

1 First Appearance Data of selected acritarch taxa and 2 correlation of Lower and Middle Ordovician Stages

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7

8 **Abstract**

9

10 First Appearance Data (FADs) of selected, easily recognizable acritarch morphotypes
11 are assessed to determine their potential contribution to correlation of Lower and Middle
12 Ordovician stages and substage divisions along the Gondwanan margin (Perigondwana) and
13 between Perigondwana and other palaeocontinents. The FADs of nineteen genera, species
14 and species groups are recorded throughout their biogeographical ranges. The taxa
15 investigated fall into three groups. Some have FADs at about the same level throughout their
16 biogeographical ranges and are useful for long-distance and intercontinental correlation.
17 Among these are: *Coryphidium*, *Dactylofusa velifera*, *Peteinosphaeridium* and
18 *Rhopaliophora* in the upper Tremadocian Stage; *Arbusculidium filamentosum*, *Aureotesta*
19 *clathrata simplex* and *Coryphidium bohemicum* in the lower–middle Floian Stage;
20 *Dicrodiacrodium* in the upper Floian Stage; *Frankea* in the Dapingian–lower Darriwilian
21 stages; and *Orthosphaeridium* spp., with FADs in the Dapingian–lower Darriwilian stages of
22 Perigondwanan regions and at about the same level in Baltica. Other taxa, however, have
23 diachronous (or apparently diachronous) FADs, and this needs to be taken into account when
24 using them for correlation. A second group of genera and species, comprising *Striatotheca*,
25 the *Veryhachium lairdii* group and the *V. trispinosum* group, have a recurring pattern of
26 FADs in the Tremadocian Stage on Avalonia and in South Gondwana and West Gondwana,
27 but in the Floian Stage of South China and East Gondwana. The third group, consisting of
28 *Arkonina*, *Ampullula*, *Barakella*, *Dasydorus*, *Liliosphaeridium* and *Sacculidium*, have FADs
29 that are markedly diachronous throughout their biogeographical ranges, although the global
30 FADs of *Arkonina*, *Ampullula*, *Liliosphaeridium* and *Sacculidium* are apparently in South
31 China and/or East Gondwana. It is possible that diachronous FADs are only apparent and an
32 artefact of sampling. Nevertheless, an alternative interpretation, suggested by recurring

33 patterns, is that some as yet undetermined factor controlled a slower biogeographical spread
34 over time, resulting in diachroneity.

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53 The Ordovician System comprises three global series (Lower, Middle and Upper Ordovician)
54 and seven global stages (Tremadocian, Floian, Dapingian, Darriwilian, Sandbian, Katian and
55 Hirnantian). The global stages have been further divided into units of shorter duration by
56 Webby *et al.* (2004), who introduced 19 time slices, and Bergström *et al.* (2009), who
57 defined 20 stage slices. Time slices and stage slices are each shorter than a stage but longer
58 than a faunal zone, and so correspond to a substage or a superzone (Fig. 1). The ages of
59 stages and the stage slice boundaries were revised by Cooper & Sadler (2012). The bases of
60 the global stages (Global Boundary Stratotype Section and Point, GSSP) are all defined on
61 the first occurrence of either a conodont species (bases of the Tremadocian and Dapingian
62 stages) or a graptolite species (bases of the Floian, Darriwilian, Sandbian, Katian and
63 Hirnantian stages) (Bergström *et al.* 2009). The same is true for the stage slices, except for
64 the uppermost Hirnantian Stage Slice H2, which extends from the end of the Hirnantian
65 Isotopic Carbon Excursion (HICE) to the top of the Ordovician. Complementing the
66 graptolite and conodont biozonations, chitinozoan biozonation schemes have been used in
67 global correlation (e.g. Cooper & Sadler 2012) although no chitinozoan marker species is
68 used to define any chronostratigraphical division.

69 Acritarchs have long been used for biostratigraphical dating and correlation of
70 Ordovician successions, often in sediments devoid of other fossils, but biozonation schemes
71 to complement those of the graptolites, conodonts and chitinozoans have not been developed
72 (e.g. Servais & Paris 2000). Nevertheless, acritarchs have the potential to correlate global
73 stages and stage slice boundaries in the Lower and Middle Ordovician. Molyneux *et al.*
74 (2007), for example, discussed biostratigraphical correlation of the Tremadocian–Floian
75 stage boundary using acritarchs, and Li *et al.* (2002a, 2010) pointed out the biostratigraphical
76 potential of acritarch morphotypes for correlation of the Floian–Dapingian (Lower–Middle
77 Ordovician) stage boundary. These examples deal mainly with correlations along the margin
78 of Gondwana, including Avalonia, but also touch upon the use of acritarchs to correlate
79 between Gondwana and other palaeocontinents.

80 The aim of this paper is to assess the First Appearance Data (FADs) of selected
81 acritarch taxa that have the potential to correlate Lower and Middle Ordovician global stage
82 and stage slice boundaries. An ultimate aim is the development of acritarch biozonation
83 schemes to complement the graptolite, conodont and chitinozoan biozonations.

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86 Figure 1 about here

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89 **Ordovician acritarch data**

90
91 A substantial body of published data exists for Ordovician acritarchs; a decade ago, Servais
92 *et al.* (2004a) estimated more than 1000 papers. Much of the data are from Europe, North
93 Africa and North America, i.e. from the palaeocontinents of Baltica, Laurentia and the
94 margins of the supercontinent Gondwana, often referred to as ‘Perigondwana’ (Fig. 2). A
95 number of investigations have also been carried out on successions in South China (Li *et al.*
96 2002b) and South America (Rubinstein 2003), particularly in the Gondwanan successions of
97 NW Argentina. In terms of palaeogeography, South China and NW Argentina (excluding the
98 Precordillera) were situated at low to intermediate latitudes on or close to the Gondwanan
99 margin (Fig. 2). In addition, a few publications deal with Lower–Middle Ordovician acritarch
100 assemblages from Australian basins, also Gondwanan and located at low palaeolatitudes
101 (Playford & Martin 1984, Playford & Wicander 1988, Foster *et al.* 2002, Quintavalle &
102 Playford 2006a, b; Foster & Wicander 2016). The geographical coverage is extensive, but
103 there are gaps, both geographically and stratigraphically. Much of the data from North
104 America, for example, are from the Upper Ordovician Series (Sandbian, Katian and
105 Hirnantian stages), with few data from the Lower and Middle Ordovician series.

106
107 Figure 2 about here

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109 Acritarchs can be extremely abundant in sedimentary successions and their diversity
110 can be high. The number of acritarch specimens in Lower Palaeozoic sediments can range
111 from a few 10s to 100s or 1000s of individuals per gram of rock (see, for example, Mullins *et al.*
112 2004), but can reach tens of thousands of specimens depending on lithology and facies. In
113 exceptional circumstances, hundreds of thousands of specimens per gram might be recorded.
114 Dorning (1999), for example, noted that many samples from the Tremadocian Shineton
115 Shales of the Welsh Borderland, UK, yielded more than 100,000 acritarchs per gram.
116 Diversity also varies with sedimentary environment, but under favourable conditions,
117 assemblages may contain 50 species or more.

118 Acritarch taxa often display a high degree of morphological variability, which in some
119 instances can make it difficult to establish where boundaries lie between species and even
120 between genera (e.g. Stricanne & Servais 2002). Some morphological changes can be
121 interpreted as ecophenotypical responses to fluctuations in palaeoenvironmental factors, such
122 as salinity (Servais *et al.* 2004b), and therefore constitute an ecological rather than a
123 biostratigraphical or evolutionary signal. Other morphological changes have more
124 biostratigraphical significance. In particular, the first appearances of new, readily
125 distinguishable, innovative morphotypes, such as those considered here, most probably
126 correspond to genotypic change rather than ecophenotypic adaptation, and consequently
127 identify taxa that have biostratigraphical potential.

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130 **Stratigraphical framework**

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132 Correlation of the British (Anglo-Welsh), Baltic, Australasian and North America regional
133 divisions with the global series and stages (Fig. 1) follows Cooper & Sadler (2012, fig. 20.9),
134 as does correlation with the stage slices of Bergström *et al.* (2009). Correlation of the
135 Australasian and Anglo-Welsh graptolite zonation, the North Atlantic conodont zonation
136 and the ‘North’ Gondwanan chitinozoan zonation also follows the correlation shown in
137 Cooper & Sadler (2012, fig. 20.1). The chronostratigraphical divisions adopted here for South
138 China and correlation of the Upper Yangtze graptolite biozones follows Zhang *et al.* (2007,
139 2010), and the chronostratigraphical divisions for the Mediterranean and ‘North’ Gondwana
140 are from Bergström *et al.* (2009). ‘North Gondwana’ has been used by authors to refer to
141 those parts of the Palaeozoic continent of Gondwana that are in the most northerly position at
142 the present day, including parts of southwestern and southern Europe, i.e. Iberia, France (e.g.
143 Armorica, the Massif Central and the Montagne Noire) and Sardinia, North Africa and the
144 Middle East (e.g. Servais & Sintubin 2009). Palaeogeographically, these areas were located at
145 high southern palaeolatitudes and along the margin of SW Gondwana (Fig. 2). In this paper
146 ‘North Gondwana’ of other authors equates to South Gondwana and West Gondwana (see
147 *Note on palaeogeographical classification* below).

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150 **First Appearance Data (FADs) of selected acritarch morphotypes**

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152 *Selection of genera, species and morphotypes*

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154 Brocke *et al.* (1995) discussed the FADs of eight taxa and Li *et al.* (2003) subsequently used
155 the FADs of 17 taxa to correlate Lower and Middle Ordovician Perigondwanan sequences.
156 We build on these earlier papers and discuss the FADs and biostratigraphical usefulness of
157 19 taxa (species, genera or morphological species groups). All occur on the Gondwanan
158 margin ('Perigondwanan acritarch province') and some are also found on other
159 palaeocontinents. All are easily recognizable with well-constrained morphologies that permit
160 confident determination, and almost all have been subject to a thorough revision of their
161 taxonomy and stratigraphical distribution. Their FADs are here correlated with the standard
162 graptolite biozonations and are plotted against the stage slices of Bergström *et al.* (2009), the
163 time slices of Webby *et al.* (2004) and the global and regional stratigraphical divisions (Fig.
164 3).

165

166 Figure 3 about here

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168 Acritarchs considered in this study include, in alphabetical order, the genera *Ampullula*,
169 *Arkonina*, *Barakella*, *Coryphidium*, *Dasydorus*, *Dicrodiacrodium*, *Frankea*, *Liliosphaeridium*,
170 *Orthosphaeridium*, *Peteinosphaeridium*, *Rhopaliophora*, *Sacculidium* and *Striatotheca*, the
171 species *Arbusculidium filamentosum*, *Aureotesta clathrata simplex*, *Coryphidium bohemicum*
172 and *Dactylofusa velifera*, and the *Veryhachium lairdii* and *Veryhachium trispinosum* groups.

173 The emphasis in this paper is on elucidating global first occurrences, but we comment
174 also on local FADs, especially where these diverge from the global FAD. The Last
175 Appearance Data (LADs) of the 19 selected taxa are not discussed. Molyneux *et al.* (2006)
176 showed that the LADs of acritarch taxa can be biostratigraphically useful, but the LADs of
177 the taxa considered here are all above the top of the interval of interest.

178 The acritarchs considered in this paper are discussed in the order of their FADs as
179 shown on Figures 3 and 4.

180

181 *Note on palaeogeographical classification*

182

183 The FADs in Figures 3 and 4 are shown in relation to established Ordovician
184 palaeocontinents and other palaeogeographical units. In order to elucidate differences in
185 FADs around the large palaeocontinent of Gondwana, FADs are classified according to
186 whether they are from South Gondwana, West Gondwana or East Gondwana. Following the
187 reconstructions of Ordovician Earth geography by Torsvik & Cocks (2017), South Gondwana
188 is defined here to include regions between a palaeolatitude of 60°S and the Ordovician South
189 Pole, principally North Africa but also including components of the Armorican Terrane
190 Assemblage, notably Bohemia, Saxothuringia and Spain (Iberia). West Gondwana comprises
191 the western margin of Gondwana from 60°S to equatorial regions and includes Saudi Arabia,
192 Oman, Pakistan and Western Australia. Although situated adjacent to the western margin of
193 Gondwana during the Early and Middle Ordovician (Torsvik & Cocks 2017, fig. 6.1), South
194 China is treated as a separate entity. East Gondwana comprises regions on the eastern margin
195 of Gondwana, but data are essentially restricted to those from NW Argentina.

196

197 *FADs*

198

199 *Dactylofusa velifera* (Fig. 5H)

200

201 The taxonomy, biostratigraphy and palaeobiogeography of *Dactylofusa velifera* were revised
202 by Wang *et al.* (2015). Molyneux *et al.* (2006) recorded the first downhole occurrence of
203 *Dactylofusa velifera* in cuttings samples from the Tremadocian Mabrouk Member in the
204 Kauther-1H1 well in Oman on the western margin of Gondwana, in an acritarch assemblage
205 that is evidently older than the late Tremadocian *messaoudensis-trifidum* assemblage. This
206 suggests a first occurrence in pre-Tr3 strata, and is indicated by a question mark in Stage
207 Slice Tr1 on Figure 3. It possibly represents the global FAD of the species. Another possible
208 occurrence in pre-Tr3 strata is from the *P. deltifer* conodont Biozone of the Fenghsiang
209 Formation on the Yangtze Platform of South China (Brocke, unpublished Ph.D. thesis,
210 Technische Universität, Berlin, 1998). An occurrence in the *P. deltifer* Biozone would
211 correspond to the uppermost part of Time Slice 1b and to Stage Slice Tr2, but the
212 biostratigraphical dating and correlation require confirmation. Again, this occurrence is
213 indicated by a question mark on Figure 3.

214 Stratigraphically well-constrained occurrences of *D. velifera* in South China, Avalonia
215 and South Gondwana are in the upper Tremadocian Stage Slice Tr3. In South China, *D.*

216 *velifera* has been recorded from the *A. murrayi* graptolite Biozone (Wang *et al.* 2013), and
217 possibly close to the base of the zone, at a level that probably corresponds to Time Slice 1c
218 (Fig. 3). The species is present in *messaoudensis-trifidum* acritarch assemblages from
219 Avalonia (NW England, South Wales and Belgium) and South Gondwana (Spain). In the
220 Lake District of NW England, its FAD is in sub-assemblage 4 of the *messaoudensis-trifidum*
221 assemblage, correlated with a level in the upper part of Stage Slice Tr3 and probably within
222 Time Slice 1d (Molyneux *et al.* 2007; Fig. 3). Occurrences in SW Spain (Servais & Mette
223 2000) and Belgium (Breuer & Vanguetaine 2004) are from assemblages that are equated
224 with the upper part of sub-assemblage 3 and/or sub-assemblage 4 of the *messaoudensis-*
225 *trifidum* assemblage in NW England (Molyneux *et al.* 2007), which again suggests
226 correlation with the upper part of Stage Slice Tr3 within Time Slice 1d (Fig. 3). The record
227 from South Wales (Molyneux & Dorning 1989) is considered to be from Stage Slice Tr3, but
228 its exact level is not constrained.

229 All the records cited above are from either high southern palaeolatitudes (NW England
230 Belgium, South Wales and Spain) or from lower palaeolatitudes on or adjacent to the western
231 margin of Gondwana (Oman, South China). Hitherto, published records of *Dactylofusa*
232 *velifera* in the Central Andean Basin of NW Argentina, on the eastern margin of Gondwana,
233 suggested a higher FAD, with the oldest recorded occurrences being from the *Tetragraptus*
234 *akzharensis* graptolite Biozone (de la Puente & Rubinstein 2013, fig. 3), correlated with the
235 upper part of Stage Slice F11. Following the adjustment of graptolite zone boundaries in NW
236 Argentina (Toro *et al.* 2015), however, the presence of *Dactylofusa velifera brevis* in the
237 lowest Floian (lower F11) *Tetragraptus phyllograptoides* Biozone (Fig. 1) is confirmed, and it
238 is possible that *D. velifera* has its FAD there in the late Tremadocian *Hunnegraptus copiosus*
239 Biozone, corresponding to the upper part of Stage Slice Tr3 (Time Slice 1d). In addition, the
240 occurrence of *D. velifera* in a newly reported *messaoudensis-trifidum* acritarch assemblage
241 (Rubinstein *et al.* in preparation) also suggests a FAD there in the early Floian (F11) or
242 possibly late Tremadocian (Tr3?), although there are no graptolites or chitinozoans for
243 independent age control. Consequently, the definite FAD of the species in NW Argentina
244 (East Gondwana) is placed at the base of the Floian on Figure 3, with a tentative FAD in the
245 upper Tremadocian at a level that corresponds to FADs in Avalonia and South Gondwana.

246

247 *Veryhachium lairdii* group (Fig. 5P)

248

249 The genus *Veryhachium* can be common in marine palynological assemblages of Ordovician

250 age and younger (Servais *et al.* 2007). Lower and Middle Ordovician forms are generally
251 either rectangular or triangular, and are assigned to the *Veryhachium lairdii* group and
252 *Veryhachium trispinosum* group, respectively (Servais *et al.* 2007; Lei *et al.* 2013). The
253 palaeobiogeographical distribution of *Veryhachium* morphotypes through the Ordovician was
254 discussed by Servais *et al.* (2014), with global first occurrences of both groups at high
255 southern palaeolatitudes of Perigondwana (Gondwana, Avalonia) in the Early Ordovician,
256 followed by spreading to mid southern palaeolatitudes in Baltica and South China by the
257 Middle Ordovician and a global distribution by the Late Ordovician. The diachronous FADs
258 are reflected in Figure 3.

259 Servais *et al.* (2007) reported the first appearance of the *Veryhachium lairdii* group to
260 be at a depth of 1590 m in the Bir Ben Tartar (Tt-1) Borehole of southern Tunisia (South
261 Gondwana). They further reported graptolites of the *Rhabdinopora flabelliformis* group to
262 occur at the same level, citing unpublished data, and referred to indirect correlation with the
263 *Lagenochitina destombesi* chitinozoan Biozone. Graptolites of the *R. flabelliformis* group
264 (Zalasiewicz *et al.* 2009, fig. 3) and correlation with the *Lagenochitina destombesi* Biozone
265 (Fig. 1; Cooper & Sadler 2012) suggest assignment to Stage Slices Tr1 or Tr2 of Bergström
266 *et al.* (2009) and to Time Slices 1a or 1b of Webby *et al.* (2004). Vecoli & Le Hérissé (2004,
267 fig. 5, taxon number 85) indicated the FAD of *V. lairdii* on the high palaeolatitude
268 ('Northern') Gondwanan margin to be in the middle of the Tremadocian Stage.

269 Specimens of *Veryhachium lairdii?* in a Tremadocian acritarch assemblage from
270 cuttings samples of the Mabrouk Member, in the Kauther-1H1 well of Oman on the western
271 margin of Gondwana (Molyneux *et al.* 2006), are probably also from the lower part of the
272 Tremadocian Stage. Although *V. lairdii* is present in a Darriwilian acritarch assemblage from
273 the same well, the preservation of specimens from the Mabrouk Member suggests that they
274 are *in situ*, not caved. The associated Tremadocian acritarchs further suggest that the
275 assemblage predates Stage Slice Tr3 and Time Slice 1c. The occurrences of the group in
276 Tunisia and Oman are tentatively taken to indicate FADs low in the Tremadocian Stage of
277 South Gondwana and West Gondwana respectively, and are indicated by question marks
278 against Stage Slice Tr1 on Figure 3.

279 Other Tremadocian occurrences of the *V. lairdii* group from Avalonia and South
280 Gondwana are from the upper Tremadocian Stage Slice Tr3. From Avalonia, specimens of
281 the group have been recorded from sub-assemblage 1 of the *Cymatiogalea messaoudensis*-
282 *Stelliferidium trifidum* acritarch assemblage in the Lake District of NW England, in the
283 lowest samples collected from the *Araneograptus murrayi* Biozone (Molyneux *et al.* 2007,

284 fig. 3), and are probably from the lower part of Stage Slice Tr3 and Time Slice 1c of Webby
285 *et al.* (2004) (Figs 1, 3).

286 Specimens also occur in a *messaoudensis-trifidum* acritarch assemblage (Molyneux *et*
287 *al.* 2007) from core between depths of 3615.8 m and 3835.3 m in the Rügen 5 borehole on
288 the island of Rügen off the northern Baltic coast of Germany (Servais & Molyneux 1997),
289 again part of Avalonia. Chitinozoa from the upper part of the same depth interval in Rügen 5
290 (3615.8–3794.7 m) were reported to indicate the *Lagenochitina destombesi* Biozone
291 (Samuelsson *et al.* 2000; Servais *et al.* 2001), which is generally correlated with Tr1-Tr2 and
292 with Time Slices 1a and 1b (Fig. 1). Recent investigation of chitinozoan faunas from NW
293 England, however, has shown that *L. destombesi* occurs there at higher stratigraphic levels in
294 the Tremadocian, in Stage Slice Tr3 and the *A. murrayi* Biozone (Amberg *et al.* in press).
295 Based on this evidence, the occurrence of the *V. lairdii* group on Rügen in the
296 *messaoudensis-trifidum* assemblage is considered to indicate a level in Stage Slice Tr3 and
297 Time Slice 1c, equivalent to its FAD in NW England.

298 Occurrences of the *V. lairdii* group reported by Nowak *et al.* (2015, 2016) from
299 Morocco (South Gondwana) are also placed in the lower part of the *messaoudensis-trifidum*
300 assemblage (Nowak *et al.* 2015, 2016) and correlated with the *A. murrayi* Biozone, Stage
301 Slice Tr3 and Time Slice 1c. Based on the records from NW England, Rügen and Morocco,
302 definite FADs of the *V. lairdii* group on Avalonia and high palaeolatitude South Gondwana
303 are placed at about the base of Stage Slice Tr3 and Time Slice 1c (Fig. 3).

304 Specimens of the *Veryhachium lairdii* group have been recorded from other upper
305 Tremadocian *messaoudensis-trifidum* acritarch assemblages of Avalonia and South
306 Gondwana. Palynofloras containing the *Veryhachium lairdii* group in the Avalonian
307 successions of Ireland (Connery & Higgs 1999; Todd *et al.* 2000) and Belgium
308 (Vanguetaine & Servais 2002; Breuer & Vanguetaine 2004) and the South Gondwanan
309 succession of Spain (Servais & Mette, 2000) are correlated with the upper part of sub-
310 assemblage 3 and/or the overlying sub-assemblage 4 of the *messaoudensis-trifidum*
311 assemblage of NW England (Molyneux *et al.* 2007). These two sub-assemblages are
312 correlated in turn with the uppermost Tremadocian (Molyneux *et al.* 2007) and therefore with
313 the upper part of Stage Slice Tr3. The associated acritarch assemblage from south Wales
314 (Avalonia; Molyneux & Dorning 1989) suggests correlation with Stage Slice Tr3 undivided,
315 and the associated chitinozoan in Bohemia (South Gondwana; Fatka 1993), *Amphorachitina*
316 *conifundus*, suggests a late Tremadocian (*murrayi* or *copiosus* graptolite biozones) or
317 possibly earliest Floian age (Paris 1990).

318 All the occurrences listed above were located at high to intermediate southern
319 palaeolatitudes on the Gondwanan margin (Fig. 2). At lower palaeolatitudes, the first
320 occurrence of the *Veryhachium lairdii* group is apparently in the lowermost Floian Stage or
321 higher (Servais *et al.* 2007). In South China, its first occurrence is in the *Tetragraptus*
322 *approximatus* graptolite Biozone (Yan *et al.* 2011), equivalent to the lower part of Stage Slice
323 Fl1 (Figs 1, 3). In NW Argentina, on the eastern margin of Gondwana, de la Puente &
324 Rubinstein (2013) recorded its first occurrence in the '*Baltograptus deflexus*' Biozone,
325 equivalent to Stage Slice Fl2, in sections from the Central Andean Basin (Fig. 2). More
326 recently, the *V. lairdii* group has also been found in the Cordillera Oriental, Central Andean
327 Basin, in levels below horizons with *Velachitina veligera* and thus possibly in the
328 Tremadocian (Rubinstein *et al.* in preparation). Based on these records, the FAD in East
329 Gondwana is placed tentatively at the base of the Floian Stage, indicated by a question mark
330 on Figure 3, and definitely at the base of Stage Slice Fl2.

331 On Baltica, rectangular specimens of *Veryhachium* spp. comparable with *V. lairdii* have
332 been recorded from the Lakity Beds of the Leetse Formation in the Lava River section of the
333 St Petersburg region (Molyneux *et al.* 2007, fig. 5). There they occur in the *T.*
334 *phyllograptoides* graptolite Biozone (lower part of Stage Slice Fl1), although not in the
335 lowest sample collected from that zone. The Lakity Beds are unconformable on the Nazya
336 Formation, which is correlated with the Varangu Regional Stage, the *Paltodus deltifer*
337 conodont Biozone and Stage Slice Tr2. Consequently, the lower part of the Hunneberg Stage,
338 equivalent to Stage Slice Tr3 and Time Slices 1c and 1d, is missing and the true FAD of
339 rectangular veryhachids in Baltica could be below the Lakity Beds. For now, the FAD of the
340 group is placed at about the base of the Floian Stage on Baltica (Fig. 3).

341
342 *Rhopaliophora* (Fig. 5L)

343
344 Li *et al.* (2014) revised the taxonomy and the biostratigraphical and palaeogeographical
345 distribution of the genus *Rhopaliophora*. The FAD of *Rhopaliophora* in North China was
346 recorded (Martin & Yin 1988, text-fig. 2) below the *Adelograptus-Clonograptus* with
347 *Kiaerograptus* graptolite 'horizon' but above the *Psigraptus* 'horizon'. The *Adelograptus-*
348 *Clonograptus* with *Kiaerograptus* graptolite 'horizon' has since been replaced in North China
349 by the *Aorograptus victoriae* Biozone (Zhang *et al.* 2004), which is equivalent to the biozone
350 of the same name in Australia (Fig. 1). This implies that the first occurrence of
351 *Rhopaliophora* in North China is in Stage Slice Tr2 or the upper part of Tr1, at a level

352 equivalent to the upper part of Time Slice 1b, and possibly represents its global FAD (Fig. 3).

353 *Rhopaliophora* is also reported to be present in the *P. deltifer* conodont Biozone of the
354 Fenghsiang Formation in South China (Brocke, unpublished Ph.D. thesis, Technische
355 Universität, Berlin, 1998). This occurrence, indicated by a question mark on Figure 3, would
356 also correlate with Stage Slice Tr2. A definite FAD in South China is placed at about the base
357 of Stage Slice Tr3 and Time Slice 1c, based on a record low in the *A. murrayi* Biozone
358 (Wang *et al.* 2013).

359 The FAD of *Rhopaliophora* is similarly placed at about the base of Stage Slice Tr3 and
360 Time Slice 1c in South Gondwana, East Gondwana, Baltica and Laurentia. In South
361 Gondwana, *Rhopaliophora* has been recorded from a *messaooudensis-trifidum* acritarch
362 assemblage low in the *A. murrayi* Biozone of Morocco (Nowak *et al.* 2016), which justifies
363 the position of the FAD in Figure 3. In East Gondwana, the FAD of *Rhopaliophora* is in the
364 *A. murrayi* Biozone of the Central Andean Basin, NW Argentina (Waisfeld *et al.* 2006; de la
365 Puente & Rubinstein 2009, fig. 2, 2013, fig. 3). In Baltica, *Rhopaliophora* has been recorded
366 from a level in the lower part of the upper Tremadocian *Paroistodus proteus* conodont
367 Biozone on the East European Platform (Paalits & Erdtmann 1993) and at an equivalent level
368 in the Oslo Region (Tongiorgi *et al.* 2003), which again suggests a level low in Stage Slice
369 Tr3 and Time Slice 1c. In Laurentia, the FAD of the genus marks the base of Microflora AU6
370 of Martin (1992), in the upper massive member of the Survey Peak Formation and the upper
371 part of trilobite zone F (equivalent to the *Rossaspis superciliosa* trilobite Biozone in the upper
372 part of the Stairsian Stage: Ross *et al.* 1997, fig. 10; see also Dean 1989). The upper part of
373 the Stairsian Stage correlates with the lower part of Stage Slice Tr3 (Fig. 1; Cooper & Sadler
374 2012).

375 For Avalonia, the FAD of the genus is slightly higher. The first occurrence of
376 *Rhopaliophora* in the *messaooudensis-trifidum* assemblage of NW England is at the base of
377 sub-assemblage 2 in the upper Tremadocian Stage, at a level above the base of the *A. murrayi*
378 graptolite Biozone and therefore above the base of Stage Slice Tr3 (Molyneux *et al.* 2007).
379 Correlation with Time Slices 1c and 1d of Webby *et al.* (2004) is uncertain, but the FAD is
380 certainly above the base of Time Slice 1c and possibly close to the boundary between 1c and
381 1d (Molyneux *et al.* 2007, fig. 4). This is where its FAD in Avalonia is placed in Figure 3.

382 Other Tremadocian occurrences of *Rhopaliophora* from Avalonia and South Gondwana
383 are higher. An assemblage with ?*Rhopaliophora* sp. from the Lierneux Member (Jalhay
384 Formation, Salm Group) of Belgium (Breuer & Vanguetaine 2004; Avalonia) is correlated
385 with the uppermost Tremadocian sub-assemblage 4 of the *messaooudensis-trifidum*

386 assemblage (Molyneux *et al.* 2007) and therefore probably with the upper part of Stage Slice
387 Tr3. An occurrence of *Rhopaliophora* in the Barriga Formation of Spain (South Gondwana)
388 is attributed to the top of sub-assemblage 3 or sub-assemblage 4 (Molyneux *et al.* 2007).
389 Nevertheless, it is below a graptolite assemblage containing *H. copiosus* (Servais & Mette
390 2000) and is therefore perhaps in the uppermost part of Time Slice 1c or in the lower part of
391 1d. In Bohemia (Fatka 1993; South Gondwana), *Rhopaliophora* is associated with the
392 chitinozoan *Amphorachitina conifundus*, which suggests a late Tremadocian (*A. murrayi* or
393 *H. copiosus* biozones) or possibly an earliest Floian age (Paris 1990), equivalent to Time
394 Slices 1c, 1d or possibly the lowest part of Time Slice 2a.

395

396 *Peteinosphaeridium* (Fig. 5M)

397

398 A revision of this widely recorded Ordovician genus, including biometrical studies, is much
399 needed. Of particular interest is the transition to the genus *Rhopaliophora*, as indicated by Li
400 *et al.* (2014). Playford *et al.* (1995) considered the FAD of *Peteinosphaeridium* to be in the
401 uppermost Tremadocian of Alberta, Canada, in the warm-water environments of Laurentia.
402 There, the FAD of *Peteinosphaeridium* coincides with that of *Rhopaliophora* at the base of
403 Microflora AU6 of Martin (1992), in the upper massive member of the Survey Peak
404 Formation and the upper part of trilobite zone F (equivalent to the *Rossaspis superciliosa*
405 trilobite Biozone in the upper part of the Stairsian Stage; Ross *et al.* 1997). The upper
406 Stairsian Stage is correlated with the lower part of Stage Slice Tr3 (Fig. 1; Cooper & Sadler
407 2012), and the FAD of *Peteinosphaeridium* is therefore shown at the base of Tr3 in Figure 3.

408 In contrast, Playford *et al.* (1995) considered the first occurrence of
409 *Peteinosphaeridium* in Perigondwanan regions to be in the Floian Stage (Arenig). However,
410 there is now evidence to show that the genus also has first occurrences in the upper
411 Tremadocian Stage Slice Tr3 around Gondwana and possibly also on Baltica.

412 In South China and East Gondwana (NW Argentina), the FAD of the genus is at the
413 same level as that of *Rhopaliophora* (Fig. 3) at about the base of Stage Slice Tr3 and Time
414 Slice 1c (Wang *et al.* 2013; de la Puente & Rubinstein 2009). In South Gondwana, the FAD
415 of *Peteinosphaeridium* in Bohemia coincides with that of *Rhopaliophora* (Fatka 1993) and is
416 therefore probably late Tremadocian or possibly earliest Floian in age, equivalent to Time
417 Slices 1c, 1d or possibly the lowest part of Time Slice 2a. Nowak *et al.* (2016), however,
418 noted a questionable occurrence low in the upper Tremadocian *A. murrayi* graptolite Biozone
419 of Morocco, at the same level as *Rhopaliophora*. The FAD of the genus in South Gondwana

420 is placed here at the same level as that of *Rhopaliophora*, at about the base of Stage Slice Tr3
421 (Fig. 3). The genus has been recorded from a *messauoudensis-trifidum* acritarch assemblage of
422 Avalonia in NW England (Molyneux & Rushton 1988), but its first occurrence in sub-
423 assemblage 2 is slightly higher (Fig. 3), probably close to the boundary between Time Slices
424 1c and 1d (Molyneux *et al.* 2007).

425 On Baltica, the genus has been recorded from the lower part of the *Paroistodus proteus*
426 conodont Biozone on the East European Platform (Paalits & Erdtmann 1993) and from the
427 Oslo Region (Tongiorgi *et al.* 2003), at levels that correlate with the upper Tremadocian and
428 probably in the lower part of Stage Slice Tr3. The first occurrence of *Peteinosphaeridium* on
429 Baltica is thus consistent with a late Tremadocian Stage Slice Tr3 age and is shown at about
430 the level of the FAD of the genus around Gondwana.

431

432 *Striatotheca* (Fig. 5O)

433

434 Servais (1997) revised the ‘veryhachid’ taxa *Arkonina* and *Striatotheca*. Both genera are
435 characteristic of the Perigondwanan acritarch province.

436 *Striatotheca* has its FAD on Avalonia in the lowest samples that have yielded the
437 *messauoudensis-trifidum* acritarch assemblage from NW England (Molyneux *et al.* 2007).
438 These are from the *Araneograptus murrayi* graptolite Biozone and probably close to the
439 bases of Stage Slice Tr3 and Time Slice 1c of Webby *et al.* (2004) (Figs 1, 3). Rare
440 specimens of *Striatotheca* were also recorded by Servais & Molyneux (1997) from the
441 *messauoudensis-trifidum* acritarch assemblage in core between depths of 3615.80 m and
442 3796.40 m in the Rügen 5 borehole on the island of Rügen. As with the *Veryhachium lairdii*
443 group, the Rügen 5 occurrences are probably close to the base of the *A. murrayi* Biozone and
444 the base of Tr3 on Avalonia. Occurrences of *Striatotheca* recorded by Nowak *et al.* (2016)
445 from Morocco are also low in the *A. murrayi* Biozone. These occurrences are used to position
446 the FAD of *Striatotheca* at the base of Stage Slice Tr3 and Time Slice 1c for Avalonia and
447 South Gondwana in Figure 3.

448 Other late Tremadocian occurrences from Avalonia and South Gondwana are from
449 higher stratigraphical levels. *Striatotheca* has been recorded from upper Tremadocian
450 *messauoudensis-trifidum* acritarch assemblages of South Wales (Molyneux & Dorning 1989)
451 and Belgium (Vanguetaine & Servais 2002; Breuer & Vanguetaine 2004), both on
452 Avalonia, and from Spain (Servais & Mette 2000), South Gondwana. The palynofloras from
453 Belgium and Spain are correlated with the upper part of sub-assemblage 3 and/or the

454 overlying sub-assemblage 4 of the *messaoudensis-trifidum* assemblage of NW England
455 (Molyneux *et al.* 2007), and therefore with the upper part of Stage Slice Tr3 and with a level
456 in Time Slice 1d. Correlation of the beds containing *Striatotheca* in South Wales is with
457 Stage Slice Tr3.

458 The upper Tremadocian occurrences of *Striatotheca* from Avalonia and South
459 Gondwana are all from high southern Early Ordovician palaeolatitudes. At lower
460 palaeolatitudes, *Striatotheca* has not yet been recorded from the Tremadocian Stage in South
461 China. The first recorded occurrence of the genus there is at the base of the Floian Stage (Yan
462 *et al.* 2011), equivalent to the bases of Stage Slice Fl1 and Time Slice 2a (Fig. 3). First
463 occurrences of *Striatotheca* in the Central Andean Basin of NW Argentina, situated at middle
464 palaeolatitudes on the eastern margin of Gondwana, are higher still, in the '*Baltograptus*
465 *deflexus*' Biozone (Ottone *et al.* 1992; Rubinstein & Toro 1999, 2001; Rubinstein *et al.* 1999;
466 de la Puente & Rubinstein 2013), and are correlated with Stage Slice Fl2 (Figs 1, 3). The
467 relatively high FAD of *Striatotheca* in NW Argentina could be a consequence of either lack
468 of samples from lower levels or environmental control on its distribution and occurrence, but
469 as no specimens have been recorded from *messaoudensis-trifidum* associations in Argentina
470 (e.g. de la Puente & Rubinstein 2009), it is possible that the progressively higher FADs of the
471 genus in South China and NW Argentina resulted from protracted migration of the genus
472 around the northern promontory of Gondwana (Fig. 2).

473

474 *Coryphidium* (Fig. 5G)

475

476 The genus *Coryphidium*, reviewed by Servais *et al.* (2008), is a common component of
477 acritarch assemblages from the Floian to Darriwilian stages of Perigondwana, but its first
478 occurrence is in the uppermost Tremadocian. The genus has not been recorded from Baltica
479 or Laurentia (Servais & Fatka 1997) and is one of the taxa used to define the Perigondwanan
480 acritarch province (Li 1989; Servais *et al.* 2003; Molyneux *et al.* 2013).

481 *Coryphidium* was reported by Fang (1986) from the Tremadocian Tangchi Formation
482 of South China, although the precise age of this record remains problematical. Wang *et al.*
483 (2013), however, recorded *Coryphidium* sp. from the Ningkuo Formation of the Jiangnan
484 Slope in South China, at the base of their Assemblage Zone C in the middle of the *A. murrayi*
485 Biozone. This is possibly its FAD in South China. It might also represent its global FAD and
486 is placed within Stage Slice Tr3 at about the base of Time Slice 1d on Figure 3.

487 In East Gondwana (NW Argentina), *Coryphidium?* sp. occurs in beds corresponding to
488 the *A. murrayi* Biozone (Stage Slice Tr3, Time Slices 1c to lower 1d), and *Coryphidium* sp.
489 (positive assignment) in beds corresponding to the *H. copiosus* Biozone (upper Stage Slice
490 Tr3, Time Slice 1d) (de la Puente & Rubinstein 2009, 2013). The former is indicated on
491 Figure 3 by a question mark at about the base of Time Slice 1d, and the latter by a definite
492 FAD within the time slice.

493 In Avalonia, the first occurrence of *Coryphidium* in NW England is in the upper part of
494 sub-assemblage 3 of the *messaooudensis-trifidum* assemblage, corresponding to the upper part
495 of Stage Slice Tr3 and probably at a level within Time Slice 1d (Molyneux *et al.* 2007). Other
496 Avalonian occurrences of *Coryphidium* at about the same level are from southern Ireland
497 (Connery & Higgs 1999; Todd *et al.* 2000) and Belgium (Vanguetaine & Servais 2002;
498 Breuer & Vanguetaine 2004), and the genus is also present at about the same level in the
499 *messaooudensis-trifidum* acritarch assemblage from the graptolitic Barriga Formation of SW
500 Spain (Servais & Mette 2000). It also occurs in possible transitional ‘latest Tremadoc-earliest
501 Arenig’ samples from south and SE Turkey (Martin 1996). The occurrences in Ireland, Spain
502 and Belgium are all probably from the upper part of Stage Slice Tr3 and within Time Slice 1d
503 (Molyneux *et al.* 2007, fig. 4). The first occurrence of *Coryphidium* throughout the
504 Perigondwana region is thus in the upper part of Stage Slice Tr3.

505

506 *Veryhachium trispinosum* group (Fig. 5S)

507

508 The first occurrence of triangular veryhachid acritarchs of the *V. trispinosum* group post-
509 dates that of the rectangular morphotypes of the *V. lairdii* group (Servais *et al.* 2007). The
510 global FAD is possibly from Avalonia, where the *V. trispinosum* group has its first
511 occurrence in sub-assemblage 3 of the *messaooudensis-trifidum* acritarch assemblage of NW
512 England (Molyneux *et al.* 2007), in the upper part of Stage Slice Tr3 and probably in the
513 lower part of Time Slice 1d (Fig. 3). Its first occurrence in Belgium (Vanguetaine & Servais
514 2002; Breuer & Vanguetaine 2004), also part of Avalonia, is in a *messaooudensis-trifidum*
515 assemblage comparable with sub-assemblage 4 in the Lake District, again in the upper part of
516 Stage Slice Tr3 and probably in the middle of Time Slice 1d.

517 The first occurrence of the group in Bohemia (Fatka 1993), part of the Armorican
518 Terrane Assemblage of South Gondwana, is in either the upper part of Tremadocian Stage
519 Slice Tr3 or possibly the lowermost part of the Floian Stage Slice Fl1. This occurrence is
520 broadly correlated with sub-assemblages 3–5 of the *messaooudensis-trifidum* assemblage in

521 NW England, and is therefore possibly at about the same level as in Avalonia or slightly
522 higher (Fig. 3). However, the group was not recorded by Nowak *et al.* (2016) from the upper
523 Tremadocian of Morocco, and Vecoli & Le Hérisse (2004) placed the FAD of *V. trispinosum*
524 at the base of the Floian Stage in their review of Ordovician acritarchs from the ‘North’
525 Gondwanan margin.

526 At lower palaeolatitudes, FADs of the *V. trispinosum* group around Gondwana are
527 currently post-Tremadocian. In South China, the *V. trispinosum* group, like the *V. lairdii*
528 group, has its FAD at the base of the Floian Stage, in the *Tetragraptus approximatus* Biozone
529 (Fig. 3; Xu 2001; Yan, unpublished Ph.D. thesis, Nanjing Institute of Geology and
530 Palaeontology 2007; Yan *et al.* 2011). In NW Argentina (East Gondwana), the *V. trispinosum*
531 group first appears at the base of Stage Slice F13 (de la Puente & Rubinstein 2013), so far its
532 highest first occurrence around Gondwana (Fig. 3). Achab *et al.* (2006) recorded the group
533 from the Suri Formation of unspecified Floian age in the Perigondwanan volcanic arc of the
534 Famatina System in NW Argentina, but Ottone *et al.* (1992) and Rubinstein *et al.* (1999)
535 recorded the lowest occurrences of *V. trispinosum* from the *Didymograptus bifidus* graptolite
536 Biozone in the Central Andean Basin, which equates with F13 (Fig. 3).

537 Although the *Veryhachium trispinosum* group is generally common and widespread
538 across palaeocontinents in the later Ordovician, its first occurrence on Baltica is apparently
539 much later than on the Perigondwanan margin (Servais *et al.* 2014). The oldest record
540 appears to be from the undivided Kunda Stage (B_{III}), equivalent to upper Stage Slice Dw1
541 and Stage Slice Dw2, in the Rapla Borehole of Estonia (Uutela & Tynni 1991). The group’s
542 FAD on Baltica is placed at the base of Stage Slice Dw2 (Fig. 3). There are no records at the
543 Tremadocian–Darriwilian level from Laurentia, but this could reflect a lack of data as much
544 as a real absence.

545
546 *Barakella* (Fig. 5E)

547
548 The genus *Barakella* was described originally from the late Arenig of Morocco (Cramer &
549 Díez 1977). It has since been reported widely around the Gondwanan margin, from high to
550 low Ordovician palaeolatitudes.

551 First definite occurrences of the genus on Avalonia and South China are in the lower–
552 middle Floian Stage. In South China, the FAD of the genus is placed in Stage Slice F11 in the
553 lower or middle Floian, in the lower part of Time Slice 2b or possibly in 2a (Yan *et al.*, in
554 press). On Avalonia, Molyneux (1987) recorded the genus from the upper part of the

555 Moridunian Stage of the Arenig Series in South Wales, approximately equivalent to Time
556 Slice 2b (Fig. 1). FADs in both areas are placed at the base of Time Slice 2b (Fig. 3), with a
557 question mark indicating its possible occurrence in Time Slice 2a in South China. However, it
558 is possible that the FAD of the genus is lower in Avalonia, based on a record of *Barakella?*
559 sp. at about the same level as the FAD of *Coryphidium* in NW England (Molyneux 2009).
560 This is in the upper part of sub-assembly 3 of the *messaoudensis-trifidum* assemblage,
561 corresponding to the upper part of Stage Slice Tr3 and probably at a level within Time Slice
562 1d (Molyneux *et al.* 2007).

563 Elsewhere around Gondwana, first occurrences of the genus tend to be in the middle or
564 upper Floian, or higher. The FAD of the genus in NW Argentina is in the ‘*B. deflexus*’
565 graptolite Biozone (de la Puente & Rubinstein 2013), which correlates with Stage Slice Fl2 in
566 the middle Floian and the upper part of Time Slice 2b (Fig. 1). Records from Pakistan
567 (Tongiorgi *et al.* 1994; Quintavalle *et al.* 2000) are slightly higher, from the *Azygograptus*
568 *suecicus* graptolite Biozone, which correlates with the upper part of Stage Slice Fl3 and the
569 lowermost Dapingian Stage Slice Dp1 (Fig. 1). The FADs for East Gondwana and West
570 Gondwana shown on Figure 3 are based on these records respectively, at the base of Stage
571 Slice Fl2 and the base of Stage Slice Dp1. However, given that there is another possible
572 middle Floian record from the Zard-Kuh Formation in the Zagros Basin of Iran (Ghavidel-
573 syooki 1996), although in this case correlation with global stages and stage slices is
574 imprecise, it is also possible that the FAD in West Gondwana is also at a level in the Floian
575 Stage.

576 Vecoli & Le Hérisse (2004) indicated the FAD of *Barakella fortunata* on the ‘northern
577 Gondwanan margin’ (corresponding largely to South Gondwana as defined herein) to be at
578 the base of the *Desmochitina ornensis* chitinozoan Biozone, which correlates approximately
579 with the base of the Dapingian (Stage Slice Dp1) and the base of Time Slice 3a (Fig. 1). The
580 FAD in South Gondwana is therefore placed at the base of the Dapingian Stage.

581 The occurrence of the genus on other palaeocontinents is unconfirmed. *Barakella?* sp.
582 was recorded from Sweden (Baltica) by Ribecai & Tongiorgi (1995), where its FAD is in the
583 Hunderum Substage of the Kunda Stage, which correlates with a level in the Darriwilian
584 (upper Dw1–lower Dw2; Fig. 1). A questionable FAD is placed at about the base of Stage
585 Slice Dw2.

586

587

Figure 4 about here

588

589 *Aureotesta clathrata simplex* (Fig. 5C)

590

591 Recorded as *Marrocanium simplex* before its taxonomic reassignment by Brocke *et al.*
592 (1998), *A. clathrata simplex* is easily recognizable. It was first described from Morocco
593 (South Gondwana; Cramer *et al.* 1974) at a level that is now correlated with the
594 *Desmochitina bulla* chitinozoan Biozone (Soufiane & Achab 1993) and therefore with the
595 lower Darriwilian Dw1 Stage Slice (Fig. 1). However, the first occurrence of *Aureotesta*
596 *clathrata simplex* in NW England (Avalonia) is in sub-assemblage 5 of the *messauoudensis-*
597 *trifidum* assemblage, considered to be of early Floian age (Molyneux *et al.* 2007) and
598 correlated with Stage Slice F11. Molyneux *et al.* (2007) considered the FAD of *A. clathrata*
599 *simplex* in NW England to be close to the base of the *T. phyllograptoides* Biozone. The first
600 occurrence of *A. clathrata simplex* in South China is also in the early Floian, in the *T.*
601 *approximatus* graptolite Biozone (Yan, unpublished Ph.D. thesis, Nanjing Institute of
602 Geology and Palaeontology 2007; Yan *et al.* 2011), and is therefore close to its FAD in NW
603 England. These records are the criteria used to place the FAD of *A. clathrata simplex* at the
604 base of the Floian Stage in both Avalonia and South China (Fig. 4).

605 The FAD of *A. clathrata simplex* in South Gondwana is uncertain, but based on a
606 record from the *Corymbograptus v-similis* graptolite Biozone (Vavrdová 1993) of Bohemia it
607 is likely to be in the Floian Stage. The *C. v-similis* Biozone is low in the Arenig Klabava
608 Formation of Bohemia and has been correlated with the *Pseudodidymograptus balticus*
609 Biozone of Baltica (Paris & Mergl 1984, table 1), which in turn is correlated with Time Slice
610 2b (Webby *et al.* 2004). The FAD of *A. clathrata simplex* in South Gondwana is placed at the
611 base of Time Slice 2b (Fig. 4), but this does not exclude the possibility that the true FAD is
612 lower and at about the same level as in Avalonia or South China.

613 The first occurrence of *A. clathrata simplex* in NW Argentina (East Gondwana) is
614 higher (Fig. 4), in the '*Baltograptus deflexus*' graptolite Biozone (Rubinstein *et al.* 2007; de
615 la Puente & Rubinstein 2013), which is correlated with Stage Slice F12 (Fig. 1). In common
616 with other taxa, *A. clathrata simplex* appears to have had a later first occurrence on the
617 eastern Gondwanan margin than at high southern palaeolatitudes.

618 *A. clathrata simplex* has not been reported from Baltica and so remains an indicator of
619 the 'Perigondwanan' acritarch bioprovince (Li 1989; Servais *et al.* 2003; Molyneux *et al.*
620 2013).

621

622 *Arbusculidium filamentosum* (Fig. 5B)

623

624 *Arbusculidium filamentosum* is another characteristic species of the Perigondwanan acritarch
625 province and has its FAD in the middle Floian around Gondwana. In Avalonia, the FAD of
626 the species is in sub-assemblage 5 of the *messauoudensis-trifidum* assemblage of NW
627 England, between beds that are correlated with the *Tetragraptus phyllograptoides* and
628 *Corymbograptus varicosus* graptolite biozones (Molyneux *et al.* 2007). This level is within
629 Stage Slice F11 and probably equates with the lower part of Time Slice 2b (Figs 1, 4). The
630 FAD of *Arbusculidium filamentosum* in Bohemia (Armorican Terrane Assemblage) is in the
631 *Corymbograptus v-similis* graptolite Biozone (Vavrdová 1993), which is correlated with
632 Time Slice 2b (see *Aureotesta clathrata simplex*). Based on these records, the FAD of *A.*
633 *filamentosum* in both Avalonia and South Gondwana is placed here at the base of Time Slice
634 2b (Fig. 4).

635 The FAD of *Arbusculidium filamentosum* might be slightly higher at lower
636 palaeolatitudes and on the eastern margin of Gondwana. Studies in South China (Yan,
637 unpublished Ph.D. thesis, Nanjing Institute of Geology and Palaeontology 2007; Yan *et al.*
638 2011) have established that its first occurrence there is in the *Didymograptus eobifidus*
639 graptolite Biozone, which is correlated with Stage Slice F12 and the upper part of Time Slice
640 2b. In NW Argentina (East Gondwana), the first occurrence of *A. filamentosum* is correlated
641 with the '*B. deflexus*' graptolite Biozone (Rubinstein & Toro 2001; Rubinstein *et al.* 2007; de
642 la Puente & Rubinstein 2013), which is again correlated with Stage Slice F12 and the upper
643 part of Time Slice 2b. The FAD of the species is placed here at the base of Stage Slice F12 in
644 both areas (Fig. 4).

645

646 *Coryphidium bohemicum* (Fig. 5F)

647

648 *Coryphidium bohemicum*, the type species of the genus, has been reported from many
649 localities around the margin of Gondwanan and is one of the characteristic species of the
650 Perigondwanan acritarch assemblages (Li 1989). It has not been recorded from other
651 palaeocontinents. FADs of the species around Gondwana are in the Floian Stage, and within
652 Time Slice 2b.

653 Cooper *et al.* (1995) defined the *Stelliferidium trifidum-Coryphidium bohemicum*
654 assemblage in the upper part of the Hope Beck Formation in NW England, overlain by beds
655 that contain the *Coryphidium bohemicum* assemblage in the Loweswater Formation. The

656 incoming of *C. bohemicum* in the *trifidum-bohemicum* Biozone is above the highest *T.*
657 *phyllograptoides* Biozone graptolite faunas, but below the lowest *C. varicosus* Biozone
658 faunas (Molyneux *et al.* 2007). Correlation of this interval is with the middle and upper parts
659 of Stage Slice F11 and the lower part of Time Slice 2b (Fig. 1). The FAD of *C. bohemicum* in
660 NW England is above that of *A. filamentosum* so is shown above the base of Time Slice 2b
661 on Figure 4, but still in its lower part and therefore in the upper part of Stage Slice F11.

662 The FAD of *C. bohemicum* in Bohemia, representing South Gondwana, is at the same
663 level as the FADs there of *Aureotesta clathrata simplex* and *Arbusculidium filamentosum*, in
664 the *Corymbograptus v-similis* graptolite Biozone (Vavrdová 1993), and is similarly placed
665 here at the base of Time Slice 2b (Fig. 4). The oldest records of *C. bohemicum* from South
666 China are from the *A. filiformis* graptolite Biozone (Yan *et al.* 2011), which also corresponds
667 to the lower part of Time Slice 2b and the upper part of Stage Slice F11, and the FAD there is
668 again placed at the base of Time Slice 2b (Fig. 4). The specimen of '*C. bohemicum*' recorded
669 by Xu (1999) from the *T. approximatus* graptolite Biozone of the Sandu area in South China
670 does not belong to the species.

671 Comparable forms have a slightly higher first occurrence on the east Gondwanan
672 margin in NW Argentina. There, *Coryphidium* cf. *bohemicum* has its first occurrence in the
673 '*B. deflexus*' Biozone (Rubinstein & Toro 1999, 2001; Rubinstein *et al.* 2007; de la Puente &
674 Rubinstein 2013), correlated with Stage Slice F12 and the upper part of Time Slice 2b. Its
675 FAD in East Gondwana is placed at the base of Stage Slice F12 (Fig. 4).

676
677 *Sacculidium* (Fig. 5N)

678
679 *Sacculidium* has been recorded from around Gondwana, from South China and from Baltica.
680 Its global FAD is in South China, where it is present in the *Acrograptus filiformis* graptolite
681 Biozone (Yan *et al.* 2013). This establishes the global FAD of *Sacculidium* in the Floian
682 Stage, equivalent to the upper part of Stage Slice F11 and the lower part of Time Slice 2b
683 (Fig. 1), and it is placed herein at the base of Time Slice 2b (Fig. 4). However, the genus is
684 not widespread below the Dapingian Stage.

685 *Sacculidium* is common in the Middle Ordovician Volkhov and Kunda regional stages
686 of Baltica. The lowest recorded occurrence in Baltica is from the Langevoja Substage of the
687 Volkhov Stage in Sweden (Ribecai & Tongiorgi, 1995, recorded as '*Peteinosphaeridium*
688 *macropylum*'; Ribecai *et al.* 2002), which correlates with the uppermost Dapingian to lowest
689 Darriwilian stages (top Dp3–lower Dw1 stage slices, top 3b–lower 4a time slices; Fig. 1).

690 The FAD of the genus in Baltica is placed at the base of Stage Slice Dw1 (Fig. 4). Other
691 records from Baltica are from around the same level. Those from Estonia (Uutela & Tynni
692 1991; Ribecai *et al.* 2002), Baltic Russia (St Petersburg region: Ribecai *et al.* 2002) and
693 Arctic Russia (Arkhangelsk region: Ribecai *et al.* 2002; Raevskaya *et al.* 2006) are reported
694 to be from the upper Volkhov Stage. In Norway, *Sacculidium* has been recorded from the
695 Hunderum Substage of the Kunda Stage (Ribecai *et al.* 1999; Ribecai *et al.* 2002; Tongiorgi
696 *et al.* 2003), corresponding to the upper Dw1–basal Dw2 stage slices and the upper 4a Time
697 Slice (Fig. 1).

698 Around Gondwana, the genus is also present in the Llanvirn Series (Darriwilian Stage)
699 of North Africa (Ribecai *et al.* 2002, previously recorded as '*Peteinosphaeridium*
700 *macropylum* s.l.' in Tunisia). In the Canning Basin of Australia (Fig. 2), Quintavalle &
701 Playford (2006a, b) recorded it from the *C. setarium* Biozone, correlated with the upper
702 Dapingian and lower Darriwilian stages, and from overlying zones. In NW Argentina, Achab
703 *et al.* (2006) recorded *Ammonidium* [*Sacculidium*] cf. *A. aduncum* Playford & Martin 1984,
704 from the Molles Formation in the Famatina System, probably equivalent to the Dapingian
705 *Baltoniodus navis* conodont Biozone. Based on these records, FADs are placed respectively
706 at the base of Stage Slice Dw2 (base Llanvirn Series) in South Gondwana, the base of the
707 Darriwilian Stage in West Gondwana, and the base of the Dapingian Stage in East
708 Gondwana.

709
710 *Dasydorus* (Fig. 5I)

711
712 First described from the Middle Ordovician of Australia by Playford & Martin (1984), the
713 genus *Dasydorus* has since been cited from other parts of Gondwana and from other
714 palaeocontinents, including Baltica. The genus is present on the Gondwanan margin from low
715 palaeolatitudes (Australia) to high palaeolatitudes. Examples of the latter include its
716 occurrences in the *Bergamia rushtoni* trilobite Biozone (regional Fennian Stage, equivalent to
717 the Dapingian and lower Darriwilian stages) of South Wales (Molyneux 1987) and the
718 Llanvirn Series of Tunisia (Vecoli 1999). Le Hérissé *et al.* (2007) recorded the genus from
719 the early Middle Ordovician of Saudi Arabia.

720 Li *et al.* (2003) indicated the first occurrences of *Dasydorus* in South China to be close
721 to the Dapingian–Darriwilian boundary. Revision of Ordovician sequences in South China,
722 however, has shown that the genus is common in the *A. suecicus* graptolite Biozone (Floian–
723 Dapingian boundary), but that its first occurrence is in the *D. eobifidus* graptolite Biozone

724 (Yan, unpublished Ph.D. thesis, Nanjing Institute of Geology and Palaeontology 2007; Yan *et*
725 *al.* 2011). The *D. eobifidus* Biozone correlates with the middle Floian Stage Slice F12 (Fig.
726 1), and the FAD of the genus in South China is accordingly positioned at the base of F12 (Fig.
727 4).

728 On Baltica, Raevskaya *et al.* (2004) indicated the occurrence of *Dasydorus* in the *O.*
729 *evae* conodont Biozone of the Billingen Stage in the St. Petersburg area, which again
730 suggests a mid to late Floian age, equivalent to Stage Slice F12 or F13 (Fig. 1). Based on this
731 evidence, the FAD of *Dasydorus* in Baltica is again placed at the base of Stage Slice F12,
732 although it could be higher (Fig. 4).

733 A specimen attributed to *Dasydorus* sp. was illustrated by Vavrdová (1993, plate 1.1)
734 from the *Corymbograptus v-similis* graptolite Biozone in the Klabava Formation of the
735 Prague Basin, Bohemia. Based on this specimen, the FAD of *Dasydorus* in Bohemia,
736 representing South Gondwana, is placed at the same level there as the FADs of *Aureotesta*
737 *clathrata simplex*, *Arbusculidium filamentosum* and *Coryphidium bohemicum*, at the base of
738 Time Slice 2b in Stage Slice F11 (Fig. 4).

739 The FADs of *Dasydorus* on Avalonia and at lower palaeolatitudes on the western
740 margin of Gondwana are higher. On Avalonia, the record from middle of the upper Arenig
741 Fennian Stage of South Wales correlates approximately with the base of the Darriwilian
742 Stage (Fig. 1), and the FAD is therefore placed at that level (Fig. 4). In the Canning Basin of
743 Western Australia, the FAD of *Dasydorus* is in the *Aremoricanium solaris* acritarch Biozone,
744 which is correlated with the upper *D. artus* and *D. murchisoni* graptolite biozones of the
745 Llanvirn Series (Quintavalle & Playford 2006b), and in Saudi Arabia is at the base of the
746 Llanvirn Hanadir Member in well QSIM-801 (Le Hérisse *et al.* 2007). Based on the
747 occurrences from Western Australia and Saudi Arabia, the FAD of *Dasydorus* in West
748 Gondwana is placed at the base of Stage Slice Dw2, correlating with the base of the Llanvirn
749 Series (Figs 1, 4).

750

751 *Ampullula* (Fig. 5A)

752

753 The genus *Ampullula* was first described by Righi (1991) and subsequently revised by
754 Brocke (1997) and Yan *et al.* (2010). The first occurrence of *Ampullula* in South China (Yan
755 *et al.* 2010, fig. 3; Yan *et al.* 2011) is in the *D. eobifidus* graptolite Biozone of the Yangtze
756 Platform (Stage Slice F12, upper Time Slice 2b), and the FAD is placed herein at the base of
757 F12 (Fig. 4). The first occurrence of the genus in Argentina could be at about the same level.

758 In the Famatina System of NW Argentina, the first occurrence of the genus is in the upper
759 Suri Formation in beds containing chitinozoans of the *Eremochitina brevis* Biozone and
760 correlated with the *Oepikodus evae* conodont Biozone (Achab *et al.* 2006). Achab *et al.*
761 (2006) suggested that the presence of *Ampullula* in the upper Suri Formation indicated a
762 probable latest Early Ordovician age, corresponding to Time Slice 2c, but correlation with the
763 *O. evae* conodont Biozone and the *E. brevis* chitinozoan Biozone does not rule out
764 equivalence to the upper part of Time Slice 2b. The FAD for East Gondwana is therefore
765 placed tentatively at the base of Stage Slice Fl2 and more definitely at the base of Time Slice
766 2c (Fig. 4).

767 The first occurrence of the genus in Baltica is also in the upper Floian Stage, in Norway
768 (Tongiorgi *et al.* 2003, Billingen Stage, *O. evae* conodont Biozone), Poland (Raevskaya *et al.*
769 2004, Billingen Stage, *Phyllograptus angustifolius elongatus* graptolite Biozone, uppermost
770 Floian Stage) and Baltic Russia (Raevskaya *et al.* 2004, Billingen Stage, *O. evae* conodont
771 Biozone). The *P. angustifolius elongatus* Biozone correlates with the upper part of Time
772 Slice 2c (Webby *et al.* 2004, fig. 2.1) so the occurrence of *Ampullula* in Poland is later than
773 its first occurrence in South China. Correlation of the other records with the *O. evae* Biozone,
774 while establishing late Floian ages, is insufficiently precise to establish whether they are
775 coeval with or younger than the first occurrence in South China. A definite FAD of
776 *Ampullula* in Baltica is therefore placed in the middle of Time Slice 2c, at about the base of
777 the *P. angustifolius elongatus* Biozone, and a tentative FAD at the base of Stage Slice Fl2,
778 coinciding with the base of the *O. evae* Biozone (Figs 1, 4).

779 On the western margin of Gondwana, *Ampullula* has been recorded from the
780 *Azygograptus suecicus* graptolite Biozone of Pakistan (Quintavalle *et al.* 2000), correlated
781 with the upper part of Floian Stage Slice Fl3 and Time Slice 2c and the lowermost part of
782 Dapingian Stage Slice Dp1 and Time Slice 3a (Fig. 1). The FAD is placed here at about the
783 base of Time Slice 3a in the uppermost Floian Stage. At higher palaeolatitudes on the
784 Gondwanan margin, the FAD seems to have been later. The species *Ampullula suetica*, for
785 example, was shown by Vecoli & Le Hérisse (2004, fig. 5) as having its first occurrence in
786 the Darriwilian *Cyathochitina calix* chitinozoan Biozone, at the base of the regional Llanvirn
787 Series (bases of Stage Slice Dw2 and Time Slice 4b). The FAD of the genus in South
788 Gondwana is therefore placed at the base of Dw2 (Fig. 4).

789
790 *Liliosphaeridium* (Fig. 5K)

791

792 *Liliosphaeridium* is closely related to *Peteinosphaeridium*. Both possess laminate processes,
793 but those of *Liliosphaeridium* are modified distally in the form of a more or less distinct
794 calyx. Although these distally elaborated processes might be an expression of ecophenotypic
795 controls within the peteinoid acritarch plexus (see also Bagnoli & Ribecai 2001),
796 *Liliosphaeridium* appears to have independent biostratigraphical value and its global FAD is
797 later than that of *Peteinosphaeridium*.

798 Playford *et al.* (1995, fig. 8) indicated the FAD of *Liliosphaeridium* to be in the Middle
799 Ordovician of Baltica. There, *Liliosphaeridium* has been recorded from the Volkhov and
800 Kunda stages. The genus has been recorded from the Langevoja Substage of the Volkhov
801 Stage in Sweden (Ribecai & Tongiorgi 1995; Bagnoli & Ribecai 2001), correlated with the
802 uppermost Dapingian to lowest Darriwilian stages (top Dp3–lower Dw1 stage slices, top 3b–
803 lower 4a time slices; Fig. 1). The earliest occurrence in NW Russia (Arkhangelsk: Raevskaya
804 *et al.* 2006) is also reported to be from the upper Volkhov Stage, and that in Estonia (Uutela
805 & Tynni 1991) is from an undivided Volkhov Stage, but probably also from the upper part of
806 the stage (Langevoja Substage: compare with records of *Sacculidium macropylum* in Ribecai
807 *et al.* 2002). In Norway, *Liliosphaeridium* has been recorded from the uppermost
808 *Didymograptus hirundo* graptolite Biozone and the *Asaphus expansus* trilobite Biozone, both
809 correlated with the Hunderum Substage of the Kunda Stage (Ribecai *et al.* 1999; Pärnaste *et*
810 *al.* 2013, fig. 3) and corresponding to the upper Dw1–basal Dw2 stage slices and the upper 4a
811 Time Slice. Based on these records, the FAD of *Liliosphaeridium* in Baltica is placed at the
812 base of the Darriwilian Stage (Fig. 4).

813 *Liliosphaeridium* also has its first appearance in the Middle Ordovician of North Africa
814 and other high latitude Perigondwanan areas, and its FAD was placed at about the base of the
815 Darriwilian Stage by Vecoli & Le Hérissé (2004, fig. 5). It is accordingly placed here at the
816 same level for South Gondwana (Fig. 4). Its FAD in West Gondwana is placed slightly
817 higher, at the base of Stage Slice Dw2 (Fig. 4), based on records of *Peteinosphaeridium*
818 *intermedium* from middle–upper Darriwilian Stage strata of Oman (Rickards *et al.* 2010), but
819 this might also reflect the lack of suitable lower Darriwilian facies meaning that its true FAD
820 in West Gondwana could be lower.

821 In contrast, *Liliosphaeridium* has been recorded from the *D. eobifidus* graptolite
822 Biozone (Yan, unpublished Ph.D. thesis, Nanjing Institute of Geology and Palaeontology
823 2007; Yan *et al.* 2011) of South China, indicating a first occurrence in the middle Floian
824 Stage Slice Fl2 and the upper part of Time Slice 2b. Its FAD in South China is here placed at
825 the base of Stage Slice Fl2 (Fig. 4).

826 The first occurrence of *Liliosphaeridium* might be at a similar level in East Gondwana,
827 where *Peteinosphaeridium trifurcatum intermedium* was recorded by Ottone *et al.* (1992) and
828 Rubinstein & Toro (2001) from the '*B. deflexus*' graptolite Biozone of NW Argentina.
829 However, de la Puente & Rubinstein (2013, fig. 3) placed the FAD of *Liliosphaeridium*
830 *intermedium* at the base of the Darriwilian Stage (base of Stage Slice Dw1 and Time Slice 4a)
831 in the Central Andean Basin, and Rubinstein *et al.* (2011) placed the FAD of the same species
832 at about the same level in the Capillas Formation of the Sierras Subandinas. Hence, the FAD
833 of *Liliosphaeridium* in East Gondwana is placed tentatively at the base of Stage Slice F12 and
834 more definitely at the base of Stage Slice Dw1 (Fig. 4).

835 The genus might therefore be an indicator for the middle Floian in low to intermediate
836 palaeolatitude Perigondwanan regions, with a first appearance in Stage Slice F12 and the
837 upper part of time-slice 2b, but with a wider biogeographical distribution including Baltica
838 and high palaeolatitude Perigondwana from the late Dapingian onwards.

839
840 *Frankea* (Fig. 5J)

841
842 Servais (1993) revised the genus *Frankea* and reviewed its stratigraphical occurrence. More
843 recently, Wang *et al.* (in press) revised its taxonomy. *Frankea* is a distinctive genus that
844 commonly occurs in assemblages from the Dapingian onwards at high to mid palaeolatitudes
845 on the western margin of Gondwanan, including Avalonia (Servais *et al.* 2003). It has not
846 been recorded from low palaeolatitudes of West Gondwana, or from South China, or from
847 East Gondwanan assemblages of NW Argentina. Nor has it been recorded from other
848 palaeocontinents. It is possibly a temperature-sensitive genus that is restricted to the margin
849 of Gondwana at higher palaeolatitudes (Fig. 2).

850 A rare early occurrence of *Frankea* is known from the Avalonian succession on the Isle
851 of Man in the British Isles, where a single specimen was recorded from an upper
852 *messaoudensis-trifidum* or *trifidum-bohemicum* assemblage (Molyneux 1999). Correlation of
853 this occurrence is with the *Tetragraptus phyllograptoides* or low *Corymbograptus varicosus*
854 graptolite Biozone and with an interval in the lower Floian Stage Slice F11 (Molyneux 1999).
855 Based on this, the FAD of the genus on Avalonia is provisionally indicated at about the base
856 of Time Slice 2b (Fig. 4). Another possible Floian occurrence on Avalonia is from the
857 Abbaye de Villers Formation in Belgium. The formation is considered to be of late Dapingian
858 to earliest Darriwilian age (Herbosch & Verniers 2014), but chitinozoans recorded by

859 Samuelsson & Verniers (2000), which include *Eremochitina brevis*, point to a possible older,
860 late Floian age (Fig. 1) for at least part of the formation (but see below).

861 Most records of the genus from Avalonia and elsewhere are from Dapingian or younger
862 successions. Cooper *et al.* (1995) indicated that their *Frankea hamata*-*Striatotheca*
863 *rarirrugulata* assemblage in NW England originated in the *I. gibberulus* graptolite Biozone
864 but above its base, so probably within Time Slice 3b. Based on these records, a definite FAD
865 of the genus on Avalonia is placed at about the base of Stage Slice Dp3 (Fig. 4).

866 Other occurrences on Avalonia are from South Wales and Belgium. The recorded
867 occurrence of *Frankea* in the Arenig succession of South Wales is in the middle of the
868 Fennian Stage (Molyneux 1987), in the upper part of the *Stapeleyella abyfrons* trilobite
869 Biozone. This level is also above the base of the *I. gibberulus* graptolite Biozone (Fortey &
870 Owens 1987, figs 5, 11), so is probably at about the same level as the FAD of the genus in
871 NW England. On the Brabant Massif of Belgium, *Frankea* is present in several formations
872 below the lower Llanvirn *Didymograptus artus* graptolite Biozone (Servais 1991; Servais *et*
873 *al.* 1993), including the Abbaye de Villers Formation at the base of the Rebecq Group
874 (Herbosch & Verniers 2014). The Abbaye de Villers Formation rests unconformably on the
875 Tremadocian Chevlipont Formation, so records from this formation do not help to establish
876 the global FAD of *Frankea*. Although as noted above chitinozoans have been interpreted as
877 suggesting a possible Floian age for the Abbaye de Villers Formation, the acritarch
878 assemblage from the formation corresponds to the late Dapingian to earliest Darriwilian *F.*
879 *hamata*-*S. rarirrugulata* assemblage of NW England (Vanguetaine & Wauthoz 2011).

880 The lowest records of *Frankea* from South Gondwana are of late Arenig age, for
881 example from Morocco (Cramer & Diez 1977; Deunff 1977; Elaouad Debbaj 1984) and
882 Bohemia (Vavrdová 1977, 1993), while Vecoli & Le Hérissé (2004) placed the first
883 occurrence of the genus at about the base of the Darriwilian Stage. The lowest recorded
884 occurrence on the Arabian Plate (West Gondwana) is also probably of late Arenig age, from
885 the Saq Formation of Saudi Arabia (Le Herisse *et al.* 2007). Based on these records, the FAD
886 of *Frankea* is placed at about the base of the Darriwilian Stage in South Gondwana and West
887 Gondwana (Fig. 4).

888
889 *Arkonia* (Fig. 5D)

890
891 Servais (1997) noted the occurrence of *Arkonia* in the upper Arenig Series (Dapingian–lower
892 Darriwilian stages), but more recent work has established its presence in lower Arenig

893 successions. In South China, for example, *Arkonia tenuata* has been recorded from the *C.*
894 *deflexus* graptolite Biozone (Yan & Li 2005; Yan *et al.* 2011), from the lower parts of Floian
895 Stage Slice Fl3 and Time Slice 2c (Fig. 1). The FAD of the genus in South China is therefore
896 placed here at the base of Fl3, representing its global FAD.

897 There are also possible upper Floian records of *Arkonia* from East Gondwana. The first
898 verified occurrences of *Arkonia* (*A. tenuata*) in NW Argentina are at the base of the Capillas
899 Formation in the Sierras Subandinas (Rubinstein *et al.* 2011), interpreted as being Darriwilian
900 in age (Stage Slice Dw1), and at the base of the Darriwilian Stage (base Dw1) in the Central
901 Andean Basin (de la Puente & Rubinstein 2013, fig. 3). However, *Striatotheca triangulata*,
902 originally *Rugulidium triangulata* Cramer *et al.*, 1974, but recombined as *Striatotheca*
903 *triangulata* by Eisenack *et al.* (1976) and then as *Arkonia triangulata* by Vavrdová (1978),
904 was recorded by Ottone *et al.* (1992) and Rubinstein & Toro (2001) from the *D. bifidus*
905 graptolite Biozone. The graptolite zone is correlated with the upper Floian Stage Slice Fl3
906 and with Time Slices 2c to basal 3a (Fig. 1). A tentative FAD is placed at the base of Stage
907 Slice Fl3, and a more definite FAD at the base of Dw1 (Fig. 4).

908 The FAD of the genus in South Gondwana is probably within the Dapingian Stage (Fig.
909 4). Vavrdová (1990) recorded *Arkonia tenuata* from the *Azygograptus ellesi-Tetragraptus*
910 *reclinatus abbreviatus* graptolite Biozone of Bohemia, which is probably of Dapingian and
911 possibly earliest Darriwilian age (e.g. Kraft & Kraft 2003, fig. 1b). The FAD of the genus in
912 South Gondwana is therefore placed at the base of the Dapingian Stage (Fig. 4), although
913 with some uncertainty over its exact level. The specimens of *Rugulidium triangulata*
914 recorded by Cramer *et al.* (1974) from the Tadla Basin of Morocco are from levels attributed
915 to the *D. bulla* chitinozoan Biozone (Soufiane & Achab 1993), which correlates with
916 Darriwilian Stage Slice Dw1 and Time Slice 4a (Fig. 1).

917 On Avalonia, *Arkonia* is questionably present in assemblages from the late Arenig
918 Kirkstile and Buttermere formations of NW England, correlated with the *Isograptus*
919 *gibberulus* and *Aulograptus cucullus* graptolite biozones, with Stage Slices Dp2–Dw1 and
920 with Time Slices 3b and 4a, and is definitely present in the Llanvirn Tarn Moor Formation,
921 correlated with Stage Slices Dw2–lower Dw3 and Time Slices 4b–lower 4c (Molyneux
922 2009). A tentative FAD is placed at the base of Stage Slice Dw1, and a definite FAD at the
923 base of Stage Slice Dw2 (Fig. 4).

924

925 *Dicrodiacrodium* (Fig. 5Q)

926

927 Servais *et al.* (1996) revised the taxonomy of *Dicrodiacrodium* and reviewed its
928 stratigraphical distribution. The genus was first described from the Llanvirn of Germany by
929 Burmann (1970), and has subsequently been used as a stratigraphical index fossil for upper
930 Arenig–lower Llanvirn successions (Servais *et al.* 1996, fig. 4). Most records of the genus,
931 however, are from strata that lack independent age control.

932 Brocke *et al.* (2000) reported the first occurrence of the genus to be at the base of the
933 *Undulograptus sinodentatus* graptolite Biozone in South China. These data were used by Li
934 *et al.* (2003) to indicate its first occurrence in the upper part of the Dapingian Stage (Time
935 Slice 3b). Investigations by Yan (unpublished Ph.D. thesis, Nanjing Institute of Geology and
936 Palaeontology 2007) and Yan *et al.* (2011) now indicate a first occurrence of the genus to be
937 at about the base of the *A. suecicus* graptolite Biozone in South China, and therefore its FAD
938 to be in the upper part of Stage Slice F13 and the upper part of Time Slice 2c (Figs 1, 4).

939 At higher palaeolatitudes around South Gondwana, Vecoli & Le Hérissé (2004) placed
940 the FAD of the genus in the *E. brevis* chitinozoan Biozone of Paris (1990), which
941 corresponds to the upper part of the Floian Stage, spanning most of Stage Slices F12 and F13
942 (Fig. 1). The FAD of the genus in South Gondwana is placed at the same level in the upper
943 Floian Stage Slice F13 as in South China (Fig. 4).

944 For Avalonia, Servais *et al.* (1996, fig. 4) indicated FADs based on graptolite control at
945 the base of the Llanvirn Series, for example in successions in the British Isles and Belgium,
946 but with possible upper Arenig occurrences in Belgium based on the associated acritarchs.
947 From this, the FAD of *Dicrodiacrodium* in Avalonia is placed tentatively at the base of the
948 Dapingian Stage, and with more certainty at the base of Stage Slice Dw2, correlated with the
949 base of the Llanvirn Series (Figs 1, 4).

950

951 *Orthosphaeridium* (Fig. 5R)

952

953 The genus *Orthosphaeridium* was described by Eisenack (1968) and comprises several
954 species. Burmann (1970) later described the morphologically similar genus *Baltisphaera*. The
955 two genera are probably synonymous, although the taxonomy has yet to be revised. The
956 genus is commonly found in Llanvirn strata (middle Darriwilian Stage) of Germany, Belgium
957 (e.g. Burmann 1976; Servais 1991) and Saudi Arabia (Le Hérissé *et al.* 2007).

958 The first occurrence of *Orthosphaeridium* in South China is in the *Expansograptus*
959 *hirundo* graptolite Biozone, correlated with the upper part of Dapingian Stage Slice Dp1 and
960 the overlying Dp2, and with the upper Time Slice 3a and lower Time Slice 3b (Yan *et al.*

961 2011; Fig. 1). The FAD of the genus in South China is placed within this interval, at the base
962 of Time Slice 3b (Fig. 4).

963 Records of the *Orthosphaeridium-Baltisphaera* complex elsewhere also suggest first
964 occurrences at about the same level, in the upper Arenig Series, but are correlated less
965 precisely. For Avalonia, Molyneux (1987) recorded *Orthosphaeridium* from the regional
966 Fennian Stage of the upper Arenig Series in South Wales, equivalent to the Dapingian–lower
967 Darriwilian stages (Dp1–Dw1), and Cooper *et al.* (1995) recorded *Orthosphaeridium*
968 *bispinosum* in the upper part of the *Frankea hamata-Striatotheca rarirrugulata* acritarch
969 assemblage in NW England, also of late Arenig age and probably from the upper Dapingian–
970 lower Darriwilian stages (Dp2–Dw1). In neither succession are there records of the genus
971 below these levels. The FAD of the genus in Avalonia is placed at the base of Stage Slice
972 Dw1 (Fig. 4).

973 In Saxothuringia, part of the Armorican Terrane Assemblage (Torsvik & Cocks 2017)
974 and therefore included here in South Gondwana, Heuse *et al.* (1994) recorded *Baltisphaera*
975 *cf. quadrinata* and *Baltisphaera* sp. from the Griffelschiefer in the Schwarzburg Anticline,
976 for which they indicated a late Arenig *hirundo* Zone (equivalent to the *A. cucullus* Biozone)
977 or possibly slightly older age. The *A. cucullus* Biozone is correlated with the lower
978 Darriwilian Stage Slice Dw1 (Fig. 1), so the FAD in South Gondwana is again placed at the
979 base of Dw1 (Fig. 4).

980 Also in South Gondwana, Elaouad Debbaj (1984) recorded *Orthosphaeridium ternatum*
981 (as '*Baltisphaeridium ternata*') from the upper Arenig–Llanvirn Tachilla Formation of
982 Morocco, and Paris *et al.* (2007) recorded *O. ternatum* (as '*Baltisphaeridium ternatum*') from
983 the TAR2 assemblage of southern and SE Turkey. The TAR2 assemblage seems to range
984 through the entire Dapingian and Darriwilian stages, based on chitinozoan dating of samples,
985 from the *Belonechitina henryi* chitinozoan Biozone to the *Linochitina pissotensis* Biozone
986 (Fig. 1). There is no indication of where *Orthosphaeridium* first occurs in the Dapingian–
987 Darriwilian interval in either Morocco or Turkey.

988 A further Dapingian–lower Darriwilian record is from Sweden and provides the FAD
989 of *Orthosphaeridium* in Baltica. The precise levels at which Ribecai & Tongiorgi (1995)
990 recorded *Orthosphaeridium densiverrucosum* and *O. ternatum* in Sweden are unknown, but
991 the relevant section spans the interval from the Langevoja Substage of the Volkhov Stage to
992 the Hunderum or possibly Valaste substages of the Kunda Stage. This interval correlates with
993 the upper Dapingian (top Dp3) to middle Darriwilian (lower Dw2) (Fig. 1). The FAD of the
994 genus in Baltica is placed at the base of the Darriwilian Stage.

995

996

997 **Recognition of Lower and Middle Ordovician stage slices and stage**

998 **boundaries**

999

1000 *Tremadocian Stage Slice Tr3*

1001

1002 The FADs of *Coryphidium*, *Peteinosphaeridium*, *Striatotheca* and the *Veryhachium*

1003 *trispinosum* group are potentially important for correlation of Tremadocian Stage Slice Tr3.

1004 Of these, *Coryphidium* and *Peteinosphaeridium* have widespread first occurrences in the

1005 stage slice. *Coryphidium* is restricted to the margin of Gondwana (Perigondwana), including

1006 derived terranes such as Avalonia, but ranges from high southern palaeolatitudes northwards

1007 to South China and eastwards to NW Argentina. Its first occurrence is in Tr3 throughout its

1008 biogeographical range, and probably in the upper part of Tr3. The first occurrence of

1009 *Peteinosphaeridium* is also in Tr3 on the Gondwanan margin, from high southern

1010 palaeolatitudes to South China and NW Argentina, and furthermore is in Tr3 on Baltica and

1011 Laurentia, suggesting a potential for correlation between palaeocontinents.

1012 *Striatotheca* has only been recorded from Perigondwana and not below Stage Slice Tr3.

1013 Its FAD is probably at the base of Tr3 at high palaeolatitudes, for example in NW England

1014 and on the island of Rügen (northern Germany), but its first recorded occurrence is in the

1015 lower Floian (F11) in South China and in the middle Floian (F12) in NW Argentina. First

1016 occurrences of the *Veryhachium trispinosum* group are also in Stage Slice Tr3 on the high

1017 palaeolatitude Gondwanan margin, but higher than that of *Striatotheca* and possibly in the

1018 upper part of Tr3. As with *Striatotheca*, FADs of the *V. trispinosum* group are in the Floian in

1019 South China (F11) and NW Argentina (F13). In addition, the *Veryhachium trispinosum* group

1020 became more widespread during later Ordovician stages (Servais *et al.* 2014), with a FAD

1021 during the Darriwilian on Baltica (Estonia) and subsequently on Laurentia. The diachronous

1022 FADs of these taxa limit their use in long-distance correlation, but nevertheless they might be

1023 used to distinguish the latest Tremadocian stage slice (Tr3) from older divisions at high

1024 palaeolatitudes.

1025 *Dactylofusa velifera*, *Rhopaliophora* and the *Veryhachium lairdii* group are also

1026 generally characteristic of later Tremadocian assemblages, although all appear to have FADs

1027 that are below Tr3. The global FAD of the *Veryhachium lairdii* group is possibly in the lower

1028 Tremadocian in North Africa and Oman (Stage Slice Tr1 or Tr2), but the group was more
1029 common and widespread during Tr3, in *messauoudensis-trifidum* acritarch assemblages at high
1030 palaeolatitudes. Its first recorded occurrences in South China and possibly Baltica (St
1031 Petersburg region) are higher, in the lower Floian (F11). The *V. lairdii* group might also have
1032 a lower Floian FAD in NW Argentina, although there is some uncertainty over the exact
1033 level. Previous published records had the FAD in the middle Floian (F12). Like the
1034 *Veryhachium trispinosum* group, the *V. lairdii* group became widespread during the later
1035 Ordovician (Servais *et al.* 2014). First occurrences of *Dactylofusa velifera*, another species
1036 restricted to Perigondwana, are mostly in Tr3, albeit with some uncertainty in NW Argentina,
1037 but possibly lower in South China (Tr2?) and Oman (Tr1-Tr2?). The distribution of
1038 *Rhopaliophora* resembles that of *Peteinosphaeridium*, with first occurrences in Tr3 on the
1039 Gondwanan margin, from high southern palaeolatitudes to South China and NW Argentina,
1040 and also on Baltica (Norway) and Laurentia (Alberta). As with *Peteinosphaeridium*, this
1041 suggests a potential for intercontinental correlation, except that *Rhopaliophora* has possible
1042 slightly older FADs in South China (Tr2?) and North China (upper Tr1–Tr2).

1043

1044 *The Tremadocian–Floian stage boundary and Floian stage slices*

1045

1046 As noted above, the FADs of *Striatotheca*, the *Veryhachium lairdii* group and the *V.*
1047 *trispinosum* group are higher in South China and/or NW Argentina than at high southern
1048 latitudes on the margin of Gondwana. The FADs of *Striatotheca*, the *Veryhachium lairdii*
1049 group and the *V. trispinosum* group are all in the lower Floian Stage Slice F11 in South China
1050 and so distinguish Floian from Tremadocian strata there. The *Veryhachium lairdii* group is
1051 also present in Stage Slice F11 on Baltica (St Petersburg region), although it remains
1052 uncertain whether this represents its FAD there because of a stratigraphical hiatus below its
1053 first occurrence. The FADs of *Striatotheca*, the *Veryhachium lairdii* group and the *V.*
1054 *trispinosum* group are higher in NW Argentina, in the middle Floian (F12) for *Striatotheca*
1055 and the *V. lairdii* group and the upper Floian (F13) for the *V. trispinosum* group. They might
1056 be useful as local markers for successive Floian stage slices.

1057 *Aureotesta clathrata simplex*, *Arbusculidium filamentosum* and *Coryphidium*

1058 *bohemicum* are all restricted to Perigondwanan assemblages and all have FADs in the lower
1059 to middle Floian Stage. They serve to distinguish Floian successions from the upper

1060 Tremadocian Stage Slice Tr3 around Gondwana. *Aureotesta clathrata simplex* has its FAD at

1061 about the base of Stage Slice F11 in NW England and South China. The FADs of *A.*
1062 *filamentosum* and *C. bohemicum* are above the base of the Floian Stage in both areas, either
1063 in the upper part of Stage Slice F11 or in Stage Slice F12. The FADs of all three species are in
1064 F12 in NW Argentina (*C. cf. bohemicum* in NW Argentina), replicating the Tremadocian
1065 pattern of taxa having later FADs there.

1066 *Ampullula*, *Dasydorus*, *Liliosphaeridium* and *Sacculidium* comprise a group of genera
1067 that occur in Floian successions from South China, East Gondwana and Baltica, and
1068 distinguish Floian from Tremadocian successions there. All have global FADs in South
1069 China in the Floian Stage, where that of *Sacculidium* is in Stage Slice F11 and those of the
1070 other genera are in Stage Slice F12. *Ampullula*, *Dasydorus* and possibly *Liliosphaeridium* also
1071 have FADs in Floian Stage Slices F12–F13 in East Gondwana (*Ampullula*, possibly
1072 *Liliosphaeridium*) and/or Baltica (Norway: *Ampullula*; St Petersburg region: *Ampullula*,
1073 *Dasydorus*). Their FADs suggest some potential as markers for the middle–upper Floian
1074 Stage in South China, East Gondwana and/or Baltica, depending on their respective
1075 distributions. *Sacculidium*, however, has not been recorded from NW Argentina below the
1076 Dapingian Stage, and *Dasydorus* has not been recorded there at all. *Liliosphaeridium* and
1077 *Sacculidium* both have first occurrences in Baltica in the uppermost Dapingian or lowest
1078 Darriwilian and are important components of acritarch assemblages there, making them
1079 potential local markers for later stages and stage slices. With the possible exception of
1080 *Dasydorus*, none of these genera have been reported from high palaeolatitude Perigondwanan
1081 successions below the Darriwilian (Fig. 4).

1082 *Arkonina*, *Barakella* and *Dicrodiacrodium* have first definite occurrences in Floian
1083 successions on the margin of Gondwana. Floian occurrences of *Arkonina* are in Stage Slice F13
1084 in South China (lower F13) and possibly East Gondwana (NW Argentina). First occurrences
1085 at higher palaeolatitudes in South Gondwana and Avalonia are in the Dapingian and/or lower
1086 Darriwilian stages. *Barakella* has been reported from the lower–middle Floian Stage of South
1087 Wales, South China and East Gondwana (NW Argentina). Records from South Gondwana
1088 and West Gondwana are generally higher, from the Dapingian Stage upwards. Apart from an
1089 uncertain record from the Darriwilian of Sweden (upper Dw1–lower Dw2), all records of
1090 *Barakella* are from the margin of Gondwana. *Dicrodiacrodium* has FADs in the upper Floian
1091 Stage of South China and South Gondwana.

1092

1093 *Lower–Middle Ordovician series (Floian–Dapingian stage) boundary*

1094

1095 *Frankea* and *Orthosphaeridium* are potential markers for the Dapingian Stage. There is an
1096 exceptionally early and very rare record of *Frankea* from the lower Floian Stage on the Isle
1097 of Man (Molyneux 1999), but the first common appearance of *Frankea*, so far only recorded
1098 from high palaeolatitudes, is placed in the upper Dapingian Stage (Stage Slice Dp3) in NW
1099 England and in the undivided Dapingian–lower Darriwilian (Dp1–Dw1) of Morocco, Saudi
1100 Arabia and South Wales. *Orthosphaeridium* is distributed more widely on the Gondwanan
1101 margin, where it occurs in the lower–middle Dapingian (Dp1–Dp2) of South China, the
1102 undivided Dapingian–lower Darriwilian (Dp1–Dw1) of NW England and South Wales, and
1103 the undivided Dapingian–Darriwilian (Dp1–Dw3) of Morocco and Turkey.
1104 *Orthosphaeridium* also occurs on Baltica but at a higher level, in the uppermost Dapingian to
1105 lower Darriwilian (top Dp3–lower Dw1) of Sweden.

1106

1107

1108 **Conclusions**

1109

1110 The acritarch genera and species considered in this paper comprise morphotypes that are
1111 easily recognizable using transmitted light microscopy. Their FADs have the potential to aid
1112 correlation of Lower and Middle Ordovician stages, stage slices and time slices, but the
1113 degree to which this applies varies. Some genera and species considered here have
1114 widespread FADs at about the same level throughout their biogeographical range and are
1115 useful for long-distance and intercontinental correlation. Others have diachronous FADs, and
1116 this needs to be taken into account when using them for correlation. They may be useful for
1117 correlation within basins and perhaps also between basins that are in proximity to each other,
1118 but on currently available evidence, care is needed when using them for correlation over
1119 longer distances.

1120 Among the genera and species that have widespread FADs at about the same level are
1121 *Coryphidium* and *Peteinosphaeridium*, but whereas *Coryphidium* is restricted to
1122 Perigondwana, *Peteinosphaeridium* also occurs in Baltica and Laurentia, suggesting a
1123 potential for correlation between palaeocontinents. The distribution of *Rhopaliophora*
1124 resembles that of *Peteinosphaeridium* and again suggests a potential for intercontinental
1125 correlation around the Tr2–Tr3 Stage Slice boundary. *Dactylofusa velifera* is a potential
1126 marker for the upper Tremadocian Stage (Tr3) throughout most of its biogeographical range,

1127 but is again restricted to Perigondwana. *Arbusculidium filamentosum*, *Aureotesta clathrata*
1128 *simplex* and *Coryphidium bohemicum* are similarly restricted to Perigondwana and their
1129 FADs are in the lower–middle Floian Stage throughout their biogeographical range. Other
1130 genera restricted in their biogeographical distribution to Perigondwana include
1131 *Dicrodiacrodium*, which has FADs in the upper Floian Stage of South Gondwana and South
1132 China, and *Frankea*, with FADs in the Dapingian–lower Darriwilian at high palaeolatitudes.
1133 *Orthosphaeridium* has FADs in the Dapingian to lower Darriwilian of Perigondwanan
1134 regions and a FAD at about the same level on Baltica. *Orthosphaeridium* is distributed
1135 widely in the Upper Ordovician, including records from Laurentia.

1136 Although FADs of these genera and species are generally at about the same level
1137 throughout their ranges, there is nevertheless a degree of diachronism in their first
1138 appearances. Diachronism is more marked in the other genera and species considered, and
1139 some recurring patterns are evident. *Striatotheca*, the *Veryhachium lairdii* group and the *V.*
1140 *trispinosum* group, for example, all have FADs in the Tremadocian Stage on Avalonia and in
1141 South Gondwana and West Gondwana, but in the Floian Stage of South China and East
1142 Gondwana. *Striatotheca*, unlike the other two, is restricted to Perigondwana whereas the
1143 *Veryhachium* spp. spread to Baltica and ultimately more widely.

1144 The other genera discussed herein, *Arkonia*, *Ampullula*, *Barakella*, *Dasydorus*,
1145 *Liliosphaeridium* and *Sacculidium*, have markedly diachronous FADs throughout their
1146 biogeographical ranges, although in the case of *Arkonia*, *Ampullula*, *Liliosphaeridium* and
1147 *Sacculidium*, the global FAD is apparently in South China and/or East Gondwana, followed
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1149
1150

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1168 **References**

1169

- 1170 Achab, A., Rubinstein, C. V. & Astini, R. A. 2006: Chitinozoans and acritarchs from the
1171 Ordovician peri-Gondwana volcanic arc of the Famatina System, northwestern
1172 Argentina. *Review of Palaeobotany and Palynology* 139, 129–149.
- 1173 Albanesi, G.L., Ortega, G. & Zeballo, G. 2008: Faunas de conodontes y graptolitos del
1174 Paleozóico inferior en la Cordillera Oriental Argentina. In Coira, B. & Zappettini, E.O.
1175 (eds.), *17° Congreso Geológico Argentino: Geología y Recursos Naturales de Jujuy,*
1176 *Relatorio*. Asociación Geológica Argentina. Buenos Aires, Argentina, 98-118.
- 1177 Amberg, C. E. A., Vandenbroucke, T. R. A., Molyneux, S. G. & Servais, T. in press.
1178 Chitinozoans from the upper Tremadocian (Lower Ordovician) Watch Hill Formation
1179 of the Lake District, northern England. *Palynology*.
- 1180 Bagnoli, G. & Ribecai, C. 2001: On the biostratigraphic significance of the Ordovician
1181 acritarch genus *Liliosphaeridium* on Öland, Sweden. *Review of Palaeobotany and*
1182 *Palynology* 117, 195–215.
- 1183 Bergström, S. T., Chen, X., Gutiérrez-Marco, J. C. & Dronov, A. 2009: The new
1184 chronostratigraphic classification of the Ordovician System and its relations to major
1185 regional series and stages and to $\delta^{13}\text{C}$ chemostratigraphy. *Lethaia* 42, 97–107.
- 1186 Breuer, P. & Vanguetaine, M. 2004: The latest Tremadocian *messaooudensis-trifidum*
1187 acritarch assemblage from the upper part of the Lierneux Member (Salm Group,
1188 Stavelot Inlier, Belgium). *Review of Palaeobotany and Palynology* 130, 41–58.
- 1189 Brocke, R. 1997: Evaluation of the Ordovician acritarch genus *Ampullula* Righi. *Annales de*
1190 *la Société Géologique de Belgique* 120, 73–98.
- 1191 Brocke, R., Fatka, O., Molyneux, S. & Servais, T. 1995: First appearance of selected Early
1192 Ordovician acritarch taxa from peri-Gondwana. In Cooper, J.D., Droser, M.L. &

- 1193 Finney, S.C. (eds.), *Ordovician Odyssey: short papers for the Seventh International*
 1194 *Symposium on the Ordovician System, SEPM Volume 77*, 473–476. Las Vegas,
 1195 Nevada, USA.
- 1196 Brocke, R., Fatka, O., Molyneux, S. & Servais, T. 1998: A review of the Ordovician
 1197 acritarchs *Aureotesta* and *Marrocanium*. *Annales de la Société Géologique de Belgique*
 1198 120, 1-22.
- 1199 Brocke, R., Li, J. & Wang, Y. 2000: Upper Arenigian to lower Llanvirnian acritarch
 1200 assemblages from South China: a preliminary evaluation. *Review of Palaeobotany and*
 1201 *Palynology 113*, 27–40.
- 1202 Burmann, G. 1970: Weitere organische Mikrofossilien aus dem unteren Ordovizium.
 1203 *Palaeontographica Abteilung B 3*, 289–332.
- 1204 Burmann, G. 1976: Übersicht über das ordovizische Mikroplankton im Südteil der DDR
 1205 (Vogtland, Wildenfelser Zwischengebirge). *Jahrbuch für Geologie 7/8*, 47–62.
- 1206 Connery, C. & Higgs, K. T. 1999: Tremdoc-Arenig acritarchs from the Annascaul
 1207 Formation, Dingle Peninsula, Co. Kerry, Ireland. *Bollettino della Società*
 1208 *Paleontologica Italiana 38*, 133–153.
- 1209 Cooper, A. H., Rushton, A. W. A., Molyneux, S. G., Hughes, R. A., Moore, R. M. & Webb,
 1210 B. C. 1995: The stratigraphy, correlation, provenance and palaeogeography of the
 1211 Skiddaw Group (Ordovician) in the English Lake District. *Geological Magazine 132*,
 1212 185–211.
- 1213 Cooper, R. A., Maletz, J., Taylor, L. & Zalasiewicz, J. 2004: Graptolites: patterns of diversity
 1214 across paleolatitudes. In Webby, B.D., Paris, F., Droser, M.L. & Percival, I.G. (eds.),
 1215 *The Great Ordovician Biodiversification Event*. Columbia University Press, New York,
 1216 281–293
- 1217 Cooper, R. A. & Sadler, P. M. 2012: Chapter 20 - The Ordovician Period. In Gradstein, F.M.,
 1218 Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (eds.), *The Geologic Time Scale 2012*, volume
 1219 2, Elsevier, Amsterdam, 489–523.
- 1220 Cramer, F. H. & Díez, M. del C. R. 1977: Late Arenigian (Ordovician) acritarchs from Cis-
 1221 Saharan Morocco. *Micropaleontology 23*, 339–360.
- 1222 Cramer, F. H., Kanes, W. H., Díez, M. del C. R. & Christopher, R. A. 1974: Early
 1223 Ordovician acritarchs from the Tadla Basin of Morocco. *Palaeontographica, Abteilung*
 1224 *B 146*, 57–64.

- 1225 Dean, W. T. 1989: Trilobites from the Survey Peak, Outram and Skoki formations (Upper
1226 Cambrian–Lower Ordovician) at Wilcox Pass, Jasper National Park, Alberta.
1227 *Geological Survey of Canada Bulletin* 389, 1–141.
- 1228 de la Puente, G. S. & Rubinstein, C. V. 2009: Late Tremadocian chitinozoans and acritarchs
1229 from northwestern Argentina (Western Gondwana). *Review of Palaeobotany and*
1230 *Palynology* 154, 65–78.
- 1231 de la Puente, G. S. & Rubinstein, C. V. 2013. Ordovician chitinozoans and marine
1232 phytoplankton of the Central Andean Basin, northwestern Argentina: a biostratigraphic
1233 and palaeobiogeographic approach. *Review of Palaeobotany and Palynology* 198, 14–
1234 26.
- 1235 Deunff, J. 1977: Un microplancton à Acritarches dans les schistes llanvirniens de l’Anti-
1236 Atlas (Zagora–Maroc). *Notes du Service géologique du Maroc* 38, 141–151.
- 1237 Dorning, K. J. 1999: Ordovician acritarch biohorizons, palaeoenvironmental interpretation and
1238 event stratigraphy. *Acta Universitatis Carolinae Geologica* 43, 237–240.
- 1239 Eisenack, A. 1968: Mikrofossilien eines Geschiebes der Borkholmer Stufe, baltisches
1240 Ordovizium, F2. *Mitteilungen aus dem Geologischen Staatsinstitut in Hamburg* 37, 81–
1241 94.
- 1242 Eisenack, A., Cramer, F. H. & Díez, M. del C. R. 1976: *Katalog der fossilen Dinoflagellaten,*
1243 *Hystrichosphären und verwandten Mikrofossilien. Band IV Acritarcha 2. Teil.* E.
1244 Schweizertbart’sche Verlagsbuchhandlung, Stuttgart, 863 pp.
- 1245 Elaouad-Debbaj, Z. 1984: Acritarches et chitinozoaires de l’Arenig–Llanvirn de l’Anti-Atlas
1246 (Maroc). *Review of Palaeobotany and Palynology* 43, 67–88.
- 1247 Fatka, O. 1993: Chitinozoans and acritarchs in latest Tremadoc-early Arenig sediments of the
1248 Prague Basin, Czech Republic. *Special Papers in Palaeontology* 48, 29–36.
- 1249 Fang, X. 1986: Ordovician micropalaeoflora in Kunming-Luquan region, Yunnan Province
1250 and its stratigraphical significance. *Professional Papers of Stratigraphy and*
1251 *Palaeontology* 16, 125-172 (in Chinese with English abstract).
- 1252 Fortey, R.A. & Owens, R.M. 1987: The Arenig Series in South Wales. *Bulletin of the British*
1253 *Museum (Natural History), Geology Series* 41, 69–307.
- 1254 Foster, C. & Wicander, R. 2016: An Early Ordovician organic-walled microphytoplankton
1255 assemblage from the Nambheet Formation, Canning Basin, Australia: biostratigraphic
1256 and paleogeographic significance. *Palynology* 40 (3), 379–409.
- 1257 Foster, C. B., Wicander, R. & Playford, G. 2002: *Eomerismopedia maureeniae* n.g. n.sp., a
1258 chroococcacean cyanobacterium from the lower Ordovician Coolibah Formation,

- 1259 Georgina Basin, Queensland, Australia. *Neues Jahrbuch für Geologie und*
1260 *Paläontologie, Monatshefte* 2002, 65–74.
- 1261 Ghavidel-syooki, M. 1996: Acritarch biostratigraphy of the Palaeozoic rock units in the
1262 Zagros Basin, Southern Iran. *Acta Universitatis Carolinae, Geologica* 40, 385–411.
- 1263 Herbosch, A. & Verniers, J. 2014: Stratigraphy of the Lower Palaeozoic of the Brabant
1264 Massif, Belgium. Part II: The Middle Ordovician to lowest Silurian of the Rebecq
1265 Group. *Geologica Belgica* 17, 115–136.
- 1266 Heuse, T., Erdtmann, B.-D. & Kraft, P. 1994: Early Ordovician microfossils (acritarchs,
1267 chitinozoans) and graptolites from the Schwarzburg Anticline, Thuringia (Germany).
1268 *Veröffentlichungen Naturhistorisches Museum Schleusingen* 9, 41–68.
- 1269 Kraft, P. & Kraft, J. 2003: Middle Ordovician graptolite fauna from Praha – Červený vrch
1270 (Prague Basin, Czech Republic). *Bulletin of Geosciences* 78, 129–139.
- 1271 Le Hérissé, A., Al-Ruwaili, M., Miller, M. & Vecoli, M. 2007: Environmental changes
1272 reflected by palynomorphs in the early Middle Ordovician Hanadir Member of the
1273 Qasim Formation, Saudi Arabia. *Revue de Micropaléontologie* 50, 3–16.
- 1274 Lei, Y., Servais, T., Feng, Q., He, W. 2013: Latest Permian acritarchs from South China and
1275 the *Micrhystridium/Veryhachium* complex revisited. *Palynology* 37, 325–344.
- 1276 Li, J. 1989: Early Ordovician Mediterranean province acritarchs for Upper Yangtze Region,
1277 South China. In Chinese Academy of Science (ed.), *Developments in Geoscience:*
1278 *contribution to the 28th Geological Congress 1989, Washington, D. C., USA*. Science
1279 Press, Beijing, 231–234.
- 1280 Li, J., Brocke, R. & Servais, T. 2002a: The acritarchs of the South Chinese *Azygograptus*
1281 *suecicus* graptolite Biozone and their bearing on the definition of the Lower-Middle
1282 Ordovician boundary. *Comptes Rendus Palevol* 1, 75–81.
- 1283 Li, J., Servais, T. & Brocke, R. 2002b: Chinese Paleozoic acritarch research: review and
1284 perspectives. *Review of Palaeobotany and Palynology* 118, 181–193.
- 1285 Li, J., Molyneux, S. G., Rubinstein, C. V. & Servais, T. 2003: Acritarchs from peri-
1286 Gondwana at the Lower and Middle Ordovician Stage boundaries. In Albanesi, G.L.,
1287 Beresi, M.S. & Peralta, S.H. (eds.), *INSUGEO, Serie Correlación Geológica* 17, 95–
1288 99.
- 1289 Li, J., Servais, T. & Yan, K. 2010: Acritarch biostratigraphy of the Lower–Middle
1290 Ordovician boundary: the Global Stratotype Section and Point (GSSP) of
1291 Huanghuachang, South China. *Newsletters on Stratigraphy* 43, 235–250.

- 1292 Li, J., Servais, T. & Yan, K. 2014: The Ordovician acritarch genus *Rhopaliophora*:
 1293 Biostratigraphy, palaeobiogeography and palaeoecology. *Review of Palaeobotany and*
 1294 *Palynology* 208, 1-24.
- 1295 Martin, F. 1992: Uppermost Cambrian and Lower Ordovician acritarchs and Lower
 1296 Ordovician chitinozoans from Wilcox Pass, Alberta. *Geological Survey of Canada*
 1297 *Bulletin* 420, 1–57.
- 1298 Martin, F. 1996: Recognition of the acritarch-based “*trifidum* flora” (Ordovician) in the
 1299 absence of the eponymous species. *Bulletin de l'Institut royal des Sciences naturelles*
 1300 *de Belgique, Sciences de la Terre* 66, 5–13.
- 1301 Martin, F. & Yin, L.-M. 1988: Early Ordovician acritarchs from Southern Jilin Province,
 1302 North-East China. *Palaeontology* 31, 109–127.
- 1303 Molyneux, S. G. 1987: Appendix. Acritarchs and Chitinozoa from the Arenig Series of
 1304 south-west Wales. *Bulletin of the British Museum (Natural History), Geology Series*
 1305 *41*, 309–364.
- 1306 Molyneux, S. G. 1999: A reassessment of Manx Group acritarchs, Isle of Man. In Woodcock,
 1307 N.H., Quirk, D.G., Fitches, W.R. & Barnes, R.P. (eds.), *In sight of the suture: the*
 1308 *Palaeozoic geology of the Isle of Man in its Iapetus Ocean context*. Geological Society
 1309 of London, Special Publication 160, 23-32.
- 1310 Molyneux, S. G. 2009: Acritarch (marine microphytoplankton) diversity in an Early
 1311 Ordovician deep-water setting (the Skiddaw Group, northern England): implications
 1312 for the relationship between sea-level change and phytoplankton diversity.
 1313 *Palaeogeography, Palaeoclimatology, Palaeoecology* 275, 59–76.
- 1314 Molyneux, S. G. & Dorning, K. J. 1989: Acritarch dating of latest Tremadoc–earliest Arenig
 1315 (early Ordovician) sediments in the Carmarthen district, south Wales. *Geological*
 1316 *Magazine* 126, 707–714.
- 1317 Molyneux, S. G. & Rushton, A. W. A. 1988: The age of the Watch Hill Grits (Ordovician),
 1318 English Lake District: structural and palaeogeographical implications. *Transactions of*
 1319 *the Royal Society of Edinburgh, Earth Sciences* 79, 43–69.
- 1320 Molyneux, S. G., Delabroye, A., Wicander, R. & Servais, T. 2013. Chapter 23 -
 1321 Biogeography of early to mid Palaeozoic (Cambrian–Devonian) marine phytoplankton.
 1322 In Harper, D.A.T & Servais, T. (eds.), *Early Palaeozoic Biogeography and*
 1323 *Palaeogeography*, Geological Society of London, Memoir 38, 365–397.

- 1324 Molyneux, S., Osterloff, P., Penney, R. & Spaak, P. 2006: Biostratigraphy of the Lower
1325 Palaeozoic Haima Supergroup, Oman; its application in sequence stratigraphy and
1326 hydrocarbon exploration. *GeoArabia 11*, 17–48.
- 1327 Molyneux, S. G., Raevskaya, E. & Servais, T. 2007: The *messaoudensis-trifidum* acritarch
1328 assemblage and correlation of the base of Ordovician Stage 2 (Floian). *Geological*
1329 *Magazine* 144, 143-156.
- 1330 Mullins, G. L., Aldridge, R. J. & Siveter, D. J. 2004: Microplankton associations, biofacies
1331 and palaeoenvironment of the type lower Ludlow Series, Silurian. *Review of*
1332 *Palaeobotany and Palynology* 130, 163–194.
- 1333 Nowak, H., Akodad, M., Lefebvre, B. & Servais, T. 2015: Discovery of the *messaoudensis-*
1334 *trifidum* acritarch assemblage (upper Tremadocian - lower Floian, Lower Ordovician)
1335 in the subsurface of Morocco. *Estonian Journal of Earth Sciences* 64, 80-83.
- 1336 Nowak, H., Servais, T., Pittet, B., Vaucher, R., Akodad, M., Gaines, R.R., Vandembroucke,
1337 T.R.A. 2016: Palynomorphs of the Fezouata Shale (Lower Ordovician, Morocco): Age
1338 and environmental constraints of the Fezouata Biota. *Palaeogeography,*
1339 *Palaeoclimatology, Palaeoecology* 460, 62–74.
- 1340 Ottone, E. G., Toro, B. A. & Waisfeld, B. G. 1992: Lower Ordovician palynomorphs from
1341 the Acoite Formation, Northwestern Argentina. *Palynology* 16, 93–116.
- 1342 Paalits, I. & Erdtmann, B. D. 1993: The acritarch biozonation in the Tremadoc–Hunneberg
1343 (?Arenig) boundary interval in selected sequences of the East European Platform
1344 (EEP). In Scholle, T. & Krauss, M. (eds.), *Rügen-Bornholm: Kristallin, Struktur und*
1345 *Sedimente am Südrand des Baltischen Schildes und dessen Beziehung zu Mitteleuropa,*
1346 *Kurzfassungen, Internationale Exkursions- und Vortragstagung*, Berlin: Gesellschaft
1347 für Geowissenschaften e.V., p. 34.
- 1348 Paris, F. 1990: The Ordovician chitinozoan biozones of the Northern Gondwana Domain.
1349 *Review of Palaeobotany and Palynology* 66, 181–209.
- 1350 Paris, F. & Mergl, M. 1984: Arenigian chitinozoans from the Klabava Formation, Bohemia.
1351 *Review of Palaeobotany and Palynology* 43, 33–65.
- 1352 Paris, F., Le Hérisse, A., Monod, O., Kozlu, H., Ghienne, J.-F., Dean, W. T., Vecoli, M. &
1353 Günay, Y. 2007. Ordovician chitinozoans and acritarchs from southern and
1354 southeastern Turkey. *Revue de Micropaléontologie* 50, 81–107.
- 1355 Pärnaste, H., Bergström, J. & Zhou, Z.-Y. 2013: High resolution trilobite stratigraphy of the
1356 Lower–Middle Ordovician Öland Series of Baltoscandia. *Geological Magazine* 150,
1357 509–518.

- 1358 Playford, G. & Martin, F. 1984: Ordovician acritarchs from the Canning Basin, Western
1359 Australia. *Alcheringa* 8, 187–223.
- 1360 Playford, G. & Wicander, R. 1988: Acritarch palynoflora of the Coolibah Formation (Lower
1361 Ordovician), Georgina Basin, Queensland. *Memoirs of the Association of Australasian*
1362 *Palaeontologists* 5, 5–40.
- 1363 Playford, G., Ribecai, C. & Tongiorgi, M. 1995: Ordovician acritarch genera
1364 *Peteinosphaeridium*, *Liliosphaeridium*, and *Cycloposphaeridium*: morphology,
1365 taxonomy, biostratigraphy, and palaeogeographic significance. *Bollettino della Società*
1366 *Paleontologica Italiana* 34, 3–54.
- 1367 Quintavalle, M. & Playford, G. 2006a: Palynostratigraphy of Ordovician strata, Canning
1368 Basin, Western Australia. Part One: acritarchs and prasinophytes. *Palaeontographica,*
1369 *Abteilung B* 275, 1–88.
- 1370 Quintavalle, M. & Playford, G. 2006b: Palynostratigraphy of Ordovician strata, Canning
1371 Basin, Western Australia. Part Two: chitinozoans and biostratigraphy.
1372 *Palaeontographica, Abteilung B* 275, 89–131.
- 1373 Quintavalle, M., Tongiorgi, M. & Gaetani, M. 2000: Lower to Middle Ordovician acritarchs
1374 and chitinozoans from Northern Karakorum Mountains, Pakistan. *Rivista Italiana di*
1375 *Paleontologia e Stratigrafia* 106, 3–18.
- 1376 Raevskaya, E. G., Vecoli, M., Bednarczyk, W. & Tongiorgi, M. 2004: Billingen (Lower
1377 Arenig/Lower Ordovician) acritarchs from the East European Platform and their
1378 palaeobiogeographic significance. *Lethaia* 37, 97–111.
- 1379 Raevskaya, E. G., Volkova, N. A. & Sivertseva, I. A. 2006: The Darriwilian acritarch
1380 assemblage from Ordovician deposits of the Arkhangelsk Oblast, the northern Russian
1381 Plate. *Stratigraphy and Geological Correlation* 14, 386–398.
- 1382 Ribecai, C. & Tongiorgi, M. 1995: Arenigian acritarchs from Horns Udde (Öland, Sweden):
1383 a preliminary report. *Review of Palaeobotany and Palynology* 86, 1–11.
- 1384 Ribecai, C., Bruton, D. L. & Tongiorgi, M. 1999: Acritarchs from the Ordovician of the Oslo
1385 Region, Norway. *Norsk Geologisk Tidsskrift* 80, 251–258.
- 1386 Ribecai, C., Raevskaya, E. G. & Tongiorgi, M. 2002: *Sacculidium* gen.nov. (Acritarcha), a
1387 new representative of the Ordovician *Stelomorpha-Tranvikium* plexus. *Review of*
1388 *Palaeobotany and Palynology* 121, 163–203.
- 1389 Rickards, R. B., Booth, G. A., Paris, F. & Heward, A. P. 2010: Marine flooding events of the
1390 Early and Middle Ordovician of Oman and the United Arab Emirates and their
1391 graptolite, acritarch and chitinozoan associations. *GeoArabia* 15, 81–120.

- 1392 Righi, E. 1991: *Ampullula*, a new acritarch genus from the Ordovician (Arenig-Llanvirn) of
 1393 Öland, Sweden. *Review of Palaeobotany and Palynology* 68, 119–126.
- 1394 Ross, R. J. Jr, Hintze, L. F., Ethington, R. L., Miller, J. F., Taylor, M. E. & Repetski, J. E.
 1395 1997: The Ibexian, lowermost series in the North American Ordovician. *United States*
 1396 *Geological Survey Professional Paper 1579-A*, 1-50.
- 1397 Rubinstein, C. V. 2003: Ordovician acritarchs from northwestern Argentina: new insights
 1398 into the biostratigraphy and paleoenvironmental aspects of the Central Andean Basin
 1399 and Famatina. In Albanesi, G.L., Beresi, M.S. & Peralta, S.H. (eds.), *INSUGEO, Serie*
 1400 *Correlación Geológica 17*, 125–130.
- 1401 Rubinstein, C. V. & Toro, B. A. 1999: Acritarch and graptolite biostratigraphy in the lower
 1402 Arenig of the peri-Gondwana related Eastern Cordillera, Argentina. *Acta Universitatis*
 1403 *Carolinae, Geologica 43*, 255–258.
- 1404 Rubinstein, C. V. & Toro, B. A. 2001: Review of acritarch biostratigraphy in the Arenig of
 1405 the Eastern Cordillera, northwestern Argentina. New data and calibration with the
 1406 graptolite zonation. In Weiss, R.H. (ed.), *Contributions to Geology and Palaeontology*
 1407 *of Gondwana in honour of Helmut Wopfner*. Geological Institute, University of
 1408 Cologne, Germany, 421– 439.
- 1409 Rubinstein, C. V., Toro, B. A. & Waisfeld, B. G. 1999: Acritarch biostratigraphy of the
 1410 upper Tremadoc–Arenig of the Eastern Cordillera, northwestern Argentina:
 1411 relationships with graptolite and trilobite faunas. *Bollettino della Società*
 1412 *Paleontologica Italiana 38*, 267–286, pl. 1–6.
- 1413 Rubinstein, C. V., de la Puente, G. S., Toro, B. A. & Servais, T. 2007: The presence of the
 1414 *messaoudensis-trifidum* acritarch assemblage (upper Tremadocian–Floian) in the
 1415 central Andean Basin, north-western Argentina: calibration with chitinozoans and
 1416 graptolite zonation. *Acta Palaeontologica Sinica 46*, 422–428.
- 1417 Rubinstein, C. V., Vecoli, M. & Astini, R. A. 2011: Biostratigraphy and palaeoenvironmental
 1418 characterization of the Middle Ordovician from the Sierras Subandinas (NW
 1419 Argentina) based on organic-walled microfossils and sequence stratigraphy. *Journal of*
 1420 *South American Earth Sciences 31*, 124–138.
- 1421 Samuelsson, J. & Verniers, J. 2000: Ordovician chitinozoan biozonation of the Brabant
 1422 Massif, Belgium. *Review of Palaeobotany and Palynology 113*, 105–129.
- 1423 Samuelsson, J., Verniers, J. & Vecoli, M. 2000: Chitinozoa faunas from the Rügen
 1424 Ordovician (Rügen 5/66 and Binz 1/73 wells), NE Germany. *Review of Palaeobotany*
 1425 *and Palynology 113*, 131–143.

- 1426 Servais, T. 1991: Contribution to the stratigraphy of the Ordovician Rigenée Formation
 1427 (Brabant Massif, Belgium) with a preliminary study on acritarchs. *Annales de la*
 1428 *Société Géologique de Belgique* 114, 233–245.
- 1429 Servais, T. 1993: The Ordovician acritarch *Frankea*. *Special Papers in Palaeontology* 48,
 1430 79–95.
- 1431 Servais, T. 1997: The Ordovician *Arkonja-Striatotheca* acritarch plexus. *Review of*
 1432 *Palaeobotany and Palynology* 98, 47–79.
- 1433 Servais, T. & Fatka, O. 1997: Recognition of the Trans-European Suture Zone (TESZ) by the
 1434 palaeobiogeographical distribution pattern of early to middle Ordovician acritarchs.
 1435 *Geological Magazine* 134, 617–625.
- 1436 Servais, T. & Molyneux, S. G. 1997: The *messaoudensis-trifidum* assemblage (early
 1437 Ordovician: latest Tremadoc to earliest Arenig) from the subsurface of Rügen (NE-
 1438 Germany, Baltic Sea). *Palaeontographia Italica* 84, 113–161.
- 1439 Servais, T. & Mette, W. 2000: The *messaoudensis-trifidum* acritarch assemblage
 1440 (Ordovician: late Tremadoc-early Arenig) of the Barriga Shale Formation, Sierra
 1441 Morena (SW-Spain). *Review of Palaeobotany and Palynology* 113, 145–163.
- 1442 Servais, T. & Paris, F. 2000: Ordovician palynology: balance and future prospects at the
 1443 beginning of the third millenium. *Review of Palaeobotany and Palynology* 113, 1–14.
- 1444 Servais, T. & Sintubin, M. 2009: Avalonia, Armorica, Perunica: terranes, microcontinents,
 1445 microplates or palaeobiogeographical provinces? In Bassett, M.G. (ed.), Early
 1446 Palaeozoic Peri-Gondwana Terranes: New Insights from Tectonics and Biogeography.
 1447 *Geological Society, London, Special Publications* 325, 103–115.
- 1448 Servais, T., Vanguetaine, M. & Herbosch, A. 1993: Review of the stratigraphy of the
 1449 Ordovician in the Brabant Massif, Belgium. *Geological Magazine* 130, 699–710.
- 1450 Servais, T., Brocke, R. & Fatka, O. 1996. Variability in the Ordovician acritarch
 1451 *Dicrodiacrodium*. *Palaeontology* 39, 389–405.
- 1452 Servais, T., Samuelsson, J., Sehnert, M., Vecoli, M., Giese, U. & Verniers, J. 2001:
 1453 Ordovician palynomorphs from the subsurface of Rügen (NE-Germany): review and
 1454 perspectives. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 222,
 1455 123–139.
- 1456 Servais, T., Li, J., Molyneux, S. & Raevskaya, E. G. 2003: Ordovician organic-walled
 1457 microphytoplankton (acritarch) distribution: the global scenario. *Palaeogeography,*
 1458 *Palaeoclimatology, Palaeoecology* 195, 149–172.

- 1459 Servais, T., Li, J., Stricanne, L., Vecoli, M. & Wicander, R. 2004a: Acritarchs. In *The Great*
1460 *Ordovician Biodiversification Event* (eds B. D. Webby, F. Paris, M. L. Droser & I. G.
1461 Percival), pp. 348–360. Columbia University Press, New York.
- 1462 Servais, T., Stricanne, L., Montenari, M. & Pross, J. 2004b: Population dynamics of galeate
1463 acritarchs at the Cambrian–Ordovician transition in the Algerian Sahara. *Palaeontology*
1464 *47*, 395–414.
- 1465 Servais, T., Vecoli, M., Li, J., Molyneux, S. G., Raevskaya, E. G. & Rubinstein, C. V. 2007:
1466 The acritarch genus *Veryhachium* Deunff 1954: taxonomic evaluation and first
1467 appearance. *Palynology* *31*, 191–203.
- 1468 Servais, T., Li, J., Molyneux, S. G. & Vecoli, M. 2008: The Ordovician acritarch genus
1469 *Coryphidium*. *Revue de Micropaléontologie* *51*, 97–120.
- 1470 Servais, T., Li, J., Molyneux, S. G., Rubinstein, C. V., Vecoli, M. & Yan, K. 2014: The
1471 palaeobiogeographical spread of the acritarch *Veryhachium* in the Early and Middle
1472 Ordovician and its impact on biostratigraphical applications. *GFF* *136*, 234–237.
- 1473 Soufiane, A. & Achab, A. 1993: Quelques assemblages de chitinozoaires de l’Ordovicien de
1474 Maroc, Bassin de Tadla. *Geobios* *26*, 535–553.
- 1475 Stricanne, L. & Servais, T. 2002: A statistical approach to classification of the Cambro–
1476 Ordovician galeate acritarch plexus. *Review of Palaeobotany and Palynology* *118*,
1477 239–259.
- 1478 Todd, S. P., Connery, C., Higgs, K. T. & Murphy, F. C. 2000: An Early Ordovician age for
1479 the Annascaul Formation of the SE Dingle Peninsula, SW Ireland. *Journal of the*
1480 *Geological Society, London* *157*, 823–833.
- 1481 Tongiorgi, M., Di Milia, A., Le Fort, P. & Gaetani, M. 1994: Palynological dating (Arenig)
1482 of the sedimentary sequence overlying the Ishkarwaz Granite (upper Yarkhun valley,
1483 Chitral, Pakistan). *Terra Nova* *6*, 595–607.
- 1484 Tongiorgi, M., Bruton, D. L. & Di Milia, A. 2003: Taxonomic composition and
1485 palaeobiogeographic significance of the acritarch assemblages from the Tremadoc–
1486 Arenig (Hunneberg, Billingen, and lower Volkhov Stages) of the Oslo Region.
1487 *Bollettino della Società Paleontologica Italiana* *42*, 205–224.
- 1488 Toro, B. & Maletz, J. 2007: Deflexed *Baltograptus* species in the early to mid Arenig
1489 biostratigraphy of Northwestern Argentina. *Acta Palaeontologica Sinica* *46*
1490 (Supplement), 489–496.
- 1491 Toro, B.A, Meroi Arcerito, F., Muñoz, D., Waisfeld, B.G. & de La Puente, G.S, 2015:
1492 Graptolite-trilobite biostratigraphy in the Santa Victoria area, northwestern Argentina.

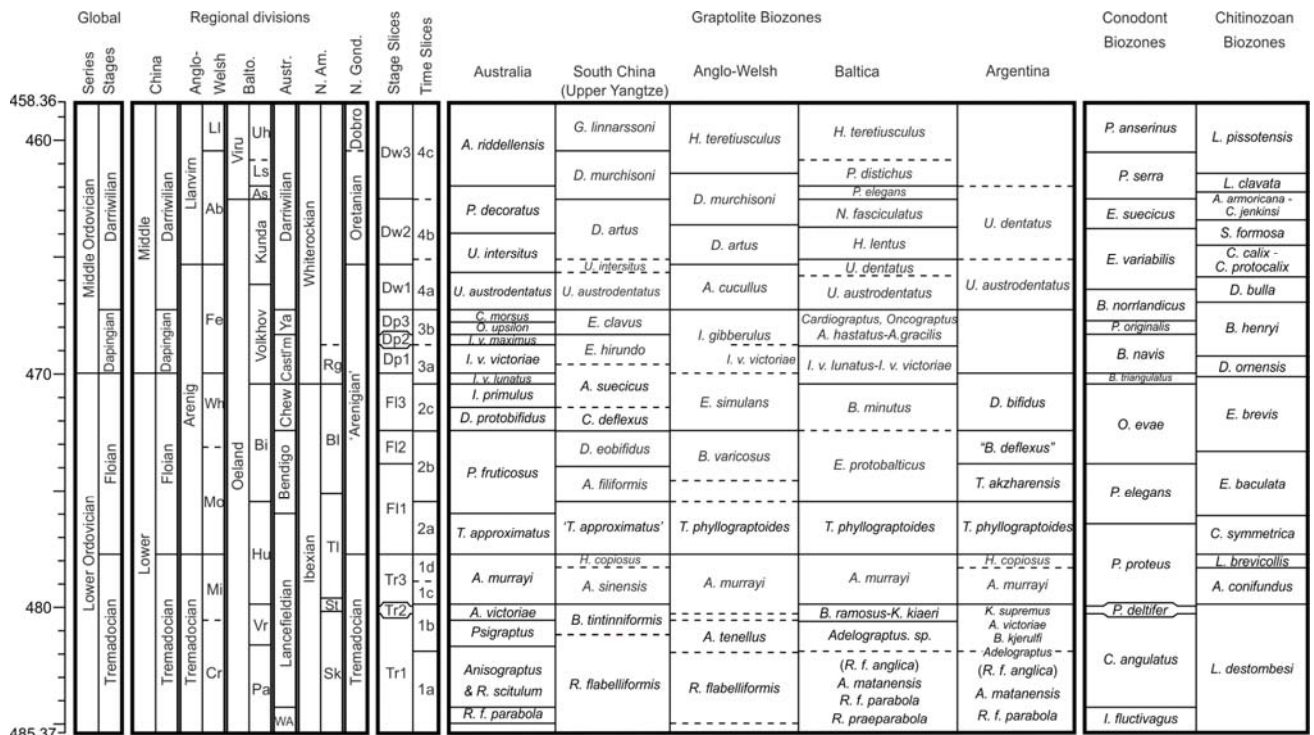
- 1493 A key for regional and worldwide correlation of the Lower Ordovician (Tremadocian–
1494 Floian). *Ameghiniana* 52, 535–557.
- 1495 Torsvik, T. H. & Cocks, L. R. M. 2017: *Earth History and Palaeogeography*. Cambridge
1496 University Press, Cambridge.
- 1497 Uutela, A. & Tynni, R. 1991: Ordovician acritarchs from the Rapla borehole, Estonia.
1498 *Bulletin of the Geological Survey of Finland* 353, 1–135.
- 1499 Vanguetaine, M. & Servais, T. 2002: Early Ordovician acritarchs of the Lierneux Member
1500 (Stavelot Inlier, Belgium): stratigraphy and palaeobiogeography. *Bulletin de la Société*
1501 *Géologique de France* 173, 561–568.
- 1502 Vanguetaine, M. & Wauthoz, B. 2011: Acritarchs from the Abbaye de Villers and Tribotte
1503 Formations in their type section of the Thyle River valley (Middle Ordovician, Brabant
1504 Massif, Belgium) and their stratigraphic implications. *Geologica Belgica* 14, 3–22.
- 1505 Vavrdová, M. 1977: Acritarchs from the Šárka Formation (Llanvirnian). *Věstník Ústředního*
1506 *ústavu geologického* 52, 109–118.
- 1507 Vavrdová, M. 1978: Nethromorphitae and some other acritarchs from the Bohemian Lower
1508 Ordovician. In Pokorný, V. (ed.), *Paleontologická Konference Katedry Paleontologie*
1509 *na Přírodovědecké Fakultě Univerzity Karlovy, Praha, 1977*, 61–74.
- 1510 Vavrdová, M. 1990: Early Ordovician acritarchs from the locality Mýto near Rokycany (late
1511 Arenig, Czechoslovakia). *Časopis pro mineralogii a geologii* 35, 239–250.
- 1512 Vavrdová, M. 1993: Acritarch assemblages in the Arenig Series of the Prague Basin. *Special*
1513 *Papers in Palaeontology* 48, 125–139.
- 1514 Vecoli, M. 1999: Cambro–Ordovician palynostratigraphy (acritarchs and prasinophytes) of
1515 the Hassi-R’Mel area and northern Rhadames Basin, North Africa. *Palaeontographia*
1516 *Italica* 86, 1–112.
- 1517 Vecoli, M. & Le Hérisse, A. 2004: Biostratigraphy, taxonomic diversity and patterns of
1518 morphological evolution of Ordovician acritarchs (organic-walled microphytoplankton)
1519 from the northern Gondwana margin in relation to palaeoclimatic and
1520 palaeogeographic changes. *Earth Science Reviews* 67, 267–311.
- 1521 Waisfeld, B. G., Vaccari, N. E., Toro, B. A., Rubinstein, C. V. & Astini, R. A. 2006: Revisión
1522 de la Zona de *Ogygiocaris araiorhachis* (Trilobita, Tremadociano tardío) en la región
1523 de Pascha-Incamayo, Cordillera Oriental Argentina. Parte 1: Bioestratigrafía.
1524 *Ameghiniana* 43, 717–728.
- 1525 Wang, W., Vecoli, M., Vandenbroucke, T. R. A., Feng, H., Li, L. & Verniers, J. 2013: Late
1526 Tremadocian–early Floian acritarchs from graptolitic shales of the Yinzhubu and

- 1527 Ningkuo formations of Yiyang, South China. *Review of Palaeobotany and Palynology*
1528 *193*, 1–14.
- 1529 Wang, W., Servais, T., Yan, K., Vecoli, M., & Li, J. 2015: The Ordovician acritarch
1530 *Dactylofusa velifera* Cocchio 1982: a biostratigraphical and palaeogeographical index
1531 species. *Palynology* 39, 125-141.
- 1532 Wang, W., Monnet, C. & Servais, T. in press: Quantitative methods used for understanding
1533 the taxonomy of acritarchs: a case study of the Middle Ordovician genus *Frankea*
1534 Burmann 1970. *Palynology*.
- 1535 Webby, B. D., Cooper, R. A., Bergström, S. M. & Paris, F. 2004: Stratigraphic frame-work
1536 and Time Slices. In Webby, B.D., Paris, F., Droser, M.L. & Percival, I.G. (eds.), *The*
1537 *Great Ordovician Biodiversification Event*. Columbia University Press, New York, 41-
1538 47.
- 1539 Xu, W. 1999: Acritarchs from the *Etagraptus approximatus* Biozone of Arenigian in the
1540 Sandu Area of Guizhou Province. *Acta Micropalaeontologica Sinica* 16, 61-75 (in
1541 Chinese with English abstract).
- 1542 Xu, W. 2001: Acritarchs and its organic stratigeochemistry from the Arenigian in the Sandu
1543 area. South China University of Mining and Technology Press, Xuzhou (in Chinese).
- 1544 Yan, K. & Li, J. 2005: Ordovician biostratigraphy of acritarchs from the Meitan Formation of
1545 Honghuayuan Section, Tongzi, Guizhou, Southwest South China. *Journal of*
1546 *Stratigraphy* 29, 236-256 (in Chinese with English abstract).
- 1547 Yan, K., Servais, T. & Li, J. 2010: Revision of the Ordovician acritarch genus *Ampullula*
1548 Righi 1991. *Review of Palaeobotany and Palynology* 163, 11-25.
- 1549 Yan, K., Servais, T., Li, J., Wu, R. & Tang, P. 2011: Biodiversity patterns of Early-Middle
1550 Ordovician marine microphytoplankton in South South China. *Palaeogeography,*
1551 *Palaeoclimatology, Palaeoecology* 299, 318-334.
- 1552 Yan, K., Li, J. & Servais, T. 2013: An Early–Middle Ordovician acritarch and prasinophyte
1553 assemblage from Houping, Chongqing city, South China: Biostratigraphical and
1554 palaeoenvironmental implications. *Review of Palaeobotany and Palynology* 198, 110-
1555 133.
- 1556 Yan, K., Li, J., Molyneux, S.G., Raevskaia, E. & Servais, T. in press: A review of the
1557 Ordovician acritarch genus *Barakella* Cramer & Díez 1977. *Palynology*.
- 1558 Zalasiewicz, J. A., Taylor, L., Rushton, A. W. A., Loydell, D. K., Rickards, R. B. &
1559 Williams, M. 2009: Graptolites in British stratigraphy. *Geological Magazine* 146, 785–
1560 850.

- 1561 Zhang, Y., Erdtmann, B.-D. & Feng, H. 2004: Tremadocian (Early Ordovician) graptolite
1562 biostratigraphy of China. *Newsletters on Stratigraphy* 40, 155–182.
- 1563 Zhang, Y., Chen, X. & Goldman D. 2007: Diversification patterns of Early and Mid
1564 Ordovician graptolite sin South South China. *Geological Journal* 42, 315–337.
- 1565 Zhang Y.-D., Chen X., Goldman D., Zhang, J., Cheng, J.-F. & Song, Y.-Y. 2010: Diversity
1566 and paleobiogeographic distribution patterns of Early and Middle Ordovician
1567 graptolites in distinct depositional environments of South China. *Science China Earth*
1568 *Sciences* 53, 1811–1827.
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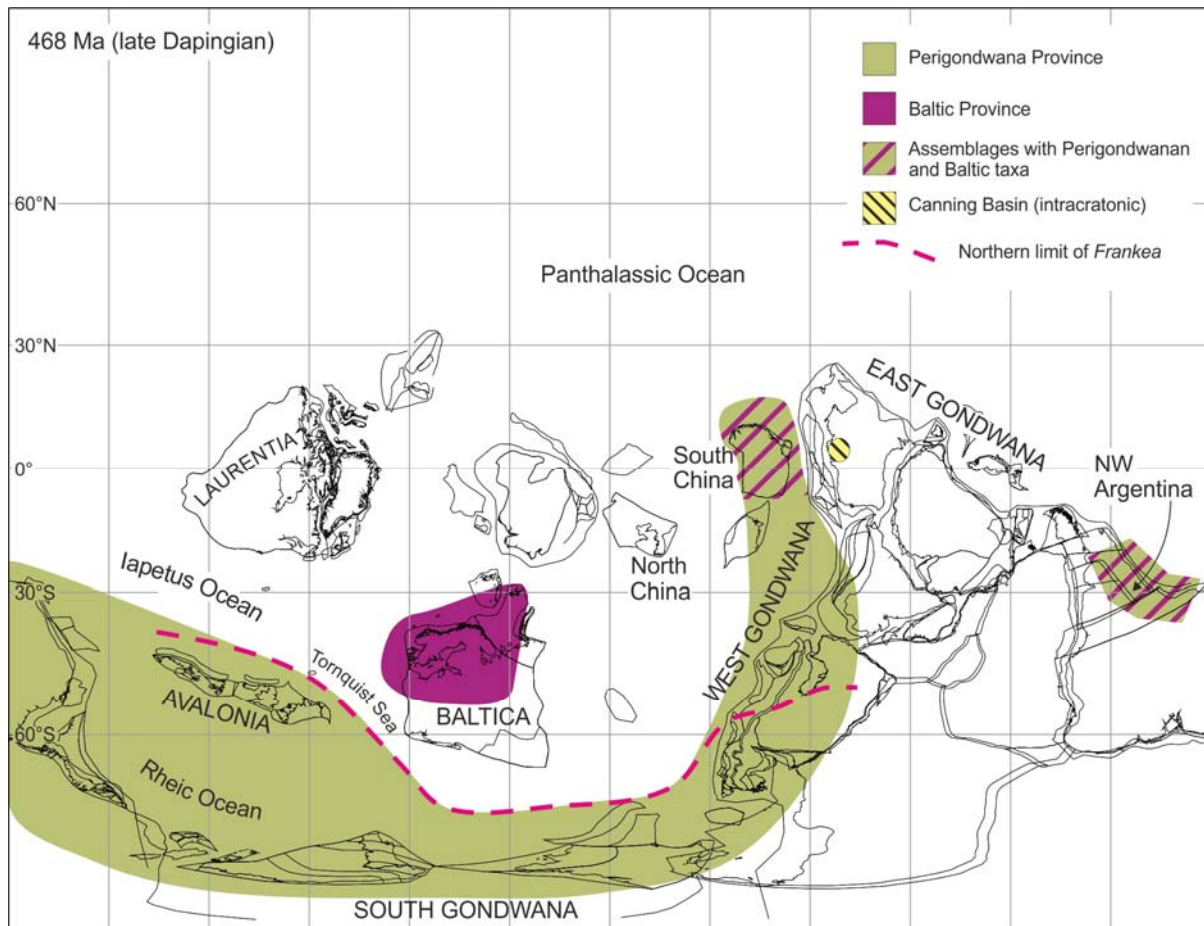
1570 **Figures and Captions**

1571



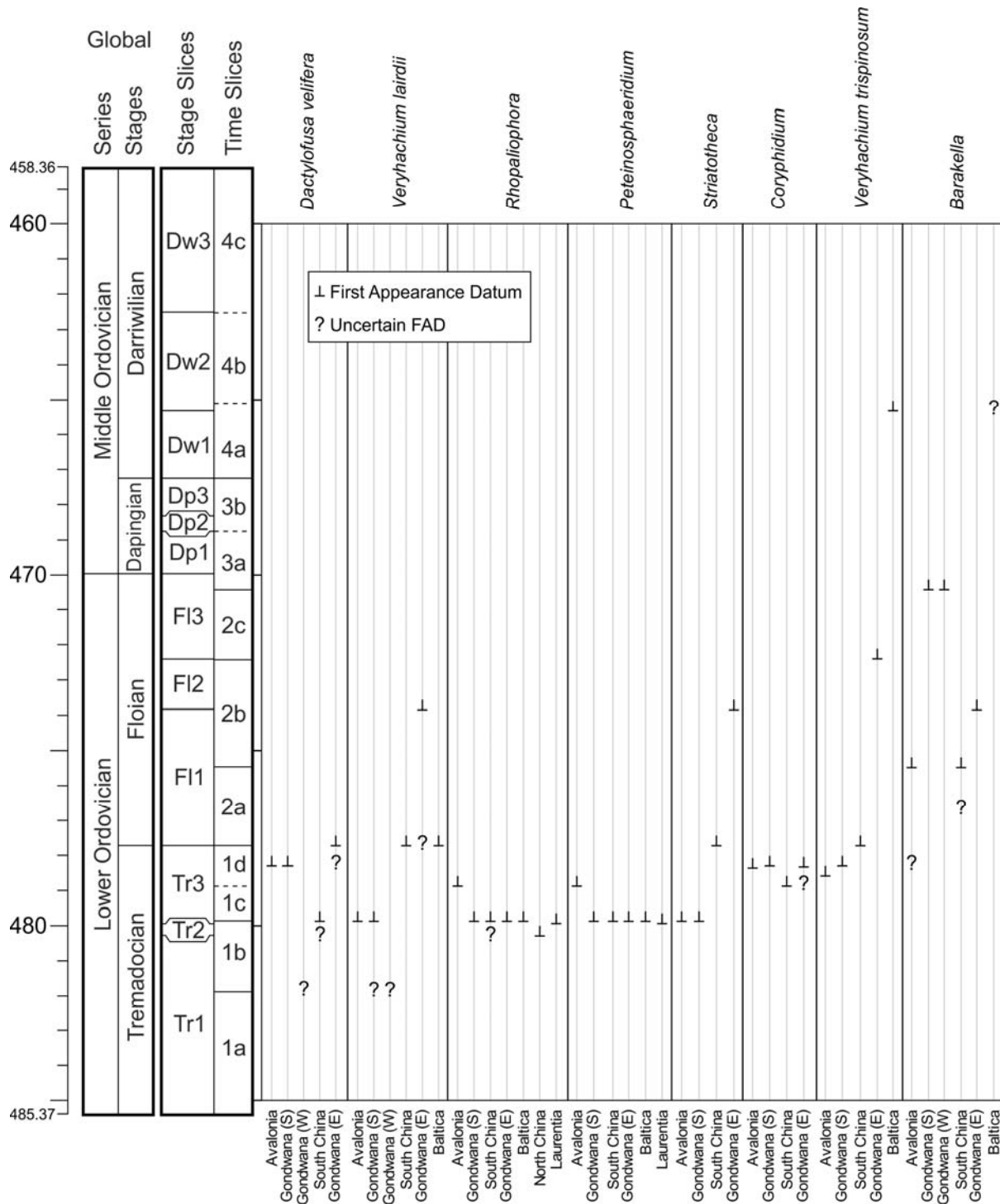
1572

1573 *Fig. 1.* Correlation of global Lower and Middle Ordovician series and stages, regional series
 1574 and stages, stage slices (Bergström *et al.* 2009), time slices (Webby *et al.* 2004), and
 1575 graptolite, conodont (North Atlantic zonation) and chitinozoan ('North Gondwana' zonation)
 1576 biozones. The South Chinese graptolite zonation is from Zhang *et al.* (2007, 2010), the Baltic
 1577 graptolite zonation is from Cooper *et al.* (2004), and the Argentinian graptolite zonation is
 1578 from de la Puente & Rubinstein (2013, based on Toro & Maletz 2007, and Albanesi *et al.*
 1579 2008). All other correlations are from TSCreator (2014; see also Cooper & Sadler 2012).
 1580 Abbreviations: Anglo-Welsh stages: Cr, Cressagian; Mi, Migneintian; Mo, Moridunian; Wh,
 1581 Whitlandian; Fe, Fennian; Ab, Abereiddian, Ll, Llandeilian. Baltoscandian stages: Pa,
 1582 Pakerort; Vr, Varangu; Hu, Hunneberg; Bi, Billingen; As, Aseri; Ls, Lasnamagi; Uh, Uhaku.
 1583 Australasian stages: WA, Warendan; Bendigo, Bendigonian; Chew, Chewtonian; Castl'm,
 1584 Castlemainian; Ya, Yapeenian. North American stages: Sk, Skullrockian; St, Stairsian; Tl,
 1585 Tulean; Bl, Blackhillsian; Rg, Rangerian. North Gondwanan stages: Dobro, Dobrotivian.

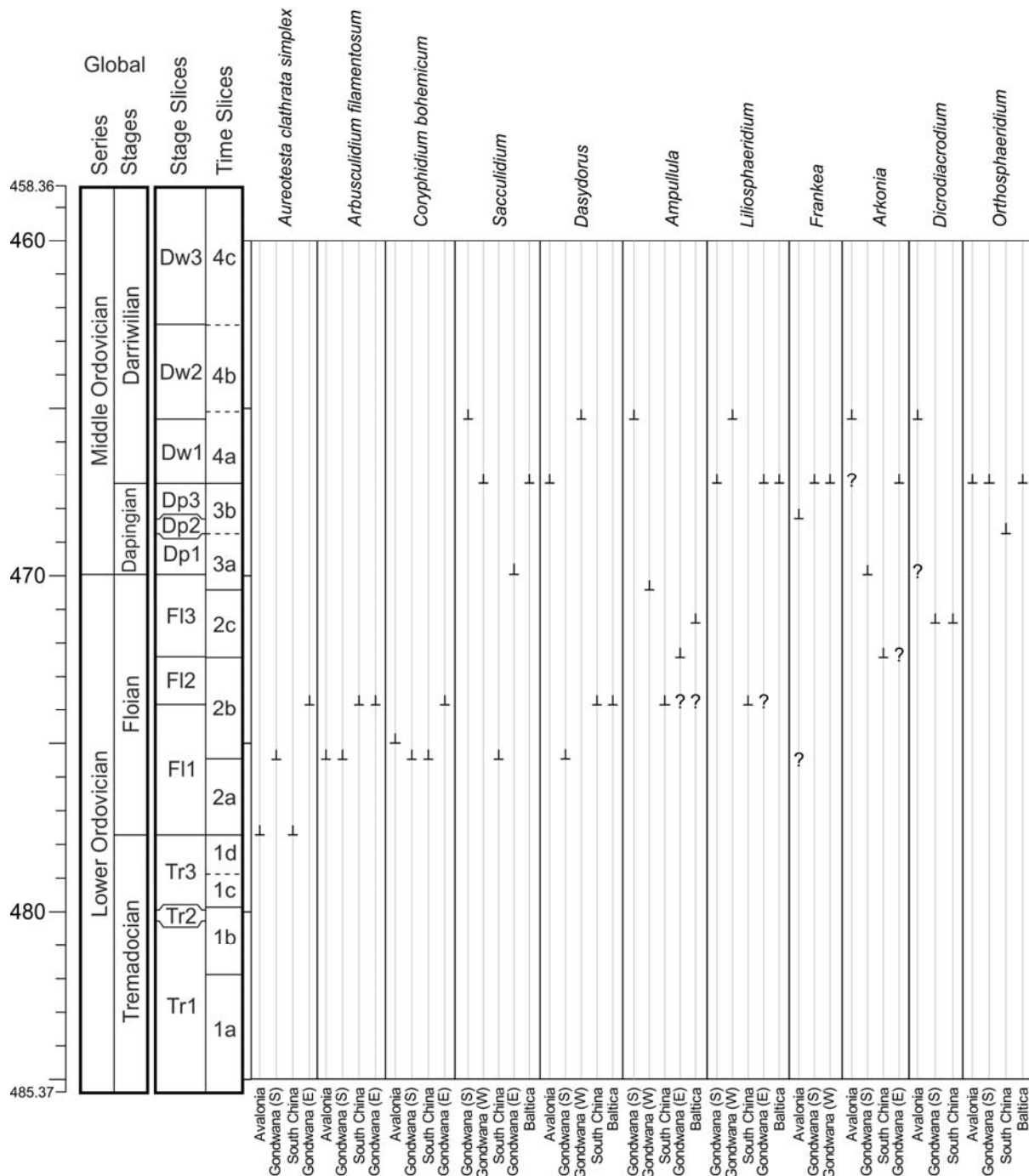


1586

1587 *Fig. 2.* Palaeogeographical reconstruction (Galls projection, using BugPlates software
 1588 [<http://www.geodynamics.no/bugs/SoftwareManual.pdf>]) for the Middle Ordovician (upper
 1589 Dapingian Stage, 468Ma) showing the distribution of the Perigondwana and Baltic acritarch
 1590 provinces, palaeocontinents and other regions mentioned in the text. See also Torsvik &
 1591 Cocks (2017) and Molyneux *et al.* (2013).



1592
 1593 *Fig. 3.* First Appearance Data (FADs) of acritarch morphotypes with FADs in the
 1594 Tremadocian Stage plotted against the global Lower–Middle Ordovician series and stages,
 1595 the stage slices of Bergström *et al.* (2009) and the time slices of Webby *et al.* (2004). Dates
 1596 are from GTS2012 (Cooper & Sadler 2012).



1597
 1598 *Fig. 4.* First Appearance Data (FADs) of acritarch morphotypes with FADs in the Floian,
 1599 Dapingian and Darriwilian stages plotted against the global Lower–Middle Ordovician series
 1600 and stages, the stage slices of Bergström *et al.* (2009) and the time slices of Webby *et al.*
 1601 (2004). Dates are from GTS2012 (Cooper & Sadler 2012).

1602



1603
 1604 *Fig. 5.* Microphotographs of the selected acritarch taxa. Taxonomic names are followed by
 1605 the palynological slide number and the England Finder coordinates. The scale bar indicates
 1606 10 μm . All specimens are housed in the collections of the Nanjing Institute of Geology and
 1607 Palaeontology, Nanjing, China, except specimens D, E, J and Q, that are housed in the
 1608 collections of the Evo-Eco-Paleo department, CNRS-University of Lille, France.
 1609 A. *Ampullula erchunensis* (Fang, 1986) Yan et al. 2010, modified from Yan et al. (2010), Pl.
 1610 2, Fig. 4, Dawan Formation (Huanghuachang section), Yichang, Hubei, China, Sample

1611 HHDW10, Slide 3, EF: L51; B. *Arbusculidium filamentosum* (Vavrdová 1965) Vavrdová
 1612 1972 emend. Fatka & Brocke, 1999, Meitan Formation (Honghuayuan section), Tongzi,
 1613 Guizhou, China, Sample AFI1033, Slide 1, EF: V47; C. *Aureotesta clathrata* var. *simplex*
 1614 (Cramer et al 1974) emend. Brocke *et al.* 1998, Meitan Formation (Honghuayuan section),
 1615 Tongzi, Guizhou, China, Sample AFI1039, Slide 3, EF: N37/3; D. *Arkonina tenuata* Burmann,
 1616 1970, Borehole BJ109m Morocco, -464m, Slide 1, EF: W35/1; E. *Barakella felix* Cramer &
 1617 Diez 1977, modified from Yan et al. (in press), Pl. I, Fig. 15, Borehole BJ109m Morocco, -
 1618 404m, Slide 2, EF: P33/3; F. *Coryphidium bohemicum* Vavrdová 1972, Meitan Formation
 1619 (Honghuayuan section), Tongzi, Guizhou, China, Sample AFI1033, Slide 1, EF: S36/1; G
 1620 *Coryphidium* sp., Fenghsiang Formation (Xiangshuidong section), Songzi, Hubei, China,
 1621 Sample AGO297, Slide 1, EF: Q51; H. *Dactylofusa velifera* Cocchio, 1982, Hungshihyen
 1622 Formation (Erchun section), Kunming, China, Sample AGC8, Slide 6, EF: K40; I. *Dasydorus*
 1623 *cirritus* Playford & Martin, 1984, Meitan Formation (Honghuayuan section), Tongzi,
 1624 Guizhou, China, Sample AFI1033, Slide 1, EF: W46/2; J. *Frankea breviscula* Burmann,
 1625 1970, Borehole BJ109, Morocco, -464m, Slide 1, EF: H29/1; K. *Liliosphaeridium kaljoi*
 1626 Uutela & Tynni, 1991 emend. Playford et al., 1995, Dawan Formation (Daping section),
 1627 Yichang, Hubei, China, Sample AFI4017, Slide 1, EF: O46/4; L. *Rhopaliophora palmata*
 1628 (Combaz & Peniguel, 1972) emend. Playford & Martin 1984, Fenghsiang Formation
 1629 (Xiangshuidong section), Songzi, Hubei, China, Sample AGO297, Slide 1, EF: M43/1; M.
 1630 *Peteinosphaeridium robustiramosum* Tongiorgi et al., 1995, Dawan Formation
 1631 (Huanghuachang section), Yichang, Hubei, China, Sample HHDW11, Slide 1, EF: L43/3; N.
 1632 *Sacculidium macropylum* (Eisenack, 1995) Ribecai et al., 2002, Dawan Formation (Daping
 1633 section), Yichang, Hubei, China, Sample AFI4016, Slide 1, EF: U51; O. *Striatotheca*
 1634 *pricipalis* var. *parva* Burmann 1970, Meitan Formation (Honghuayuan section), Tongzi,
 1635 Guizhou, China, Sample AFI1030, Slide 4, EF: F38/4; P. *Veryhachium lairdii* group,
 1636 Hungshihyen Formation (Erchun section), Kunming, China, Sample AGC8, Slide 1, EF:
 1637 S46/1; Q. *Dicrodiacrodium ancoriforme* Burmann, 1968 emend Servais et al., 1996,
 1638 Borehole BJ109, Morocco, -464m, Slide 1, EF: G53/4; R. *Orthosphaeridium* sp. Dawan
 1639 Formation (Huanghuachang section), Yichang, Hubei, China, Sample HHDW28, Slide 2, EF:
 1640 M40; S. *Veryhachium trispinosum* group, Meitan Formation (Honghuayuan section), Tongzi,
 1641 Guizhou, China, Sample AFI1039, Slide 2, EF: M47/2.
 1642
 1643