

Chitinozoan biostratigraphy of the Upper Ordovician Greenscoe section, Southern Lake District, UK

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Abstract

Nineteen samples taken in the Upper Ordovician Kirkley Bank Formation at the recent Greenscoe section yielded a rich and moderately to well preserved chitinozoan assemblage, in spite of a high Conodont Colour Alteration Index. Within the assemblage, the Baltoscandian *Fungochitina spinifera* Biozone could be recognized, indicating a strong faunal exchange between the Baltica palaeocontinent and the Avalonian palaeomicrocontinent during the Late Ordovician. This biozone allowed a strong correlation with new chitinozoan biozonations in the Cautley district and Cross Fell Inlier, resulting in a late Onnian to early Cautleyan age for the Kirkley Bank Formation at Greenscoe.

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1. Introduction

During the Late Ordovician, the study area was situated on the northern edge of the palaeomicrocontinent Avalonia (Cocks et al., 1997, and references therein). The palaeocontinent drifted away from polar northern Gondwana in the Early to Mid Ordovician (Cocks and Fortey, 1982; Cocks et al., 1997). As it drifted northwards across the shrinking Tornquist Sea and Iapetus Ocean, it approached low latitude Baltica, and by Caradoc time intermingling of some of the benthic faunas of the two continents was apparent (Cocks and Fortey, 1982; Cocks, 2001). In Late Ordovician times, almost certainly in the

Ashgill (Cocks, 2001; Vecoli and Samuelsson, 2001), the Tornquist Sea had been consumed completely, and Avalonia collided with Baltica. After their collision, the two united palaeocontinents drifted towards equatorial Laurentia and slowly collided with it from Silurian to Middle Devonian times to form the new supercontinent of Laurussia (Ziegler, 1989; Woodcock and Strachan, 2000; Cocks, 2001).

The Greenscoe-roadcutting section [SD 2201 7558] is situated along the east side of the A595 between Askam-in-Furness and Dalton-in-Furness (Fig. 1). The outcrop is approximately 118m long and consists mainly of the limestones, silty limestones and calcitic siltstones of the Kirkley Bank Formation. The beds have a more or less constant strike and dip of 070/69 on average. At the top of the section, the 12.05m thick rhyolitic deposits of the High Haume Tuff Formation are observed. Both formations are part of the Upper Ordovician Dent Group. The rhyolitic sediments are separated from the

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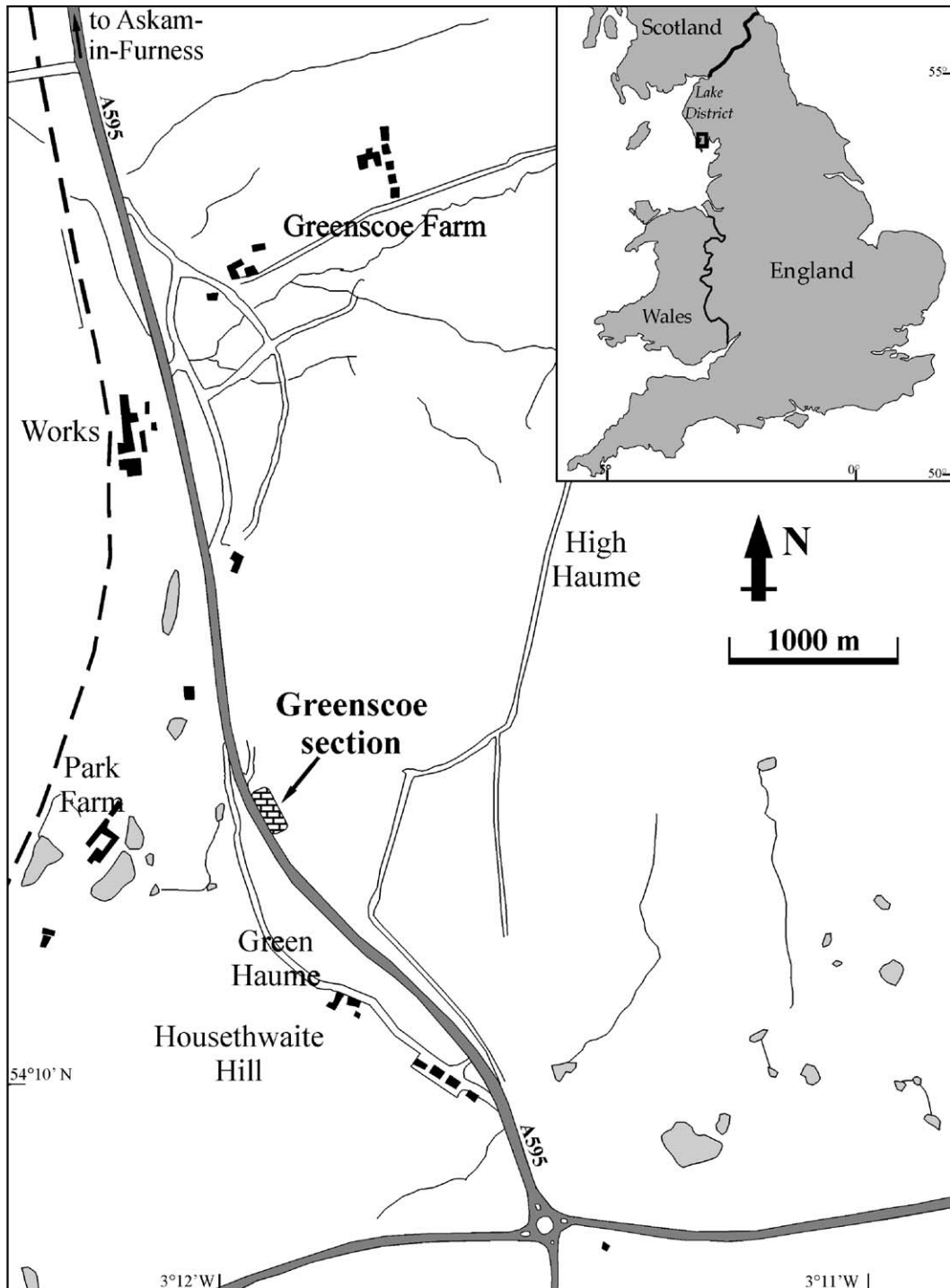


Fig. 1. Location of the Greenscoe section.

silty limestone deposits by 13.30m fault breccia. Some minor faults occur, but they do not significantly disturb the stratigraphical continuity. The contact with the underlying Skiddaw Group was not seen in the field,

even not in the direct surroundings of the outcrop. The northernmost point where the limestone could be observed, was taken as the datum point of the outcrop. At the level of the road, this corresponds with the point

situated 6.20 m north of the southern end of a little brick wall (Fig. 2).

Since the section was excavated only recently, it had not been studied thoroughly. A first, general lithostratigraphy of the outcrop was proposed by Johnson, 1997; Johnson et al., 2001 shortly after excavation. The only palaeontological study on the section prior to this one, was carried out by Smith (1999, unpublished Ph.D. Thesis, University of Durham), who studied the conodont content of the deposits (see Section 1.1).

The Kirkley Bank Formation was introduced by Scott and Kneller (1990) and Kneller et al. (1994), and comprises the Kentmere Limestone Formation, the Applethwaite Formation and Torver Formation of McNamara (1979). These formations were downgraded to members and incorporated in the Kirkley Bank Formation (Kneller et al., 1994). At Greenscoe and other outcrops in the area, a clear limestone unit can be distinguished at the base of the formation. This basal Ireleth Member (Kneller et al., 1994) was formerly known as Ireleth Limestone (Sedgwick, 1846), High Haume Limestone (Rose and Dunham, 1977; Table 5, p. 45 in Johnson et al., 2001) and Kentmere Limestone Member (McNamara, 1979). More profound stratigraphic details can be found in the publications cited above as in Basset et al. (1992) and Rushton and Ingham (2000).

1.1. Biostratigraphy of the Kirkley bank formation

The eight shelly fauna biozones recognized by Ingham (1966) in the nearby Cautley and Dent districts, using trilobites and brachiopods, act as a framework for the subdivision of the Ashgill Series. Later on, Ingham and Wright (1970) included the Puschgillian in the Ashgill series, and introduced the Cautleyan, Rawtheyan and Hirnantian stages, corresponding with Ingham's (1966) Zone 1–4, Zone 5–7 and Zone 8, respectively (Fig. 3).

McNamara (1979) correlated the Upper Ordovician rocks of the southern Lake District with the trilobite fauna of the Cautley District, and concluded that the base of the Kirkley Bank Formation lies within the upper half of Ingham's (1966) Zone 2, thus being mid Cautleyan in age (Fig. 3). This conclusion is based on the numerous occurrences of the trilobites *Calymene subdiademata* and *Gravicalymene susi*. The formation continues into Zone 3, the transition being characterized by the disappearance of *Tretaspis convergens convergens* and the appearance of *T. c. deliqua*. The top of the formation yielded *Stenopareia bowmanni*, *T. c. deliqua*, *Primaspis bucculenta* and *Phillipsinella parabola aquilonia*. This assemblage is typical for Ingham's (1966) Zone 3, meaning that the formation does not reach into Zone 4

(Fig. 3). Kneller et al. (1994) hold the same opinion concerning the upper boundary of formation. However, according to these authors, the base of the formation correlates with the base of Zone 2 in the south-western Lake District and the Furness area, and approximately with the middle of Zone 2 in the south-eastern Lake District (Kneller et al., 1994, Fig. 5 p 227) (Fig. 3); this is lower than suggested by McNamara (1979).

Until now, the Kirkley Bank Formation was assumed to fall completely within the *Dicellograptus anceps* graptolite Biozone, however, without any direct evidence from graptolite fossils. The *D. anceps* Biozone was believed to correlate with Ingham's (1966) Zone 1 to 7. New graptolite data from the type area of the Ashgill Series, obtained by Rickards (2002), show that this correlation may not longer be correct: the *Pleurograptus linearis* Biozone (two zones below the *D. anceps* Biozone) whose upper limit was formerly believed to fall into the lower Puschgillian Stage, probably reaches up into Zone 6 (Fig. 3).

A conodont study of the Greenscoe section (Smith, 1999, unpublished Ph.D. Thesis, University of Durham), revealed the presence of *Amorphognathus superbus* in the lower half of the outcrop, implying that the basal part of the Kirkley Bank Formation lies within the *A. superbus* conodont Biozone and is Puschgillian–early Cautleyan in age (Fig. 3). This is a considerably older age for the base of the formation than previously suggested elsewhere in the Lake District (see above). It must be pointed out that Smith (1999, *ibid.*) did find the contact with the underlying Skiddaw Group. This hampers slightly direct correlation with the conodont samples, since her datum point could slightly differ from ours. The formation's transgressive nature probably explains the diachronic lower boundary (Smith, 1999, *ibid.*). This diachronic nature is clearly shown in the recently revised correlation of the Ordovician rocks (Rushton and Ingham, 2000). Orchard (1980, Fig. 1, p. 11) reported *A. superbus* in the lower part of the Dent Group, as well as in the Puschgillian to lower Cautleyan of the Murthwaite Inlier in the Cautley district. Therefore, he concluded that the boundary between the *A. superbus* Biozone and the *A. ordovicicus* Biozone probably occurs within the Cautleyan Zone 2, what also had been suggested by North-American studies (see Armstrong et al., 1996 and references herein) (Fig. 3).

2. Fieldwork, sampling and palynological preparation

Samples were collected during the summer of 2003, following a detailed stratigraphical study of the section.

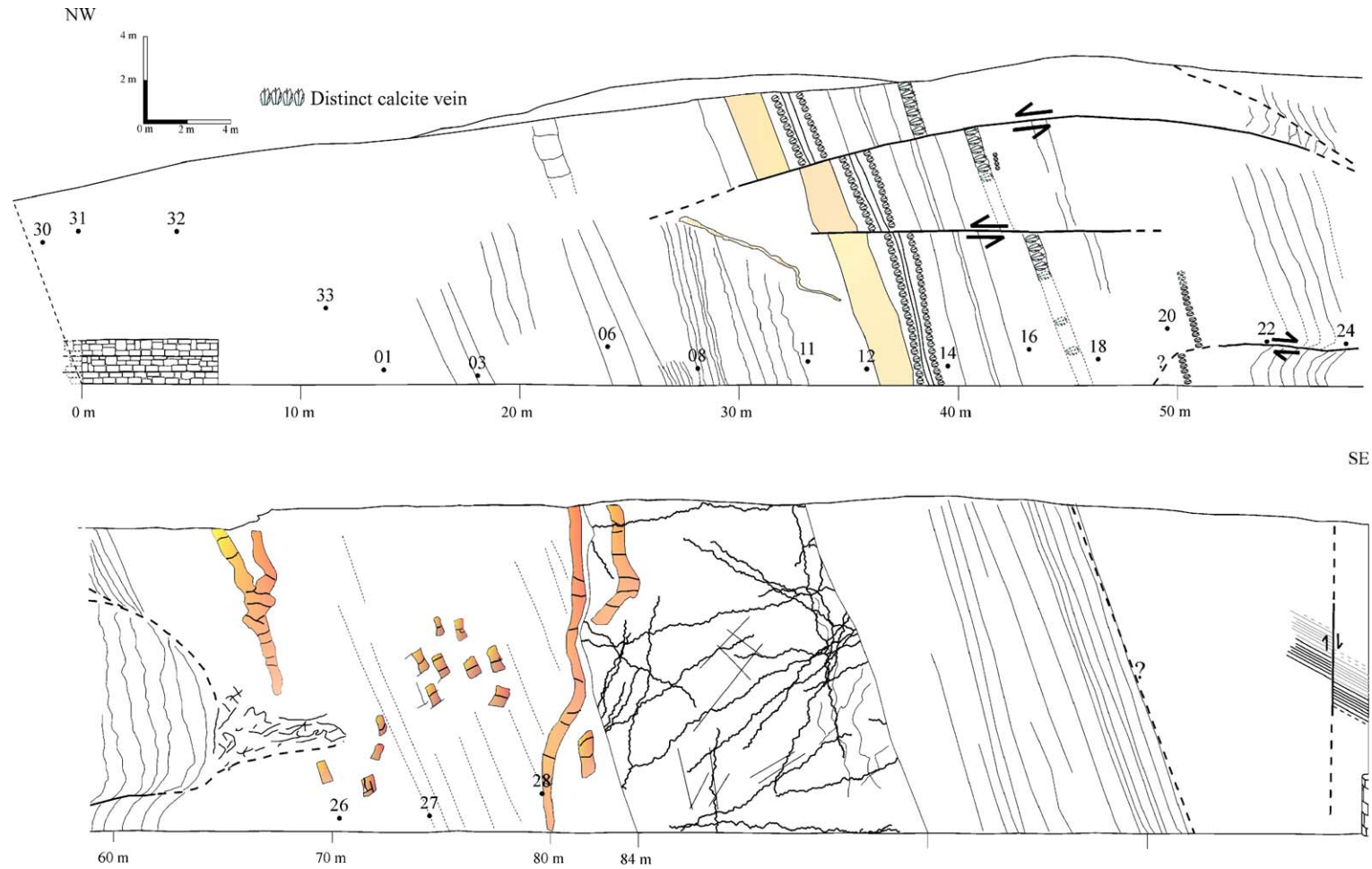


Fig. 2. Scaled sketch of the Greenscoe section, showing the most easily observable structural features and stratifications, and the position of the studied samples in the outcrop, number XX corresponding with sample NVN 03-XX. The small crystal symbols represent distinct calcite veins.

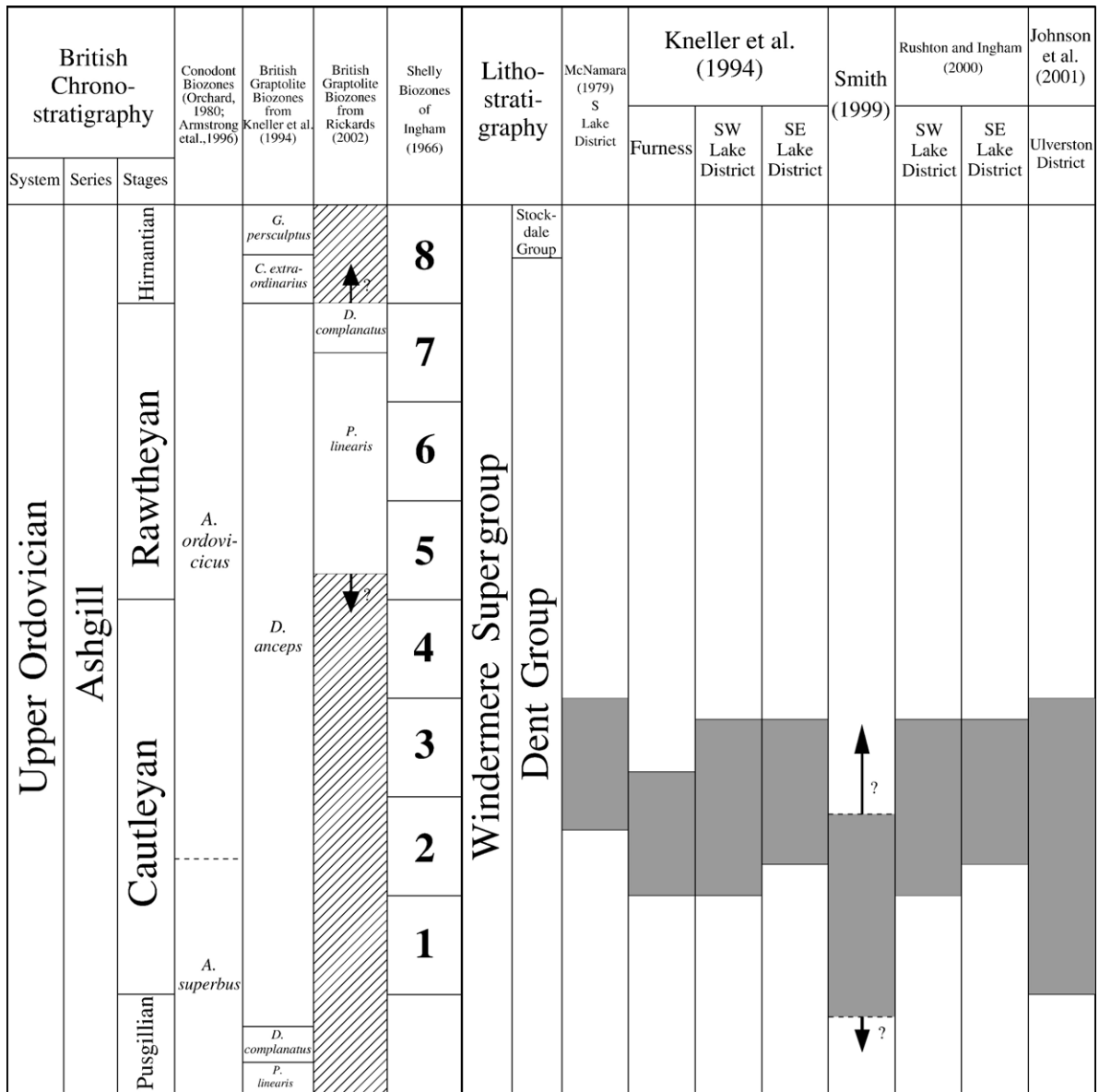


Fig. 3. Correlation chart showing the chronostratigraphical, lithostratigraphical and biostratigraphical position of the Kirkley Bank Formation according to previous studies. It should be mentioned that the correlation was achieved only by means of trilobites and conodonts (Smith, 1999, unpublished Ph.D. thesis, University of Durham); there is no direct evidence from graptolite fossils.

Badly weathered intervals were also sampled, in order to obtain a continuous sampling throughout the entire outcrop. The exact position of the investigated samples is given in Fig. 2, while their exact stratigraphic position is shown in Fig. 4. The chitinozoans were extracted from the rock samples by means of standard palynological methods, using HF and HCl (Paris, 1981), handpicked from the organic residue and mounted on slides for study with the Scanning Electron Microscope (Jeol 6400) of the Department of Geology and Pedology, Ghent University. The SEM micrographs were taken at

12kV. All specimens are stored in the collections of the Research Unit Palaeontology, Department of Geology and Pedology, Ghent University, Belgium.

3. Palynological results

The nineteen studied samples yielded moderately to well preserved chitinozoans, with exception of the 5 lowermost samples where chitinozoans are rare. This is most likely due to the badly weathered state of the basal part of the outcrop. In total, 4609 chitinozoans were

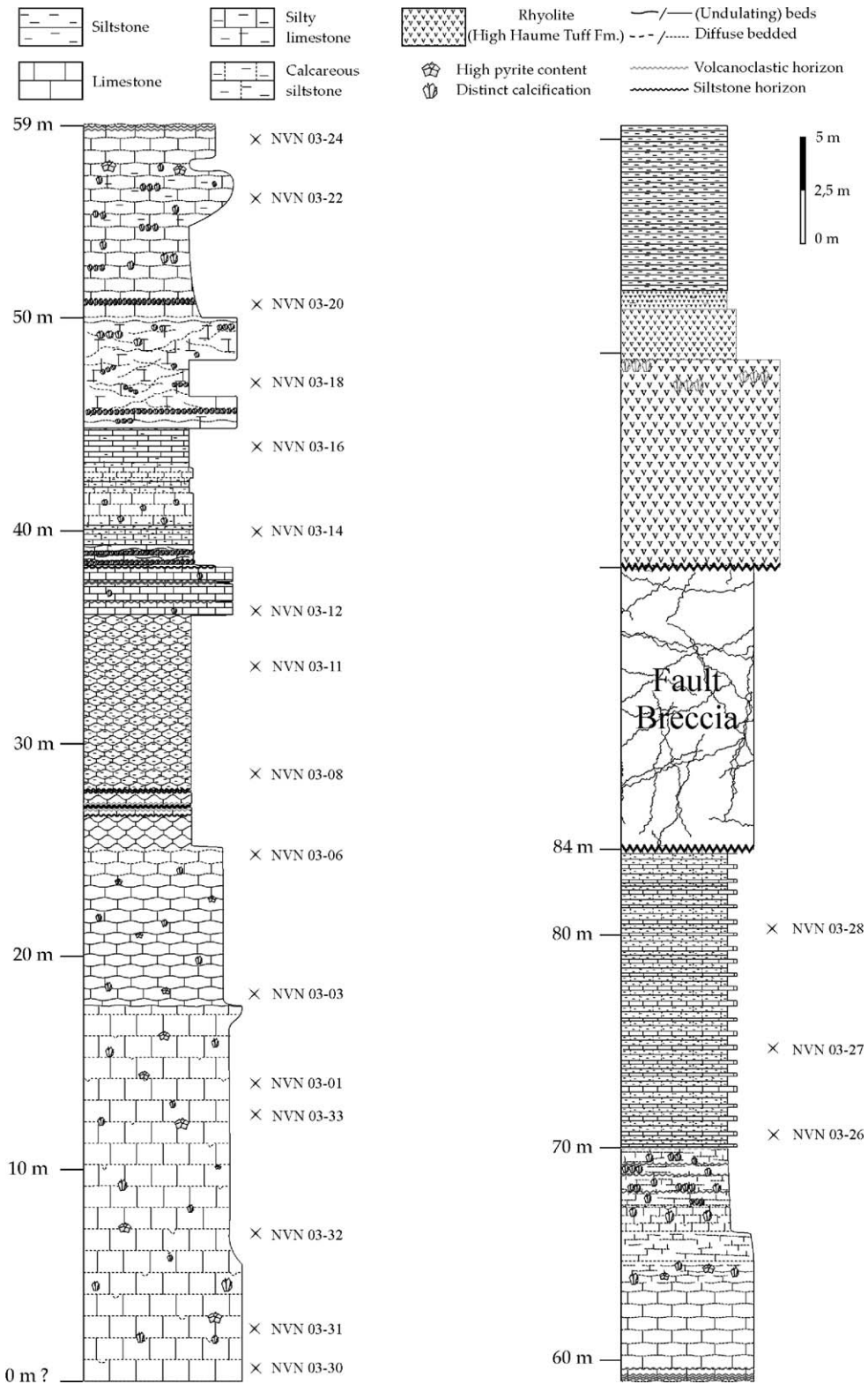


Fig. 4. Scaled lithologic log of the Greenscoe section, indicating the exact stratigraphic position of the studied samples. Because the contact with the underlying Skiddaw Group was not seen in the field, the base of the section is marked with a question mark.

handpicked and studied under the SEM. Generally seen, the samples are relatively rich in chitinozoans (Table 1), with an average of 14.59 and a maximum of 97.34 chitinozoans/g of rock. The high number of specimens per sample made determination up to species level fairly easy and reliable. Some other microfossils, such as scolecodonts and pyritized microfossils, possibly ostracods, were also present in the organic residue. Nearly all the chitinozoan specimens are preserved three-dimensionally and filled with pyrite. The vesicle wall is opaque and black in colour. These features correspond with a value of 3 to 4 on the coalification-scale of Correia (1967), indicating a heating temperature of at least 180°C. Conodonts of the section have a Colour Alteration Index value of 5 (Smith, 1999, unpublished Ph.D. Thesis, University of Durham) suggesting that the temperature even reached more than 300°C, possibly 400°C. Still, despite the high alteration, the chitinozoans are well preserved, probably due to the limestone composition of the host rock, protecting the specimens against compaction.

The distribution of the species throughout the section is numerically shown in Table 1 and graphically in Fig. 5. The first species to occur, in sample NVN 03-30, is *Cyathochitina campanulaeformis*? (Eisenack, 1931). Because of the bad preservation and the fact that only one specimen was found, the species is left in open nomenclature, following the guidelines of Bengtson (1988). Moreover, the species occurrence is restricted to this single sample. Sample NVN 03-31 proved barren and NVN 03-32 yielded only one, poorly preserved chitinozoa, determined as *Rhabdochitina*? sp.

The next species to appear in the section is *Belonechitina robusta* (Eisenack, 1959). The specimens in sample NVN 03-33 are poorly preserved, but were tentatively assigned to the species based on the typical multirooted spines. *B. robusta* is present without any doubt in samples NVN 03-01, NVN 03-03 and NVN 03-08. Absent from a large interval of the section, the species reappears in sample NVN 03-22 and makes its final yet doubtful appearance in sample NVN 03-28.

As already stated, the badly weathered state of the lowermost section of the outcrop has surely had a negative influence on the preservation of the organic walled microfossils. Consequently, it is impossible to evaluate the first occurrence of the species cited in the paragraph below. This is well illustrated in sample NVN 03-03: from this level upwards, the chitinozoan preservation ameliorates markedly, a large number of species appear “at the same time”, and the samples are quite rich in chitinozoans. This corresponds with an improved preservation of the rocks in the section.

The two most important species to appear in sample NVN 03-03 are *Conochitina elegans* Eisenack, 1931 and *Fungochitina spinifera* (Eisenack, 1962), both occurring in large numbers. Other species to appear are *Saharochitina fungiformis* (Eisenack, 1931), *Rhabdochitina*? cf. *gallica* (Taugourdeau, 1961) sensu Paris (1979), *Belonechitina* aff. *capitata* (Eisenack, 1962) and *Conochitina*? sp. 2. It is worth mentioning that both *F. spinifera* and *S. fungiformis* formerly were subspecies of the zonal index species *Fungochitina fungiformis* (Nölvak and Grahn, 1993). The spiny subspecies *Fungochitina fungiformis spinifera* was elevated to species rank by Paris et al. (1999), who made *F. spinifera* the neotype for the *Fungochitina* genus. A new genus, *Saharochitina*, was created by Paris et al. (1999) for the smooth *Fungochitina fungiformis fungiformis* morphotype. Following the revisions by Paris et al. (1999), Nölvak (in press) changes the name of the *F. fungiformis* Biozone to the “*F. spinifera* Biozone”. It is often hard to unambiguously recognise ornamentation in badly preserved specimens, and therefore the abundance of *F. spinifera* can be slightly underestimated. However, this has no biostratigraphical consequences in this study, since well-preserved specimens of both *F. spinifera* and *S. fungiformis* occur regularly throughout the section.

Conochitina incerta Eisenack, 1962 and *Angochitina communis* Jenkins, 1967 might also have their first occurrence in sample NVN 03-03, but their bad preservation hampers positive determination. *C. incerta* and *A. communis* are without doubt present in sample NVN 03-06, the latter having its last occurrence in this sample. *C. incerta* was found regularly, up to the highest investigated sample.

The specimens of sample NVN 03-06 are moderately well preserved. *Saharochitina fungiformis* dominates the assemblage, while *Conochitina primitiva*? Eisenack, 1939, *Lagenochitina baltica* Eisenack, 1931 and (tentatively, due to bad preservation) *Conochitina* sp. 1 have their first occurrence. *C. primitiva*? was left in open nomenclature because all specimens lack their neck. The distinction between *S. fungiformis* and *C. primitiva*? was made based on chamber shape, the former species being shorter and having more concave flanks around the shoulder than the latter species.

Sample NVN 03-08 marks the appearance of *Desmochitina ovulum*? Eisenack, 1962 (badly preserved, hence the open nomenclature), *Belonechitina micracantha* (Eisenack, 1931), *Spinachitina* sp. 1 and *S. coronata*? (Eisenack, 1931), the latter making up over 50% of the assemblage and dominating the assemblages of samples NVN 03-14 and NVN 03-16 as well.

Table 1
Numerical results from the chitinozoan study of 19 samples of the Greenscoe section

	NVN 03-30	NVN 03-31	NVN 03-32	NVN 03-33	NVN 03-01	NVN 03- 03	NVN 03- 06	NVN 03-08	NVN 03-11	NVN 03-12	NVN 03-14	NVN 03- 16	NVN 03-18	NVN 03- 20	NVN 03-22	NVN 03- 24	NVN 03-26	NVN 03-27	NVN 03- 28
<i>Rhabdochitina</i> ? spp.	1		1																
<i>Cyathochitina campanulaeformis</i> ? (Eisenack, 1931)	1																		
<i>Cyathochitina</i> spp.	2								1								1		
<i>Conochitina</i> spp.				2	1	18	32	94	13	4	30	2	12	60	30	12	5	14	31
<i>Belonechitina robusta</i> (Eisenack, 1959)			(2)	6		38		14							7				(1)
<i>Belonechitina</i> aff. <i>capitata</i> (Eisenack, 1962)						41													
<i>Conochitina elegans</i> Eisenack, 1931						107 (11)	(31)	(65)	12		(11)	18 (15)	127	33 (19)	25	41 (11)	(4)	(32)	10 (32)
<i>Conochitina incerta</i> Eisenack, 1962						(7)	22					(1)	5	65	8	30			19
<i>Conochitina</i> ? sp. 2						8													
<i>Rhabdochitina</i> ? cf. <i>gallica</i> (Taugourdeau, 1961) sensu Paris, 1979						7						14	43				1	2	
<i>Hercochitina</i> spp.						1									7				
<i>Spinachitina</i> spp.						3		5	1										
<i>Saharochitina fungiformis</i> (Eisenack, 1931)						35	69 (18)		13	3	28	31	8 (7)	73	5	293			
<i>Fungochitina spinifera</i> (Eisenack, 1962)						46	19 (4)		(9)		13	16		58	5	54	(1)		
<i>Angochitina communis</i> Jenkins, 1967						(8)	4 (3)												
<i>Desmochitina</i> spp.						6							4	2	1	2			
<i>Conochitina primitiva</i> ? Eisenack, 1939						9						1		11		77			
<i>Conochitina</i> sp. 1						(10)	37				55	6		23			4	(5)	3
<i>Tanuchitina</i> spp.						(4)			(1)		(4)	2		90	8 (7)				
<i>Lagenochitina baltica</i> Eisenack, 1931						1				(24)									5
<i>Lagenochitina</i> spp.						6				2				3	1		9	2	
<i>Desmochitina ovulum</i> ? Eisenack, 1962							9												2
<i>Belonechitina micracantha</i> (Eisenack, 1931)							15							10 (6)	31 (2)		8 (1)		16
<i>Spinachitina coronata</i> ? Eisenack, 1931							358			113	225						(2)	8	2
<i>Spinachitina</i> sp. 1							1												
<i>Spinachitina</i> ? sp. 2									12										
<i>Cyathochitina</i> sp. 1									5										
<i>Saharochitina</i> aff. <i>fungiformis</i> (Eisenack, 1931)									41										
<i>Armoricochitina</i> aff. <i>reticulifera</i> (Grahn, 1981a)													30						
<i>Desmochitina minor</i> Eisenack, 1931														(2)	3				
<i>Spinachitina</i> sp. 3																5		9	
<i>Ancyrochitina</i> sp. 1																13			
<i>Belonechitina americana</i> (Taugourdeau, 1965)																	3	2	
<i>Pistillachitina</i> sp. 1																			10
Chitinozoa indet	5				8	167	117	70	32	45	54	96	30	132	31	172	31	38	60
Number of chitinozoans	9	0	1	4	15	497	355	668	140	78	308	427	269	585	170	720	64	108	191
Amount of dissolved rock (g)	40.40	24.05	40.43	38.40	25.16	56.57	17.79	20.33	24.96	28.13	23.28	16.19	12.62	6.01	23.20	25.55	19.34	39.25	29.23
Number of chitinozoans per gram of dissolved rock	0.22	0.00	0.02	0.10	0.60	8.79	19.96	32.86	5.61	2.77	13.23	26.37	21.32	97.34	7.33	28.18	3.31	2.75	6.53

Numbers between brackets represent poorly identifiable specimens.

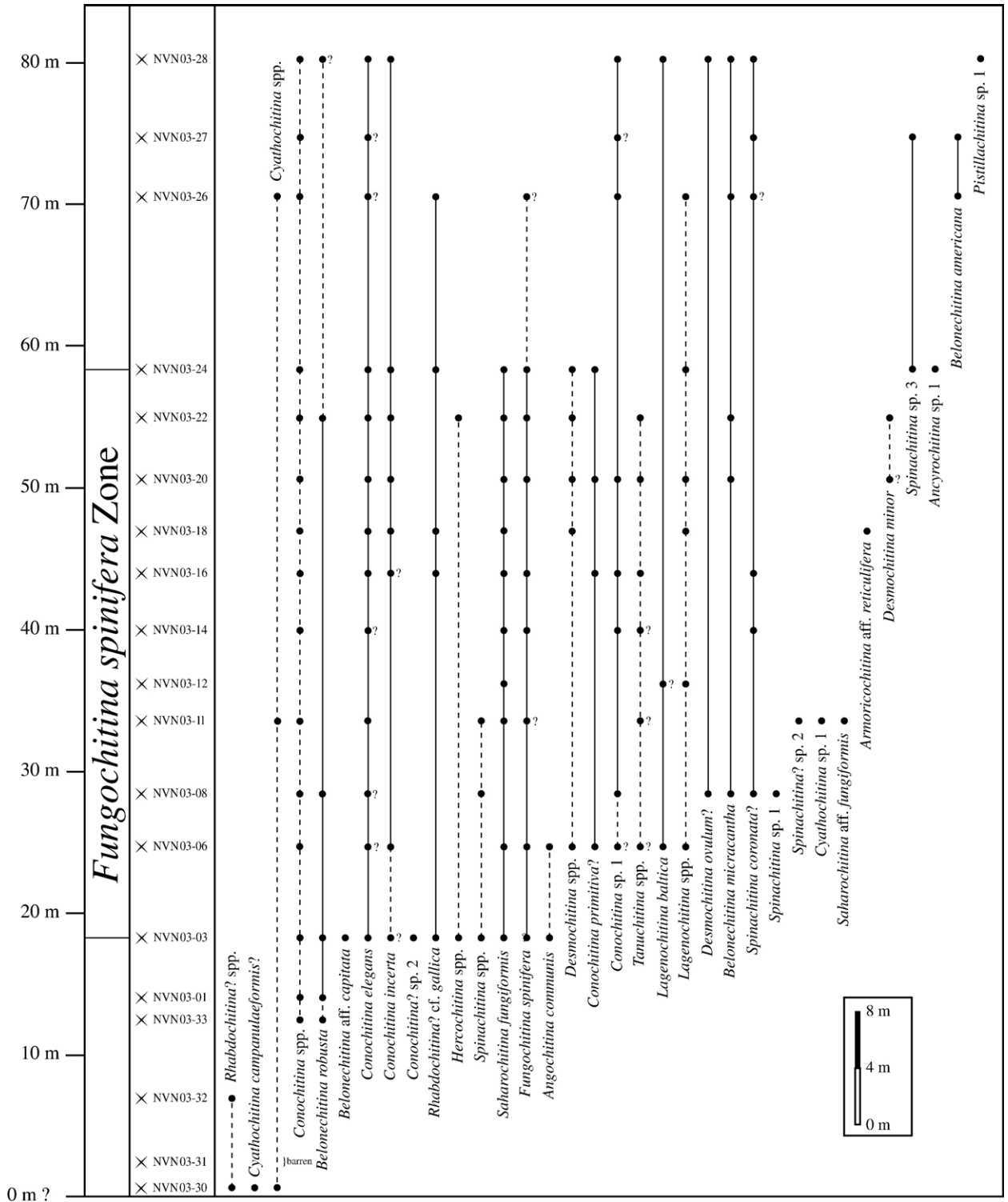


Fig. 5. Range chart of the chitinozoans from the Greenscoe section. The abundances are given in Table 1.

Sample NVN 03-11 is marked by the appearance of a few species whose occurrence is restricted to this single sample: *Spinachitina?* sp. 2, *Cyathochitina* sp. 1 and *Saharochitina* aff. *fungiformis* (Eisenack, 1931). The latter species is linked to *S. fungiformis* because of the similar vesicle shape, but differs from it in having much larger dimensions (the chamber is 40–75% wider, while the length of the “most complete” *S. aff. fungiformis* specimen exceeds the largest *S. fungiformis* specimen by 22%).

Specimens clearly belonging to the genus *Tanuchitina* have their lowest occurrence in sample NVN 03-16. The rather poor preservation of the specimens in this and other samples does not allow further determination.

The occurrence of *Armoricochitina* aff. *reticulifera* (Grahn, 1981a) is restricted to sample NVN 03-18. There are a number of reasons (see section selected systematics) why the specimens of this study have not been assigned to the stratigraphically important (see further) index fossil *A. reticulifera*.

Some biostratigraphically less important species appear in the upper half of the investigated part of the section. Poorly preserved specimens of *Desmochitina minor* Eisenack, 1931 show up in sample NVN 03-20. The species has its uppermost occurrence in the section in sample NVN 03-22, higher up section. The latter sample also shows the last occurrence of *Tanuchitina*-specimens and *Belonechitina robusta*. However, some fragments possibly belonging to the latter species were found in sample NVN 03-28 (the highest investigated sample). *Ancyrochitina* sp. 1 and *Spinachitina* sp. 3 both appear in sample NVN 03-24, whose assemblage is dominated by *Saharochitina fungiformis*, having its last occurrence in this sample. The same is true for *Conochitina primitiva?*.

Sample NVN 03-26 marks the appearance of *Belonechitina americana* (Taugourdeau, 1965), a species that resembles *B. micracantha*, but differs from it in its more claviform shape and heavier, rather blunted spines. Preservation becomes very poor from sample NVN 03-26 on, and chitinozoans do not occur in high numbers anymore. This sudden switch coincides with a distinct increase of the silt fraction in the rocks. The stratigraphically highest investigated sample NVN 03-28 yielded an assemblage consisting of *Conochitina elegans*, *C. incerta*, *C. sp. 1*, *Lagenochitina baltica*, *Desmochitina ovulum?*, *B. micracantha*, *Spinachitina coronata?* and *Pistillachitina* sp. 1, the latter species having its first occurrence in this sample.

4. Biozonation of the Greenscoe section

In the Greenscoe section, the Baltoscandian *Fungochitina spinifera* Biozone, defined as corresponding

with the total range of the index fossil and correlating with the middle Oandu up to middle Vormsi (Nölvak and Grahn, 1993; Nölvak, in press) (Fig. 6), can be recognized, indicating a Baltoscandian affinity of the Avalonian assemblage. In the Greenscoe section, the biozone is the body of rocks between sample NVN 03-03 and NVN 03-24. Possibly the biozone reaches up to sample NVN 03-26, but the specimens of this sample are badly preserved and do not allow a doubtless determination. A likewise uncertainty exists for the lower boundary due to the strong weathering of the basal part of the outcrop.

Nölvak and Grahn (1993) described two subbiozones in the *Fungochitina spinifera* Biozone: the *Cyathochitina angusta* Subzone and the *Armoricochitina reticulifera* Subzone (Fig. 6). The former index fossil has not been found in the Greenscoe section. In our opinion the specimens found in sample NVN 03-18, situated in the upper half of the *F. spinifera* Biozone at Greenscoe, differ too much from the holotype of *A. reticulifera* to be determined as the index fossil (hence the open nomenclature; see section selected systematics).

5. Correlation and interpretation

As in Baltoscandia (Nölvak and Grahn, 1993), *Lagenochitina baltica* seems to appear shortly above *Fungochitina spinifera*. Because of this, one could conclude that the *F. spinifera* Biozone is present from its base at Greenscoe. A bit higher up section however, *Spinachitina coronata?* appears. The species is known to occur in the topmost part of the *F. spinifera* Biozone (Nölvak and Grahn, 1993). Since no evidence for a hiatus between sample NVN 03-06 and NVN 03-08 was found, it seems likely that only the top part of the biozone is present at Greenscoe. The fact that the bottom part of the biozone is missing is confirmed by the co-occurrence of *L. baltica* and *Conochitina incerta* in sample NVN 03-06. Unlike on Baltoscandia, *Belonechitina robusta* still occurs in the upper part of the *F. spinifera* Biozone at Greenscoe. This could mean that 1) the uppermost part of the *F. spinifera* Biozone is also missing in the section, or 2) *B. robusta* has a longer stratigraphical range in this section of Avalonia than on Baltica, or 3) we are dealing with a morphologically very similar species that erroneously was lumped with *B. robusta*, or 4) we are dealing with reworked *B. robusta*-specimens. There is no direct evidence however for this last interpretation. The fact that, in contrast to the Greenscoe section, *B. robusta* and *S. coronata* do not coexist in Baltoscandia seems to favour the second interpretation, but the third interpretation cannot be excluded.

Time Slices (Webby et al., 2004)	Balto-scandian Chronostratigraphy		Chitinozoan Biozonation				British Chronostratigraphy		Time Slices (Webby et al., 2004)
			Baltoscandia		Gondwana	U.K. Greenscoe			
	Series	Stages	Nölvak and Grahn, 1993	Webby et al., 2004	Webby et al., 2004	this study	Series	Stages	
6c	Harju	Porkuni	C. <i>scabra</i>	C. <i>scabra</i> / S. <i>taugourdeaui</i>	S. <i>oulebsiri</i>	Correlation based on Cautley District & Cross Fell Inlier (Vandenbroucke et al., 2005)	Ashgill	Hirnantian	6c
			S. <i>taugourdeaui</i>	H. <i>gamachiana</i>	T. <i>elongata</i>				6c
6b	Harju	Pirgu	C. <i>rugata</i>	C. <i>rugata</i>	A. <i>merga</i>		Ashgill	Rawtheyan	6b
									6b
6a	Harju	Vormsi	T. <i>bergstroemi</i>	T. <i>bergstroemi</i>	A. <i>nigerica</i>		Ashgill	Cautleyan	6a
			A. <i>barbata</i>	A. <i>barbata</i>	A. <i>barbata</i>				6a
5d	Viru	Nabala	F. <i>fungiformis</i>	F. * <i>spinifera</i>	C. <i>fistulosa</i>		Caradoc	Sireiffordian	5d
			A. <i>reticulifera</i>	A. <i>reticulifera</i>	B. <i>robusta</i>				5d
5c	Viru	Rakvere	C. <i>angusta</i>	C. <i>angusta</i>	F. <i>tanvillensis</i>		Caradoc	Cheneyan	5c
			Oandu	S. <i>cervicornis</i>	Ancyrochitina sp. 1				5c

Fig. 6. Correlation chart of Upper Ordovician time slices, British and Baltoscandian chronostratigraphies, and chitinozoan biozonations for Baltoscandia, Gondwana and the Greenscoe section. This figure should not be “over-interpreted”. It mainly serves to show the position of the *F. spinifera* Biozone (former *F. fungiformis* Biozone) within these chronostratigraphical and biostratigraphical schemes and the discrepancy between the two correlations (see further and text). The boundaries of the *F. spinifera* Biozone at Greenscoe are indicated with dashed lines, since parts of the biozone might be missing due to the weathered state of parts of the outcrop. The *F. spinifera* Biozone from Webby et al. (2004) is marked with an asterisk, since the biozone is not mentioned explicitly in their schemes (type error?). The Baltoscandian chitinozoan biozones are tightly correlated with the Baltoscandian chronostratigraphy. The British Series and Stages are based on the shelly biozones of Ingham (1966). The chitinozoan biozones of Gondwana are included mainly to show the position of the *Belonechitina robusta* Biozone (Paris, 1990). Time slices were tied to the Ordovician chronostratigraphical scheme by Webby et al. (2004). Their boundaries correlate mostly with graptolite and/or conodont zonal boundaries. Correlation of the *F. spinifera* Biozone at Greenscoe with the British chronostratigraphical scheme is based on a recent chitinozoan study in the Cautley District and Cross Fell Inlier by Vandenbroucke et al. (2005). They show that the Caradoc/Ashgill boundary lies within the *F. spinifera* Biozone rather than in the *Tanuchitina bergstroemi* Biozone.

A similar assemblage as the one at Greenscoe has recently been found in the Dent Group sediments in the type Ashgill area (Cautley district) and the Pus Gill

section (Cross Fell Inlier) (Vandenbroucke et al., 2005). The study allowed a direct correlation between the Baltoscandian chitinozoan biozones and the British

chronostratigraphical scheme. It showed that the Caradoc/Ashgill boundary lies within the *Fungochitina spinifera* Biozone and not within the *Tanuchitina bergstroemi* Biozone as carefully suggested by Nölvak and Grahn (1993) and Webby et al. (2004) (Fig. 6).

Both the Greenscoe section and the Cautley district seem to contain only the upper part of *Fungochitina spinifera* Biozone, while in the Cross Fell Inlier, the lower part of the biozone is present as well (Vandenbroucke et al., 2005). An interpolated correlation of the Greenscoe section containing the *F. spinifera* Biozone with the two latter areas leads to a late Onnian (upper Caradoc)–earliest Cautleyan age interval for this part of the outcrop. This refutes the early to late Cautleyan age for the Kirkley Bank Formation proposed by Johnson et al. (2001). In addition, findings of the conodont species *Amorphognathus superbus* in the lower part of the outcrop (Smith, 1999, unpublished Ph.D. Thesis, University of Durham) co-occurring with the *F. spinifera* assemblage corroborates the similar co-occurrence of assemblages of both fossil groups in the type Ashgill area (Orchard, 1980; Vandenbroucke et al., 2005).

6. Systematics of selected species

This section explains why certain species were treated in open nomenclature. When measurements are given, the same abbreviations are used as in Paris (1981), where *L* = total length; *Lp* = chamber length; *Dp* = maximal chamber width; *Dc* = diameter of oral

tube/neck; *n* = number of measured specimens. The chamber length is given instead of the length of the neck, because in nearly all the specimens the neck is (partly) missing. All measurements were made on three-dimensionally preserved specimens by means of the SEM, with an accuracy of 2 µm. The dimensions are given in micrometer as minimum–mean–maximum values of the parameter. The dimensions of the species not described herein are given in Table 2. The suprageneric classification proposed by Paris et al. (1999) is here applied.

Incertae sedis group *Chitinozoa* Eisenack, 1931

Order *Prosomatifera* Eisenack, 1972

Family *Conochitinidae* Eisenack, 1931 emend. Paris, 1981

Subfamily *Conochitinae* Paris, 1981

Genus *Conochitina* Eisenack, 1931 emend. Paris et al., 1999

Conochitina sp. 1

(Plate II,7)

Material: 128 specimens from samples NVN 03-08, NVN 03-14, NVN 03-16, NVN 03-20, NVN 03-26 and NVN 03-28, and 15 poorly preserved specimens from samples NVN 03-06 and NVN 03-27.

Dimensions: *L*: 171–211–258; *Dp*: 59–71–85; *Dc*: 28–41–51 (*n*: 10)

Description: *Conochitina* specimens with a subcylindrical chamber and a subcylindrical to subconical neck.

Table 2

Dimensions in micrometers of the chitinozoan species not discussed in the selected systematics section

Chitinozoan species	Vesicle length (<i>L</i>)			Maximal chamber width (<i>Dp</i>)			Diameter of oral tube (<i>Dc</i>)			Chamber length (<i>Lp</i>)			<i>n</i>	Plate
	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.		
<i>Cyathochitina campanulaeformis</i> ?	92			116		116	43		43				1	I: 1
<i>Belonechitina robusta</i>	245	259	275	86	93	103	43	51	64				4	II: 11
<i>Conochitina elegans</i>	200	312	450	52	63	90	35	50	65				13	II: 12
<i>Conochitina incerta</i>	174	308	445	61	74	105	31	49	80				8	II: 13
<i>Rhabdochitina</i> ? cf. <i>gallica</i> sensu Paris, 1979	177			62	67	77	57	60	65				4	I: 9
<i>Saharochitina fungiformis</i>	90	105	180	55	70	88	25	31	36	56	63	75	20	I: 12–13
<i>Fungochitina spinifera</i>	87	106	174	57	67	92	22	30	35	55	61	70	14	I: 10–11
<i>Angochitina communis</i>	98		98	64		64	40		40	78		78	1	I: 17–18
<i>Conochitina primitiva</i>	84	97	117	66	70	76	25	34	45				14	I: 14
<i>Lagenochitina baltica</i>	160		160	107		107	48		48				1	I: 5
<i>Desmochitina ovulum</i> ?	72	91	138	50	58	81							5	I: 2
<i>Belonechitina micracantha</i>	148	204	265	56	70	87	30	44	60				8	II: 8
<i>Saharochitina</i> aff. <i>fungiformis</i>	221			100	119	131	35	41	50	100	114	146	8	II: 9
<i>Desmochitina minor</i>	75		82	47		61							2	I: 3
<i>Belonechitina americana</i>	172		184	74		78	40		55				2	II: 5

Abbreviations are used as in Paris (1981). *n* is the number of measured specimens. The chamber length is given instead of the length of the neck, because in nearly all the specimens, the neck is (partly) missing.

The chamber shows abrupt but modest basal widening, with the angle between the upper part of the chamber and the basal widening never exceeding 5°. The flexure is very faint; the basal margin is rounded to moderately sharp. The base is flat to slightly convex and a small basal scar can be present.

Discussion: In all *C. sp. 1* specimens the neck was partly missing. The overall shape and size of *C. sp. 1* strongly resembles that of *Spinachitina coronata?*. However, the basal margin of *C. sp. 1* shows no marks of spines, unlike *S. coronata?*, even when badly preserved. Moreover, the basal widening of *C. sp. 1* is markedly less pronounced than the basal widening of *S. coronata?*.

Conochitina? sp. 2

(Plate I,6)

Material: 8 specimens from sample NVN 03-03.

Dimensions: L: 85; Dp: 61; Dc: 33 (*n*: 1)

Description: Small chitinozoans with a claviform to conical chamber, widest in the lower half of the chamber. The basal margin is rounded. The base is slightly convex. The vesicle wall is smooth.

Discussion: The neck was (partly) missing in all specimens, but a flexure could always be observed. Therefore, the specimens were assigned to *Conochitina* and not to *Desmochitina*.

Genus *Pistillachitina* Taugourdeau, 1966

Pistillachitina sp. 1

(Plate I,16)

Material: 10 specimens from sample NVN 03-28.

Dimensions: L: 114-122-131; Lp: 62-63-66; Dp: 107-111-117; Dc: 35-40-45 (*n*: 13)

Description: Chitinozoans with a lenticular chamber making up half the total vesicle length. The neck is perfectly cylindrical in most cases, but sometimes widens towards the aperture. A typical merlon-like structure characterises the apertural pole. The Dp/Dc ratio lies between 2.7 and 3.1. The concave shoulders are pronounced. The basal margin is rounded, the base is distinctly concave. The vesicle wall is smooth.

Discussion: The specimens were assigned to *Pistillachitina* because of the pronounced “basal” widening which in these specimens actually encompasses the whole chamber. This is not in contradiction with the definition of the genus, since Paris et al. (1999) remarked that the transition between chamber and neck is within the tubular part of the vesicle. The overall shape of *P. sp. 1* resembles the one of *Saharochitina fungiformis*, but the former species is much wider and has a higher Dp/Dc ratio than the latter species.

Subfamily Belonechitininae Paris, 1981

Genus *Belonechitina* Jansonius, 1964

Belonechitina aff. *capitata* (Eisenack, 1962)

(Plate II,10)

Material: 41 specimens from sample NVN 03-03.

Dimensions: L: 208-233-265; Dp: 45-52-60; Dc: 37-45-52 (*n*: 3)

Description: *Belonechitina* species with an elongated (sub)cylindrical vesicle without flexure and a rounded basal margin. The vesicle wall is smooth except for the basal part where simple blunted spines can be observed.

Discussion: *Belonechitina* aff. *capitata* is linked to *B. capitata* because of the long, (sub)cylindrical vesicle and the rounded base ornamented with simple spines. In contradiction to the holotype, described by Eisenack (1962), and the specimens of Grahn (1981a), the specimens of this study do not have a widened, conical base.

Subfamily Spinachitininae Paris, 1981

Genus *Spinachitina* Schallreuter, 1963 emend. Paris et al., 1999

Spinachitina coronata? (Eisenack, 1931)

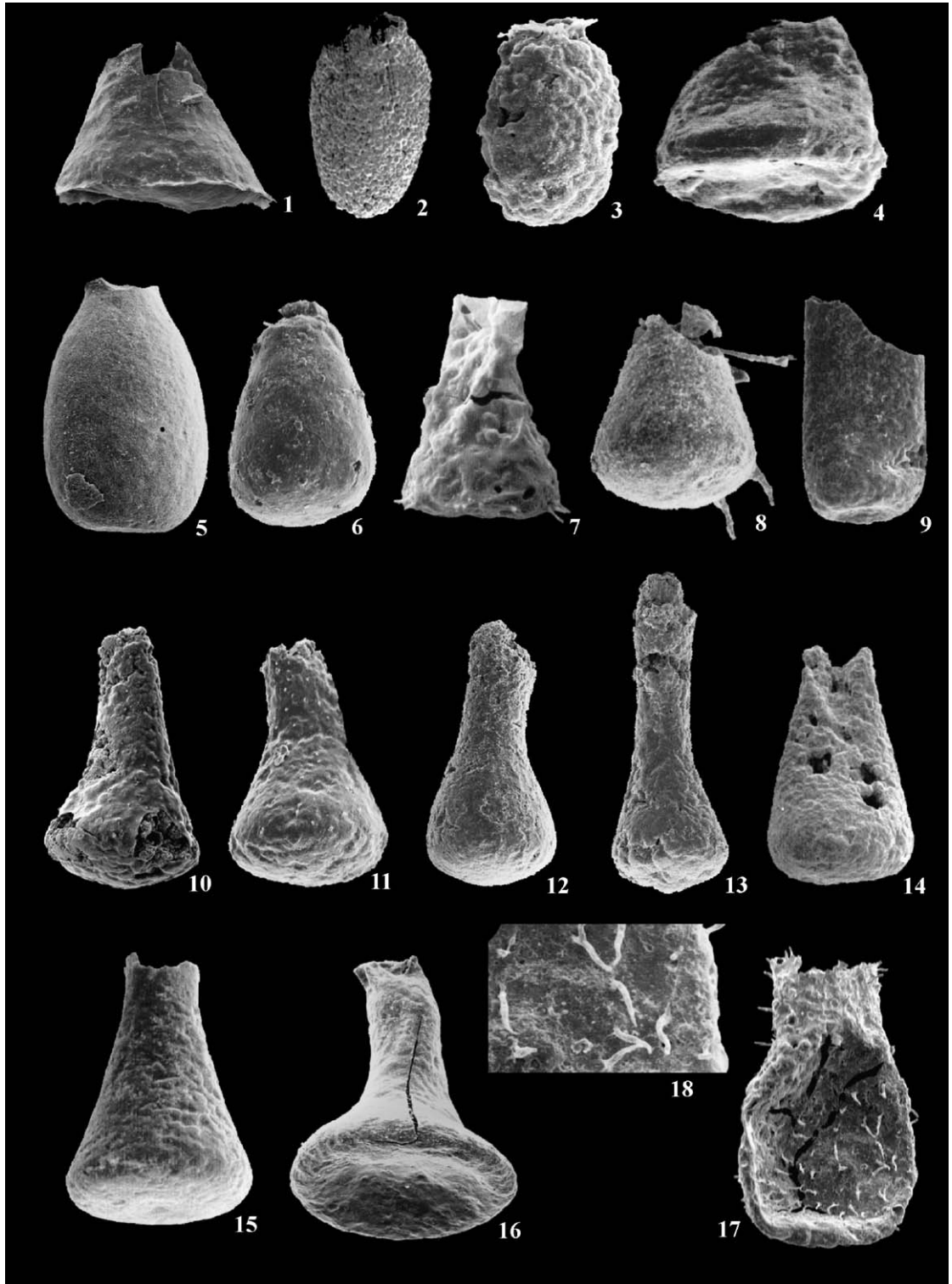
(Plate II,6)

Material: 706 specimens from samples NVN 03-08, NVN 03-14, NVN 03-16, NVN 03-27, NVN 03-28, and possibly 2 poorly preserved specimens from sample NVN 03-26.

Dimensions: L: 130-192-248; Dp: 55-68-83; Dc: 25-34-46 (*n*: 13)

Description: *Spinachitina* species with a conical to subconical chamber and a cylindrical to subcylindrical neck. The chamber widens sharply towards the base, making an angle of 10° to 25° with the part of the chamber above. The flexure is inconspicuous. In some specimens the flanks are more convex, pronouncing the shoulders a bit more. The sharp basal margin is ornamented with a row of 15 to 30 simple spines.

Discussion: Despite its occurrence in large numbers, only few complete *Spinachitina coronata?* specimens were found. The few complete specimens are quite a bit smaller than the holotype described by Eisenack (1931) and the specimens of Grahn (1982, 1994). For that reason, and because (marks of) the basal row of spines often is hard to recognize, the species is left in open nomenclature. Moreover, Eisenack (1931) notes a strong widening of the neck towards the apertural pole, a feature that has only been observed in a few specimens in this study. Another difference between the holotype and Greenscoe specimens, is the more sudden and much sharper chamber-



basal widening transition in the latter. The Greenscoe specimens strongly resemble *S. coronata?* from the Cautley district (Vandenbroucke et al., 2005). The main difference between *Conochitina* sp. 1 and *S. coronata?* is the lack of spines in the former species.

Spinachitina sp. 1
(Plate I,7)

Material: 1 specimen from sample NVN 03-08.

Dimensions: L: 70; Lp: 46; Dp: 50; Dc: 24 (*n*: 1)

Description: Small *Spinachitina* with a conical chamber gradually passing up into a cylindrical neck. The base is flat. The basal margin is sharp to weakly rounded and ornamented with a row of irregularly spaced, fine, simple spines. These spines are about 1.5–2 µm wide at the base and narrow distally. Their (observed) maximum length is 8 µm.

Discussion: Most of the spines seem to be fragmented, as is suggested by their flat terminations. Only one complete spine, with a pointy termination, was observed.

Spinachitina? sp. 2
(Plate I,15)

Material: 12 specimens from sample NVN 03-11.

Dimensions: L > 154; Dp: 105-113-127; Dc: 43-50-62 (*n*: 3)

Description: Chitinozoa with a wide, conical chamber with straight to concave flanks. The chamber passes gradually into the (sub)cylindrical neck. The basal margin is rounded and seems to be ornamented with hollow spines. The base is flat.

Discussion: No complete specimens were retrieved and only hollow, circular marks were observed, probably

representing the remains of broken spines; hence the open nomenclature and the uncertain assignment to *Spinachitina*.

Spinachitina sp. 3
(Plate II,14)

Material: 14 specimens from samples NVN 03-24 and NVN 03-27.

Dimensions: L: 127-132; Dp: 72-74; Dc: 34-45 (*n*: 2)

Description: Conical to subcylindrical chitinozoans with straight flanks and no clear flexure. The basal margin is rounded. The base is flat to weakly concave. The vesicle is ornamented with a crown of slender spines situated at the transition between the basal margin and the base, in such way that they appear to be “underneath” the vesicle rather than at the maximal curvature of the basal margin.

Discussion: *Spinachitina* sp. 3 differs from *S. coronata?* by the typical position of the spines in the former species.

Family Lagenochitinidae Eisenack, 1931 emend. Paris, 1981

Subfamily Cyathochitinininae Paris, 1981

Genus Cyathochitina Eisenack, 1955 emend. Paris et al., 1999

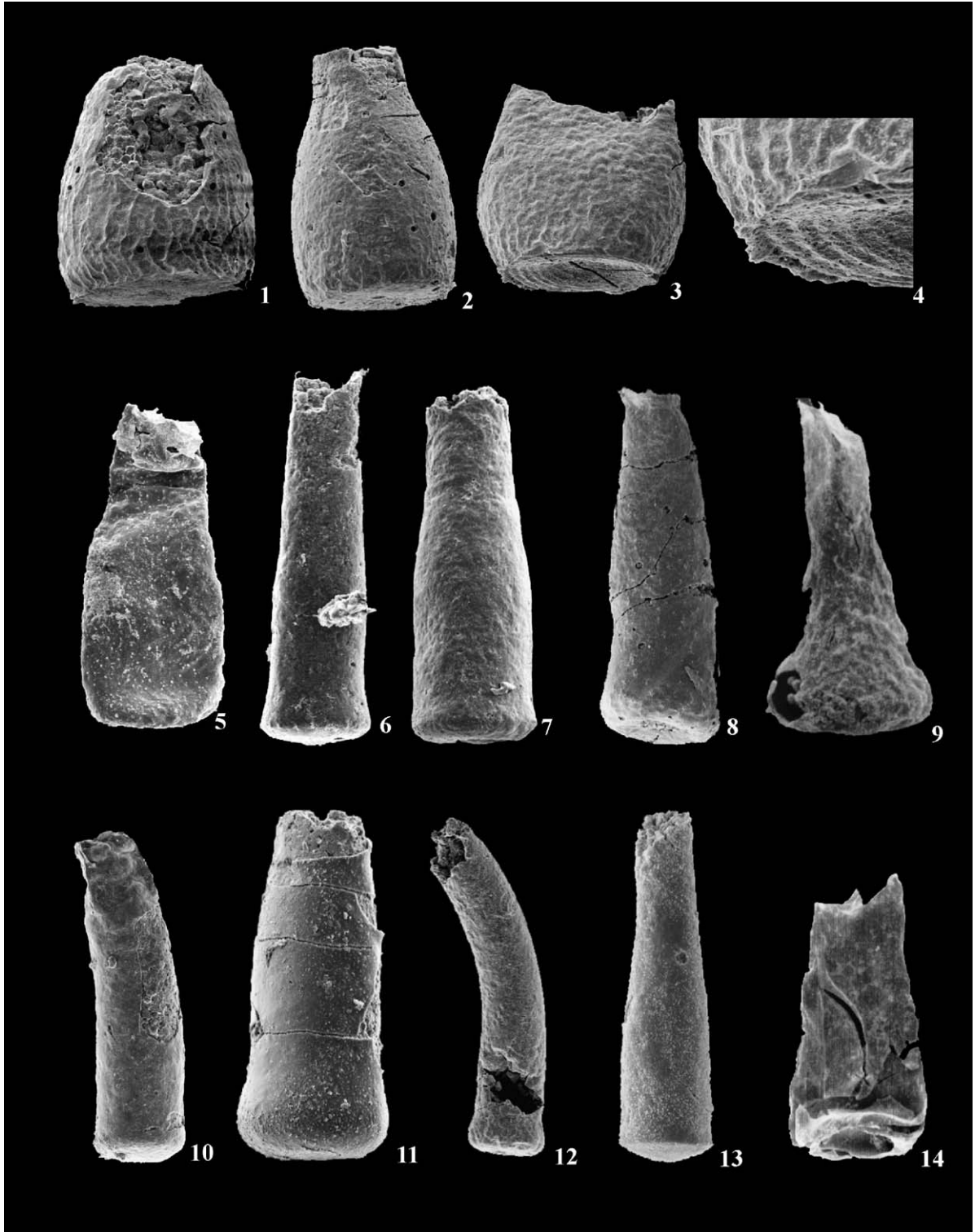
Cyathochitina sp. 1
(Plate I,4)

Material: 5 specimens from sample NVN 03-11.

Dimensions: L > 158; Lp: 80-93-105; Dp: 97-116-142; Dc: 15-52-75 (*n*: 3).

Plate I. All measurements in microns (L x Dp x Dc or L x Dp x Dc x Lp). Abbreviations as in Paris (1981): L = total length, Dp = maximal chamber width, Dc = diameter of neck, Lp = chamber length. The chamber length is given instead of the length of the neck because in nearly all the specimens, the neck was (partly) missing. All measurements were made on three-dimensionally preserved specimens.

1. *Cyathochitina campanulaeformis?* (Eisenack, 1931) (92 x 116 x 43/sample NVN 03-30)
2. *Desmochitina ovulum?* Eisenack, 1962 (138 x 81/sample NVN 03-28)
3. *Desmochitina minor* Eisenack, 1931 (75 x 47/sample NVN 03-22)
4. *Cyathochitina* sp. 1 (+79 x 109/sample NVN 03-11)
5. *Lagenochitina baltica* Eisenack, 1931 (173 x 107 x 48/sample NVN 03-28)
6. *Conochitina?* sp. 2 (85 x 61 x 33 (?)/sample NVN 03-03)
7. *Spinachitina* sp. 1 (70 x 50 x 24 x 46/sample NVN 03-08)
8. *Ancyrochitina* sp. 1 (76 x 70 x 30 (?)/sample NVN 03-24)
9. *Rhabdochitina* cf. *gallica* (Taugourdeau, 1961) sensu Paris, 1979 (121 x 68 x 65/sample NVN 03-18)
10. *Fungochitina spinifera* (Eisenack, 1962) (125 x 78 x 30 x 55/sample NVN 03-03)
11. *Fungochitina spinifera* (Eisenack, 1962) (100 x 67 x 30 x 62/sample NVN 03-03)
12. *Saharochitina fungiformis* (Eisenack, 1931) (136 x 65 x 32 x 66/sample NVN 03-20)
13. *Saharochitina fungiformis* (Eisenack, 1931) (180 x 64 x 30 x 75/sample NVN 03-20)
14. *Conochitina primitiva?* Eisenack, 1939 (117 x 73 x 35/sample NVN 03-20)
15. *Spinachitina?* sp. 2 (154 x 108 x 43/sample NVN 03-11)
16. *Pistillachitina* sp. 1 (120 x 107 x 35 x 55/sample NVN 03-28)
17. *Angochitina communis* Jenkins, 1967 (98 x 64 x 40 x 78/sample NVN 03-06)
18. Detail of 17.



Description: *Cyathochitina* with a wide conical chamber with straight flanks, passing into a (probably) (sub) cylindrical neck via a relatively well-pronounced flexure. The basal margin is sharp to slightly rounded and carries a laterally protruding carina. The base is flat.
Discussion: No complete specimens were recovered, so only a minimum length could be given. The diameter of the neck was measured at flexure height. The remains of the carina at the basal margin were sufficiently clear to unambiguously assign the specimens to the *Cyathochitina* genus.

Subfamily *Ancyrochitininae* Paris, 1981

Genus *Ancyrochitina* Eisenack, 1959

Ancyrochitina sp. 1

(Plate I,8)

Material: 13 specimens from sample NVN 03-24.

Dimensions: L: 70-76; Dp: 66-70; Dc: 26-30 (*n*: 2)

Description: Chitinozoans with a conical chamber, a rounded basal margin and a convex to hemispherical base. The vesicle wall is smooth. The basal margin carries 7 to 10 equally spaced and relatively heavy appendices. These appendices are about 5 µm at the base and can be simple or bipodal. The limbs of the bipodal appendices merge close to the base of the appendices and are positioned closely together on the basal margin. The appendices reach up to 20 µm.

Discussion: All retrieved specimens lacked their neck, making determination up to species level impossible. The diameter of the neck was measured at (supposed) flexure height.

Order *Operculatifera* Eisenack, 1931

Family *Desmochitinidae* Eisenack, 1931 emend. Paris, 1981

Subfamily *Pterochitininae* Paris, 1981

Genus *Armoricochitina* Paris, 1981

Armoricochitina aff. *reticulifera* (Grahn, 1981a)

(Plate II,1–4)

Material: 30 specimens from sample NVN 03-18 treated quantitatively. An extra amount of rock sample was dissolved and investigated only on the presence of this species in order to obtain better preserved specimens, however, without positive result.

Dimensions: L > 265; Lp: 160-192-250; Dp: 107-133-152; Dc: 55-75-95 (*n*: 9)

Description: Chitinozoa with a wide, conical to hemispherical chamber. The flanks are convex, in a way that the maximal vesicle width can be observed halfway the chamber. A few specimens show a constriction towards the base. A clear flexure is present and the neck seems to be (sub)cylindrical. The Dp/Dn ratio varies from 1.7 to 2.3, the Lp/Dp ratio from 1.2 to 1.6. In most specimens, the flat to slightly concave base carries concentric ridges and a 10 to 15 µm wide scar in its centre, while the vesicle wall is ornamented with crests orientated randomly or more or less parallel to the body axis.

Discussion: The specimens resemble *A. reticulifera* very well: the dimensions lie within the same range, concentric ridges are present on the base and crests ornament the vesicle wall. Still, there are a number of reasons why the specimens are treated under open nomenclature. First of all, no complete specimens were found, the neck and carina are always (partly) missing. Secondly, the crests on the vesicle walls are less robust than those on the holotype, described by Grahn (1981a). Later on, Grahn (1981b, 1982) did describe less heavy ornamented specimens as being *A. reticulifera*. However, the specimens of Grahn (1981b) were later on assigned to the new species *A. granulifera* by Nölvak

Plate II. Remarks and abbreviations: see Plate I

1. *Armoricochitina* aff. *reticulifera* (Grahn, 1981a)(180 x 142 x 70 (?)/sample NVN 03-18)
2. *Armoricochitina* aff. *reticulifera* (Grahn, 1981a) (227 x 137 x 75/sample NVN 03-18)
3. *Armoricochitina* aff. *reticulifera* (Grahn, 1981a) (140 x 108 x 90 (?)/sample NVN 03-18)
4. Detail of 3.
5. *Belonechitina americana* (Taugourdeau, 1965) (187 x 74 x 40/sample NVN 03-26)
6. *Spinachitina coronata*? Eisenack, 1931 (247 x 68 x 41/sample NVN 03-14)
7. *Conochitina* sp. 1 (226 x 76 x 51/sample NVN 03-20)
8. *Belonechitina micracantha* (Eisenack, 1931) (265 x 87 x 41/sample NVN 03-28)
9. *Saharochitina* aff. *fungiformis* (Eisenack, 1931) (221 x 108 x 43 x 71/sample NVN 03-11)
10. *Belonechitina* aff. *capitata* (Eisenack, 1962) (225 x 56 x 37/sample NVN 03-03)
11. *Belonechitina robusta* (Eisenack, 1959) (224 x 95 x 63/sample NVN 03-03)
12. *Conochitina elegans* Eisenack, 1931 (310 x 70 55/sample NVN 03-18)
13. *Conochitina incerta* Eisenack, 1962 (261 x 75 x 43/sample NVN 03-24)
14. *Spinachitina* sp. 3 (176 x 80 x 54/sample NVN 03-27).

and Grahn (1993). The most distinct difference between *A. reticulifera* and the specimens of the Greenscoe section is the pronounced basal constriction. This feature is clearly present in the assemblage containing the holotype (Grahn, 1981a), but has only been observed in a few specimens from Greenscoe, where, moreover, the constriction was rather faint.

7. Conclusions

The Kirkley Bank Formation from the recently excavated outcrop at Greenscoe, between Askam-in-Furness and Dalton-in-Furness, yielded a moderately to well preserved and rich chitinozoan assemblage. This relatively good preservation is remarkable, since conodonts from the section show a CAI 5 (Smith, 1999, unpublished Ph.D. Thesis, University of Durham). The Baltoscandian *Fungochitina spinifera* Biozone (Nölvak and Grahn, 1993; Nölvak, in press) could be recognized, allowing correlation between Baltica and Avalonia, and indicating a Baltoscandian influence on the Avalonian chitinozoan assemblage during this interval of the Late Ordovician. The *F. spinifera* Biozone also offers a strong correlation with the Cautley District and Cross Fell Inlier. This allows to stipulate a late Onnian–earliest Cautleyan age for the part of the Greenscoe section enclosing the *F. spinifera* Biozone. We propose an older age for the Kirkley Bank Formation than proposed by Johnson et al. (2001). Moreover, the conodont-chitinozoa biozone relations (*Amorphognathus superbus*–*Fungochitina spinifera*) described in this study are the same as in the type Ashgill area (Orchard, 1980; Vandembroucke et al., 2005). This clearly corroborates the co-occurrence of *Fungochitina spinifera* Biozone-assemblages and *Amorphognathus superbus* Biozone-assemblages.

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