

Original Article

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Acritarchs from the Duolbagáisá Formation (Cambrian Series 2, Miaolingian) on the Digermulen Peninsula, Finnmark, Arctic Norway: towards a high-resolution Cambrian chronostratigraphy

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Abstract

New information on acritarchs from the Duolbagáisá Formation, Digermulen Peninsula, Arctic Norway, enable recognition of the three Cambrian Series 2 acritarch-based zones: the *Skiagia ornata*–*Fimbriaglomerella membranacea*, *Heliosphaeridium dissimulare*–*Skiagia ciliosa* and *Volkovia dentifera*–*Liepaina plana* Assemblage zones. Acritarchs of the *Skiagia ornata*–*Fimbriaglomerella membranacea* Zone (Cambrian Stage 3) appear near the base of the unit, close to an undetermined trilobite. In the Upper Member of the Duolbagáisá Formation, in levels with *Kjerulfia* n. sp. and *Elliptocephala* n. sp., appears an assemblage with abundant *Skiagia ciliosa*, indicative of the *Heliosphaeridium dissimulare*–*Skiagia ciliosa* Zone. A few metres higher appear *Liepaina plana*, *Heliosphaeridium notatum* and *Retisphaeridium dichamerum*, which indicate the *Volkovia dentifera*–*Liepaina plana* Zone (Cambrian Stage 4). The transition between the Duolbagáisá Formation and the overlying Kistedalen Formation is marked by the appearance of *Comasphaeridium longispinosum*, *Multiplicisphaeridium llynense* and *Eliasum llaniscum*, diagnostic of the Miaolingian Series. This coincides with the disappearance of *Skiagia*; occurrences of *Skiagia* in Miaolingian strata consist of reworked material related to the Hawke Bay regression at the Cambrian Stage 4–Wuliuan transition. The absence of *Skiagia* in higher levels of the Duolbagáisá Formation and Kistedalen Formation suggests that no unconformity formed during the Hawke Bay regression in this area. The chronostratigraphical significance of the *Skiagia ornata*–*Fimbriaglomerella membranacea*, *Heliosphaeridium dissimulare*–*Skiagia ciliosa* and *Volkovia dentifera*–*Liepaina plana* zones is critically analysed. Correlation of the Duolbagáisá Formation with peri-Gondwanan terrains of Avalonia and Iberia is established. The Digermulen Peninsula has great potential as a reference section for establishing a Cambrian chronostratigraphy based on acritarchs.

1. Introduction

The Digermulen Peninsula (Fig. 1) in Arctic Norway includes one of the most complete successions of Cryogenian–Lower Ordovician strata in the world with an important record of diverse organic-walled microfossils (Vidal, 1981; Welsch, 1986; Högström *et al.* 2013; Palacios *et al.* 2015, 2017*b*) well suited for establishing a high-resolution Cambrian chronostratigraphy. Acritarchs represent a polyphyletic group of form-taxa, most of which represent organic-walled cysts. These fossils are essential for Cambrian biochronology as they were generally cosmopolitan in distribution and can often be extracted in great numbers from fine-grained siliciclastic rocks deposited under marine conditions.

Cambrian acritarch zonations were first established in the western part of the East European Platform (western Russia, the Baltic States, Ukraine, Belarus and Poland). The stratigraphical distribution was recognized within ‘horizons’ of the lower Cambrian comprising in stratigraphically ascending order the Rovno, Lontova, Talsy, Vergale and Rausve horizons (Volkova *et al.* 1983). A comparable formal zonation based on studies of numerous drillcores was established in southeastern Poland (Moczyłowska, 1991), comprising in stratigraphically ascending order the

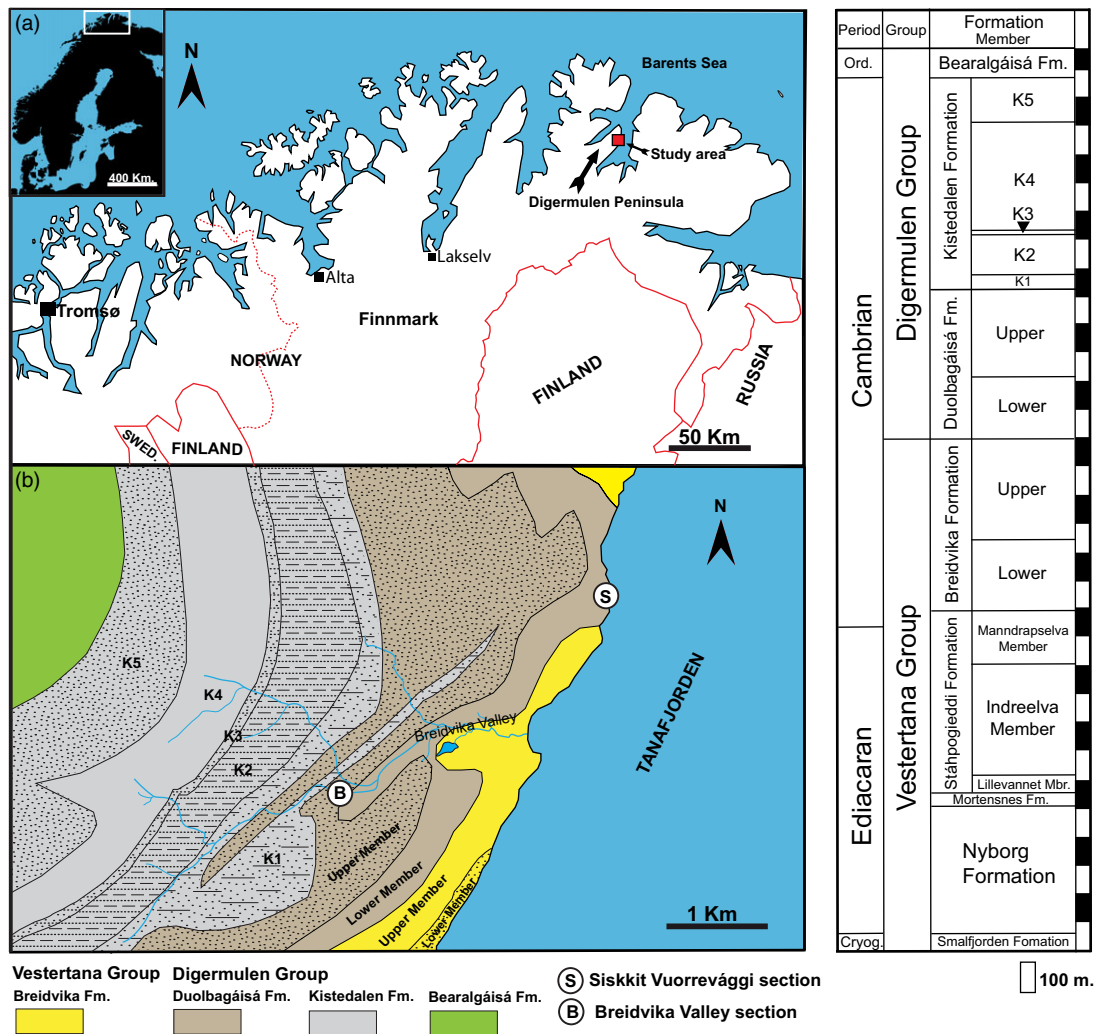


Fig. 1. (Colour online) Location and geological setting of study area on the Digermulen Peninsula, Arctic Norway. (a) Geographical location of the Digermulen Peninsula. (b) Geology of the Breidvika Valley area with location of the Duolbagáisá Formation sections of this study. See the column for key to the geological units.

Asteridium tornatum–*Comasphaeridium velvetum*, *Skiagia ornata*–*Fimbriaglomerella membranacea*, *Heliosphaeridium dissimulare*–*Skiagia ciliosa* and *Volkovia dentifera*–*Liepaina plana* Assemblage zones (in the following given in abbreviated form). The *Asteridium*–*Comasphaeridium* Zone and the Rovno and Lontova horizons have been correlated with the Terreneuvian Series, with an approximate duration of 20 Ma (Cohen *et al.* 2013). The Rovno horizon is approximately equivalent to the Fortunian Stage, and is characterized by morphologically simple acritarchs (leiosphaerids) and filamentous sheaths. The Lontova Horizon, equivalent to the *Asteridium*–*Comasphaeridium* Zone, corresponds to the Fortunian and Stage 2 in part. However, the correlation of these zones outside their original source areas is sometimes problematic. On the Digermulen Peninsula, as well as in sections on Newfoundland and in New Brunswick, Canada, the name-bearing taxa of the *Asteridium*–*Comasphaeridium* Zone are absent from basal Fortunian strata, which instead are characterized by acritarchs lacking processes (*Leiosphaeridia* spp., *Granomarginata squamacea* and *G. prima*) (Palacios *et al.* 2011, 2017b, 2018; Högström *et al.* 2013). The first assemblages in well-exposed successions with a good record of organic-walled microfossils, including those diagnostic of the *Asteridium*–*Comasphaeridium* Zone, have been located in New Brunswick at levels dated to 531 Ma (Palacios *et al.* 2011) and

on Newfoundland at levels above the *Watsonella crosbyi* Zone (Palacios *et al.* 2018). Following Palacios *et al.* (2018) and herein we therefore identify the *Asteridium*–*Comasphaeridium* Zone only when the index taxa are present. Low-diversity Fortunian assemblages dominated by *Granomarginata*, which were previously included in this zone (i.e. Moczyłowska, 1991), are instead included in an assemblage that encompass the *Granomarginata* Zone (Palacios *et al.* 2018) and a lower assemblage dominated by leiosphaerids. The succeeding acritarch zones, the *Skiagia*–*Fimbriaglomerella*, *Heliosphaeridium*–*Skiagia* and *Volkovia*–*Liepaina* zones, allow a more detailed division of the Cambrian Series 2 (approximate duration of 12 Ma; Cohen *et al.* 2013) compared to that of the Terreneuvian (approximate duration of 20 Ma; Cohen *et al.* 2013). On Baltica the base of the *Skiagia*–*Fimbriaglomerella* Zone approximates the position of the earliest trilobites of the *Schmidtellus* Zone (Moczyłowska, 1991). More broadly, *Skiagia* has been suggested to have a global first appearance close to the appearance of trilobites and to the base of the yet-undefined Cambrian Series 2 (Moczyłowska & Zang, 2006). The appearance of *Skiagia* coincides with a substantial increase in the diversity of phytoplankton that signals the onset of the Cambrian phytoplankton radiation (e.g. Vidal & Moczyłowska-Vidal, 1997; Moczyłowska, 2011; Palacios *et al.* 2018).

In the present paper, the first data on acritarchs from the Duolbagáisá Formation on the Digermulen Peninsula is presented, establishing for the first time an acritarch-based chronostratigraphic framework for this part of Baltica. A critical analysis of current acritarch zonations and their potential for chronostratigraphy of the Cambrian Series 2 is made.

2. Geological setting

The Digermulen Peninsula, Arctic Norway (Fig. 1a), includes a thick parautochthonous succession of Cryogenian–Lower Ordovician strata (Føyn, 1937; Banks *et al.* 1971) divided into the Cryogenian–Terreneuvian Vestertana Group and the Cambrian Series 2 – Lower Ordovician Digermulen Group (Reading, 1965) (Fig. 1b). The basal formations of the Vestertana Group include, in ascending order, the Cryogenian glaciogenic diamictites of the Smalfjorden Formation, the Nyborg Formation and the Ediacaran diamictite of the Mortensnes Formation correlated with the Gaskiers glaciation of Newfoundland (Rice *et al.* 2011; *c.* 580 Ma, Pu *et al.* 2016). The Nyborg and Mortensnes formations contain organic-walled microfossil assemblages of low diversity (Vidal, 1981), with the Nyborg Formation notable for an organically preserved multicellular eukaryote (Agić *et al.* 2019). The presence of Doushantou–Pertataka-type acritarchs in the Nyborg Formation points to an Ediacaran age and corroborates other lines of evidence for a Gaskiers-equivalent age for the Mortensnes glacial deposits (Agić *et al.* 2018). The succeeding Ståhpogieddi Formation comprises lower quartzitic sandstones (Lillevannet Member), blue-green and red-violet mudrock (Indreelva Member) and the Manndrapselva Member (Banks *et al.* 1971), the latter with a basal quartzitic sandstone followed by two coarsening-upward successions of greywacke sandstone and mudstone and sandstone. The Ediacaran–Cambrian transition is recognized within the Manndrapselva Member on the basis of ichnofossils (i.e. *Treptichnus pedum*) and organic-walled microfossils (Högström *et al.* 2013; Palacios *et al.* 2017b; Jensen *et al.* 2018). The lower part of the Breidvika Formation, the uppermost unit of the Vestertana Group, yields *Platysolenites antiquissimus* and *Rusophycus* sp., and acritarchs diagnostic of the *Asteridium–Comasphaeridium* Zone (Vidal, 1981; Högström *et al.* 2013; Palacios *et al.* 2017b). Banks (1970) reported *Platysolenites antiquissimus* from the lower part of the formation, but McIlroy *et al.* (2001) documented specimens only from the upper part. The Digermulen Group is made up of three formations. At the base, the Duolbagáisá Formation (Reading, 1965; Banks *et al.* 1971) includes two members. The Lower Member is well exposed along the coast to the northeast of Breidvika Valley, in the Siskkit Vuorrevággi section (Fig. 1b), where it consists of 256 m of siltstone, mudstone and quartzitic sandstone (Fig. 2). This member contains abundant trace fossils (Banks, 1970; McIlroy & Brasier, 2017), an unidentified trilobite (Ebbestad *et al.* 2018) and, near the base of the member, the enigmatic agglutinated tube-shaped fossil *Volborthella tenuis* (Crimes & McIlroy, 1999; McIlroy & Brasier, 2017), which is taken to mark a point at around the base of the Cambrian Series 2 (McIlroy & Brasier, 2017). The Upper Member of the Duolbagáisá Formation is well exposed in the Breidvika Valley (Figs 1, 3). Here it consists of 382 m of quartzitic sandstone with minor intercalations of fine-grained sandstone, siltstone and mudstone that have their maximum thickness in the middle part, where trilobites occur, including *Kjerulfia* n. sp., *Elliptocephala* n. sp. and rare ellipsocephalids (Nikolaisen & Henningsmoen, 1990; Ebbestad *et al.* 2017, 2018). The overlying Kistedalen Formation contains trilobites and acritarchs of Miaolingian–Furongian age (Nikolaisen & Henningsmoen, 1985,

1990; Welsch, 1986; Palacios *et al.* 2015). The boundary between the Duolbagáisá and Kistedalen formations has been suggested to approximate the Cambrian Series 2–Miaolingian boundary (Nielsen & Schovsbo 2015; but see below). Nielsen & Schovsbo (2015) considered the possibility that the upper sandstone-dominated part of the Duolbagáisá Formation represents low-stand deposits related to the Hawke Bay regression, which is concurred herein. The Kistedalen Formation is divided into five members, K1–K5. The lower member, consisting of sandstone with interbedded mudstone and siltstone (K1), yields Miaolingian trilobites near the base (*Eccaparadoxides* cf. *pusillus*, *Ellipsocephalus* cf. *hoffi*, *Hydrocephalus* cf. *carens*), of uncertain zonal assignment, but Nikolaisen & Henningsmoen, (1990, p. 77) suggested the *Eccaparadoxides insularis* Zone. The K2 member consists of mudstone intercalated with dark grey to black sandstone at the top, and yields abundant acritarchs (Welsch, 1986; Palacios *et al.* 2015). The K3 ‘black quartzite member’ and the K4 (black shale) member yield Furongian acritarchs (Welsch, 1986). The formation culminates with a massive sandstone (K5). The Digermulen Group terminates with the Bearalgáisá Formation, consisting mainly of shale and sandstone in the lower part and sandstone and minor shale in the upper part, and yields Tremadocian trilobites and acritarchs (Nikolaisen & Henningsmoen, 1985; Welsch, 1986).

3. Material and methods

This study is based on shale and siltstone samples from the Duolbagáisá Formation collected by the authors between 2011 and 2017. A total of 55 samples (Figs 2, 3) have been processed, mainly of shales with colours ranging from green and light grey to olive green and dark grey. Stratigraphic levels and quantitative distribution of the identified acritarch species in positive samples are shown in Figures 2 and 3. Samples of *c.* 50 g were treated with standard palynological methods, mounted on glass slides with Petropoxy 154 resin and studied under transmitted light with a Zeiss Axio Imager M1 microscope with a computerized AxioCam HRC microscope camera. The positive samples contain relatively well-preserved (brown to dark brown, TAI 3–4 *sensu* Hayes *et al.* 1983) acritarchs. Studied and illustrated material (Figs 4–7, 9, 10) is stored with the palaeontological collection of the Arctic University Museum of Norway, prefix TSGf, with the exception of comparable material from the Hanford Brook Formation, New Brunswick, Brigus Formation, Newfoundland and Láncara and Vallehondo formations, Spain (Fig. 8), which is deposited in the collections of Área de Paleontología of the Universidad de Extremadura, Badajoz. Museum numbers are referred to in the figure captions, which also provide sample numbers and England finder coordinates.

4. Acritarch assemblages from the Duolbagáisá Formation

The distribution of fossiliferous samples through the Duolbagáisá Formation has allowed recognition of the three Cambrian Series 2 acritarch assemblage zones: the *Skiagia–Fimbriaglomerella* Zone (Stage 3), *Heliosphaeridium–Skiagia* Zone (Stages 3–4) and *Volkovia–Liepaina* Zone (Stage 4). *Comasphaeridium longispinosum*, *Eliasum llaniscum* and *Multiplicisphaeridium llynense* at the transition between the Duolbagáisá and Kistedalen formations indicate the beginning of the Wulian Stage. In the following section, we present a critical analysis of these assemblages and their chronostratigraphic implications.

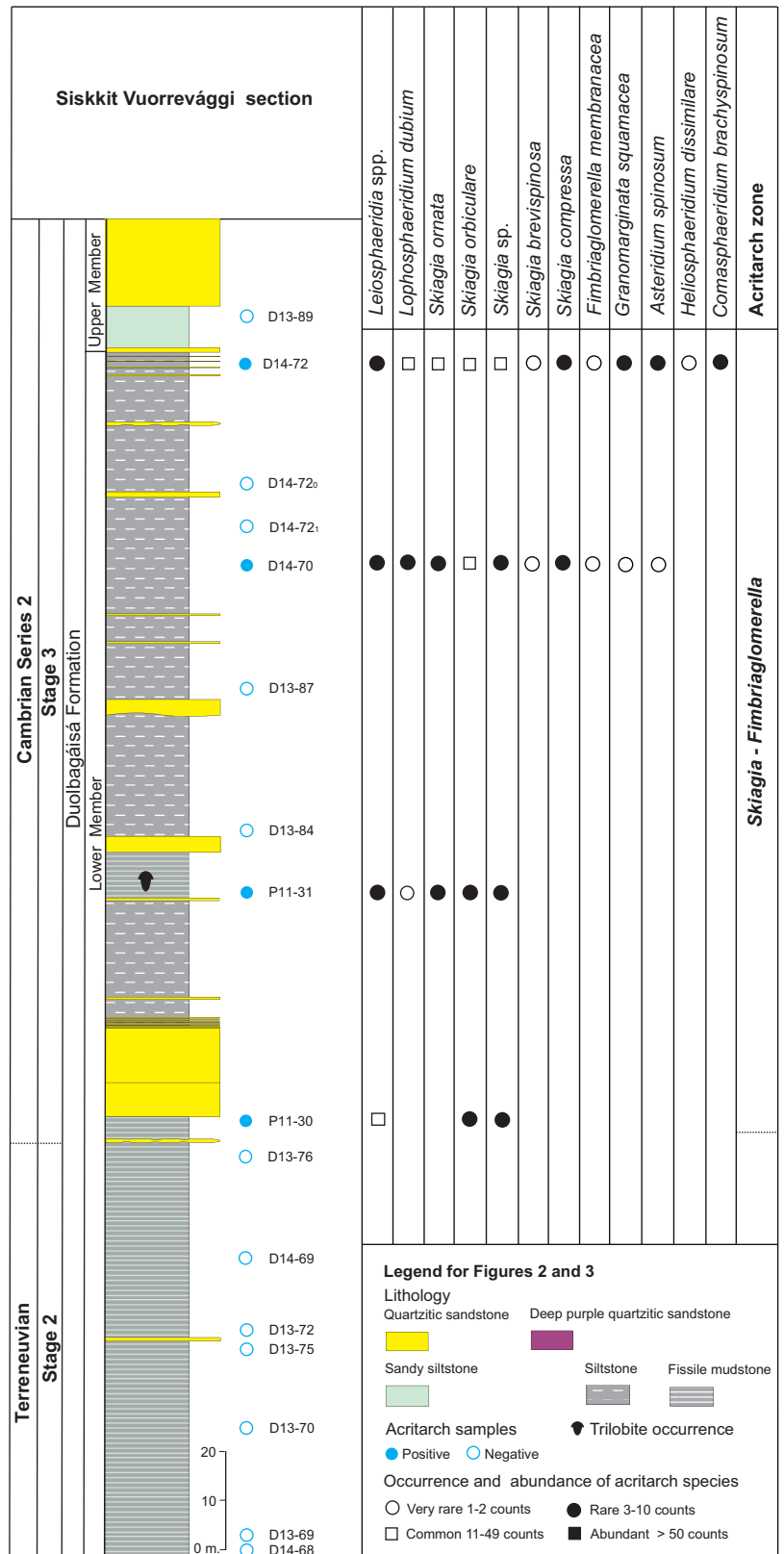


Fig. 2. (Colour online) Lithostratigraphic column of Siskkit Vuorrevággi coastal section north of Breidvíka Valley (Lower Member of the Duolbagáissá Formation) showing location of samples and their sample number, occurrence and abundance of acritarch species in each slide.

4.a. Skiagia ornata–Fimbrianglomerella membranacea Zone

The first diagnostic acritarchs, *Skiagia orbiculare* (Fig. 4a) and *Skiagia* sp., occur in the lower part of the Lower Member of the Duolbagáissá Formation (Fig. 2). Acritarchs in the middle-upper part of the Lower

Member are more diverse and abundant, including *Skiagia ornata* (Fig. 4d, e), *S. orbiculare* (Fig. 4b), *S. compressa* (Fig. 4f, g), *S. brevispinosa* (Fig. 4c), *Fimbrianglomerella membranacea* (Fig. 5a), *Comasphaeridium brachyspinosum* (Fig. 5b) and *Lophosphaeridium*

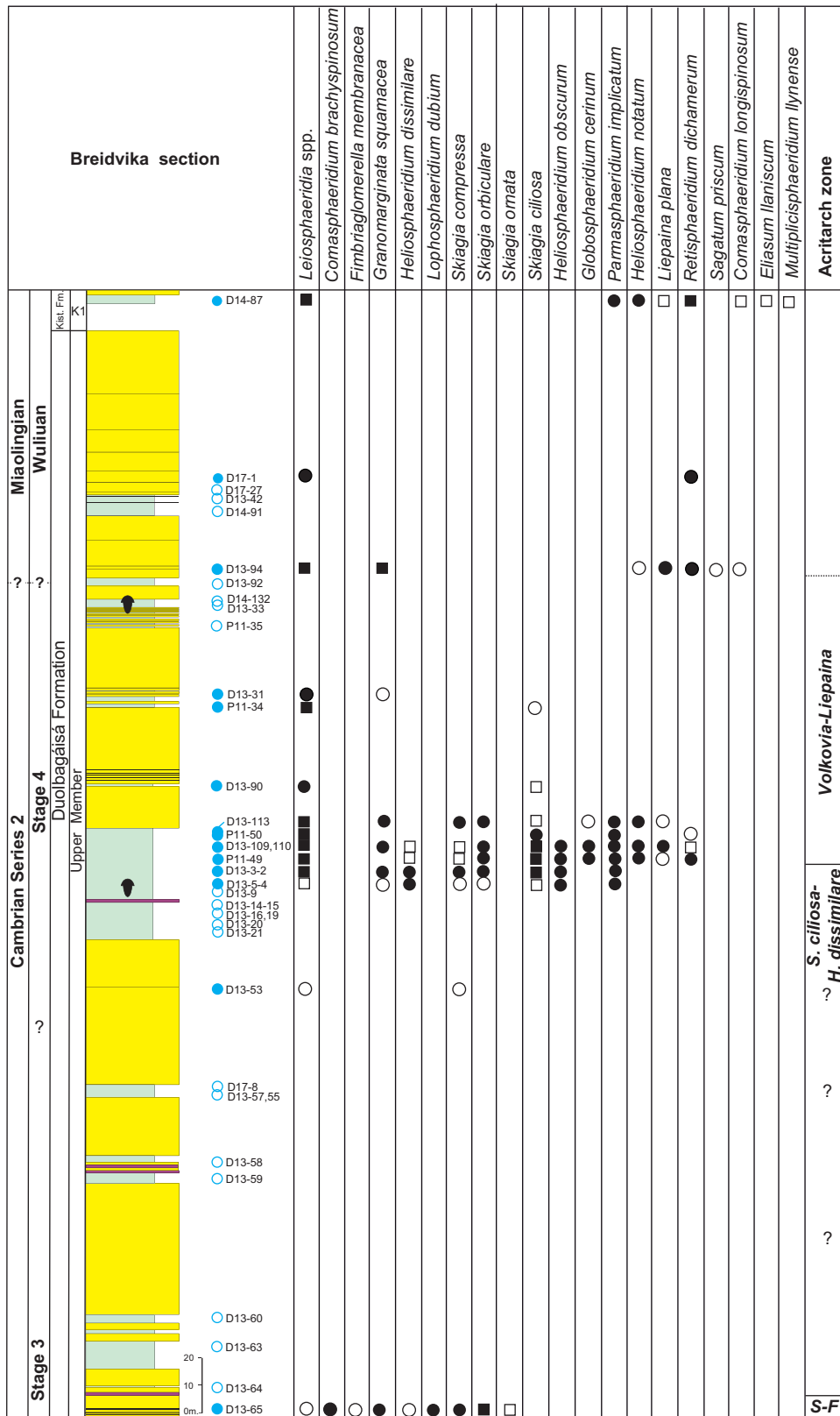


Fig. 3. (Colour online) Lithostratigraphic column of the Breidvika Valley section (Upper Member of the Duolbagáisá Formation) showing location of samples and their sample number, occurrence and abundance of acritarch species. See Figure 2 for legend.

dubium (Fig. 5c, d). Additionally, there are very scarce Heliosphaeridium dissimilare (Fig. 6e, f) in levels transitional between the Lower and Upper members (Fig. 2).

All identified acritarch species have their first appearances in the Skiagia-Fimbrigliomerella Zone (Moczyłowska, 1991, fig. 5)

except for H. dissimilare, which together with S. ciliosa defines the Heliosphaeridium-Skiagia Zone (Moczyłowska, 1991). However, H. dissimilare is a species with poor diagnostic characters and it has been reported both from the Terreneuvian (lower Cordubian) in Iberia (Central Iberian Zone; Díez Balda & Fournier Vinas, 1981;

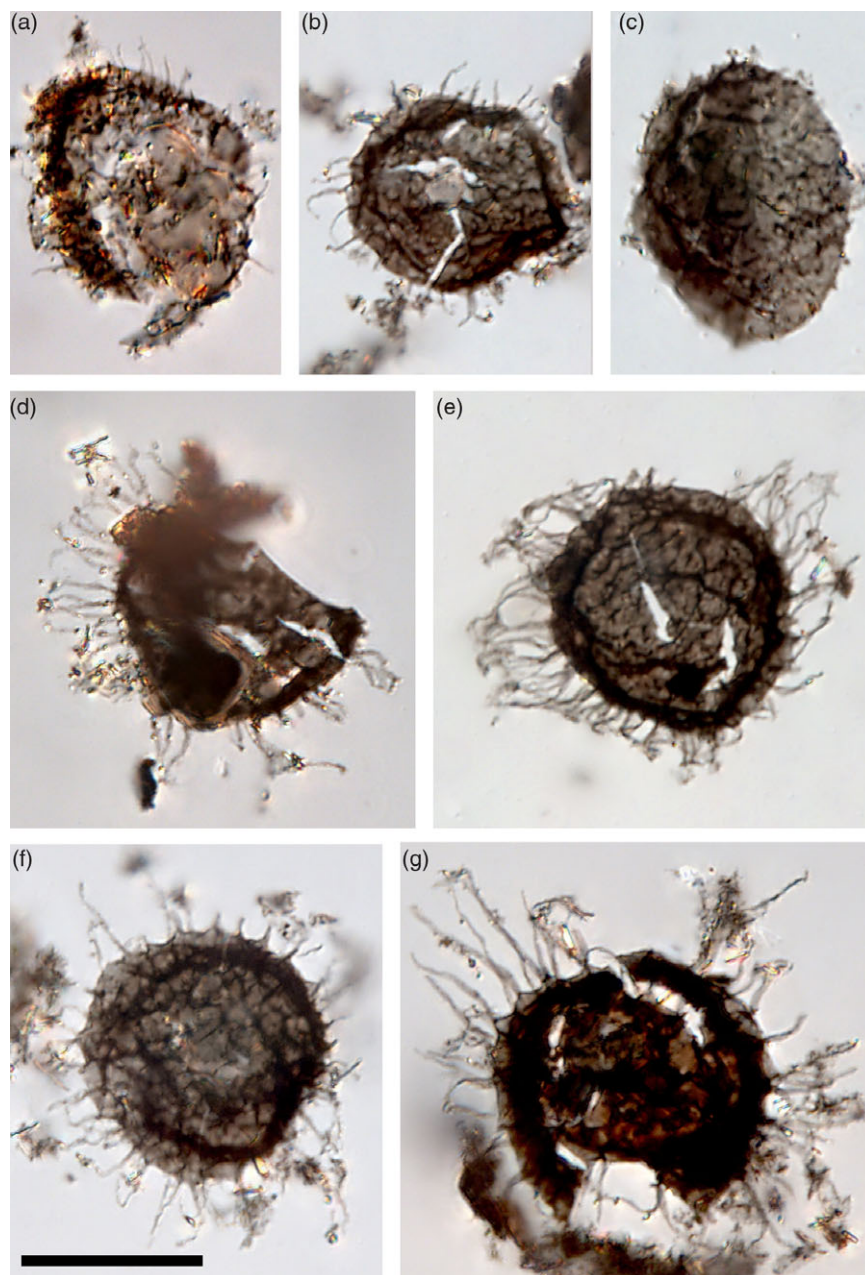


Fig. 4. (Colour online) Acritarchs from the Duolbagáisá Formation (Lower Member), Siskkit Vuorrevággi section. Given in this and the following figures are the sample number, museum number and England finder coordinates. Scale bar = 20 μm . (a, b) *Skiagia orbiculare* (Volkova) Downie: (a) P11-30, TSGf 18435, Q-33; (b) D14-72, TSGf 18438a, T-26-2. (c) *Skiagia brevispinosa* Downie, D14-70, TSGf 18437a O-29. (d, e) *Skiagia ornata* (Volkova) Downie: (d) P11-31, TSGf 18436, K-33-3; (e) D14-72, TSGf 18438b, M-44-4. (f, g) *Skiagia compressa* (Volkova) Downie: (f) D14-72, TSGf 18438c, E-26-1-3; (g) D14-72, TSGf 18438d, C-38-3.

Vidal *et al.* 1994) and Series 2 (Ovetian) in the *Skiagia–Fimbriaglomerella* Zone (Palacios & Vidal, 1992) in the Cambrian Zone, much lower than the first appearance of *S. ciliosa* and the first trilobite record (Fig. 11). In Tarim and South China, the *Asteridium–Heliosphaeridium–Comasphaeridium* acritarch assemblage has a comparable stratigraphic position to the *Asteridium–Comasphaeridium* Zone (Ahn & Zhu, 2017). This indicates that regionally *H. dissimulare* occurs much earlier than *S. ciliosa*, and that the latter is the more diagnostic zonal fossil. Although a few *Heliosphaeridium* species were present already in the Cambrian Age 2, significant diversification of the genus occurred later, around the Cambrian Age 3.

The *Skiagia–Fimbriaglomerella* Zone represents globally the greatest increase in diversity of Cambrian acritarchs (Vidal & Moczyłowska-Vidal, 1997) and the beginning of the Palaeozoic phytoplankton radiation (Palacios *et al.* 2018) close to the first appearance of trilobites. This event, well documented in the fossil

record, has been proposed to define the base of the Cambrian Series 2 (Moczyłowska & Zang, 2006) and has been used as such by several authors (Moczyłowska, 2011; Rushton & Molyneux, 2011; Palacios *et al.* 2011, 2018). Landing *et al.* (2013, fig. 4) and Zhang *et al.* (2017, fig. 3) considered this zone diachronic, with an appearance in Avalonia that pre-dates trilobites (Stage 2). This argument was based on a reinterpretation of the data on organic-walled microfossils that Palacios *et al.* (2011) presented from sections in New Brunswick. Landing *et al.* (2013) assigned the 530 Ma ash layer from the Somerset Street section to the *Skiagia–Fimbriaglomerella* Zone in the Hanford Brook section, where it is associated with a shelly fauna that Landing and colleagues attributed to the sub-trilobitic *Watsonella crosbyi* Zone. However, Palacios *et al.* (2011, fig. 7), based on the succession of acritarchs in these two sections, advocated a different correlation between these two sections, in which the 530 Ma ash pre-dates the *Skiagia–Fimbriaglomerella* Zone acritarchs. The same succession

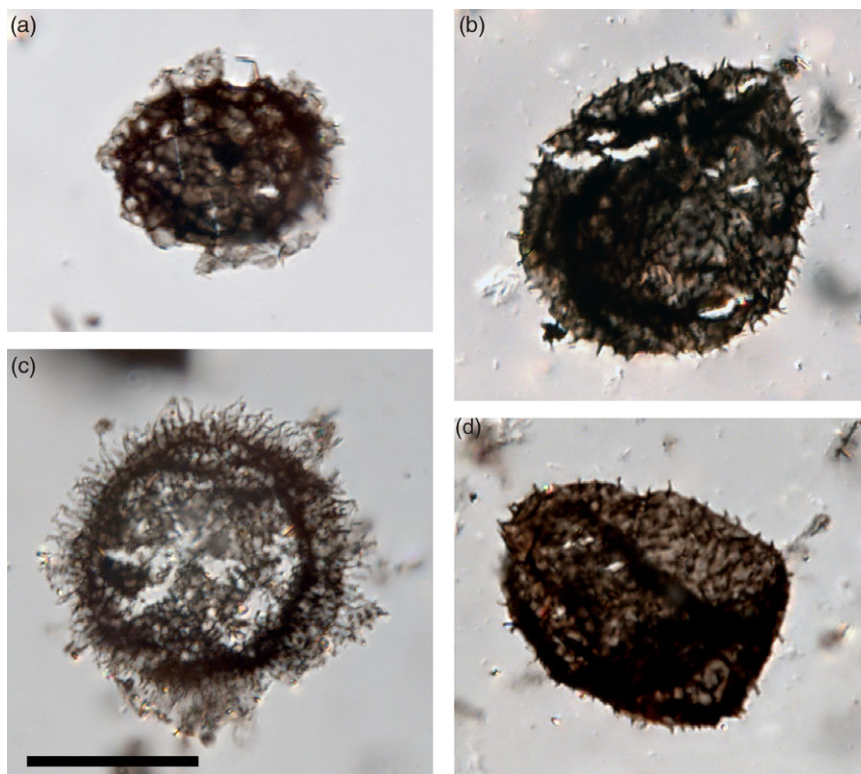


Fig. 5. (Colour online) Acritarchs from the Duolbagáisá Formation. Scale bar = 20 μm . (a, b) Lower Member, Siskkit Vuorrevággi section. (c, d) Upper Member, Breidvika Valley section. (a) *Fimbriaglomerella membranacea* (Kirjanov) Moczyłowska & Vidal, D14-72, TSGf 18438e, L-18-2. (b) *Comasphaeridium brachyspinosum* (Kirjanov) Moczyłowska & Vidal, D14-70, TSGf 18437b, W-17-1. (c, d) *Lophosphaeridium dubium* (Volkova) Moczyłowska: (c) D13-65, TSGf 18439a, D-17; (d) D13-65, TSGf 18439b, R-14-1-3.

of acritarch assemblages that was recognized in New Brunswick (*Asteridium–Comasphaeridium*; *Skiagia–Fimbriaglomerella*) is recognized also in Newfoundland (Palacios *et al.* 2018), where the sub-trilobitic *Watsonella crosbyi* Zone pre-dates both the *Asteridium–Comasphaeridium* (*sensu* Palacios *et al.* 2018) and *Skiagia–Fimbriaglomerella* zones.

Acritarch data from the Terreneuvian–Cambrian Series 2 on the Digermulen Peninsula show a similar succession, with acritarchs of the *Asteridium–Comasphaeridium* Zone in the Lower Breidvika Member (Fig. 11) (Högström *et al.* 2013). The absence of acritarch data from the Upper Breidvika Member and lowermost part of the Duolbagáisá Formation does not exclude a lower range of the *Skiagia–Fimbriaglomerella* Zone.

In Iberia (Fig. 11), acritarchs diagnostic of the *Skiagia–Fimbriaglomerella* Zone appear in the Herrería Formation with Ovetian (Cambrian Series 2) trilobites (Jensen *et al.* 2010; Liñán *et al.* 2015). In central Iberia (Central Iberian Zone), the first trilobites are located in the upper part of the Pusa Formation, overlying levels that contain a *Scenella*-like mollusc and acritarchs of the *Asteridium–Comasphaeridium* Zone (Fig. 11). There are no data indicating that the appearance of *Skiagia–Fimbriaglomerella* Zone acritarchs occurs much earlier than the first appearance of trilobites. On the other hand, if it is accepted that the first appearance of trilobites is diachronic and strongly facies dependent (Zhang *et al.* 2017), it is inconsistent to use them as calibration of the *Skiagia–Fimbriaglomerella* Zone; we need an independent means of calibration in successions with good stratigraphic control. A clear example of this situation is given in Spain (Central Iberian Zone) where controversy arose from finding trilobites and archaeocyathids in the Pusa Formation (Jensen *et al.* 2010) at levels that had been classically attributed to the lower Cordubian correlated with the Fortunian (Liñán *et al.* 2002).

The first appearances of trilobites and *Skiagia* assemblages may not coincide (Zhang *et al.* 2017); however the latter, being cosmopolitan and less facies dependent, is more likely to represent an isochronous event, which we consider a solid candidate to define the base of the Cambrian Series 2 (*cf.* Moczyłowska & Zang, 2006).

4.b. *Heliosphaeridium dissimilare–Skiagia ciliosa* Zone

The middle part of the Upper Member of the Duolbagáisá Formation includes a thick mudstone/siltstone interval with a good record of acritarchs in its upper half (Fig. 3). The first levels include the first appearance of very abundant *Skiagia ciliosa* (Fig. 7a–f), while rare *Globosphaeridium cerinum* (Fig. 6a, b), *Parmasphaeridium implicatum* (Fig. 6c, d) and *Heliosphaeridium obscurum* (Fig. 6g, h) appear close to levels with the olenelloid trilobites *Kjerulfia* n. sp. and *Elliptocephalus* n. sp. (Ebbestad *et al.* 2017, 2018).

Moczyłowska (1991) defined the *H. dissimilare–S. ciliosa* Zone by the First Appearance Datum (FAD) of both species. However, given the occurrence of *H. dissimilare* at much lower stratigraphic levels than the first appearance of *S. ciliosa* (discussed earlier) we consider *Skiagia ciliosa* to be the more diagnostic form. Other cosmopolitan and highly diagnostic species such as *Parmasphaeridium implicatum* (Fridrichsone) Jachowicz-Zdanowska, 2013 (Fig. 6c, d) and *Globosphaeridium cerinum* have their first appearances in this zone (Moczyłowska, 1991).

Skiagia ciliosa shows diagnostic morphological features that allow easy identification, although it also has the highest morphological variability among species of *Skiagia*. The original diagnosis of *Baltisphaeridium ciliosum* given by Volkova (1969, p. 260) included ‘central body is dark, compact, translucent’, morphological features also listed by Downie (1982, table 1). Later revisions by

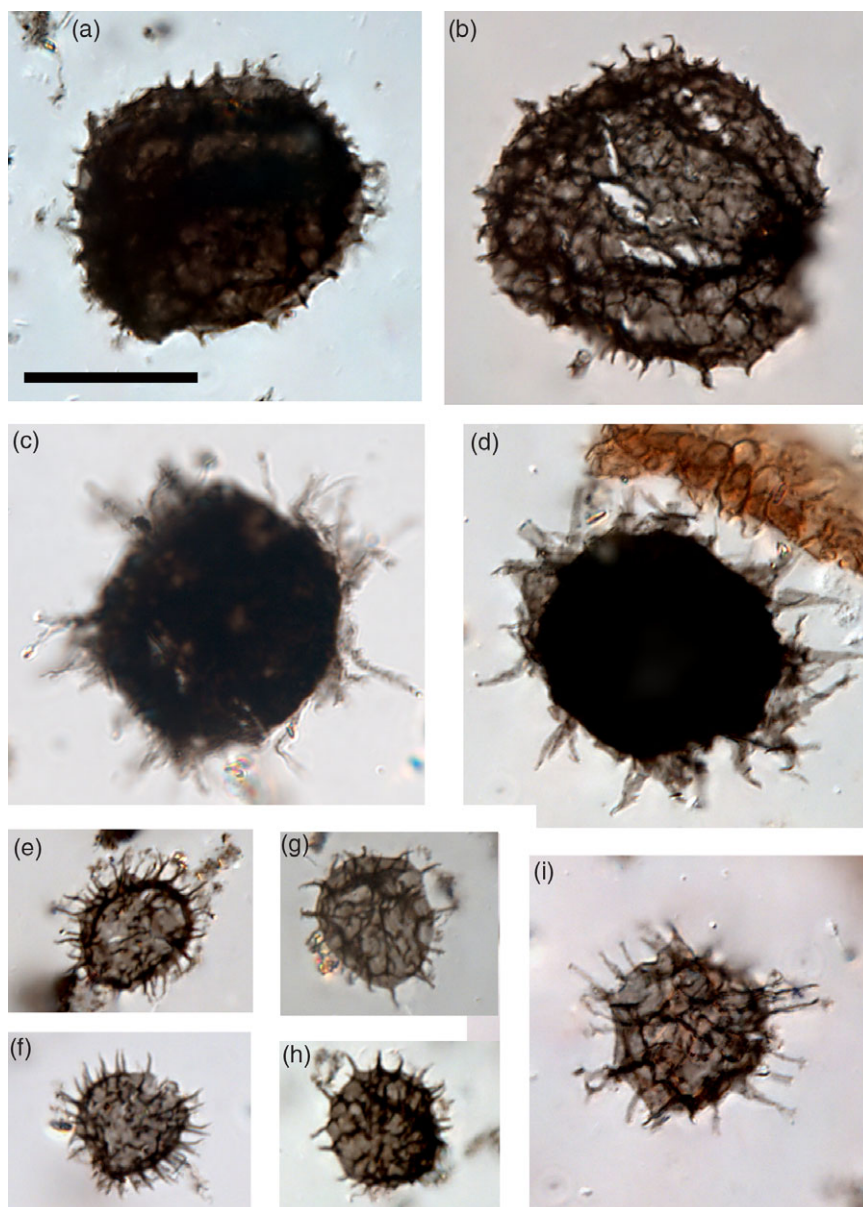


Fig. 6. (Colour online) Acritarchs from the Duolbagáisa Formation (Upper Member), Breidvika Valley section. Scale bar = 20 μm . (a, b) *Globosphaeridium cerinum* (Volkova) Moczyłowska: (a) D13-110, TSGf 18441a, C-38-4; (b) D13-109, TSGf 18440a, E-25-1. (c, d) *Parmasphaeridium implicatum* (Fridrichsone) Jachowicz-Zdanowska: (c) P11-49, TSGf 18443a, B-18-1-2; (d) D13-113, TSGf 18444a, R-40-4. (e, f) *Heliosphaeridium dissimulare* (Volkova) Moczyłowska: (e) D13-110, TSGf 18442a, E-45; (f) P11-49, TSGf 18443b, Q-22-2. (g, h) *Heliosphaeridium obscurum* (Volkova) Moczyłowska: (g) D13-110, TSGf 18442b, A-19-2; (h) D13-110, TSGf 18441b, A-26-2. (i) *Heliosphaeridium notatum* (Volkova) Moczyłowska, D13-113, TSGf 18444b, C-17-1.

Moczyłowska (1991, p. 66, plate 7a, b, d, f) included new characters: 'bases of the processes are conical' and 'separated from the central body cavity by a plug'. In well-preserved material from New Brunswick (Palacios *et al.* 2017a, figs 5a–c, 8a–d) and in specimens studied here (Fig. 7a–f), the conical base of the process (Fig. 7a–d) is seen to have a thick and resistant wall, whereas the tubular part of the process (Figs 7a, b, 8a–c), separated by the plug, is thinner and more delicate. The transition to the plug is an area of weakness where the process regularly breaks (Figs 7b, 8c, e, f). This variability in preservation is a result of the development of the dark internal body and the thickening of the wall, which favours a preservation of the vesicle with the conical bases and the loss of the tubular part of the delicate processes (Fig. 8c, e, f). The tubular part of the processes exhibits a certain variability (Moczyłowska, 1991) and does not constitute the most diagnostic character of *S. ciliosa*. The *Skiagia*-plexus concept of Moczyłowska (2010) has introduced a certain confusion (Zhang *et al.* 2017, p. 135) into the identification of morphospecies of *Skiagia*, especially in *S. ciliosa*, by extending a very specific

morphological feature of this species (the dark internal body: a suggested endocyst) to all species of the plexus as part of a life cycle of the cyst. The presence of a dark internal body in *Skiagia* has been clearly identified in species that appear in the *Heliosphaeridium*–*Skiagia* Zone. Species that have their FAD in the *Skiagia*–*Fimbriaglomerella* Zone, such as *S. orbiculare*, *S. compressa* and *S. ornata*, lack the internal body. Moczyłowska (2010, p. 132) placed *Baltisphaeridium bimacerium*, a species with a dark nucleus that appears in the *Heliosphaeridium*–*Skiagia* Zone (Zang *et al.* 2007, fig. 8), in synonymy with *S. ornata*, suggesting that it was 'a mature stage' while *S. ornata* was considered 'an -immature cyst'. If this is correct it would be necessary to justify the absence of the mature stage in the abundant and diverse associations of *Skiagia*, older than *S. ciliosa*, described in numerous assemblages. We do not think the interpretation by Moczyłowska (2010) is tenable, and therefore consider *Skiagia* species to be morphospecies that have been recorded in well-exposed sections with good stratigraphic control. Using this criterion, we have established the correlations shown in Figure 11 with areas of Avalonia and Iberia

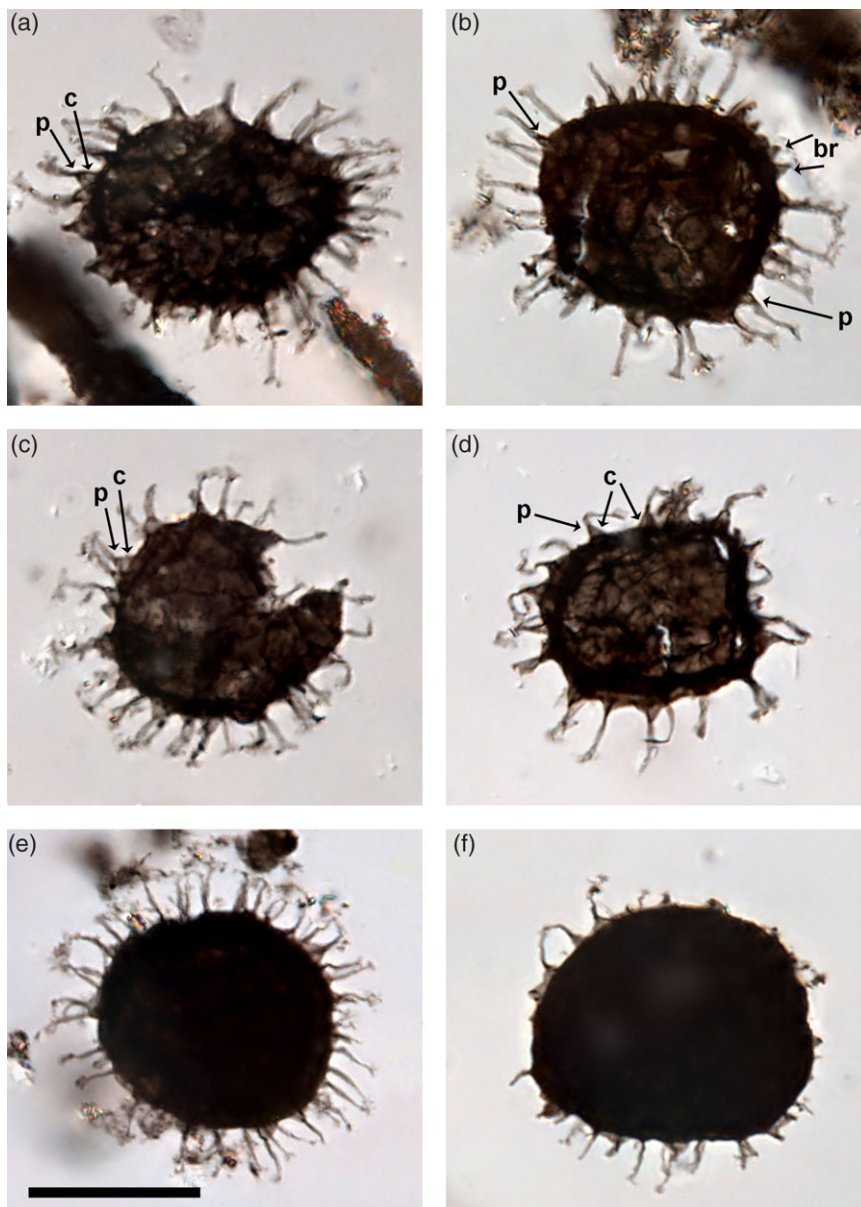


Fig. 7. (Colour online) Acritarchs from the Duolbagáisá Formation (Upper Member), Breidvika Valley section. Scale bar = 20 μm . (a–f) *Skiagia ciliosa* (Volkova) Downie. In Figures 7 and 8, the arrows show the clear and distinctive plug (p), conical base (c) and some broken (br) processes. (a) D13-109, TSGf 18440b, L-38-1. (b) D13-113, TSGf 18444c, U-37-4. (c) D13-109, TSGf 18440c, B-33-4. (d) D13-109, TSGf 18440d, D-34-1-2. (e) Specimen with a dark internal body (a possible endocyst) D13-110, TSGf 18441c, E-20-2. (f) Specimen with dark internal body D13-3, TSGf 18445, H-17-2-4

in which there is a good control on the first appearances of the *S. ciliosa* morphospecies. Some species attributed to *S. ciliosa*, such as those from the middle-upper Tommotian to lower Atdabanian stages of Siberia (Vidal *et al.* 1995, fig. 7, 3, 4; see Grazhdankin *et al.* 2020 for discussion on age) do not show the diagnostic features of *S. ciliosa* discussed above, and their assignment should be reviewed.

4.c. *Volkovia dentifera*–*Liepaina plana* Zone

The upper portion of the siltstone-rich interval in the upper part of the Upper Member of the Duolbagáisá Formation records the first appearance of *Liepaina plana* (Fig. 9a), *Heliosphaeridium notatum* (Fig. 6i) and *Retisphaeridium dichamerum* (Fig. 9c) a few metres above the trilobite occurrences (Fig. 3).

Liepaina plana and *H. notatum* have a cosmopolitan distribution, and their first appearances indicate the *Volkovia*–*Liepaina* Zone. However, *L. plana* is a very rare species in Cambrian Stage 4 rocks in Baltica, and its maximum abundance is recorded

in the Miaolingian, equivalent to the *Acadoparadoxides oelandicus* Superzone (Volkova *et al.* 1983). A similar situation occurs in New Brunswick (Palacios *et al.* 2017a), and is also observed in the study area, with maximum abundance of *L. plana* in the lower part of the Kistedalen Formation (Figs 3, 9b). *Heliosphaeridium notatum*, a diagnostic species of the *Volkovia*–*Liepaina* Zone, is more abundant than *L. plana* and has a global distribution, and is therefore more useful for correlation. For a detailed discussion on the distribution of *L. plana* and *H. notatum* we refer to Palacios *et al.* (2017a). *R. dichamerum*, first found in the Miaolingian *Albertella* Zone of Alberta, Canada (Staplin *et al.* 1965), has a cosmopolitan distribution with reports from Laurentia, Baltica, Gondwana and the peri-Gondwanan terrains of Avalonia, Ganderia and Iberia (Downie, 1982; Martin & Dean, 1988; Vidal & Peel, 1993; Molyneux *et al.* 1996; Rushton & Molyneux, 2011; Palacios *et al.* 2012, 2017a; Palacios, 2015). Identification of *R. dichamerum* can be difficult as flattened specimens may be confused with *Cymatiosphaera* or flattened *Leiosphaeridia*, because the diagnostic character that allows its easy identification is the rupture of the vesicle into plates

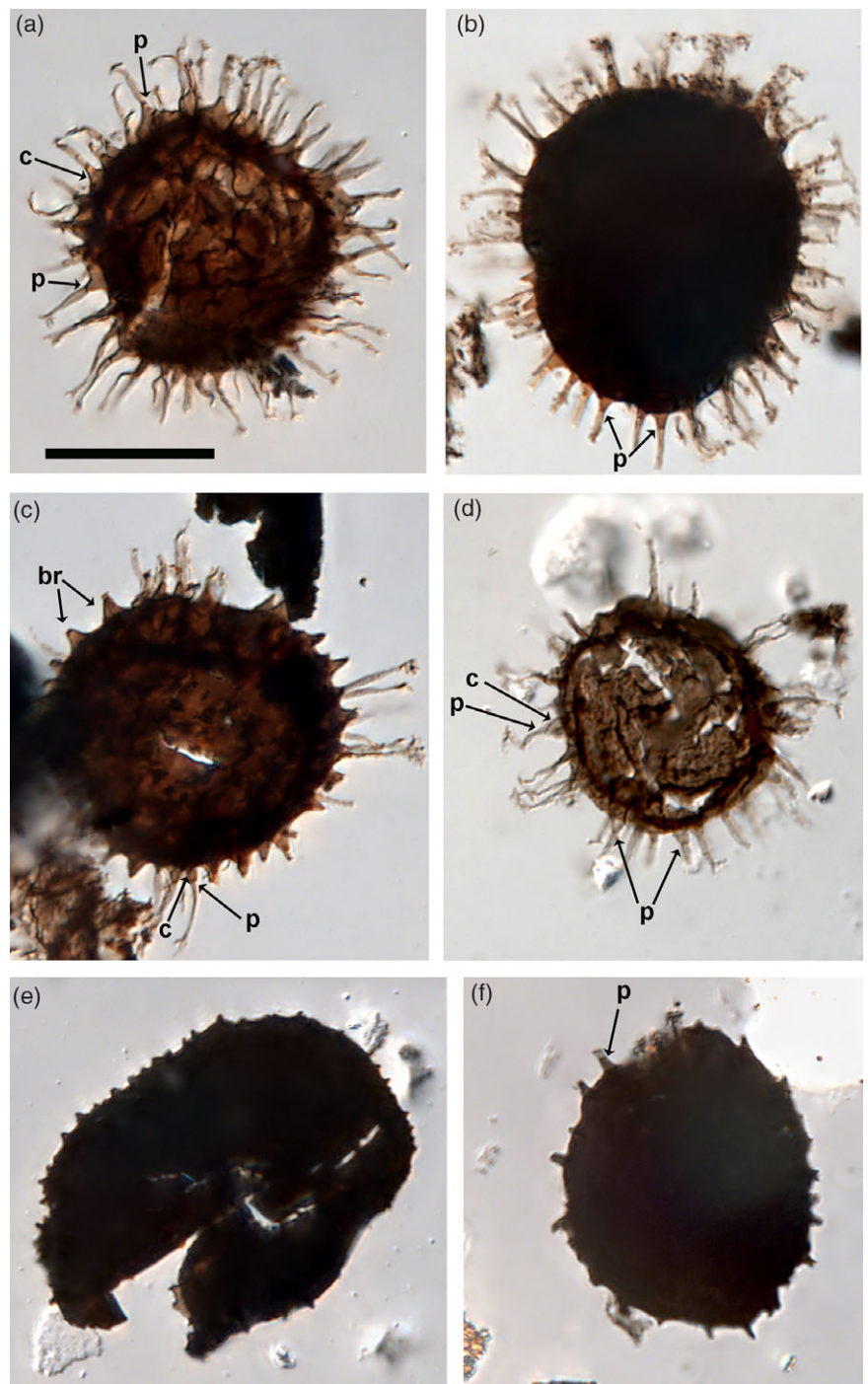


Fig. 8. (Colour online) *Skiagia ciliosa* from Avalonia. Scale bar = 20 μm . (a–c) New Brunswick, St Martins Member, Hanford Brook Formation. (e) Newfoundland, Brigus Formation, Dantzig Cove section. (d, f) Iberian Peninsula: (d) Cantabrian Zone, Lower Member, Láncara Formation; (f) Ossa-Morena Zone, Lower Member, Vallehondo Formation. (a) Hanf09-3, slide 2, B-24. (b) Specimen with dark internal body, Hanf09-3, slide 2, H-27-2. (c) Specimen with broken processes, Hanf09-3, slide 2, B-46-2. (d) BL14-1, slide 1, C-20. (e) Specimen with broken processes, DC17-12, slide 2, T-16-3. (f) Specimen with broken processes, CA06-4, slide 1, C-44-1.

(Downie, 1982, fig. 11p; Palacios, 2015; Palacios *et al.* 2017a). The rupture into plates is a morphological feature of Miaolingian acritarchs similar to some modern dinoflagellates, and it marks the important evolutionary innovation of ‘placoid acritarchs’. These include some of the most diagnostic genera of the Miaolingian and Furongian, such as *Eliasum*, *Cristallinium*, *Timofeovia*, *Vulcanisphaera* and *Stelliferidium* (Palacios *et al.* 2009, 2017a; Palacios, 2015). *Retisphaeridium dichamerum* has been reported from the *Heliosphaeridium–Skiagia* Zone (Eklund, 1990; Hagenfeldt, 1989; Vidal & Peel, 1993), and is clearly present at higher levels (upper Series 2) in Scotland

(Downie, 1982, fig. 11p) and Newfoundland. In Newfoundland, *R. dichamerum* is abundant in the highest Cambrian Series 2, Brigus Formation (*Catadoxides* Zone of Howell, 1925) and the *Triplagnostus gibbus* Zone of the lowest part of the Chamberlains Brook Formation (Martin & Dean, 1983, 1984, 1988).

In our opinion, *R. dichamerum* is a diagnostic species whose first appearance is close to that of the species defining the base of the *Volkovia–Liepaina* Zone. As with *L. plana*, the maximum abundance of *R. dichamerum* is in the Wuliuan Stage. This trend is clearly observed on the Digermulen Peninsula (Fig. 3). Proposed correlations of the *Volkovia–Liepaina* Zone are shown in Figure 11.

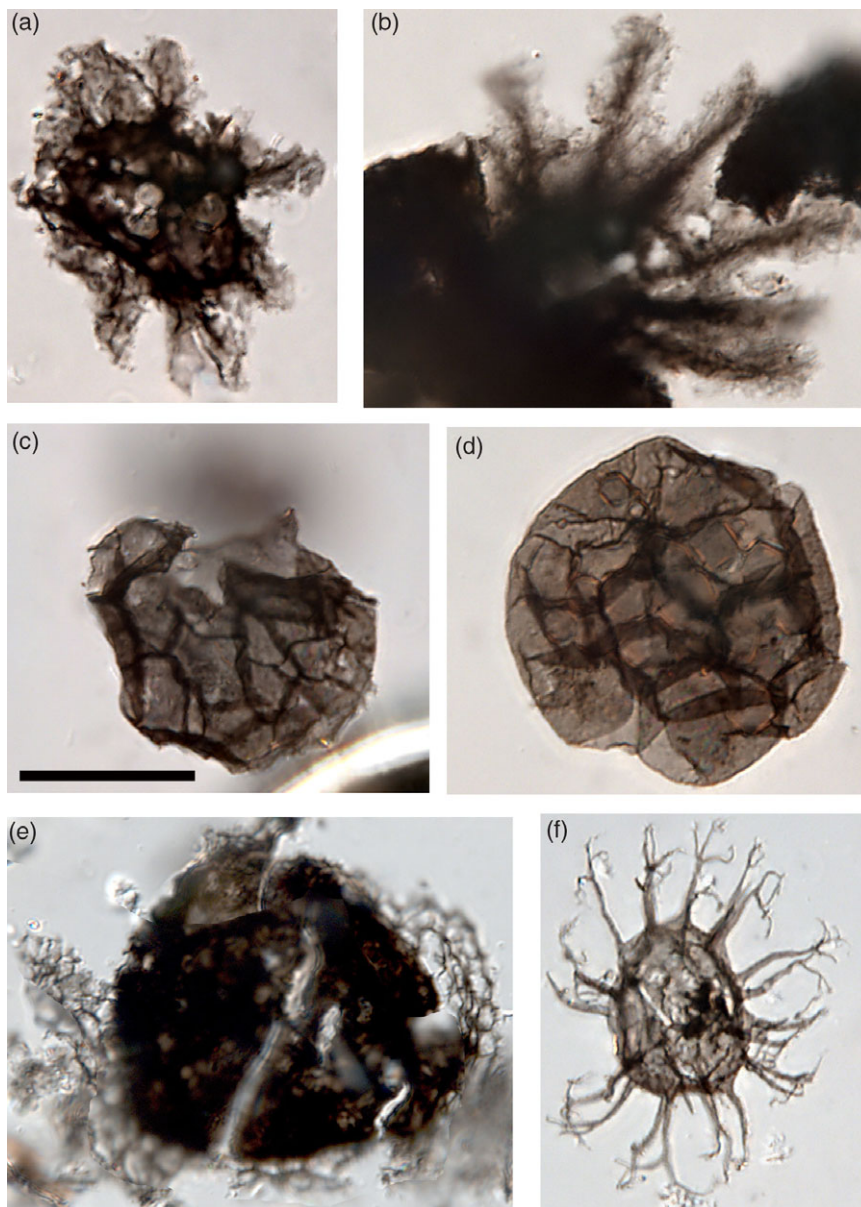


Fig. 9. (Colour online) Acritarchs from the Upper Member of the Duolbagáisá Formation (a, c, e) and K1 Member of the Kistedalen Formation (b, d, f), all Breidvíka Valley section. (a, b) *Liepaina plana* Jankauskas & Volkova: (a) D13-109, TSGf 18440e, L-42; (b) D14-87, TSGf 18447a, E-16-3. (c, d) *Retisphaeridium dichamerum* Staplin, Jansonius & Pocock: (c) D13-109, TSGf 18440f, D-24-3-4; (d) D14-87, TSGf 18447b, D-32-3. (e) *Sagatum priscum* (Kirjanov & Volkova) Vavrdová & Bek, D13-94, TSGf 18446a, B-22-4. (f) *Multiplicisphaeridium lly-nense* (Martin) Jachowicz-Zdanowska, D14-87, TSGf 18447c, N-28. Scale bar = 20 μ m.

5. Cambrian Series 2–Miaolingian transition assemblages and the Hawke Bay regression

The upper levels of the Upper Member of the Duolbagáisá Formation, dominated by quartzitic sandstone with scarce siltstone, record the last occurrence of *Skiagia* (Fig. 3). At this level, there is a low-diversity assemblage dominated by abundant *Leiosphaeridia* spp. and rare acritarchs indicative of the *Volkovia*–*Liepaina* Zone. The transition between the Cambrian Stage 4 and the Wuliuan Stage marks a significant decrease in the diversity of acritarchs, well documented in continuous sections without a significant hiatus. The disappearance of *Skiagia* species in the upper Cambrian Stage 4 has been verified in different continuous and well-exposed sections of Avalonia (Palacios *et al.* 2017a), Iberia (Palacios *et al.* 2006) and in the Brunovistulicum terrain (Jachowicz-Zdanowska, 2013), while possible redeposition in the *oelandicus* beds of Baltica has been suggested (Jachowicz-Zdanowska, 2013, p. 15). A possible explanation for the presence of *Skiagia* in Miaolingian deposits may be reworking of Cambrian

Series 2 acritarchs including the *Skiagia* assemblages dominated by *S. ciliosa* during the Hawke Bay regression at the Cambrian Stage 4–Wuliuan transition. Palynomorphs, such as acritarchs, commonly occur in great abundance and are especially sensitive to reworking because of their small size. Reworking may involve material of very different ages and result in well-preserved acritarchs, such as the reworked Ordovician acritarchs of the Barrancos Formation (Portugal) in Carboniferous continental strata that contain abundant spores (Lopes *et al.* 2014). In this case, the reworking is evidenced from known stratigraphical ranges, not from state of preservation. However, in material with a similar diagenetic or metamorphic history and deposited in similar environments, recognition may be problematic. Different studies show the presence of reworked palynomorphs in regressive series (Habib *et al.* 1994, p. 331; Stover *et al.* 1996, p. 706), and also show concentrations in the basal sequence of the new transgressive event above the boundary unconformity (Stover *et al.* 1996, p. 706). This model is applied in our hypothesis.

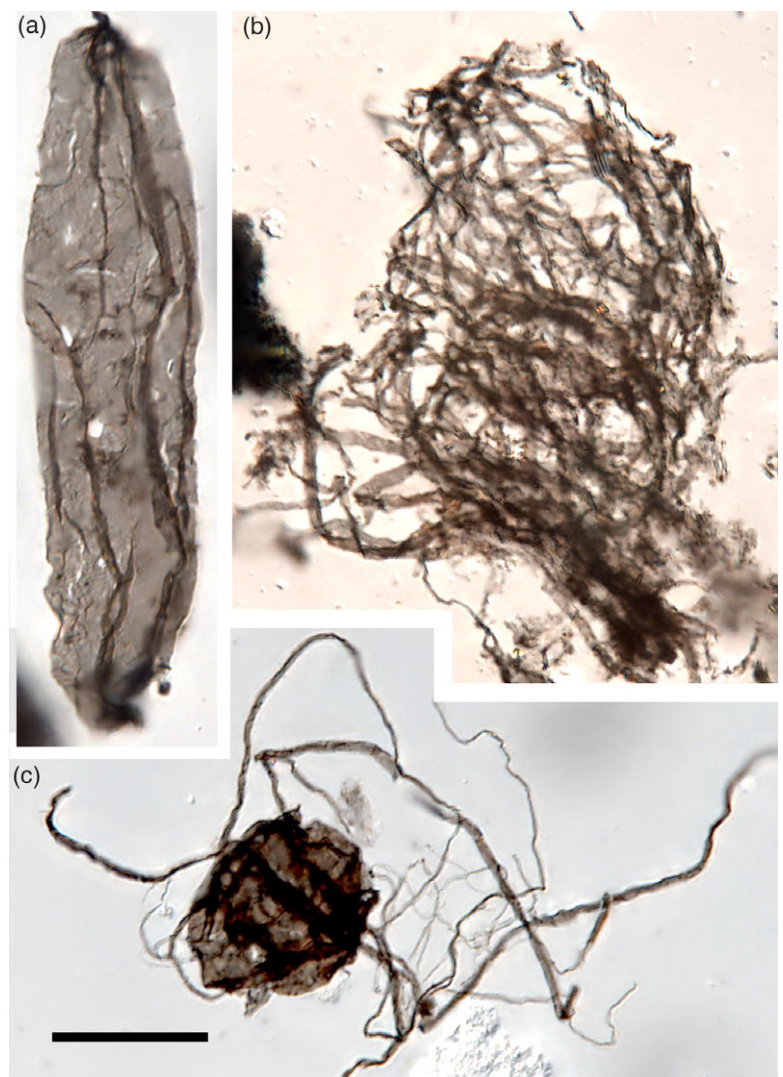


Fig. 10. (Colour online) Acritarchs from the Upper Member of the Duolbagáisá Formation (b), and K1 Member of the Kistedalen Formation (a, c), all Breidvika Valley section. (a) *Eliasum llaniscum* Fombella, D14-87, TSGf 18447d, Q-45-1. (b, c) *Comasphaeridium longispinosum* Hagenfeldt: (b) D13-94, TSGf 18446b, J-46-1; (c) D14-87, TSGf 18447e, M-34. Scale bar = 20 μ m.

The Cambrian in Baltica includes a highly condensed series of poorly lithified sediments in several areas, which under lowstand sea level conditions would be easily remobilized. The pattern observed in sections with a good record of organic-walled microfossils in Baltica is (1) a great abundance of *Skiagia* (mainly *S. ciliosa*) in *Holmia* beds (*S. ciliosa*–*H. dissimulare* Zone, Moczyłowska, 1991), (2) a disappearance (Eklund, 1990) or a major decrease of *Skiagia* in the regressive series corresponding to the *Volkovia*–*Liepaina* Zone (Moczyłowska, 1991, Radzyn IG-1 and Łopiennik boreholes; Jankauskas, 2002, Kibartai-22 borehole), and (3) a reappearance of *Skiagia* (mainly *S. ciliosa*) in the generally discordant transgressive series of *oelandicus* beds (Volkova *et al.* 1983; Hagenfeldt, 1989; Eklund, 1990; Moczyłowska, 1991; Jankauskas, 2002). In our opinion, the most abundant forms having more resistant walls, such as *S. ciliosa*, will be the most prone to being remobilized and incorporated into Wuliuian sediments of the *oelandicus* Superzone (Moczyłowska, 1991, 1998), where they become mixed with typical Miaolingian assemblages, increasing the overall biodiversity. Another hypothesis to explain this trend is the reappearance of *Skiagia* in Miaolingian strata. However, the observations of our study do not support this, and reworking is the most plausible hypothesis for the observed pattern. The presence of *Skiagia* in *oelandicus* beds therefore artificially modifies patterns of biodiversity (cf. Vidal & Moczyłowska-Vidal, 1997;

Nowak *et al.* 2015) Thus, the important extinction signal at the Cambrian Series 2–Miaolingian transition, marked by the disappearance of typical assemblages of the Cambrian Series 2 dominated by *Skiagia* and the diversification of the ‘placoid acritarchs’ that dominate the Miaolingian, becomes distorted. Sections with a good record of acritarchs in Baltica support this notion. Eklund (1990) described assemblages dominated by *Skiagia* in the Mickwitzia Sandstone Member (Assemblage B) of southern Sweden, followed by their disappearance in the Lingulid Sandstone Member in levels that contain *Volkovia dentifera* (Assemblage C), and their reappearance in the ‘Glauconite sandstone’ and *oelandicus* mudstone (Assemblage D), which are contemporary with the Wuliuian (Kibartai Stage). A similar situation occurs in northern Spain with the disappearance of *Skiagia* at the top of Huérmeda Formation and the reappearance of reworked *Skiagia* in the regressive Daroca Formation (Palacios & Moczyłowska, 1998). In comparison with material in the Huérmeda Formation, *Skiagia* in the Daroca Formation are more poorly preserved and have broken processes.

It therefore appears probable that the presence or absence of reworked *Skiagia* in Miaolingian strata serves as an indicator of the intensity of the regressive events at the Stage 4–Wuliuian transition. It follows that the absence of *Skiagia* in the upper Duolbagáisá and Kistedalen formations indicates limited reworking.

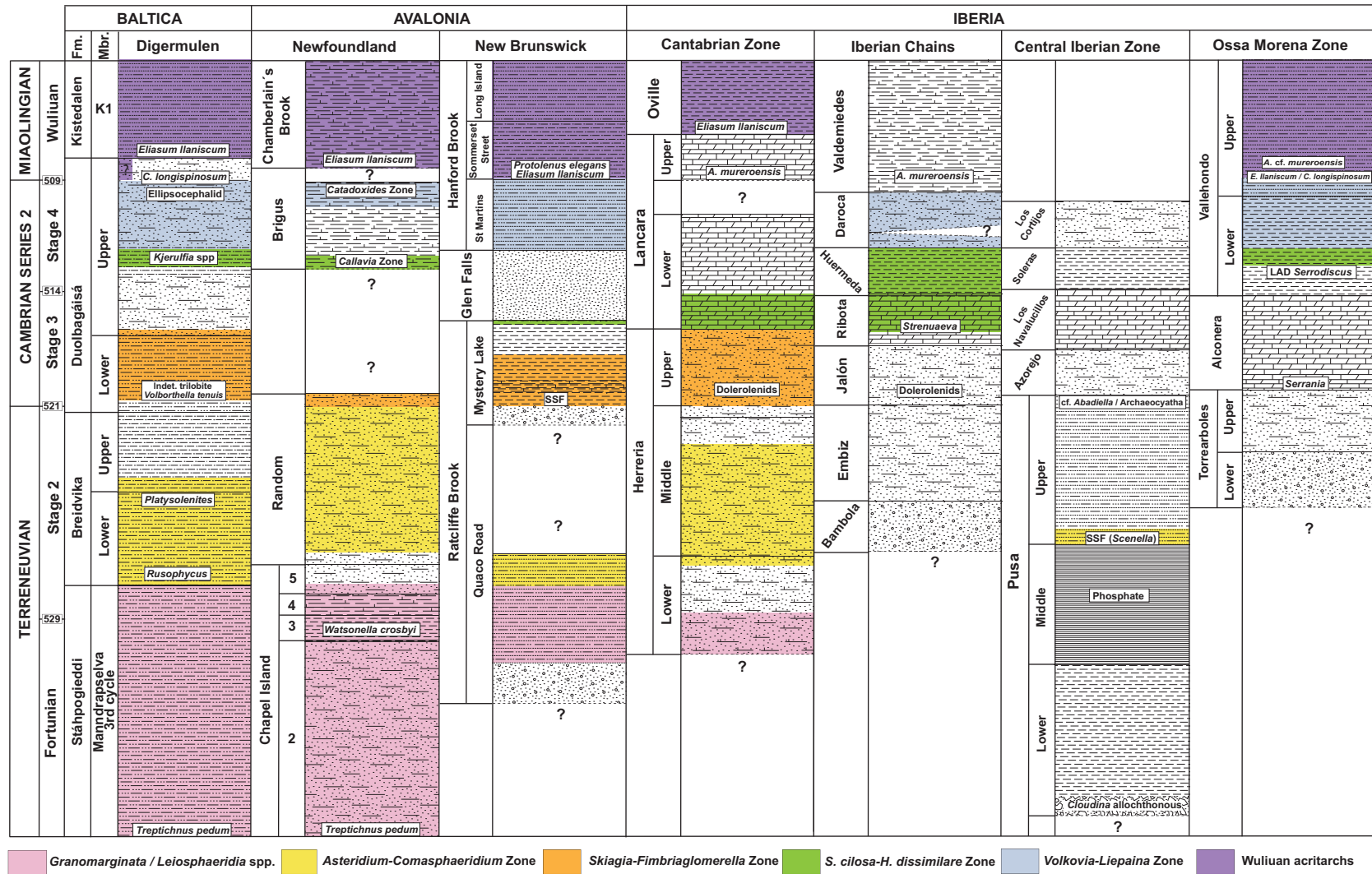


Fig. 11. (Colour online) Acritarch-based correlation chart of the Cambrian Terreneuvian–Miaolingian (Wuliuian) of the Digermulen Peninsula, Avalonia (New Brunswick and Newfoundland) and Iberia. Sources: New Brunswick – Palacios *et al.* (2011, 2017a); Newfoundland – Palacios *et al.* (2016, 2018) for Chapel Island, Random and Brigus (lower part) formations and Martin & Dean (1983) for the upper part of the Brigus and Chamberlain Brooks formations; Cantabrian Zone, northern Spain – Palacios (2015), Palacios & Vidal (1992), Palacios *et al.* (2014) and T. Palacios unpub. data; Iberian Chains, northern Spain – Palacios & Moczyłowska (1998); Central Iberian Zone, central Spain – Jensen *et al.* (2010); Ossa-Morena Zone, southern Spain – Palacios *et al.* (2006) and T. Palacios unpub. data.

This is also consistent with the sedimentology and ichnology of these units. Marine conditions are indicated by the presence of trace fossils throughout the Duolbagáisá Formation with forms typical of the *Skolithos* and *Cruziana* ichnofacies (Banks, 1973), and by acritarchs in fine-grained interbeds. Deposition of thick sandstone beds in the Upper Member of the Duolbagáisá Formation was dominated by strong tidal currents in a shoreface to offshore setting (cf. Banks, 1973; Crimes & McLroy, 1999). The lower member of the Kistedalen Formation similarly yields trace fossils and acritarchs. The Hawke Bay regression on the Digermulen Peninsula therefore is represented by shallow marine facies without evidence for an unconformity, which is consistent with an originally distal position of the area compared to units formed upon the craton (cf. Nielsen & Schovsbo, 2015, figs 12–15).

The appearance of a single specimen of *Comasphaeridium longispinosum* (Fig. 10b), an acritarch so far known only from the Miaolingian (Jachowicz-Zdanowska, 2013; Palacios *et al.* 2017a), at the top of the Duolbagáisá Formation suggests that the Cambrian Series 2–Miaolingian boundary is located close to the top of this unit (Fig. 3). The first siltstone levels of the K1 Member of the Kistedalen Formation yield a more diverse assemblage with abundant *Retisphaeridium dichamerum* (Fig. 9d), *C. longispinosum* (Fig. 10c) and *Liepaina plana* (Fig. 9b), and the first appearance of *Multiplicisphaeridium llynense* (Fig. 9f; see revision of Jachowicz-Zdanowska, 2013) and *Eliasium llaniscum* (Fig. 10a), clearly diagnostic of the Miaolingian.

6. Conclusions

The Duolbagáisá Formation contains one of the more complete successions of acritarch assemblages of the Cambrian Series 2. The Cambrian Series 2–Miaolingian acritarch associations indicate an essentially transitional record across this boundary.

Skiagia assemblages are limited to Cambrian Series 2 strata, following the same trends observed in the peri-Gondwanan terrains of Avalonia and Iberia, confirming the existence of an important acritarch extinction at the end of the Cambrian Series 2.

Occurrences of *Skiagia* in Miaolingian strata of Baltica are interpreted as reworked material related to the Hawke Bay unconformity at the Cambrian Series 2–Miaolingian transition. The absence of reworked *Skiagia* in the Kistedalen Formation indicates that the Hawke Bay regression did not result in an unconformity in this area.

The base of the Wuliuian Stage is located in the uppermost part of the Duolbagáisá Formation, whereas the acritarch association from the lowermost part of K1 Member of the Kistedalen Formation contains taxa attributable to the Miaolingian Series.

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References

- Agić H, Högström AES, Jensen S, Ebbestad JOR, Meinhold G, Palacios T, Taylor WL and Høyberget M (2018) Life through the ‘Varanger Ice Ages’: microfossil record of late Neoproterozoic glacial-interglacial units from Arctic Norway. *Geological Society of America, Abstracts with Programs* **50**, doi: 10.1130/abs/2018AM-322291.

- Agić H, Högström AES, Moczyłowska M, Jensen S, Palacios T, Meinhold G, Ebbestad JOR, Taylor WL and Høyberget M (2019) Organically-preserved multicellular eukaryote from the early Ediacaran Nyborg Formation, Arctic Norway. *Scientific Reports* **9**, 14659, doi: 10.1038/s41598-019-50650-x.
- Ahn SY and Zhu M (2017) Lowermost Cambrian acritarchs from the Yanjiahe Formation, South China: implications for defining the base of the Cambrian in the Yangtze Platform. *Geological Magazine* **154**, 1217–31.
- Banks NL (1970) Trace fossils from the late Precambrian and Lower Cambrian of Finnmark, Norway. In *Trace Fossils* (eds TP Crimes and JC Harper), pp. 19–34. Geological Journal Special Issue 3. Liverpool: Seel House Press.
- Banks NL (1973) Tide-dominated offshore sedimentation, Lower Cambrian, northern Norway. *Sedimentology* **20**, 213–28.
- Banks NL, Edwards MB, Geddes WP, Hobday DK and Reading HG (1971) Late Precambrian and Cambro-Ordovician sedimentation in East Finnmark. *Norges Geologiske Undersøkelse* **269**, 197–236.
- Cohen KM, Finney SC, Gibbard PL and Fan JX (2013; updated 2019/5) The ICS International Chronostratigraphic Chart. *Episodes* **36**, 199–204.
- Crimes TP and McLroy D (1999) A biota of Ediacaran aspect from Lower Cambrian strata on the Digermulen Peninsula, Arctic Norway. *Geological Magazine* **136**, 633–42.
- Díez Balda MA and Fournier Vinas C (1981) Hallazgo de acritarcos en el Complejo Esquistos-Grauváquico al Sur de Salamanca. *Acta Geológica Hispánica* **16**, 131–4.
- Downie C (1982) Lower Cambrian acritarchs from Scotland, Norway, Greenland and Canada. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **72**, 257–85.
- Ebbestad JOR, Høyberget M, Högström AES, Palacios T, Jensen S, Taylor WL and Meinhold G (2017) Holmiid trilobites from the lower Cambrian of the Digermulen Peninsula, Arctic Norway. In *Abstracts, 6th International Conference on Trilobites and their Relatives. Tallinn, Estonia, 7–10 July 2017* (ed. H Pärnaste), pp. 15–16. Tallinn: Abstracts Libris Est OÜ.
- Ebbestad JOR, Högström AES, Palacios T, Jensen S, Meinhold G, Høyberget M, Agić H, and Taylor WL (2018) Biostratigraphy and palaeontology of the lower Cambrian Duolbagáisá Formation on the Digermulen Peninsula, Arctic Norway. In *Session Abstracts, International Conference on Arctic Margins VIII, Stockholm, Sweden, 11–14 June 2018*.
- Eklund C (1990) Lower Cambrian acritarch stratigraphy of the Bårstad 2 core, Östergötland, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* **112**, 19–44.
- Føyn S (1937) The Eo-Cambrian series of the Tana district, northern Norway. *Norges Geologiske Undersøkelse* **17**, 65–161.
- Grazhdankin DV, Marusin VV, Izokh OP, Karlova GA, Kochnev BB, Markov GE, Nagovitsin KE, Sarsembaev Z, Peek S, Cui H and Kaufman AJ (2020) Quo vadis, Tommotian? *Geological Magazine* **157**, 22–34.
- Habib D, Eshet Y and van Pelt R (1994) Palynology of sedimentary cycles. In *Sedimentation of Organic Particles* (ed. A Traverse), pp. 311–35. Cambridge: Cambridge University Press.
- Hagenfeldt SE (1989) Lower Cambrian acritarchs from the Baltic Depression and south-central Sweden, taxonomy and biostratigraphy. *Stockholm Contributions in Geology* **41**, 1–176.
- Hayes JM, Kaplan LR and Wedeking W (1983) Precambrian organic geochemistry, preservation of the record. In *Earth’s Earliest Biosphere* (ed. JW Schopf), pp. 93–134. Princeton: Princeton University Press.
- Högström AES, Jensen S, Palacios T and Ebbestad JOR (2013) New information on the Ediacaran–Cambrian transition in the Vestertana Group, Finnmark, northern Norway, from trace fossils and organic-walled microfossils. *Norwegian Journal of Geology* **93**, 95–106.
- Howell BF (1925) The faunas of the Cambrian *Paradoxides* beds at Manuels, Newfoundland. *Bulletin of American Paleontology* **11**, 1–149.
- Jachowicz-Zdanowska M (2013) Cambrian phytoplankton of the Brunovistulicum–taxonomy and biostratigraphy. *Polish Geological Institute Special Papers* **28**, 1–150.
- Jankauskas T (2002) *Cambrian Stratigraphy of Lithuania*. Vilnius: Institute of Geology of Lithuania, 256 pp.

- Jensen S, Högström AES, Almond J, Taylor WL, Meinhold G, Høyberget M, Ebbestad JOR, Agić H and Palacios T (2018) Scratch circles from the Ediacaran and Cambrian of Arctic Norway and southern Africa, with a review of scratch circle occurrences. *Bulletin of Geosciences* **93**, 287–304.
- Jensen S, Palacios T and Martí Mus M (2010) Revised biochronology of the Lower Cambrian of the Central Iberian zone, southern Iberian massif, Spain. *Geological Magazine* **147**, 690–703.
- Landing E, Geyer G, Brasier MD and Bowring SA (2013) Cambrian evolutionary radiation: context, correlation, and chronostratigraphy-overcoming deficiencies of the first appearance datum (FAD) concept. *Earth-Science Reviews* **123**, 133–72.
- Liñán E, Gámez Vintaned JA and Gozalo R (2015) The middle lower Cambrian (Ovetian) *Lunagraulos* n. gen. from Spain and the oldest trilobite records. *Geological Magazine* **152**, 17–29.
- Liñán E, Gozalo R, Palacios T, Gámez Vintaned JA, Ugidos JM and Mayoral E (2002) Cambrian. In *The Geology of Spain* (eds W Gibbons and T Moreno), pp. 17–29. London: The Geological Society of London.
- Lopes G, Pereira Z, Fernandes P, Wicander R, Matos JX, Rosa D and Oliveira JT (2014) Significance of reworked palynomorphs (middle Cambrian to Tournaisian) in the Visean Toca da Moura Complex (South Portugal). Implications for the geodynamic evolution of Ossa Morena Zone. *Review of Palaeobotany and Palynology* **200**, 1–23.
- Martin F and Dean WT (1983) Late Early Cambrian and Early Middle Cambrian acritarchs from Manuels River, eastern Newfoundland. *Current Research, Part B. Geological Survey of Canada, Paper 83-1B*, 353–63.
- Martin F and Dean WT (1984) Middle Cambrian acritarchs from the Chamberlains Brook and Manuels River Formations at Randon Island, eastern Newfoundland. *Current Research, Part A. Geological Survey of Canada, Paper 84-1A*, 429–40.
- Martin F and Dean WT (1988) Middle and Upper Cambrian acritarch and trilobite Zonation at Manuels River and Randon Island, eastern Newfoundland. *Geological Survey of Canada Bulletin* **381**, 1–91.
- McIlroy D and Brasier MD (2017) Ichnological evidence for the Cambrian explosion in the Ediacaran to Cambrian succession of Tanafjord, Finnmark, northern Norway. In *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier* (eds AT Brasier, D McIlroy and N McLoughlin), pp. 351–68. Geological Society of London, Special Publication no. 448.
- McIlroy D, Green OR and Brasier MD (2001) Palaeobiology and evolution of the earliest agglutinated Foraminifera: *Platysolenites*, *Spirosolenites* and related forms. *Lethaia* **34**, 13–29.
- Moczyłowska M (1991) *Acritarch Biostratigraphy of the Lower Cambrian and the Precambrian–Cambrian Boundary in Southeastern Poland*. Fossils and Strata no. 29. Oslo: Universitetsforlaget, 127 pp.
- Moczyłowska M (1998) *Cambrian Acritarchs from Upper Silesia, Poland – Biochronology and Tectonic Implications*. Fossils and Strata no. 46. Oslo: Scandinavian University Press, 121 pp.
- Moczyłowska M (2010) Life cycle of early Cambrian microalgae from the *Skiagia*-plexus acritarchs. *Journal of Paleontology* **84**, 216–30.
- Moczyłowska M (2011) The early Cambrian phytoplankton radiation: acritarch evidence from the Lükati Formation, Estonia. *Palynology* **35**, 103–45.
- Moczyłowska M and Zang WL (2006) The Early Cambrian acritarchs *Skiagia* and its significance for global correlation. *Palaeoworld* **15**, 328–47.
- Molyneux SG, Le Hérisse A and Wicander R (1996) Paleozoic phytoplankton. In *Palynology: Principles and Applications* (eds J Jansonius and DC McGregor), pp. 493–529. College Station, Texas: American Association of Stratigraphic Palynologists Foundation.
- Nielsen AT and Schovsbo NH (2015) The regressive Early-Mid Cambrian ‘Hawke Bay Event’ in Baltoscandia: epeirogenic uplift in concert with eustasy. *Earth-Science Reviews* **151**, 288–350.
- Nikolaisen F and Henningsmoen G (1985) Upper Cambrian and Lower Tremadoc olenid trilobites from the Digermul Peninsula, Finnmark, N.-Norway. *Norges Geologiske Undersøkelse Bulletin* **400**, 1–49.
- Nikolaisen F and Henningsmoen G (1990) Lower and Middle Cambrian trilobites from the Digermul peninsula, Finnmark, northern Norway. *Norges Geologiske Undersøkelse Bulletin* **419**, 55–95.
- Nowak H, Servais T, Monnet C, Molyneux SG and Vandenbroucke TR (2015) Phytoplankton dynamics from the Cambrian Explosion to the onset of the Great Ordovician Biodiversification Event: a review of Cambrian acritarch diversity. *Earth-Science Reviews* **151**, 117–31.
- Palacios T (2015) Acritarch assemblages from the Oville and Barrios Formations, northern Spain: a pilot proposal of a middle Cambrian (Series 3) acritarch biozonation in northwestern Gondwana. *Review of Palaeobotany and Palynology* **219**, 71–105.
- Palacios T, Högström A, Ebbestad JOR, Jensen S, Høyberget M, Meinhold G and Taylor WL (2015) Acritarchs from the Duolbagáisá and Kistedalen formations (Cambrian Series 2–3), Digermulen Peninsula, northern Norway. In *Abstract Book, CIMP Meeting 2015, University of Bergen, Bergen, Norway, 17–18 September 2015* (eds G Mangerud, G Lopes, M Vecoli and R Wicander), p. 32.
- Palacios T, Jensen S and Apalategui O (2006) Biostratigrafía de acritarcos en el Cámbrico Inferior y Medio del margen septentrional de Gondwana (Área de Zafra, Suroeste de la Península Ibérica). In *XXII Jornadas de la Sociedad Española de Paleontología, Libro de Resúmenes* (ed. E Fernández-Martínez), pp. 156–61. León: Universidad de León.
- Palacios T, Jensen S, Barr SM and White CE (2009) Acritarchs from the MacLean Brook Formation, southeastern Cape Breton Island, Nova Scotia, Canada: new data on Middle Cambrian–Lower Furongian acritarch zonation. *Palaeogeography, Palaeoclimatology, Palaeoecology* **273**, 123–41.
- Palacios T, Jensen S, Barr SM, White CE and Myrow PM (2018) Organic-walled microfossils from the Ediacaran–Cambrian boundary stratotype section, Chapel Island and Randon formations, Burin Peninsula, Newfoundland, Canada: global correlation and significance for the evolution of early complex ecosystems. *Geological Journal* **53**, 1728–42.
- Palacios T, Jensen S, Cortijo Sánchez I and Martí Mus M (2014) First Lower Cambrian record of *Wiwaxia* from north-west Gondwana: small carbonaceous fossils from the Lánacara Formation, Cantabrian Mountains, northern Spain. In *Programme, Abstracts and AGM Papers, 58th Annual Meeting of the Palaeontological Association, University of Leeds, Leeds, UK, 16–19 December 2014*, p. 90.
- Palacios T, Jensen S, White CE and Barr SM (2011) New biostratigraphical constraints on the lower Cambrian Ratcliffe Brook Formation, southern New Brunswick, Canada, from organic-walled microfossils. *Stratigraphy* **8**, 45–60.
- Palacios T, Jensen S, White CE and Barr SM (2012) Cambrian acritarchs from the Bourinot belt, Cape Breton Island, Nova Scotia: age and stratigraphic implications. *Canadian Journal of Earth Sciences* **49**, 289–307.
- Palacios T, Jensen S, White CE and Barr SM (2016) Organic-walled microfossils from the Ediacaran–Cambrian Global boundary stratotype section, Chapel Island, Randon, and Brigus formations, southeastern Newfoundland, Canada. *Geological Society of America Abstracts with Programs* **48**, doi: [10.1130/abs/2016NE-271964](https://doi.org/10.1130/abs/2016NE-271964)
- Palacios T, Jensen S, White CE, Barr SM and Miller R (2017a) Acritarchs from the Hanford Brook Formation, New Brunswick, Canada: new biochronological constraints on the *Protolenus elegans* Zone and the Cambrian Series 2–3 transition. *Geological Magazine* **154**, 571–90.
- Palacios T and Moczyłowska M (1998) Acritarch biostratigraphy of the Lower–Middle Cambrian boundary in the Iberian Chains, province of Soria, northeastern Spain. *Revista Española de Paleontología, Numero Extraordinario, Homenaje al Prof. Gonzalo Vidal*, 65–82.
- Palacios T, Ou Z, Agić H, Högström AES, Jensen S, Høyberget M, Meinhold G, Taylor WL and Ebbestad JOR (2017b) Organic-walled microfossils and organic fossils across the Ediacaran–Cambrian boundary on the Digermulen Peninsula, Arctic Norway. In *Abstract Volume, International Symposium on the Ediacaran–Cambrian Transition (ISECT) 2017, Saint John's, Newfoundland, Canada, 20–22 June 2017* (ed. D McIlroy), p. 91.
- Palacios T and Vidal G (1992) Lower Cambrian acritarchs from northern Spain: the Precambrian–Cambrian boundary and biostratigraphic implications. *Geological Magazine* **129**, 421–36.
- Pu JP, Bowring SA, Ramezani J, Myrow P, Raub TD and Landing E (2016) Dodging snowballs: geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota. *Geology* **44**, 955–8.

- Reading HG** (1965) Eocambrian and Lower Palaeozoic geology of the Digermulen Peninsula, Tanafjord, Finnmark. *Norges Geologiske Undersøkelse* **367**, 77–104.
- Rice AHN, Edwards MB, Hansen TA, Arnaud E and Halverson GP** (2011) Glaciogenic rocks of the Neoproterozoic Smalfjord and Mortensnes formations, Vestertana Group, E. Finnmark, Norway. In *The Geological Record of Neoproterozoic Glaciations* (eds E Arnaud, GP Halverson and G Shields-Zhou), pp. 593–602. Geological Society of London, Memoirs no. 36.
- Rushton AWA and Molyneux SG** (2011) Welsh Basin. In *A Revised Correlation of the Cambrian Rocks in the British Isles* (eds AWA Rushton, PM Brück, SG Molyneux, M Williams and NH Woodcock), pp. 21–7. Geological Society of London, Special Report no. 25.
- Staplin FL, Jansonius J and Pocock SAJ** (1965) Evaluation of some acritarchous hystrichosphere genera. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* **123**, 167–201.
- Stover LE, Brinkhuis H, Damassa SP, de Verteuil L, Helby RJ, Monteil E, Partridge AD, Powell AJ, Riding JB, Smelror M and Williams GL** (1996) Mesozoic–Tertiary dinoflagellates, acritarchs and prasinophytes. In *Palynology: Principles and Applications*, vol 2 (eds J Jansonius and DC McGregor), pp. 641–750. Dallas: American Association of Stratigraphic Palynologists Foundation.
- Vidal G** (1981) Micropaleontology and biostratigraphy of the Upper Proterozoic and Lower Cambrian sequence in east Finnmark, northern Norway. *Norges Geologiske Undersøkelse* **362**, 1–53.
- Vidal G and Moczyłowska-Vidal M** (1997) Biodiversity, speciation and extinction trends of Proterozoic and Cambrian phytoplankton. *Paleobiology* **23**, 230–46.
- Vidal G, Moczyłowska M and Rudavskaya V** (1995) Constraints on the early Cambrian radiation and correlation of the Tommotian and Nemakit-Daldynian regional stages of eastern Siberia. *Journal of the Geological Society, London* **152**, 499–510.
- Vidal G, Palacios T, Díez Balda MA, Gámez Vintaned JA and Grant SWF** (1994) Neoproterozoic–early Cambrian geology and palaeontology of Iberia. *Geological Magazine* **131**, 729–65.
- Vidal G and Peel JS** (1993) Acritarchs from the Lower Cambrian Buen Formation in North Greenland. *Grønlands Geologiske Undersøgelse Bulletin* **164**, 1–35.
- Volkova NA** (1969) Acritarchs of the north-west Russian Platform. In *Tommotian Stage and the Cambrian Lower Boundary Problem* (eds A Yu Rozanov, VV Missarzhevsky, NA Volkova, LG Voronova, IN Krylov, BM Keller, IK Korolyuk, K Lenzion, R Michniak, NG Pykhova and AD Sidorov), pp. 224–36. Trudy Geologicheskogo Instituta Akademii Nauk SSSR, no. 206 (in Russian).
- Volkova NA, Kirjanov VV, Piscun LV, Paškevičienė LT and Jankauskas TV** (1983) Plant microfossils. In *Upper Precambrian and Cambrian Palaeontology of the East-European Platform* (eds A Urbanek and A Yu Rozanov), pp. 7–46. Warszawa: Wydawnictwa Geologiczne.
- Welsch M** (1986) Die Acritarchen der höheren Digermul-Gruppe, Mittelkambrium bis Tremadoc, Ost-Finnmark, Nord-Norwegen. *Palaeontographica, Abteilung B* **201**, 1–109.
- Zhang X, Ahlberg P, Babcock LE, Choi DK, Geyer G, Gozalo R, Stewart J, Hollingsworth SH, Li G, Naimark EB, Pegel T, Steiner M, Wotte T and Zhang Z** (2017) Challenges in defining the base of Cambrian Series 2 and Stage 3. *Earth-Science Reviews* **172**, 124–39.
- Zang WL, Moczyłowska M and Jago JB** (2007) Early Cambrian acritarch assemblage zones in South Australia and global correlation. In *South Australia 2006 – Papers from the XI International Conference of the Cambrian Stage Subdivision Working Group* (eds JR Laurie, JR Paterson and JB Jago), pp. 141–77. Memoirs of the Association of Australasian Palaeontologists no. 33.