern Africa are not well controlled stratigraphically (Le Hérissé et al., 2013).

MICROPHYTOPLANKTON ABUNDANCE AND TOTAL ORGANIC CARBON

Organic matter is primarily defined as derived from the accumulation and preservation of organic compounds that directly or indirectly come from cells or tissues of living organisms. In the case of shale rocks, the TOC content is influenced not only by phytoplankton (e.g., acritarchs and prasinophytes in the present study) but also by graptolites, algae and other organisms.

The total organic carbon content in rocks from the Bardo Stawy section was studied by Mustafa et al. (2015). It is very interesting to compare the microphytoplankton (prasinophyte and acritarch) abundance with the TOC curve in the same time interval (Fig. 9). Similar comparison of TOC and acritarch and prasinophyte abundance was presented by Vecoli et al. (2009), but the Silurian in the borehole from the Ghadamis Basin begins from the *vesiculosus* Biozone. In the Bardo Stawy section, the O/S transiton is continuous so that the data obtained from the *ascensus–acuminatus* Biozone gives a fuller picture of changes on the boundary of these two systems. The prasinophyte and acritarch abundance and the TOC trend are very similar in the uppermost Ordovician deposits (low values). From the beginning of the Silurian, the TOC and acritarch–prasinophyte curves show a general increasing trend, although both curves demonstrate variations. Deviations of both curves are concordant in the lower part of the *ascensus–acuminatus* Biozone, but they are opposite in its upper part (Fig. 9).

It is very probable that that time another source of organic carbon played a significant role. It is highly possible that this role was played by graptolites during the post-Hirnantian glaciation biotic recovery phase.

The comparison of the TOC and microphytoplankton curves was possible only for sediments from the Bardo Stawy regarding our available data. Preliminary data are propitious and it is worth to continue such investigations.

CONCLUSIONS

1. Acritarch and prasinophyte assemblages at the Ordovician/Silurian boundary appear to be good indicators of climatic

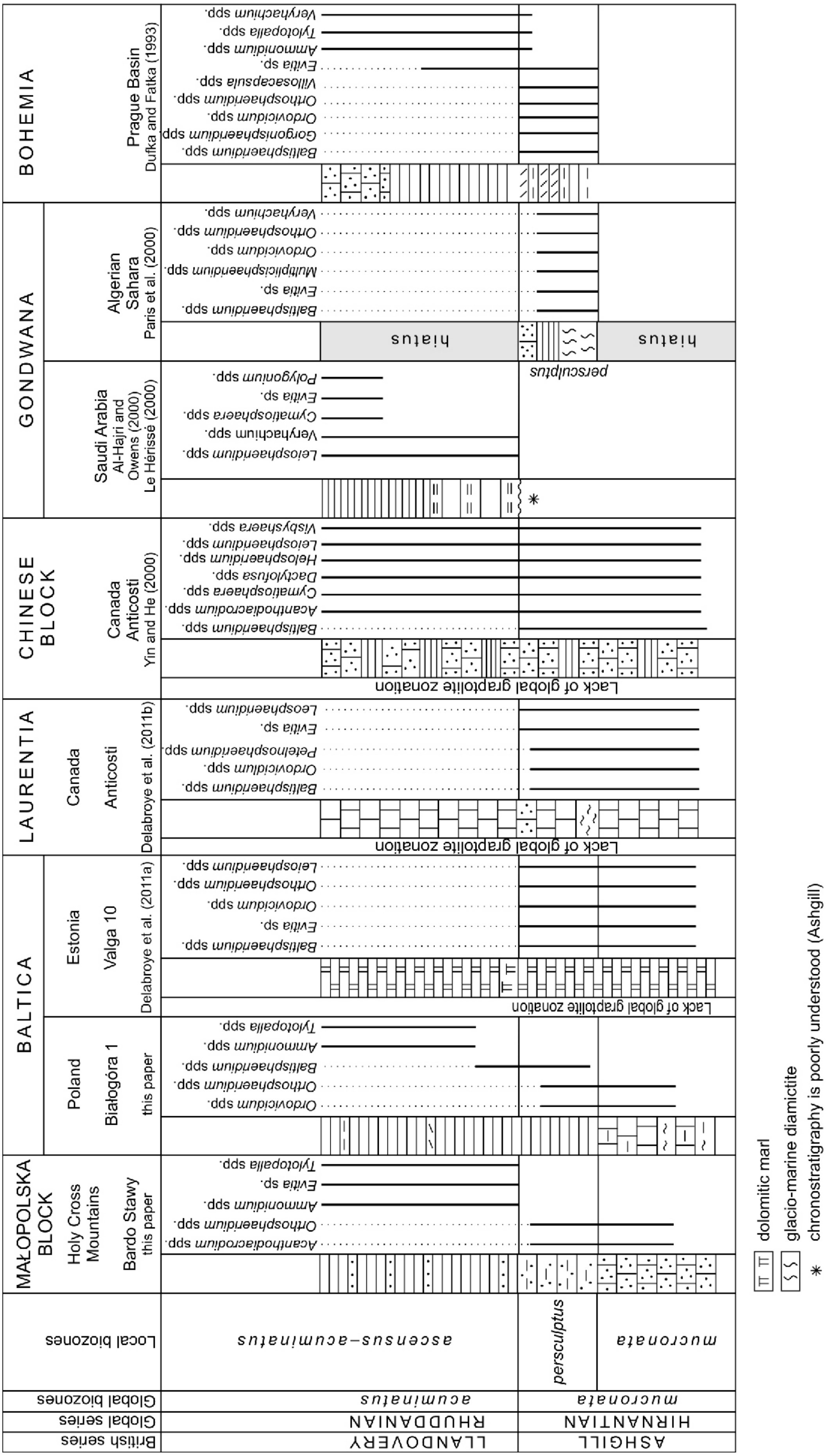

Fig. 9. Comparison of data from Poland with other regions

Other explanations as in Figure 2

changes connected with deglaciation of Gondwana and associated glacioeustatic changes.

2. There are only a few known palynomoprh-yielding profiles with a continuous O/S transition. The profiles from Poland, especially from the Holy Cross Mts., are very good for investigations of global climatic and eustatic events in the latest Ordovician to earliest Silurian, recorded in palynological assemblages.

3. Bathymetry played the key role in taxonomic diversification of the microphytoplankton assemblages, which supports the existing models of distribution (e.g., Al-Ameri, 1983).

4. Dominance of prasinophytes (leiospheres) and crypotospores is characteristic for shallow-water environments. In deeper water, dominance of acanthomorphs is observed. In the deepest-water zones – mixed assemblages occurred. The model presented in Delabroye et al. (2011b) has been verified only in the shallower environments.

5. The analysis of acritarch diversity trends vs. Total Organic Carbon (TOC) profiles shows parallel trends through the section: a low value in the Upper Ordovician and an increasing trend from the beginning of the Silurian. Opposite deviations on the TOC and arcitarch–prasinophyte abundance curves may indicate that other organisms significantly contributed to the accumulation of organic carbon in sediments during that time.

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