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The oldest rocks of the Holy Cross Mountains, Poland – biostratigraphy of the Cambrian Czarna Shale Formation in the vicinity of Kotuszów

ZBIGNIEW SZCZEPANIK[1] and ANNA ŻYLIŃSKA[2]

[1] *Holy Cross Branch of the Polish Geological Institute-National Research Institute, Zgoda 21, PL-25-953 Kielce, Poland. E-mail: zbigniew.szczepanik@pgi.gov.pl*
[2] *Faculty of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland. E-mail: anna.zylinska@uw.edu.pl*

ABSTRACT:

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Three lower Cambrian acritarch assemblages recognized in four outcrops in the vicinity of Kotuszów in the southernmost part of the Palaeozoic inlier of the Holy Cross Mountains span a stratigraphic interval from the uppermost part of the *Asteridium tornatum–Comasphaeridium velvetum* Assemblage Zone to the *Skiagia ornata–Fimbriaglomerella membranacea* Assemblage Zone (most probably its lower part). According to current views (Moczydłowska and Yin 2012), this interval corresponds to the upper part of the Fortunian and to Stage 2 of the Terreneuvian Series. The strata yielding the oldest assemblage are thus the oldest precisely documented rocks in the Palaeozoic succession of the Holy Cross Mountains, and the oldest Cambrian rocks exposed on the surface in Poland. The current biostratigraphic scheme for the pre-trilobitic part of the Cambrian System in the Holy Cross Mountains should be modified so that it is based on local acritarch interval subzones.

Key words: Cambrian; Fortunian; Terreneuvian; Holy Cross Mountains; Kotuszów; Acritarcha; Biostratigraphy.

INTRODUCTION

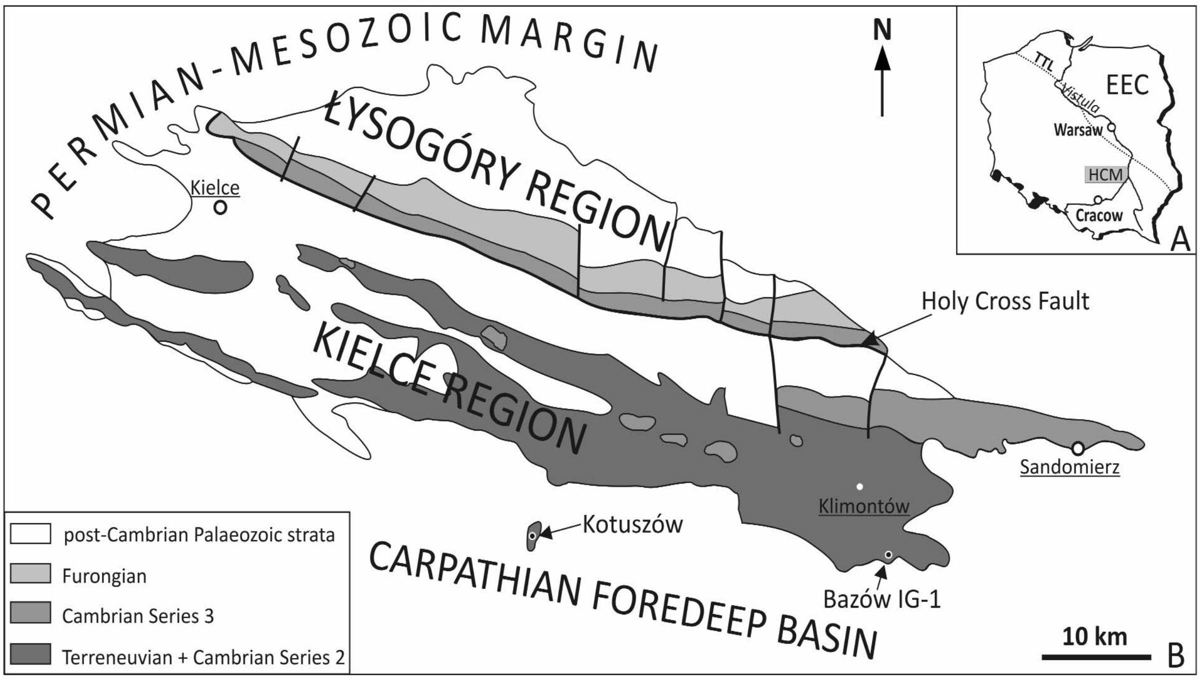
Since the mid-19th century, the rocks exposed in the vicinity of the village of Kotuszów have been considered as the oldest strata in the entire Holy Cross Mountains. However, their exact stratigraphic position varied from pre-Cambrian to the upper part of the lower Cambrian in the views of different authors, or even to the Silurian in the oldest reports (see below). According to the most recent biostratigraphic data based on acritarch studies (Kowalczewski *et al.* 1987), the strata correspond to Cambrian Series 2, as do the strata in the nearby Bazów IG-1 borehole (Lendzion *et al.* 1982). In turn, the existing biostratigraphic scheme for that lowermost part of the Cambrian which is devoid of trilobite fossils is based on rare, in some cases poorly described macrofossils with an extremely patchy distribution (Samsonowicz 1962; Michniak and Rozanov 1969; Żakowa and Jagielska 1970; Lendzion *et al.* 1982; Orłowski and Waksmundzki 1986), this part of the succession being referred to the Terreneuvian, i.e., the basal series of the Cambrian. However, this biostratigraphic scheme is not applicable for other parts of the Palaeozoic inlier of the Holy Cross Mountains. To solve these inconsistencies it is necessary to reinvestigate the biostratigraphy of the Czarna Formation using a novel approach to the different fossil assemblages.

Historically, the best exposures yielding macro- and microfossils are located in and around the village of Kotuszów in the southern part of the Holy Cross Mountains, within a small inlier of Cambrian and Devonian rocks surrounded by Miocene sediments (Text-fig. 1). Preliminary analysis of existing and newly collected Cambrian macrofossils from the study area indicates that the low-frequency assemblage is relatively diverse, dominated by algae and hyoliths, with rare bradoriids, protomonaxonid sponges, anomalocaridiids and other, so far unrecognized taxa (Samsonowicz 1962; Orłowski and Waksmundzki 1986; AŻ unpublished data). The assemblage seems to be a mixture of benthic and nektonic organisms, and thus its interpretation requires detailed studies of its allo- or autochthonous components, coupled with geochemical and petrographic assessments (AŻ *et al.* in preparation). Unfortunately, the patchy distribution and low stratigraphic significance of those taxa hampers the application of macrofossils in precise biostratigraphic analyses. Consequently, we have decided to resample the exposed succession for acritarchs and to determine the age of the strata based on microfossil assemblages.

GEOLOGICAL SETTING

The Holy Cross Mountains (HCM) represent low (the highest peak at 612 m a.s.l.), WNW–ESE oriented hills located in south-central Poland, to the west of the Vistula River (Text-fig. 1A). In terms of geology, these hills represent an area unique in Europe. They contain an almost complete succession of non-metamorphosed Palaeozoic rocks that developed in the direct vicinity of the Teisseyre-Tornquist Line, that has been exposed from underneath a Permian–Mesozoic cover due to Late Cretaceous–Early Paleogene tectonic inversion and uplift (Kutek and Głazek 1972; Krzywiec *et al.* 2009). Thus the area shows successions developed on a basement that is part of the Trans-European Suture Zone (Berthelsen 1992), an important geotectonic domain separating the East European Craton from Variscan Western Europe. The Palaeozoic inlier of the Holy Cross Mountains is surrounded by Permian and Mesozoic formations to the north, west, and south-west (the Permian–Mesozoic margin), whereas to the south and south-east occur the sediments of the last marine transgression in the area, viz. the Miocene strata of the Carpathian Foredeep Basin (e.g., Radwański 1969) (Text-fig. 1B).

The Cambrian succession in the Holy Cross Mountains consists of siliciclastic facies with an estimated thickness of 2500-3500 m (e.g., Orłowski 1988), sub-di-



Text-fig. 1. (A) Sketch-map of Poland with the location of the Holy Cross Mountains (HCM) in relation to the East European Craton (EEC) and the Teisseyre-Tornquist Line (TTL). (B) Geological sketch-map of the HCM showing the distribution of Cambrian deposits. Modified from Orłowski (1975, 1992), with location of Kotuszów and the Bazów IG-1 borehole vided into a series of lithostratigraphic units and encompassing almost the entire Cambrian System. Intense research on the Cambrian of the Holy Cross Mountains began almost a century ago with contributions mainly by Jan Czarnocki and Jan Samsonowicz (e.g., Samsonowicz 1918; Czarnocki 1919). During the last fifty years or so, research has been focused on trilobites in both taxonomic and stratigraphic aspects (Samsonowicz 1959a, b, c; Orłowski 1964, 1965, 1968a, b, 1974, 1985a, b, 1987), and consequently this fossil group became the most important tool for the Cambrian biostratigraphy of the area. The bio- and lithostratigraphic scheme was refined and synthesized by Orłowski (1975, 1988, 1992), and later new lithostratigraphic units were proposed by Kowalczewski (1990, 1995), Szczepanik *et al.* (2004a, b) and Kowalczewski *et al.* (2006). Increased knowledge of the relationships of Cambrian trilobites resulted in new taxonomic assignments and, subsequently, novel or refined stratigraphic schemes (Żylińska 2001, 2002, 2013a, b; Żylińska and Masiak 2007; Żylińska and Szczepanik 2009). These were reinforced by a modern approach to the analysis of acritarch assemblages, which began with the reports by Lendzion *et al.* (1982) and Szczepanik (1988, 1997, 2001), and continued in correlation with trilobite assemblages (Żylińska and Szczepanik 2002, 2009; Żylińska *et al.* 2006; Szczepanik and Żylińska 2008, 2012). The recent advances in trilobite studies are strongly supported by sophisticated morphometric analyses (e.g., Żylińska *et al.* 2013; Nowicki 2014, 2015), whereas the research on acritarch assemblages is focused on the establishment of local assemblages for the entire Cambrian succession in the Holy Cross Mountains, and, where possible, tying them to the biostratigraphic scheme based on trilobites. This report on the acritarch assemblages from the Czarna Formation in the Kotuszów area further supplements and refines the biostratigraphic scheme.

<table>
<tr><th rowspan="2">units / authors</th><th colspan="3">Czarna Shale Formation (eastern Holy Cross Mountains)</th></tr>
<tr><th>Kotuszów beds</th><th>Jasień beds</th><th>Bazów beds</th></tr>
<tr><td rowspan="3">Samsonowicz (1955, 1960)
Michniak and Orłowski (1963)</td><td>Riphean</td><td>Lower Cambrian</td><td rowspan="3">-</td></tr>
<tr><td rowspan="2">Kotuszów Stage</td><td>sub-Holmia</td></tr>
<tr><td>Jasień Shales</td></tr>
<tr><td rowspan="2">Pawłowski (1965)</td><td rowspan="2">Upper Eocambrian</td><td>Lower Cambrian</td><td rowspan="2">-</td></tr>
<tr><td>sub-Holmia</td></tr>
<tr><td rowspan="3">Pożaryski and Tomczyk (1968)
Michniak (1969)
Michniak and Rozanov (1969)</td><td rowspan="2">Riphean</td><td colspan="2">Lower Cambrian</td></tr>
<tr><td colspan="2">sub-Holmia</td></tr>
<tr><td>Kotuszów beds</td><td>Jasień beds</td><td>Bazów beds</td></tr>
<tr><td rowspan="3">Orłowski (1975)</td><td rowspan="2">Vendian</td><td colspan="2">Lower Cambrian</td></tr>
<tr><td colspan="2">sub-Holmia (Coleoloides + Platysolenites)</td></tr>
<tr><td>Kotuszów Shale Member</td><td colspan="2">Czarna Shale Formation</td></tr>
<tr><td>Lendzion et al. (1982)</td><td>-</td><td>-</td><td>Holmia</td></tr>
<tr><td rowspan="3">Kowalski (1983)</td><td colspan="3">Lower Cambrian</td></tr>
<tr><td>Sabellidites</td><td>Platysolenites</td><td>Mobergella</td></tr>
<tr><td>Kotuszów Shale Member</td><td colspan="2">Czarna Shale Formation</td></tr>
<tr><td rowspan="3">Orłowski (1987)</td><td colspan="3">Lower Cambrian</td></tr>
<tr><td>Sabellidites</td><td>Coleoloides + Hyolithes-Allatheca</td><td>?</td></tr>
<tr><td>Kotuszów Shale Member</td><td colspan="2">Czarna Shale Formation</td></tr>
<tr><td>Kowalczewski (1995)</td><td>sub- Holmia+ Holmia</td><td colspan="2">Holmia + Protolenus</td></tr>
</table>

Text-fig. 2. Chrono-, bio- and lithostratigraphic assignments for the components of the Czarna Shale Formation. Grey shading indicates the Precambrian

The Neoproterozoic–Cambrian boundary has not been recognized in the area so far, although rocks of Precambrian age have been radiometrically dated in the basement of the Miechów Basin to the south of the Holy Cross Mountains (Compston *et al.* 1995). Although the rocks exposed in Kotuszów crop out in the small inlier to the south, beyond the southern margin of the main Palaeozoic inlier, they are part of the Czarna Shale Formation, a lowermost Cambrian lithostratigraphic formation known from numerous localities in the southern part of the Palaeozoic inlier (Orłowski 1975; Kowalczewski 1990; Kowalczewski *et al.* 2006). Historically, the Czarna Formation encompasses three informal units, all of which have been distinguished in, or close to, the study area. To date, their stratigraphic order is: 1) the Kotuszów beds (Samsonowicz 1960; Kotuszów Shale Member of Orłowski 1975); 2) the Jasień beds (Jasień Shales of Samsonowicz 1960); and 3) the Bazów beds (Bazów Shales of Samsonowicz 1960). The first two units have their type sections in the study area, although distinguishing between them in the field is practically impossible, and it is recommended that in the future the names of these units should be abandoned. The type succession for the Bazów beds is the Bazów IG-1 borehole, drilled in the early 1960s in the south-eastern tip of the Palaeozoic inlier (Jagielska 1963, 1965; Żak 1963, 1965, 1966; Żakowa and Jagielska 1970; Lendzion *et al.* 1982). The three informal units will be, however, used in the next chapter and in Text-fig. 2 for clarity in presenting the history of their study.

PREVIOUS STRATIGRAPHIC ASSESSMENT OF THE KOTUSZÓW ROCKS

Sediments cropping out in the vicinity of Kotuszów were first mentioned in the geological literature in the third decade of the 19th century, when they were considered as the basement of all rock complexes in the Holy Cross Mountains, and were assigned to the Silurian (Pusch 1833-1836). A Silurian or younger age was likewise postulated in subsequent papers (Kontkiewicz 1882; Siemiradzki 1887, 1903). After the first report on the discovery of Cambrian rocks at Gieraszowice in the Holy Cross Mountains by Samsonowicz (1918), Czarnocki (1919) attributed the Kotuszów rocks to the Cambrian as well. This view continued until the early 1950s, and was presented for example in standard texts such as in the geological map of the Holy Cross Mountains in the scale 1:300 000 (in Książkiewicz and Samsonowicz 1952). However, Samsonowicz (1955) pointed out that metamorphism and stronger tectonic deformation are present in the olive green shales outcropping in Kotuszów and thus there are differences compared to the Cambrian of the Holy Cross Mountains. The non-fossiliferous rocks cropping out beneath the Lower Cambrian *Holmia* horizon were attributed to the Precambrian, with an angular unconformity between the Precambrian and Cambrian and a sedimentary hiatus being postulated. Their assignment to the 'metacarpathic ridge', extending from the Holy Cross Mountains area to the Dobrogea region along the Black Sea in Romania, was suggested (Samsonowicz 1955). Accordingly, the Kotuszów beds were assigned to the Riphean, Upper Eocambrian, or the Vendian (see Text-fig. 2 for details and references). In turn, the Jasień and Bazów beds of the Czarna Formation were repeatedly assigned to the Lower Cambrian, either to the sub-*Holmia* or to the *Holmia* zones (see Text-fig. 2 for details and references), based on rare finds of macro- or microfossils (e.g., Michniak 1959; Samsonowicz 1962; Jagielska 1963, 1965; Michniak and Rozanov 1969; Żakowa and Jagielska 1970; Lendzion *et al.* 1982; Kowalski 1983). Thus, the Czarna Shale Formation in its original definition (Orłowski 1975) included strata assigned both to the Vendian (Kotuszów beds) and the Lower Cambrian (Jasień and Bazów beds).

In turn, Łydka (1978), based on petrographic studies, suggested that the entire formation may be of Cambrian age. The evidence provided concentrates on the presence of the same type of terrigenous material in all members of the Czarna Formation coupled with an identical degree of secondary changes in the mobile components, but this evidence is not conclusive. This view was, however, independently corroborated by Kowalski (1983) based on studies of acritarch assemblages and trace fossils in several boreholes from south of the Palaeozoic inlier. Although palynomorphs had been recognized in the Kotuszów, Jasień, and Bazów beds (Michniak 1959, 1969; Jagielska 1963, 1965; Żakowa and Jagielska 1970), their allocation to currently recognized genera and species is not possible, as they were described and illustrated prior to the modern concept of the Acritarcha, following the works of Downie *et al.* (1963), Evitt (1963a, b), and Sarjeant (1964). Kowalski (1983) distinguished and illustrated a number of genera and species from boreholes in the vicinity of Kotuszów. His stratigraphic conclusions, however, were restricted to the assignment of the Czarna Shales to the Cambrian System (Text-fig. 2). In reality, the specimen illustrated by Kowalski (1983, pl. 7, fig. 1a-b) as *Baltisphaeridium ornatum* Volk. [currently: *Skiagia ornata* (Volkova) Downie, 1982] from the Korytnica 2 borehole suggests a *Skiagia*-bearing interval of mid-early Cambrian age (e.g., Volkova *et al.* 1979; Moczydłowska 1991). Stratigraphic assignments based on acritarchs by Gozalo Vidal and Małgorzata Moczydłowska were briefly mentioned in Kowalczewski *et al.* (1987), but without photographic documentation. The main conclusion was that the Czarna Shale Formation comprises solely sediments corresponding to different intervals of the Cambrian *Holmia* and probably also the *Protolenus* trilobite zones.

Independently, Orłowski (1987) revised the biostratigraphic scheme of the lower Cambrian in the Holy Cross Mountains. Based on finds of the annelids *Sabellidites* (Kowalski 1983; see Moczydłowska *et al.* 2014 for affinities of *Sabellidites*) and *Coleoloides* sp. (Samsonowicz 1962), hyoliths (Orłowski and Waksmundzki 1986), and the foraminifer *Platysolenites* (Michniak and Rozanov 1969; see McIlroy *et al.* 1994 for affinities of *Platysolenites*), he distinguished four biostratigraphic zones corresponding to the Kotuszów Stage and the sub-*Holmia* interval of Samsonowicz (1960). In ascending order, these are the *Sabellidites*, *Hyolithes–Allatheca*, and *Coleoloides* zones, and a barren interzone (Text-fig. 2).

MATERIAL

The samples used in this study were collected from five localities in and around Kotuszów village (Text-fig. 3):

Locality 1: south of the village centre, comprising small exposures in embankments of country roads located to the west of the Kotuszów–Kurozwęki road;

Locality 2: in the village centre; this is an approximately 6 m long and 4 m high exposure on the western embankment of the Czarna River valley;

Locality 3: east of the village centre; this is an approximately 10 m long and 4 m high exposure located on the eastern embankment of the Czarna River valley, about 180 m to the east of the bridge across Czarna River;

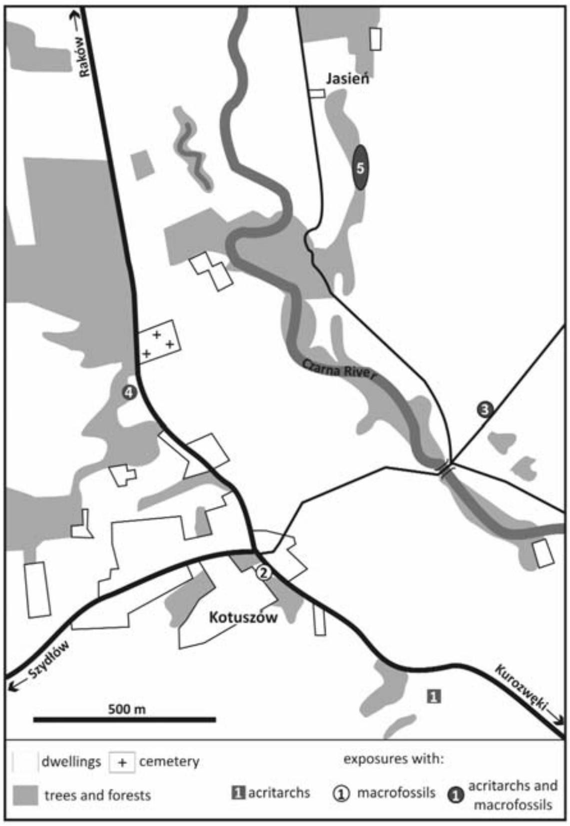
Locality 4: north of the village centre, comprising small exposures near artificial ponds opposite the cemetery;

Locality 5: north-east of the village centre and south of Jasień village; this is a series of small exposures along the eastern embankment of the Czarna River valley, at present mostly overgrown by prickly bushes.

A total of 21 samples were tested for their acritarch content, but only 8 yielded a recognizable acritarch flora. Unfortunately, the classical exposure of the Kotuszów shales in Kotuszów village (here: Locality 2), known for the presence of macrofossils, did not yield any acritarchs.

The abundance of the microfloral assemblages was rather low and rarely exceeded 30 to 50 specimens per slide, reaching about 80 specimens in the most productive slides. A characteristic feature of the material studied is the very uneven distribution of the microfossils in the studied rocks. Despite a similar lithology and short distances between the sampling sites, abundant samples often occurred adjacent to completely barren ones.

All recognized palynomorphs are characterized by a preservation with a brown colour, with the shade depending on the thickness of the walls. The colour corresponds to stadia 5+ to 6 of the Thermal Alteration Index (Engelhardt *et al.* 1992) pointing to the oil and gas windows. When compared with other palynomorph assemblages from the Cambrian of the Holy Cross Mountains (Szczepanik 1997, 2007), this is a high maturity index, probably owing to the fact that the Kotuszów rocks are the basal units of the Palaeozoic succession and were deeply buried at various times in their history. Despite high thermal maturity,



Text-fig. 3. Sketch-map of the vicinity of Kotuszów showing the locations of the studied exposures the preservation state of the acritarch specimens is good, sometimes excellent, which excludes strong diagenesis and intense tectonic deformation of the Kotuszów rocks, contrary to earlier suggestions (e.g., Samsonowicz 1955).

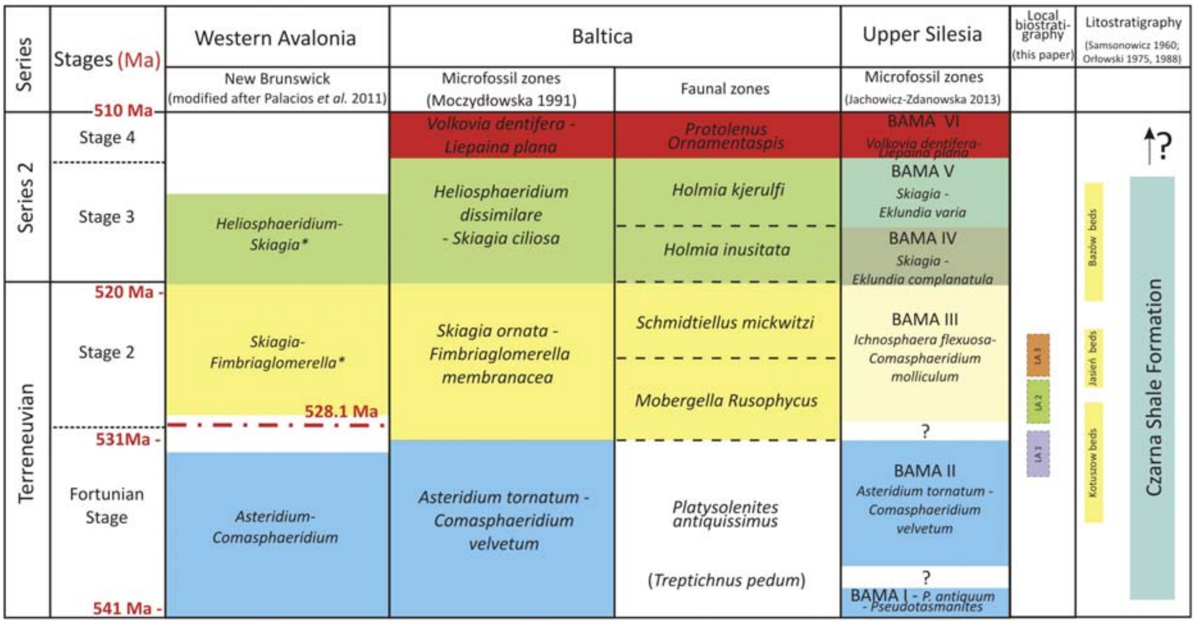
METHODOLOGY

The samples were subject to classical palynologic maceration. Ca. 100 g samples were macerated first in cold hydrofluoric acid, subsequently in hot hydrochloric acid, filtrated on 15 mm mesh membranes, and macerated once again in cold hydrofluoric acid. The obtained residuum was next centrifuged in heavy liquid. Later, glycerine-gelatine mounts were made, which were analyzed in bright-field microscopy (Olympus BX51 microscope) in magnifications between 300 and 1200. The recognized acritarch specimens were documented as graphic files with the help of a microcamera attached to a computer.

BIOSTRATIGRAPHICAL BACKGROUND

The palynomorph assemblages recognized in the Kotuszów succession largely correspond to lower Cambrian microfloral acritarch associations as known from different parts of the world (Text-fig. 4). In the neighbourhood of the Holy Cross Mountains, similar acritarchs have been recognized in boreholes in the basement of the Miechów Basin (Pożaryski *et al*. 1981), in over a dozen boreholes pierced in the north-eastern part of the Carpathian Foredeep (Stalowa Wola–Lubaczów zone; Jachowicz-Zdanowska 2011), in the Upper Silesia Block (e.g., Moczydłowska 1998; Jachowicz-Zdanowska 2013) and the structurally related Brno Block (Jachowicz and Prichystal 1997; Fatka and Vavrdová 1998; Vavrdová and Beck 2001; Vavrdová 2006). Key studies for the development of global lower Cambrian acritarch biostratigraphy include those conducted on the Lublin Slope of the EEC (Volkova 1969; Volkova *et al.* 1979, 1983; Moczydłowska and Vidal 1986; Moczydłowska 1989). Acritarchs with a similar age are known from other parts of the EEC in Poland (e.g., Moczydłowska 1981; Jankauskas and Lendzion 1992; Szczepanik 2000), eastern Baltic region (e.g., Volkova 1968; Yankauskas 1972, 1975; Yankauskas and Posti 1976; Paskeviciene 1980), and Scandinavia, both from the margin of the Baltic Shield and from the Caledonides (e.g., Vidal 1981; Tynni 1982; Moczydłowska and Vidal 1986, 1992; Hagenfeldt 1989; Eklund 1990; Vidal and Nystuen 1990; Vidal and Moczydłowska 1996; Moczydłowska *et al.* 2001; Högström *et al*. 2013). Comparable assemblages are known from the Cambrian of Volhynia (Kiryanov 1974; Volkova *et al*. 1979, 1983) and the Moscow Syneclise (Volkova 1996). Correlatives of the lower Cambrian microfloral associations known from the Baltic area have also been noted in Siberia (e.g., Ogurtsova 1977; Vidal *et al.* 1995; Kiryanov 2005). Typical lower Cambrian acritarch assemblages have been recognized in southern Australia (East Gondwana; e.g., Zang *et al*. 2007), southern China (Yangtze Block; e.g., Zang 1992), and Iberia (West Gondwana; Palacios and Vidal 1992). This type of microflora is known also from Laurentia (e.g., Downie 1982), East Avalonia (Vanguestaine 1992; Bruck and Vanguestaine 2004), and West Avalonia (Palacios *et al.* 2011, 2014), although in the latter case there are serious doubts concerning the definition of particular assemblages, and their correlation with SSF zones and geochronological dates (Landing *et al.* 2013).

The succession of distinctive assemblages of lower Cambrian microflora and their wide geographic range allows their application as a rough correlation tool for the often unfossiliferous rock series in which they occur. However, there are a number of obstacles that restrict the precise determination of the chronostratigraphic position of the acritarch zones, of which some have been extensively disputed recently (e.g., Moczydłowska and Yin 2012; Landing *et al.* 2013). A significant issue in the recognition and application of acritarch zones is the often imprecise definition of particular zones and their different interpretation by various authors. Initially recognized on the Lublin Slope of the EEC, but also in other parts of the craton, the stratigraphic sequence present there (Moczydłowska and Vidal 1986, 1988; Moczydłowska 1989) was presented by Moczydłowska (1991) as a partly formalized acritarch zonation. Three formal zones: *Asteridium tornatum–Comasphaeridium velvetum*, *Skiagia ornata–Fimbriaglomerella membranacea* and *Heliosphaeridium dissimilare–Skiagia ciliosa* have been distinguished as assemblage zones and defined by the general composition and contribution of particular taxa. Such definition facilitates recognizing the particular microfloristic associations and allows for determining the rough stratigraphic position of the sequences, but hampers precise location of stratigraphic boundaries and may sometimes lead to different stratigraphic interpretations. A good illustration of the problems related to the interpretation of zones defined in this manner may be an example



Text-fig. 4. Biostratigraphic and correlation scheme for the lower Cambrian, based on acritarchs (modified from Moczydłowska and Yin 2012 and Jachowicz-Zdanowska 2013, with supplementation from Palacios *et al.* 2011), showing the stratigraphic position of the recognized local biostratigraphical units. The asterisk (*) for the upper two acritarch zones recognized in New Brunswick by Palacios *et al.* (2011) marks uncertainties in the recognition of these zones, as indicated by Landing *et al.* (2013). The 528.1 Ma date corresponds to the 531 Ma date of Moczydłowska and Yin (2012), recalculated by Compston *et al.* (2008) (see also Landing *et al.* 2013)

from the lower Cambrian of the Cantabrian Zone in Spain (Palacios and Vidal 1992), where two zones were distinguished, for which representatives of *Skiagia* are index taxa despite the lack of acritarchs representing the genus *Skiagia*. The assignment of an acritarch assemblage from the Chapel Island Formation in New Brunswick to the *Skiagia–Fimbriaglomerella* Zone (Palacios *et al.* 2011) has also been disputed, as most elements of this assemblage occur in the overlying *Heliosphaeridium–Skiagia* Zone, whereas the assignment of the two index taxa raises doubts (Landing *et al*. 2013). The *Asteridium tornatum–Comasphaeridium velvetum* Zone is often distinguished when the relevant samples contain simple microfloral assemblages without the index taxa but with numerous specimens of *Granomarginata.* In this case, the zone is sometimes replaced by a similar, but otherwise defined zone (Jankauskas and Lendzion 1992), or additional subzones are proposed (Palacios *et al*. 2014).

Another concern is the chronostratigraphic position of the distinguished acritarch zones. This issue has been extensively discussed over the last few years (Moczydłowska and Yin 2012; Landing *et al*. 2013). The correction of the chronostratigraphic position of the *Skiagia ornata–Fimbriaglomerella membranacea* Zone and its correlation with the upper part of the Terreneuvian (Moczydłowska and Yin 2012) is of key significance for Cambrian stratigraphy in the Holy Cross Mountains.

LOCAL BIOSTRATIGRAPHY

Local assemblage 1

The assemblage was recognized in one sample collected from Locality 1. It is a low-abundance palynomorph assemblage (30 specimens per slide), composed of numerous sphaeromorphs such as *Leiosphaeridia* sp. (Pl. 1, Figs 1–5), accompanied by representatives of *Granomarginata* (Pl. 1, Figs 15–17), *Comasphaeridium* (Pl. 1, Figs 13, 14, 18, 19), and acritarchs of the genus *Lophosphaeridium*, generally with small surface sculpture elements (mainly *L. tentativum*; Pl. 1, Fig. 22). The composition of the assemblage resembles a typical association of the Terreneuvian *Asteridium tornatum–Comasphaeridium velvetum* Zone, distinguished on the Lublin Slope of the EEC (Moczydłowska 1991), in Upper Silesia (Jachowicz-Zdanowska 2013), and in the Brno Block (Vavrdová *et al.* 2003; Vavrdová 2006). The presence of this zone as exemplified by the studied assemblage is also supported by the occurrence of *Comasphaeridium* cf. *velvetum* (Pl. 1, Figs. 13, 14) and *As-*

teridium tornatum (Pl. 1, Fig. 23). However, the assemblage contains representatives of the genus *Fimbriaglomerella*, including *F. membranacea* (Pl. 1, Figs 9, 10), which are characteristic of the overlying *Skiagia ornata–Fimbriaglomerella membranacea* Zone in the scheme proposed by Moczydłowska (1991). The studied sample, however, lacks other taxa typical of this zone. Both zones distinguished by Moczydłowska (1991) are defined as assemblage zones, and their definitions are based on characteristic contributions of particular taxa in the assemblages rather than on the stratigraphic ranges, so that the association recognized in Locality 1 appears to characterize the *Asteridium tornatum–Comasphaeridium velvetum* Zone.

The *Asteridium tornatum–Comasphaeridium velvetum* Zone was recognized in a number of boreholes drilled in the Lublin Slope of the EEC (Moczydłowska 1991) and in the north-eastern part of the Carpathian Foredeep (Szczepanik 2009). Typical assemblages of this zone have also been noted in the Upper Silesia Block (e.g., Jachowicz-Zdanowska 2013) and southern Moravia (Jachowicz and Prichystal 1997; Vavrdová and Beck 2001; Vavrdová 2006). A fully developed assemblage of this zone was also found in lower Cambrian successions drilled in the western part of the Peribaltic Syneclise (Szczepanik 2000). Among other parts of the EEC, assemblages of this type are known from the Moscow Syneclise (Volkova 1996), Volhynia, and the Baltic area (e.g., Volkova *et al.* 1979, 1983; Jankauskas and Lendzion 1992). Palacios *et al.* (2014) have indicated that the well-developed *Asteridium tornatum–Comasphaeridium velvetum* Zone does not appear directly at the base of the Terreneuvian in the GSSP locality in Newfoundland, but is preceded by a low-diversity association composed mainly of *Granomarginata*. Interestingly, a similar situation is observed in some sections documented by Moczydłowska (1991: appendix 6, p. 93) and proposed for sections from northern Norway (Finnmark) (Palacios *et al.* 2014). Most probably, this association is a correlative of the oldest Cambrian BAMA I subzone distinguished for the Brunovistulicum by Jachowicz-Zdanowska (2013). According to the modified scheme of Moczydłowska and Yin (2012), the *Asteridium tornatum–Comasphaeridium velvetum* Zone corresponds to the lower Terreneuvian (Fortunian Stage). The assemblage from Kotuszów, transitional between the *Asteridium tornatum–Comasphaeridium velvetum* and *Skiagia ornata–Fimbriaglomerella membranacea* assemblages may correspond to the boundary interval between the Fortunian Stage and the Stage 2 of the Terreneuvian, and the strata in which it occurs can be considered as the oldest documented Cambrian (and Palaeozoic) rocks in the Holy Cross Mountains.

Local assemblage 2

The assemblage was recovered from two samples collected in Localities 3 and 4. The relatively abundant sample from Locality 3 contains quite numerous and morphologically diverse representatives of *Lophosphaeridium* (Pl. 2, Figs 18–23), with the predominant *L. truncatum* (Pl. 2, Figs 20–23) and representatives of *Globosphaeridium cerinum* (Pl. 2, Figs 24–27). The palynomorphs are accompanied by taxa occurring in the older assemblage (although less abundant), such as *Leiosphaeridia* sp. (Pl. 2, Figs 2–4), *Tasmanites* sp. (Pl. 2, Fig. 5), *Comasphaeridium* spp. (Pl. 2, Figs. 10–13), *Granomarginata* spp. (Pl. 2, Figs. 14–16), palynomorphs identified as *Fimbriaglomerella* spp. (Pl. 2, Fig. 17), *Cymatiosphaera* sp. (Pl. 2, Fig. 9), and representatives of probably new acritarch genera (Pl. 2, Figs 6–8). The low-abundance palynomorph assemblage from Locality 4 is very similar to that recorded in Locality 3. It contains numerous diverse acritarchs of the genus *Lophosphaeridium* (Pl. 3, Figs 6–13), with *L. dubium* (Pl. 3, Figs 8–10) and *L. truncatum* (Pl. 3, Figs 11–13), ?*Ichnosphaera* sp. (Pl. 3, Fig. 22) and ?*Skiagia* sp. (Pl. 3, Fig. 21). These taxa are characteristic of the *Skiagia ornata–Fimbriaglomerella membranacea* Assemblage Zone. The presence of the relatively abundant *Fimbriaglomerella* cf. *membranacea* (Pl. 3, Figs 18–20) also supports such an age assignment. *Comasphaeridium mollicum* (Pl. 3, Fig. 15) is the index taxon of the contemporary *Ichnosphaera flexuosa–Comasphaeridium mollicum* Assemblage Zone (Jachowicz-Zdanowska 2013). This is the first assemblage from the Kotuszów area with specimens assigned to ?*Ichnosphaera* sp. and ?*Skiagia* sp., which may indicate a slightly younger age of this series in Locality 4 in comparison to the strata in Locality 3, although this supposition requires further studies.

The assemblages from Localities 3 and 4 are similar to those characterizing the *Skiagia ornata–Fimbriaglomerella membranacea* Assemblage Zone (Moczydłowska 1991) and the *Ichnosphaera flexuosa–Comasphaeridium mollicum* Assemblage Zone distinguished on the Upper Silesia Block (Jachowicz-Zdanowska 2013). However, they contain only a few specimens of the genus *Skiagia*, which is also very rare in assemblages from Upper Silesia (Jachowicz-Zdanowska 2013). Assemblages characteristic of this zone commonly occur on all Cambrian continents (see compilations in Moczydłowska and Yin 2012; Landing *et al.* 2013) (Text-fig. 4). Accordingly, the studied assemblage may correspond to the lower part of the *Skiagia ornata–Fimbriaglomerella membranacea* and *Ichnosphaera flexuosa–Comasphaeridium mollicum* assemblage zones and, after Moczydłowska and Yin (2012), may be correlated with the Cambrian Stage 2 (upper Terreneuvian).

Worth noting is the fact that the studied assemblage has been assigned to the *Skiagia ornata–Fimbriaglomerella membranacea* Zone despite the very scarce occurrence of *Skiagia*. In most known successions, representatives of *Fimbriaglomerella*, *Skiagia* and *Globosphaeridium* usually appear simultaneously. However, in some borehole logs from the Lublin Slope of the EEC (e.g., the Parczew IG-1 Borehole; Moczydłowska 1991), specimens of *Fimbriaglomerella* and *Globosphaeridium cerinum* appear below specimens of *Skiagia*. A similar situation exists in boreholes pierced in the Upper Silesia Block (see Jachowicz-Zdanowska 2013, p. 31), where specimens of *Skiagia* are extremely scarce, and in Fennoscandia (Hagenfeldt 1989: p. 88). Worth mentioning is the lower Cambrian acritarch microflora from the Cantabrian Zone in Spain (Palacios and Vidal 1992), where *Skiagia* does not occur at all, although the assemblages contain many other typical elements supposedly characteristic of this type of lower Cambrian palynoflora.

Local assemblage 3

A relatively abundant (up to 70 specimens in the slide) and more diverse assemblage has been recognized in Locality 5. The assemblage generally comprises the same palynomorphs as the previous samples, but contains for the first time acritarchs representing *Skiagia* spp. (Pl. 4, Figs 29, 31, 33–36) and a single specimen of ?*Ichnosphaera* sp. (Pl. 4, Fig. 32). The assemblage displays features of a fully developed acritarch association as known from the *Skiagia ornata–Fimbriaglomerella membranacea* and *Ichnosphaera flexuosa–Comasphaeridium mollicum* assemblage zones and may be correlated with the middle part of Cambrian Stage 2, according to the revised scheme by Moczydłowska and Yin (2012).

This fully developed acritarch association of the *Skiagia ornata–Fimbriaglomerella membranacea* Zone can be correlated with similar associations in many parts of the world (e.g., Volkova *et al.* 1979, 1983; Moczydłowska and Vidal 1986; Moczydłowska 1989, 1991, 1998). It corresponds to the local "assemblage A" of Eklund (1990) and the BAMA III *Ichnosphaera flexuosa–Comasphaeridium mollicum* Zone proposed by Jachowicz-Zdanowska (2013). However, compared with the latter unit, the association from Kotuszów lacks forms that can be assigned to *Ichnosphaera* with certainty. This may be a result of ecological or geographic factors, but another explanation is that samples from Locality 5 contain a relatively low-abundance assemblage of palynomorphs, among which only slightly more than a dozen represent "spiny" (acanthomorph) acritarchs. Additional data and more abundant samples may allow recognition of more convincing *Ichnosphaera* specimens, all the more because this taxon is present in other samples from the Holy Cross Mountains area (ZS unpublished data).

Biostratigraphic conclusions

The sequence of acritarch assemblages recognized in the vicinity of Kotuszów indicates the presence of an interval encompassing the upper part of the *Asteridium tornatum–Comasphaeridium velvetum* Zone to the *Skiagia ornata–Fimbriaglomerella membranacea* Zone (probably its middle part), corresponding to the mid and upper part of the Terreneuvian Series (Moczydłowska and Yin 2012). It thus represents a relatively short stratigraphic interval in a rather thick (c. 800 m according to Orłowski 1988) sequence of mudstones, indicating a relatively high sedimentation rate, although it should be taken into account that the lower Cambrian rock series in the southern part of the Holy Cross Mountains are strongly folded and contain numerous tectonic repetitions (Lendzion *et al.* 1982). Analysis of the acritarch flora with the successive appearance of *Fimbriaglomerella*, *Globosphaeridium* and *Skiagia* may be used to distinguish local acritarch interval subzones. Owing to the scarcity of macrofossils in the lowermost part of the Cambrian sequence in the Holy Cross Mountains, this scheme may become a useful stratigraphic tool for these strata. Similar evolution of the studied acritarch assemblages in the Holy Cross Mountains and in the Upper Silesia Block and Spain (see above for references) may confirm the palaeogeographic position of the Holy Cross margin of Baltica directed towards Perigondwana and Gondwana, as postulated by Cambrian Series 2 trilobite assemblages (Żylińska 2013a, b).

CONCLUSIONS

1. Cambrian strata exposed in the Kotuszów area, southern Holy Cross Mountains, yield three local acritarch assemblages, corresponding to the uppermost part of the *Asteridium tornatum–Comasphaeridium velvetum* Zone and the *Skiagia ornata–Fimbriaglomerella membranacea* Zone (most probably its lower and middle part) that, according to the scheme proposed by Moczydłowska and Yin (2012), span the mid-Terreneuvian, from the late Fortunian Stage through to the middle part of the Cambrian Stage 2. Correlation with the trilobite-bearing beds of the Ociesęki Sandstone Formation is not possible due to the lack of data on acritarchs from the latter unit. In turn, correlation with the trilobite-

bearing beds of the Kamieniec Shale Formation (Szczepanik and Żylińska 2012) indicates that the youngest local assemblage in Kotuszów is older than the oldest known assemblage from that formation. The large thickness of the sequence corresponds to a relatively short period, which appears to indicate a high sedimentation rate, although tectonic repetitions are also possible.

2. Rocks exposed to the south of Kotuszów (Locality 1) represent the upper part of the Fortunian Stage of the Terreneuvian Series, and are the oldest documented rocks in the Palaeozoic succession of the Holy Cross Mountains and the oldest documented rocks exposed at the surface in Poland.

3. The lower part of the *Skiagia ornata–Fimbriaglomerella membranacea* Assemblage Zone contains very scarce representatives of *Skiagia* (observations in the study area and data from a few sections studied by Hagenfeldt 1989, Moczydłowska 1991, and Jachowicz-Zdanowska 2013). New data might make it possible to distinguish this part of the zone as a distinct subzone.

3. The current biostratigraphic scheme for the lower Cambrian of the Holy Cross Mountains, based on rare and patchily occurring macrofossils with limited stratigraphic value, should be modified. Future studies should focus on defining lowermost Cambrian local acritarch interval subzones, based on the FADs of the successively appearing acritarch genera *Fimbriaglomerella*, *Globosphaeridium*, and *Skiagia*, in other parts of the Palaeozoic inlier of the Holy Cross Mountains.

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PLATES 1–4

PLATE 1

Acritarchs from local assemblage 1, Locality 1, south of Kotuszów, Holy Cross Mountains; transition from Terreneuvian to Cambrian Stage 2

1-4 – *Leiosphaeridia* sp., 1 – 4992 C38_1; 2 – 4992 D36_1; 3 – 4992z E31_4; 4 – 4992z Q31_2
5 – ?*Leiosphaeridia* sp., 4992z T29
6 – *Synsphaeridium* sp., 4992z N30_3
7 – *Liepaina* sp., 4992 Q43_4
8 – *Pulvinosphaeridium* sp., 4992 L22_3
9-10 – *Fimbriaglomerella membranacea* (Kiryanov) Moczydłowska and Vidal, 1988, 9 – 4992 A25; 10 – 4992 K40
11-12 – *Fimbriaglomerella* sp., 11 – 4992z J35_4; 12 – 4992 D29_4
13-14 – *Comasphaeridium* cf. *velvetum* Moczydłowska, 1991, 13 – 4992z O30; 14 – 4992z O30_3
15-16 – *Granomarginata prima* Naumova, 1960, 4992; 15 E38_3; 16 T439_4
17-18 – *Granomarginata squamacea* Volkova, 1968, 17 – 4992z O31_4; 18 – 4992 R38_3
19 – *Comasphaeridium* cf. *agglutinatum* Moczydłowska, 1991, 4992 O29
20 – *Comasphaeridium* cf. *strigosum* (Yankauskas) Downie, 1982, 4992 043_2
21 – *Comasphaeridium sp.;* 4992 S24_1
22 – *Lophosphaeridium tentativum* Volkova, 1968, 4992 Z44
23 – *Asteridium tornatum* (Volkova) Moczydłowska, 1991, 4992 Z44_3
24 – *Pterospermella vitalis* Yankauskas in Volkova *et al*., 1979, 4992 B40_2
25 – ? Cyanobacteria, 4989 E41_3, 4992 Y43_2

Symbols refer to number of slide and location of specimen according to England Finder. Scale bar equals 10 μm

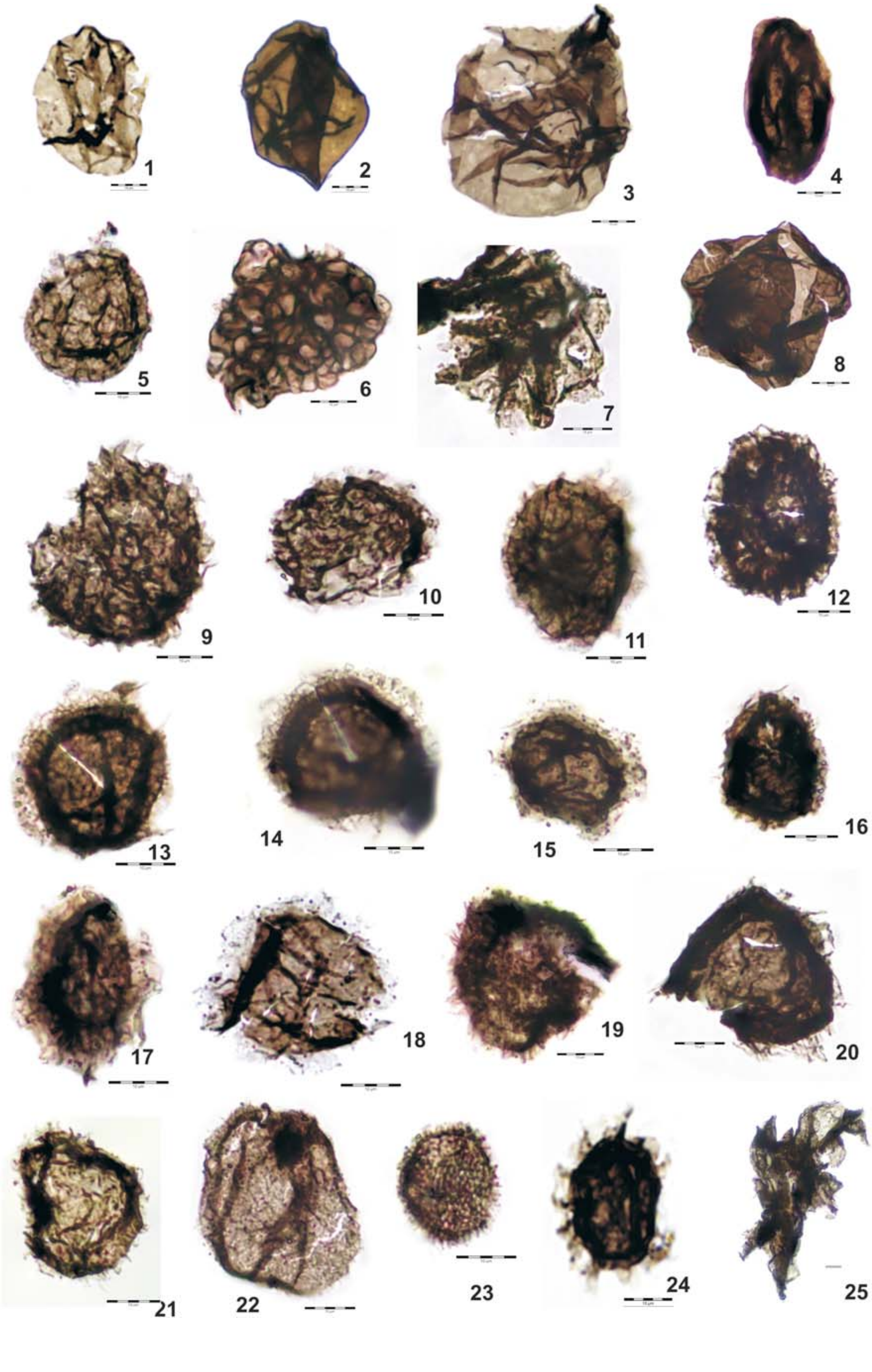
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PLATE 2

Acritarchs from local assemblage 2, Locality 3, east of Kotuszów, Holy Cross Mountains; Cambrian Stage 2

1 – Cyanobacteria, 4989 E41_3
2-3 – *Leiosphaeridia* sp., 2 – 4989 E40_3; 3 – 4989 V49
4 – ?*Leiosphaeridia* sp., 4989 L32_3
5 – *Tasmanites* sp., 4989 M35
6-8 – Gen. indet. 1, 6 – 4989 K39_2; 7 – 4989 E34_3; 8 – 4989 H46_1
9 – *Cymatiosphaera* sp., 4989 L50
10-11 – ?*Comasphaeridium* sp., 10 – 4989 J33; 11 – 4989 J39
12 – *Comasphaeridium mollicum* Moczydłowska and Vidal, 1988, 4989 Q37
13 – *Comasphaeridium strigosum* (Yankauskas) Downie, 1982, 4989 L34_2
14 – *Granomarginata* cf. *prima* Naumova, 1960, 4989 K43
15 – *Granomarginata* cf. *squamacea* Volkova, 1968, 4989 U39_4
16 – *Granomarginata squamacea* Volkova, 1968, 4989 D32
17 – *Fimbriaglomerella* cf. *membranacea* (Kiryanov) Moczydłowska and Vidal, 1988, 4989 D31
18-19 – *Lophosphaeridium tentativum* Volkova, 1968, 18 – 4989 N35; 19 – 4989 X30
20-23 – *Lophosphaeridium truncatum* Volkova, 1969, 20 – 4989 J30; 21 – 4989 H29_4; 22 – 4989 O50; 23 – 4989 H48
24-27 – *Globosphaeridium cerinum* (Volkova) Moczydłowska, 1991, 24 – 4989 U26; 25 – 4989 Z39_2; 26 – 4989 Y46; 27 – 4989 O55
28 – *Alliumella baltica* Vanderflit in Umnova and Vanderflit, 1971, 4989 N38
29 – *Heliosphaeridium* cf. *longum* (Moczydłowska) Moczydłowska, 1991, 4989 Z37
30 – *Asteridium lanatum* (Volkova) Moczydłowska, 1991, 4989 P41

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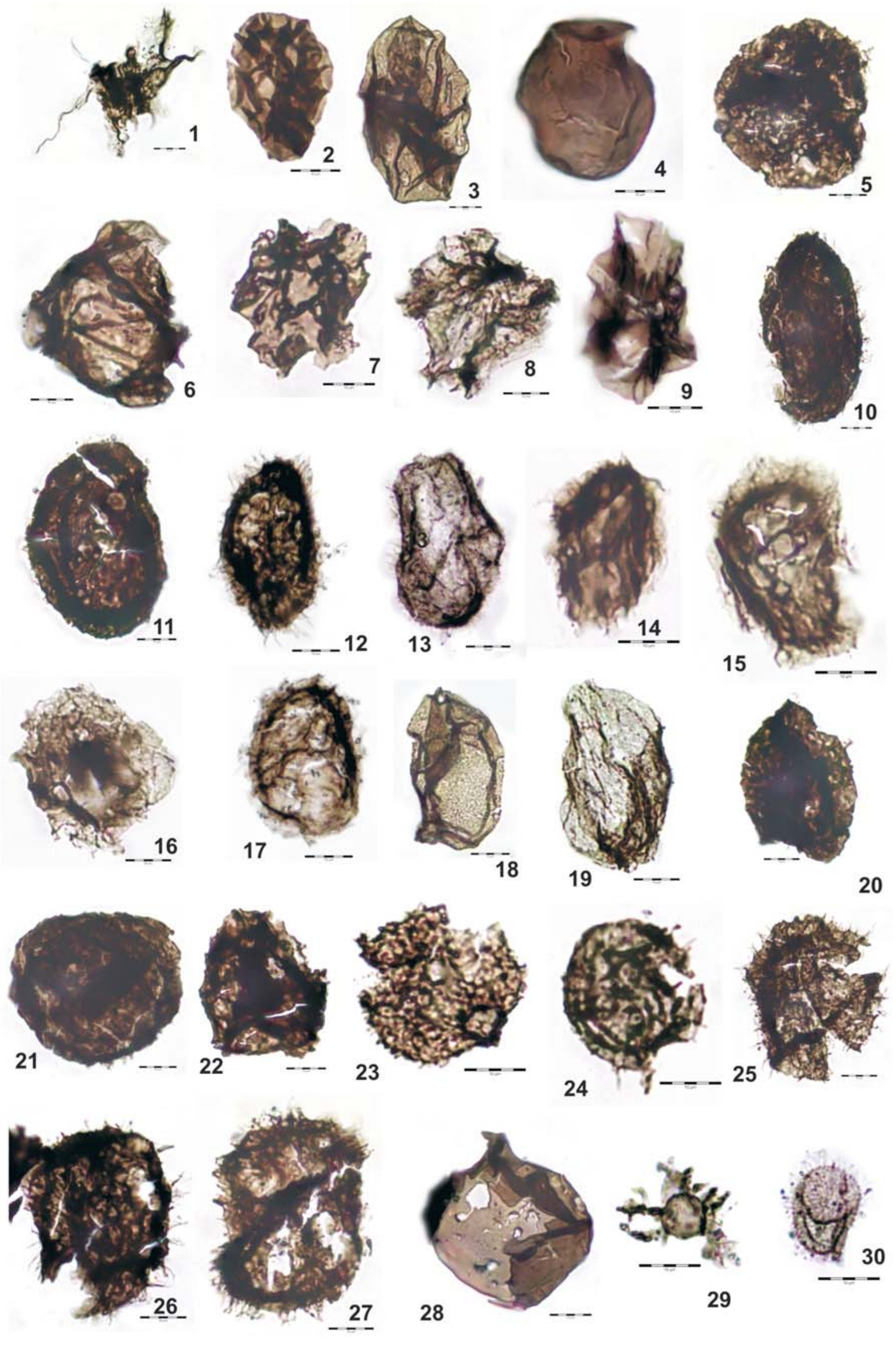
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PLATE 3

Acritarchs from local assemblage 2, Locality 4, north of Kotuszów, Holy Cross Mountains; Cambrian Stage 2

1-2 – *Leiosphaeridia* sp., 1 – 4990n B49_2; 2 – 4990n C45
3-4 – *Synsphaeridium* sp., 3 – 4990n E44_2; 4 – 4990n G39
5 – *Asteridium* sp., 4990n E44_4
6-7 – *Lophosphaeridium tentativum* Volkova, 1968, 6 – 4990n B48; 7 – 4990n U27
8, 10 – *Lophosphaeridium dubium* (Volkova) Moczydłowska, 1991, 8 – 4990n M26_1; 10 – 4990n G36_2
9 – *Lophosphaeridium* cf. *dubium* (Volkova) Moczydłowska, 1991, 4990n W31_3
11-13 – *Lophosphaeridium truncatum* Volkova, 1969, 11 – 4990n M43_2; 12 – 4990n X30_3; 13 – 4990n T44_4
14 – *Comasphaeridium strigosum* (Yankauskas) Downie, 1982, 4990n Z50_2
15 – *Comasphaeridium mollicum* Moczydłowska and Vidal, 1988, 4990n F48
16 – *Comasphaeridium* sp., 4990n L31_3
17 – *Cymatiosphaera* sp., 4990n W50_3
18-20 – *Fimbriaglomerella* cf. *membranacea* (Kiryanov) Moczydłowska and Vidal, 1988, 18 – 4990n W40; 19 – 4990n F37_2; 20 – 4990n Q46
21 – ?*Skiagia* sp., 4990n K40_4
22 – ?*Ichnosphaera* sp., 4990n A51margin
23-24 – *Granomarginata squamacea* Volkova, 1968, 23 – 4990n Q28; 24 – 4990n U37_3
25 – *Granomarginata prima* Naumova, 1960, 4990n T33_4
26 – *Pterospermella* cf. *solida* (Volkova) Volkova in Volkova *et al*., 1979, 4990n S30_4
27-28 – *Pterospermella vitalis* Yankauskas, 1979, 27 – 4990n A30margin; 28 – 4990n S41
29 – *Heliosphaeridium* cf. *longum* (Moczydłowska) Moczydłowska, 1991, 4990n P32_1
30 – ?*Heliosphaeridium* sp., 4990n P39_2

Symbols refer to number of slide and location of specimen according to England Finder. Scale bar equals 10 μm

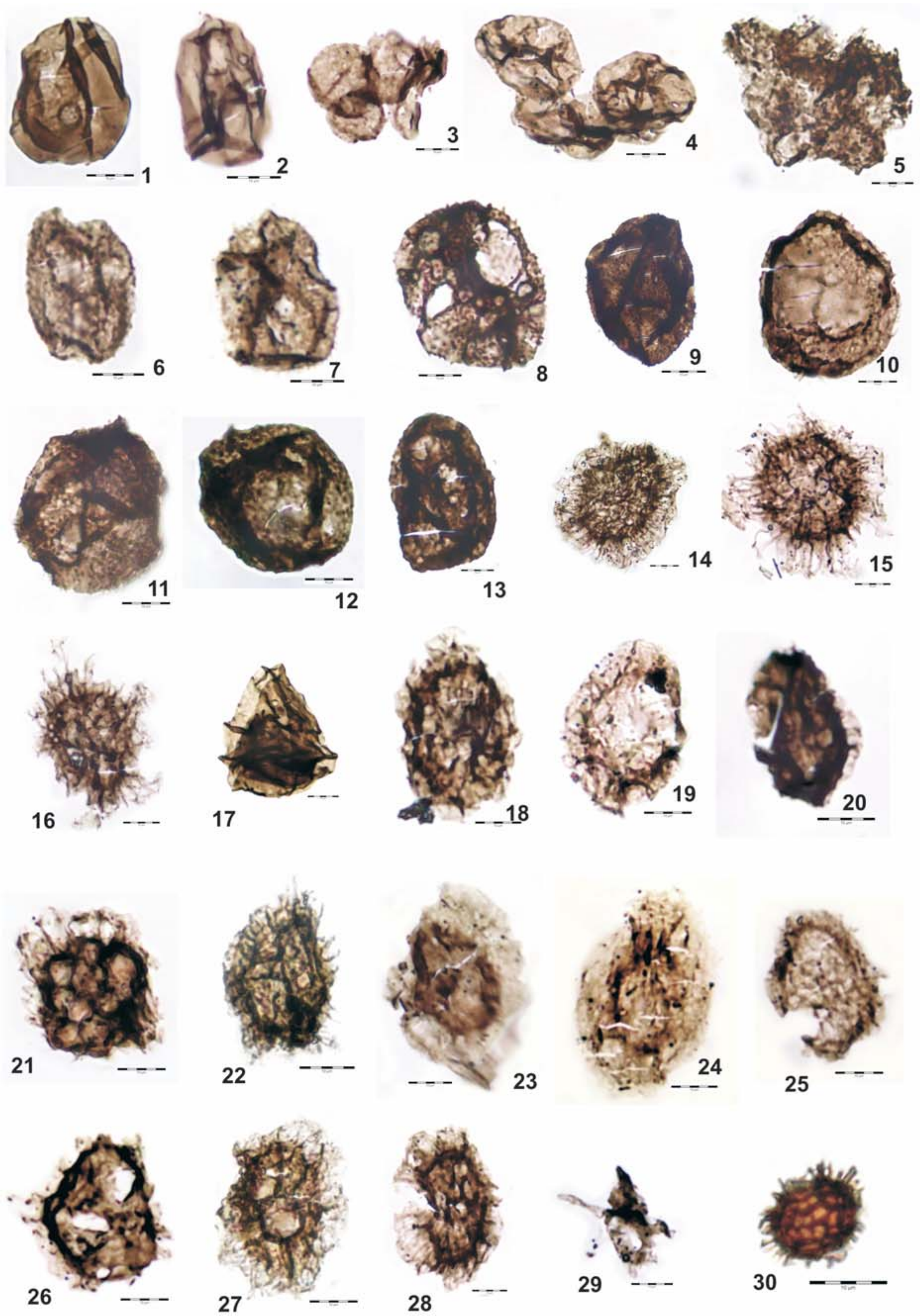
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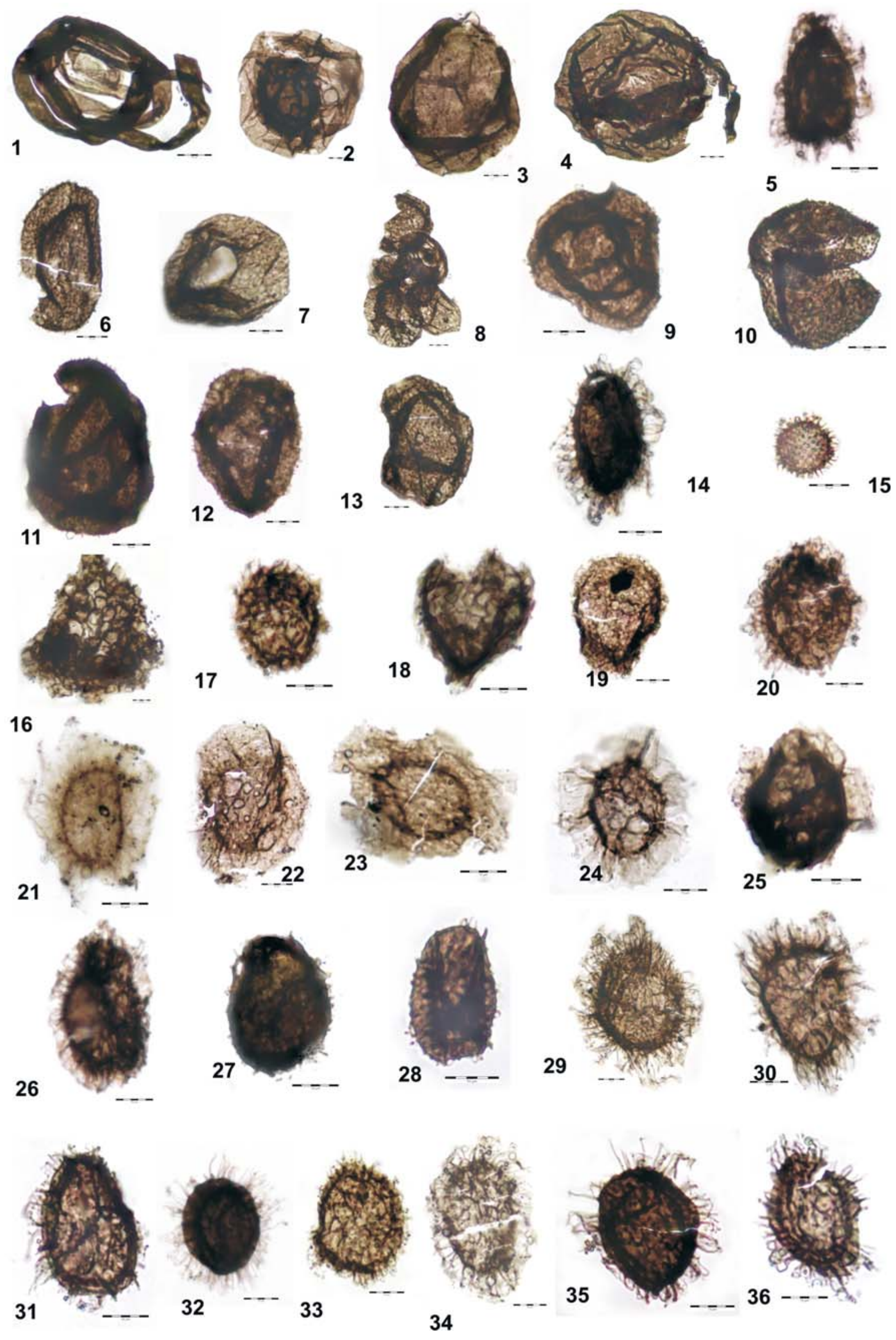
PLATE 4

Acritarchs from local assemblage 3, Locality 5, north-east of Kotuszów, Holy Cross Mountains; Cambrian Stage 2

1 – Cyanobacteria, 7535 H53_4
2 – *Pterospermopsimorpha* sp., 7535B G38_1
3-4 – *Leiosphaeridia* sp., 3 – 7535, D41_3; 4 – 7516 G37_A'
5 – *Fimbriaglomerella* sp., 7516 G37_B
6 – *Comasphaeridium* cf. *velvetum* Moczydłowska, 1991, 7535 K50_3
7 – *Lophosphaeridium tentativum* Volkova, 1968, 7535B J26_2
8 – ?*Lophosphaeridium* sp., 7535 L36_3
9, 11-12 – *Lophosphaeridium* cf. *dubium* (Volkova) Moczydłowska, 1991, 9 – 4990n W31_3; 11 – 7535 R43_2; 12 – 7535 E49_2
10, 13 – *Lophosphaeridium truncatum* Volkova, 1969, 10 – 7516 Q30_3; 13 – 7535B U36
14 – *Comasphaeridium* cf. *strigosum* (Yankauskas) Downie, 1982, 7535B P34
15 – *Asteridium tornatum* (Volkova) Moczydłowska, 1991, 7518 O38_1
16 – *Retisphaeridium* sp., 7535 L39_4
17-20, 26 – *Fimbriaglomerella* cf. *membranacea* (Kiryanov) Moczydłowska and Vidal, 1988, 17 – 7535B M30; 18 – 7535 40_2; 19 – 7535 F38_3; 20 – 7535B F31; 26 – 7535B P40
21-23 – *Granomarginata squamacea* Volkova, 1968, 21 – 7535B Q40; 22 – 7535 H39; 23 – 7535B Q40
24 – *Pterospermella vitalis* Yankauskas in Volkova *et al.,* 1979, 7516 M43_2
25 – *Pterospermella* cf. *vitalis* Yankauskas in Volkova *et al*., 1979, 7535 H45_2
27-28 – *Globosphaeridium* cf. *cerinum* (Volkova) Moczydłowska, 1991, 27 – 7535B H41_2 ; 28 – 7516 Q35_4
29, 34 – *Skiagia ornata* (Volkova) Downie, 1982, 29 – 7535B T39; 34 – 7518Z Q27
30 – *Comasphaeridium strigosum* (Yankauskas) Downie, 1982, 7535B J31
31, 33 – *Skiagia* cf. *orbiculare* (Volkova) Downie, 1982, 31 – 7516 S37; 33 – 7535 H36_2
32 – ?*Ichnosphaera* sp., 7535B Q30
35-36 – *Skiagia* cf. *ornata* (Volkova) Downie, 1982, 35 – 7516 T41_2; 36 – 7516B Q34

Symbols refer to number of slide and location of specimen according to England Finder. Scale bar equals 10 μm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