Geol. Mag. **142** (6), 2005, pp. 783–807. © 2005 Cambridge University Press
doi:10.1017/S0016756805000944 *Printed in the United Kingdom*

Upper Ordovician chitinozoan biostratigraphy from the type Ashgill area (Cautley district) and the Pus Gill section (Dufton district, Cross Fell Inlier), Cumbria, Northern England

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(*Received* 7 October 2004; *accepted* 5 April 2005)

Abstract – Seventy-five samples from the classic sections through the historical type area of the Ashgill Series in the Cautley district and along Pus Gill in the Cross Fell Inlier have been examined for chitinozoans. The results of this study allowed the recognition of five internationally recognized biozones and the definition of two new Avalonian chitinozoan zones. From bottom upwards, these are: the *Fungochitina spinifera*, the *Tanuchitina bergstroemi*?, the *Conochitina rugata*, the *Spinachitina fossensis*, the *Bursachitina umbilicata* sp. n., the *Ancyrochitina merga* and the *Belonechitina postrobusta* zones. One new species is described: *Bursachitina umbilicata* sp. n. This biozonation enables a correlation between the Cautley district and the Baltoscandia and Gondwana palaeocontinents based on chitinozoans. The Baltoscandic chitinozoan zones are, therefore, now better correlated with the British chronostratigraphical scheme, which is still widely used. It is stratigraphically significant that the base of the Ashgill in its type area does not fall within the *Tanuchitina bergstroemi* Zone, as widely believed before, but in the *Fungochitina spinifera* Zone. In addition, chitinozoans from the Onnian (Caradoc) section of the Cross Fell Inlier provide a link with the type Caradoc section in Shropshire.

Keywords: Chitinozoa, Ashgill, biozonation, Cautley, Pus Gill, Avalonia.

1. Introduction

The present study deals with the chitinozoans from the Taythes, Westerdale and Murthwaite inliers from the Howgill Fells, north of the town of Sedbergh in the Cautley district, and with those from the Pus Gill section in the Cross Fell Inlier, near Dufton, both in Cumbria, northern England (Fig. 1).

1.a. Cautley district

The Cautley district is a classic region in British stratigraphy as it is the type area for the Ashgill Series (Marr, 1913, p. 13; Ingham & Wright, 1970, p. 233; Fortey *et al*. 1991, p. 18), having a more complete succession than can be seen in the Ash Gill section of the Coniston area in the Lake District, which originally gave its name to the series.

Following the pioneering studies of Marr (1913), Ingham (1966) made a thorough study of the Ordovician inliers of the Cautley and Dent districts, resulting in a subdivision of the Ashgill Series (at the time excluding the Pusgillian) into eight shelly faunal biozones, using trilobites and brachiopods. His maps and shelly faunal biozonation were used as the main references for sampling in the area (Figs 2–5). Ingham & Wright (1970) revised the classification of the Ashgill Series and type areas of the stages; they included the Pusgillian in the Ashgill Series, introduced the Cautleyan (Ingham's 1966 zones 1–4) and Rawtheyan stages (Ingham's 1966 zones 5–7), and designated the Hirnantian (Ingham's 1966 zone 8) as the upper stage of the Ashgill Series. Ingham & Wright (1972) made some minor modifications to the scheme.

More recently, Ingham, Owen & Harper (*in* Fortey *et al*. 1991) proposed the Foggy Gill Section (Fig. 6) in the Murthwaite Inlier as the stratotype for the base of the Pusgillian Stage and the Ashgill Series, using brachiopod and trilobite biostratigraphy. We refer to Ingham & Wright (1970) for a full description of the classification of the Ashgill Series and to Fortey *et al*. (1995, 2000) for a recent revision of the series and stages and further discussion.

We shall continue to use local stratigraphical terms throughout the paper, because at the time of writing, no formal decisions have been made as to the nomenclature of the new global stratigraphical subdivisions of the Upper Ordovician, except for the Hirnantian Stage.

Lithostratigraphically, samples have been collected from the Cautley Mudstone Formation (Onnian,

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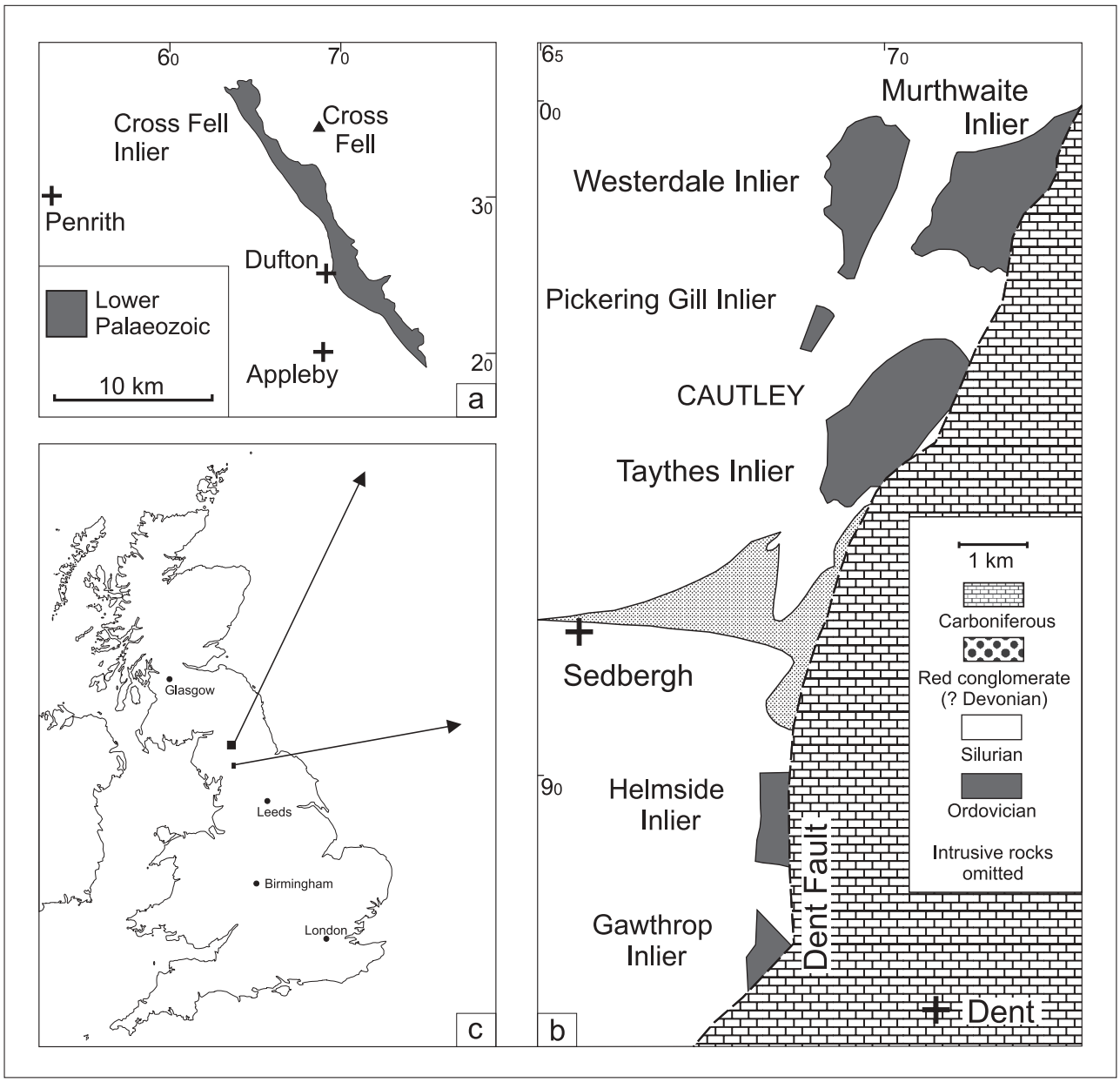

Figure 1. Location of the Cross Fell Inlier (a) and the Cautley district Inliers (b) in the UK (c). Redrawn after Ingham (1966) and Arthurton & Wadge (1981).

Pusgillian, Cautleyan and Rawtheyan in age; including the Cautley Volcanic Member) and the Ashgill Formation (late Rawtheyan–Hirnantian in age and including the Cystoid Limestone and Wharfe members), both belonging to the Dent Group of the Windermere Supergroup. The few Silurian samples were taken from the Skelgill Formation. Stratigraphical divisions follow Ingham (1966), Rickards (1988) and revisions in Kneller *et al*. (1994), summarized in Fortey *et al*. (2000). There is an intra-Rawtheyan unconformity immediately below the Cystoid Limestone Member.

Several graptolite studies have been undertaken in the area. The most recent revision is that of Rickards (2002), to which we refer for a historical overview of the graptolite biostratigraphy. Orchard (1980) studied the conodonts from the area. Williams *et al*. (2001) wrote about the ostracods from the Cautley district. No systematic chitinozoan study has been published until now.

1.b. Pus Gill section (Cross Fell Inlier)

The classic section near the village of Dufton, in a small stream alongside Pus Gill House, is the type area of the Pusgillian, as introduced by Bancroft (1945) for the post-Onnian part of the Dufton Shale Formation (Dent Group). Later, the Pusgillian was included in the Ashgill (Ingham & Wright, 1970). Dean (1959) revisited the section and mentions one place, between his localities A.5 and A.6, as the 'most likely place' for a

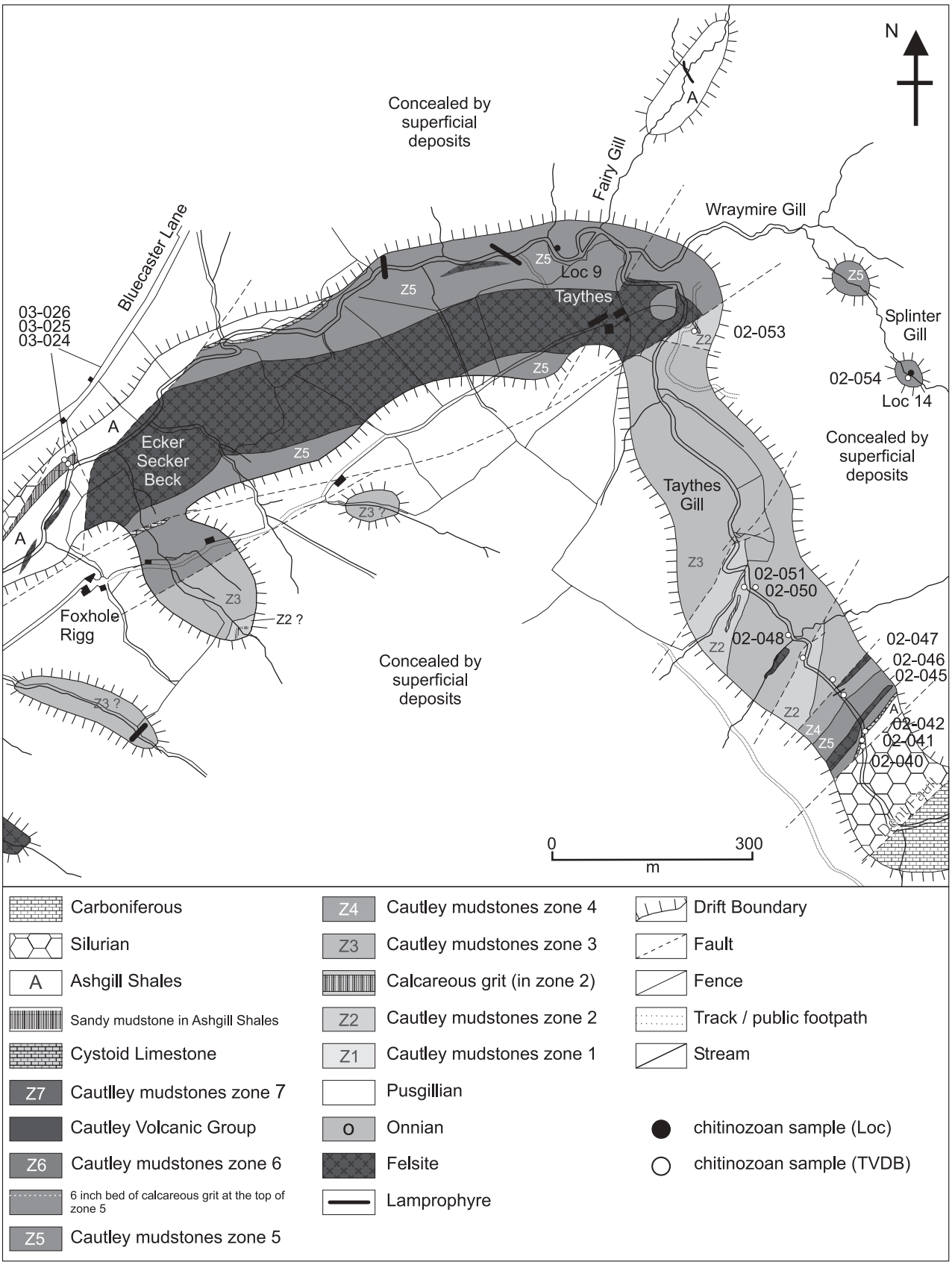

Figure 2. Geological map of the Taythes North Inlier with the sample localities (after Ingham, 1966).

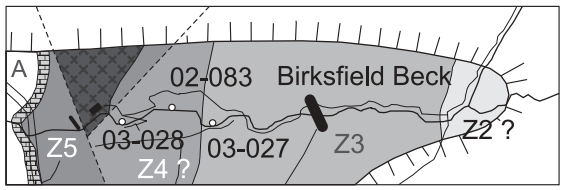

Figure 3. Geological map of the Taythes South Inlier with the sample localities (after Ingham, 1966). For legend, see Figure 2.

normal contact between the Pusgillian and the Onnian, 'though details of the section are obscured by drift'. Burgess & Holliday (1979) generally support Dean's conclusions in their geological sheet memoir, but only show faulted Pusgillian–Onnian contacts on their Pus Gill map (Burgess & Holliday, 1979, fig. 8, p. 12). The latter map was used during fieldwork and interpretation (Fig. 7). Only the Onnian and Pusgillian successions from this section have been studied herein. Cross Fell Inlier chitinozoans have previously only been reported from the northern part of the inlier, in the stratigraphically lower Skiddaw Group, which underlies the Borrowdale Volcanic Group, and not from the Dent Group (Arthurton & Wadge, 1981; lithostratigraphical revision according to Kneller *et al*. 1994).

2. Sampling, fieldwork and chemical treatment

Samples were collected on three different occasions. Firstly, a batch of samples was subsampled from the graptolite slabs from Rickards' (2002) most recent graptolite study of the Howgill Fells area. They are indicated by 'Loc' throughout the paper (Figs 2–5). For a detailed description of the localities, see Rickards (2002). Subsampling of the graptolite-bearing slabs ensures very accurate correlation between the graptolite and chitinozoan biozonation. A second group of samples was collected from the Cautley district during the summer of 2002 by two of us (TVDB and RBR). They are labelled (TVDB) 02-xxx (Figs 2–6). A smaller group of samples from the Taythes and Westerdale inliers was taken in September 2003 by TVDB and JV (Figs 2–4). At the same time, following poor results from the Onnian samples of the Cautley district (see below), the Pus Gill samples were collected from the Cross Fell Inlier, by TVDB (Fig. 7). All 2003 samples are indicated by a (TVDB) 03-xxx label. Following collection, the samples were treated according to standard palynological methods (Paris, 1981); chitinozoans were handpicked from the organic residue and mounted on slides for study with the Scanning Electron Microscope (Jeol 6400) or normal optical light microscope (Zeiss axioskop 2).

3. Chitinozoan results

3.a. Cautley district

Of the 67 samples from the Cautley district, only seven were barren of chitinozoans. The remaining sixty yielded 5748 chitinozoan specimens in total, resulting in a moderately well-preserved, rather rich and diverse assemblage. The results of the chitinozoan study in the type Ashgill area are shown quantitatively on Tables 1, 2 and 3 and partly qualitatively on Figure 8.

The lowermost two samples (TVDB 02-068 and 02-067), collected from the Onnian outcrops along the upper reaches of Foggy Gill, only yield poorly preserved chitinozoans. Amongst these, the most important are *Lagenochitina baltica* and *Belonechitina* ?*robusta*. Slightly higher up the section, the samples taken across the base of the Ashgill (or the base of the Pusgillian) as proposed in Fortey *et al*. (1991) proved to be barren. Both the lack of chitinozoans and poor preservation in these lowermost levels can be explained by the badly weathered state of the outcrops, which makes it extremely difficult to recover organic walled microfossils such as chitinozoans. This also means that within the type Ashgill area, it is impossible to evaluate the first occurrences of the species cited below, as no other sections through this stratigraphical level are known from the Cautley district. Hence, fresher samples were sought from the Pus Gill section in the Cross Fell Inlier (see below).

Stratigraphically higher samples from the Pusgillian, and much fresher outcrops along Foggy Gill and at other Murthwaite Inlier localities (Sally Brow section, Sally Beck), yield a pyritized but well-preserved, very specific and easily recognizable chitinozoan fauna, with *Lagenochitina baltica*, *L. prussica*, *Conochitina* ?*incerta*, *Conochitina elegans*, *Desmochitina nodosa*, *Saharochitina fungiformis* and *Spinachitina* ?*coronata*.

Tanuchitina bergstroemi is the next important species to appear in the section, although there are some problems with its identification. In the study area, only fragments were recovered. The lower occurrences of the species were even more doubtful than the higher ones, hence the open nomenclature (*Tanuchitina* cf. *bergstroemi*) in samples TVDB 02-063 and 02-051. Higher up the section, several observations of the species remain tentative (*Tanuchitina* ?*bergstroemi*). In addition to the fragmented findings of the species, it is also quite difficult to distinguish between *T. bergstroemi* and *Conochitina* species with a sharp basal margin, such as *C*. ?*incerta* (see below). However, in contrast with the above, Paris (pers. comm. 2002) reported full relief *Tanuchitina* (possibly *T. bergstroemi* or a new species close to it) from pilot samples taken from the higher, more calcareous beds of Ingham's (1966) zone 6 of the Cautley Mudstone Formation. He also mentions other chitinozoans from Ingham's (1966) zone 5, including *Lagenochitina baltica* and *Desmochitina minor*.

Belonechitina americana has a rather long range in the section (Fig. 8), and is at times not easily separated from *Belonechitina micracantha*, especially in samples with a poor preservation, hence the use of a *B. americana*/*B. micracantha* group in some

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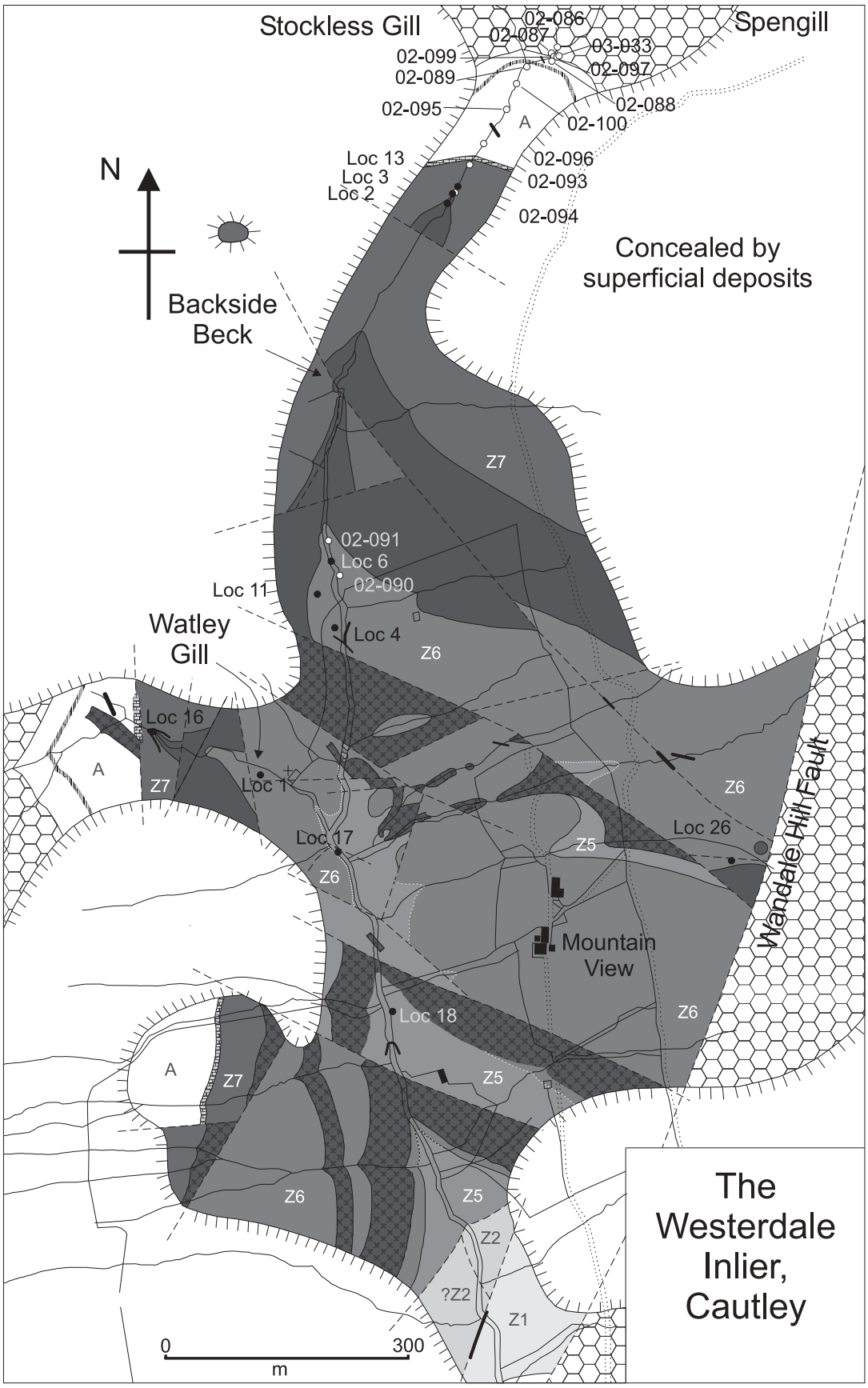

Figure 4. Geological map of the Westerdale Inlier with the sample localities (after Ingham, 1966). For legend, see Figure 2.

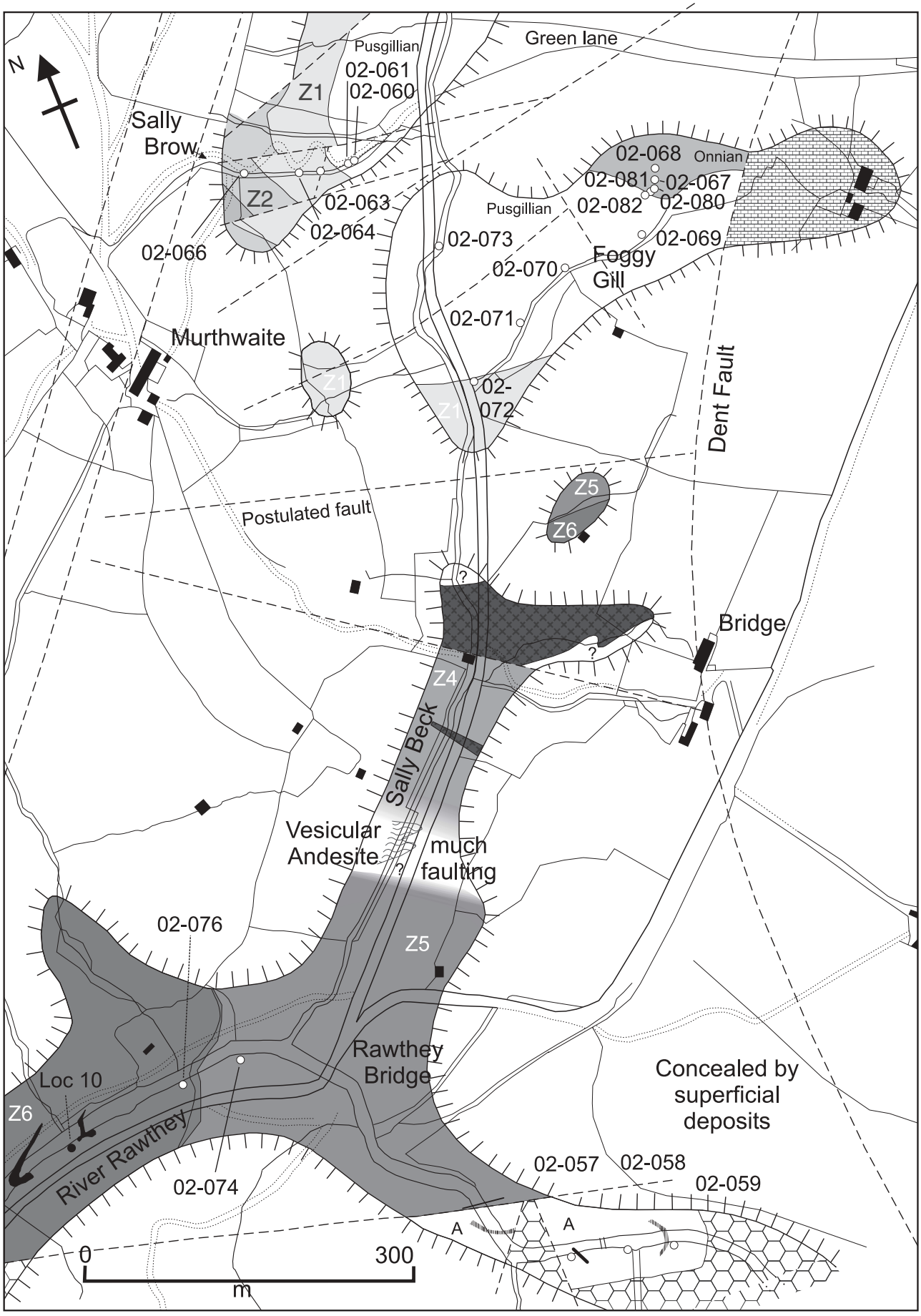

Figure 5. Geological map of the Murthwaite Inlier with the sample localities (after Ingham, 1966). For legend, see Figure 2.

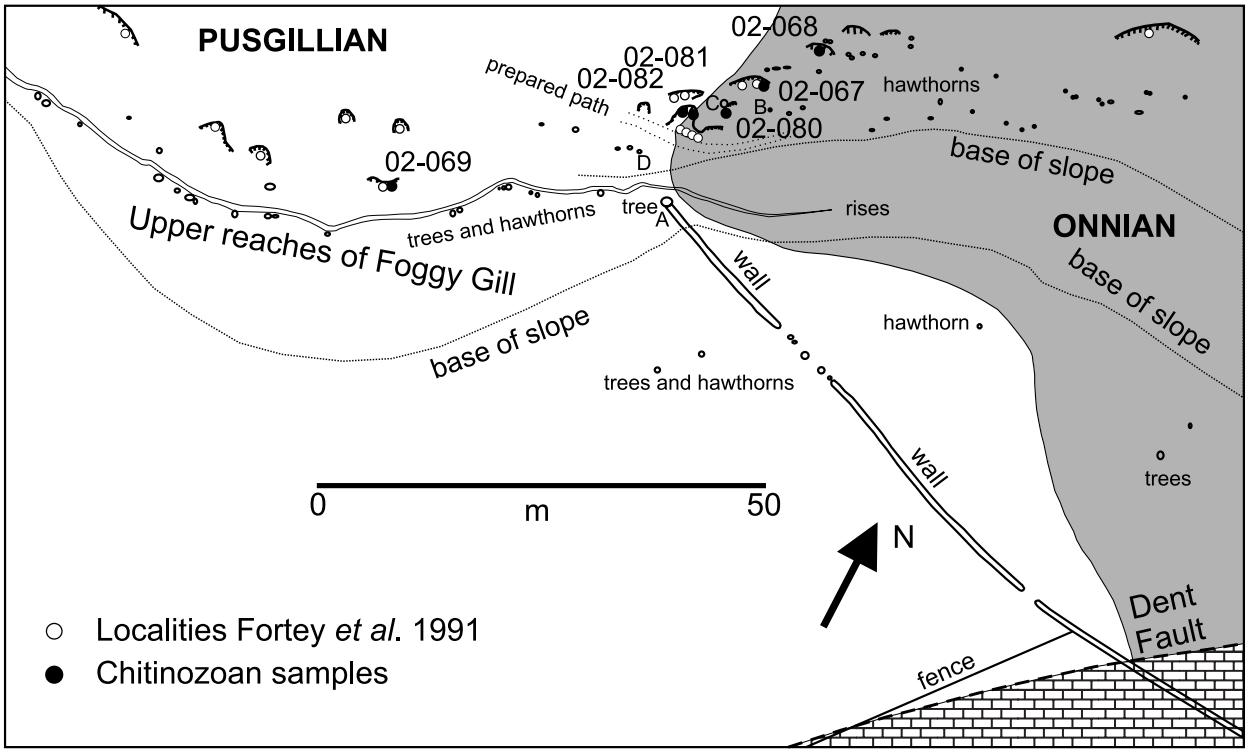

Figure 6. Detailed geological map of the Foggy Gill Section, Murthwaite Inlier (adapted after Fortey *et al*. 1991). For legend, see Figure 2. A, B, C, D are trees used as reference points and are referred to in the Appendix.

samples. *Spinachitina bulmani* has a much shorter range, in samples TVDB 02-051 (?), 02-050 and 02–046. *Spinachitina* sp. 1 has a short range as well, between samples TVDB 02-048 and 02-045 (in the upper Cautleyan).

Numerous *Hercochitina* specimens were recovered from the section, although determination to species level proved less straightforward, and the preservation of the vesicles allowed identification only of *Hercochitina* aff. *seriespinosa*, *Hercochitina* sp. 1 and *Hercochitina* sp. 2 (for the respective ranges, see Fig. 8).

Conochitina rugata is recognized in five samples within the succession: certainly in samples TVDB 03-028, Loc 14 and Loc 17, and doubtfully in TVDB 02-054 and 02-090. There is, however, a problem with the stratigraphical position of TVDB 03-028, the lowermost sample yielding *C. rugata*. Ingham (1966) marks its locality in Birksfield Beck (Taythes south inlier) as '? Zone 4'. There are thus two possibilities: either Ingham's (1966) zone 4 is correct and *C. rugata* ranges from the upper Cautleyan (TVDB 03-028; zone 4) to the middle Rawtheyan zone 5 (TVDB 02-054, Loc 14 and Loc 17) and possibly zone 6 (doubtful appearance in TVDB 02-090), or Ingham's (1966) zone 4 is incorrect and the occurrence of *C. rugata* in Birksfield Beck suggests that the locality indicated '? Zone 4' stratigraphically belongs to levels referable to the Rawtheyan (zone 5). In the latter case, the range of *C. rugata* would be restricted to the Rawtheyan. Both options are shown on Figure 8.

Belonechitina sp. 3 is restricted to the Rawtheyan. The lowermost occurrence of *Spinachitina fossensis* is observed in Loc 1 (Ingham's 1966 zone 6), preceded by two doubtful findings of the species (*Spinachitina* ?*fossensis*) in Ingham's (1966) zones 5 and 6. The species ranges up to Loc 2, a sample collected 2–3 m below the top of the Cautley Volcanic Member (Rickards, 2002), which is in between Ingham's (1966) zones 6 and 7. *Spinachitina* sp. 2, a species close to *S. fossensis*, has a similar range within the Rawtheyan, from Loc 26 up to Loc 2 (see above). *Spinachitina* ?*bulmani sensu* Achab (1977) has restricted occurrences in Loc 1, TVDB 02-091 and Loc 16, all within the Rawtheyan.

Bursachitina umbilicata sp. n., a new and easily recognizable species, has a restricted range in the upper Rawtheyan, between Loc 6 and Loc 13.

Ancyrochitina merga and *Euconochitina lepta* are both reported from two isolated levels, in Loc 11 and Loc 2 (respectively upper zone 6 of the Cautley Mudstone Formation and the top of the Cautley Volcanic Member). The latter species has an earlier but doubtful occurrence in sample TVDB 02-083. Species close to these two (*Ancyrochitina* aff. *merga* and *Conochitina* sp. 1) have been observed in Ingham's (1966) lower zone 5 (sample TVDB 02-076).

The Cystoid Limestone is barren of chitinozoans. Samples from the Hirnantian Ashgill Shales Formation

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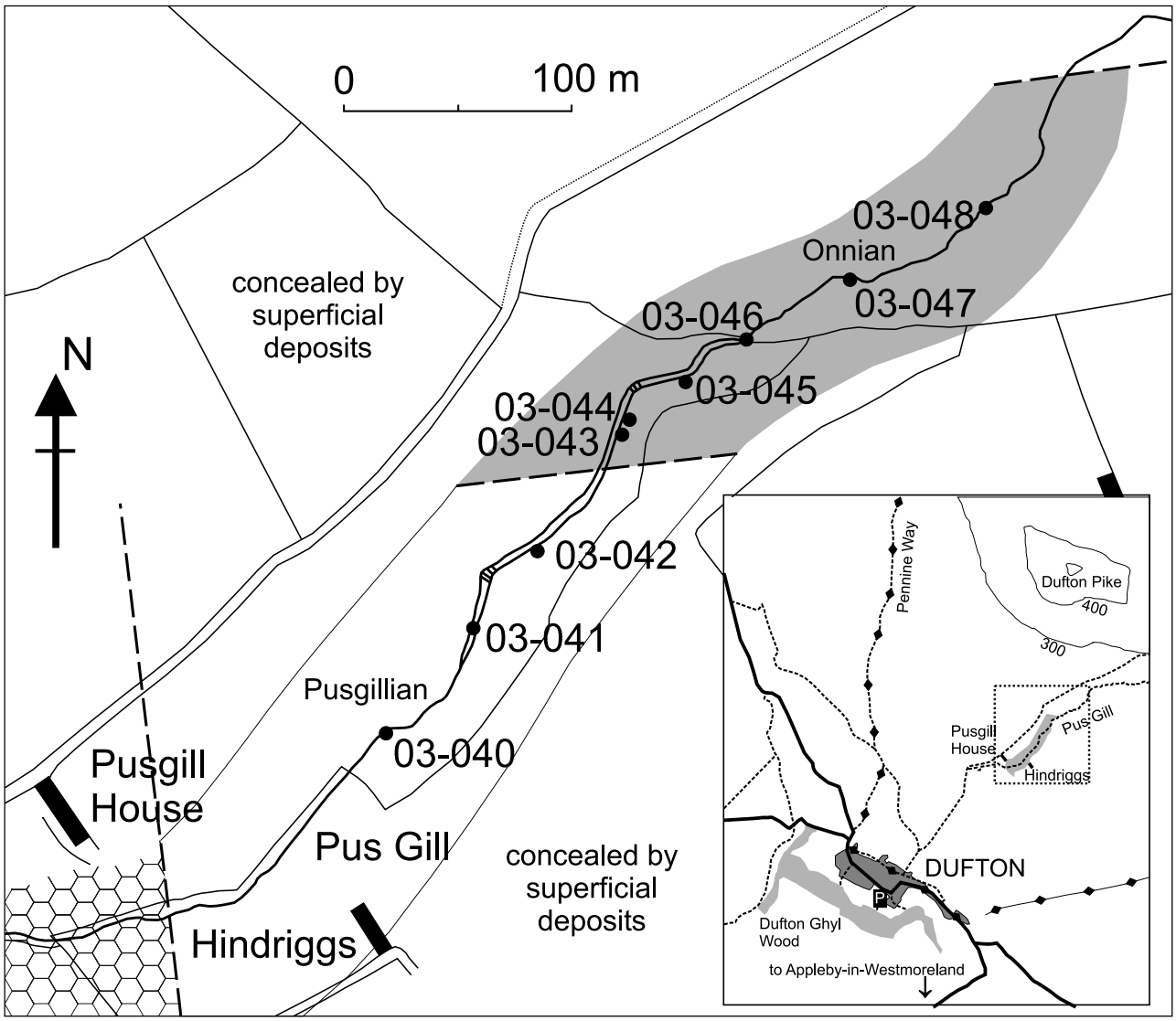

Figure 7. Geological map and detailed location of the Pus Gill section (Cross Fell Inlier) with the sample localities (after Burgess & Holliday, 1979).

yielded chitinozoans, although none of them are of great stratigraphical importance.

Above the base of the Silurian, sample TVDB 02-086 from the Skelgill Formation yielded a huge number of the lower Silurian index fossil *Belonechitina postrobusta*.

3.b. Cross Fell Inlier

The eight samples studied from Pus Gill yielded abundant chitinozoans (2126 specimens) to overcome the poor chitinozoan data from the lower, weathered levels in the Cautley district. All results are shown quantitatively on Table 4 and qualitatively on Figure 9. Unfortunately, the contact between the Onnian and the Pusgillian is faulted, so a (probably small) part of the succession is missing in the section (Burgess & Holliday, 1979, fig. 8, p. 12).

Several species are restricted to the Onnian samples, including *Belonechitina robusta*, *Belonechitina capitata* and *Angochitina communis*, although the last has one possible (doubtful) occurrence in the Pusgillian part of the section. *Conochitina elegans* ranges through the entire section. *Saharochitina fungiformis* has a first doubtful occurrence in sample 03-047 (Fig. 9), and ranges from sample 03-046 up to the topmost sample. *Conochitina* ?*incerta* has a comparable range. *Spinachitina* ?*coronata* is found in sample TVDB 03-045, *Hercochitina* ?*turnbulli* in sample TVDB 03-044. *Lagenochitina baltica* ranges from the latter level upwards. *Lagenochitina prussica* has a doubtful occurrence in sample TVDB 03-044, but is definitely present in the Pusgillian part of the section. In short, the same easily recognized fauna recovered from the Pusgillian and lowermost Cautleyan of Foggy Gill, Sally Beck and Sally Brow in the Cautley district can be found in this section, at least from sample TVDB 03-046 upwards and with some additional species.

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Table 1. Numbers of specimens recorded in samples from the Taythes North and South inliers

	02-047	02-053	02-051	02-050	02-046	02-048	03-027	02-083	03-028	02-045	Loc 9	02-054	Loc 14	02-090	02-042	02-041	02-040	03-024	03-025	03-026
Chitinozoa indet.	8	44	15	20	24	9	2	44	39	13	4	79	13	28	–	–	22	10	2	–
Belonechitina spp.	1	10	4	1	5	5	–	10	2	4	1	1	4	2	–	–	3	–	–	–
Conochitina spp.	–	2	6	3	–	5	–	1	2	4	–	–	3	2	–	–	–	–	–	–
Hercochitina spp.	–	–	3	1	–	–	–	–	–	–	–	–	–	32	–	–	1	2	1	–
Lagenochitina baltica	1	–	2	1?	–	–	–	–	11	1	–	38	3	–	–	–	–	–	–	–
Euconochitina spp.	3	–	–	–	1	2	–	–	–	–	–	2	–	–	–	–	1	1	–	–
Tanuchitina spp.	–	–	1?	–	–	–	–	–	1?	–	–	1	–	–	–	–	–	–	–	–
Belonechitina sp. 2	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cyathochitina campanulaeformis	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Desmochitina minor	–	–	–	1	–	–	–	–	–	–	–	4+1?	–	–	–	–	–	–	–	–
Lagenochitina prussica	–	–	–	2	–	2	–	–	–	–	–	18	1?	–	–	–	–	–	–	–
Cyathochitina spp.	1	–	3	4	1	1	–	–	–	–	–	4	–	–	–	–	3	2	1	1
Lagenochitina spp.	–	–	–	5	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–
Rhabdochitina spp.	–	–	–	1	1	1	–	3	–	–	–	3	1	–	–	–	–	–	–	1
Tanuchitina cf. *bergstroemi*	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Spinachitina spp.	–	–	–	–	–	–	–	3	8	1	–	1	–	2	–	–	–	–	1	–
Belonechitina americana	–	34+11?	17	20	9?	16	–	–	2?	–	–	–	–	5	–	–	–	–	–	–
Spinachitina bulmani	–	–	11?	10	5+9?	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Angochitina aff. *communis*	–	–	–	2?	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Euconochitina sp. 1	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Laufeldochitina sp.	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Tanuchitina bergstroemi	–	–	–	1	–	–	–	–	–	–	–	4?	–	2	–	–	–	–	–	–
Spinachitina sp. 1	–	–	–	–	–	2	31	7	–	13	–	–	–	–	–	–	–	–	–	–
Euconochitina lepta	–	–	–	–	–	–	–	2?	–	–	–	–	–	–	–	–	–	–	–	–
Hercochitina aff. *seriespinosa*	–	–	–	–	–	–	–	8	–	6	–	4	2	18	–	–	–	–	–	–
Conochitina rugata	–	–	–	–	–	–	–	–	32	–	–	4?	6	2?	–	–	–	–	–	–
Desmochitina erinacea	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–
Belonechitina americana/ micracantha group	–	–	–	–	–	–	–	–	–	–	–	70	2	–	–	–	–	–	–	–
Belonechitina sp. 3	–	–	–	–	–	–	–	–	–	–	–	–	2	5	–	–	–	–	–	–
Spinachitina fossensis	–	–	–	–	–	–	–	–	–	–	–	–	–	56	–	–	–	–	–	–
Spinachitina sp. 2	–	–	–	–	–	–	–	–	–	–	–	–	–	32	–	–	–	–	–	–
Rhabdochitina magna	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–
Hercochitina sp. 2	–	–	–	–	–	–	–	–	–	–	–	–	–	30	–	–	–	–	–	–
Spinachitina sp. 3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	–	–	–
Belonechitina sp. 6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	14
Scolecodonts	X	X	X	X	X	X	–	–	–	X	–	X	–	X	–	–	X	–	–	–
Acritarchs	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Total number of chitinozoans	16	101	63	75	55	127	33	80	98	42	5	234	37	217	0	0	33	15	6	16
Amount of dissolved rock (g)	16.48	16.28	16.60	16.68	19.15	27.15	19.74	19.84	15.32	16.62	10.41	16.94	3.24	16.75	20.88	20.51	16.16	15.64	15.10	15.22

Numbers with '?' represent poorly identifiable specimens, e.g. '34 + 11?' represents 34 *B. americana* specimens + 11 *B*. ?*americana* specimens. X – specimens present but not counted.

Table 2. Numbers of specimens recorded in samples from the Murthwaite Inlier

	02-068	02-067	02-080	02-081	02-082	02-069	02-070	02-073	02-071	02-060	02-061	02-072	02-063	02-064	02-066	02-074	02-076	Loc 10	Loc 7	02-057	02-058	02-059
Chitinozoa indet.	59	112	–	–	–	39	23	32	25	10	1	12	32	19	–	54	40	–	4	31	23	36
Belonechitina ?robusta	53	30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Belonechitina sp. 1	115	83	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Belonechitina spp.	125	143	–	–	–	2	4	–	5	–	5	–	2	–	P	3	6	11	1	1	8	–
Conochitina spp.	1	–	–	–	–	3	3	1	3	–	–	–	2	1	P	5	4	–	–	3	1	–
Hercochitina spp.	12	3	–	–	–	–	–	–	–	1	–	–	–	–	–	3	10	3	4	2	1	2
Lagenochitina baltica	4 + 3?	7?	–	–	–	–	1?	6	1?	–	–	–	–	–	–	19	–	–	–	–	–	–
Euconochitina spp.	–	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	2
Tanuchitina spp.	–	1	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Belonechitina sp. 2	–	–	–	–	–	11	–	–	–	14	–	–	–	–	P	–	–	–	–	–	–	–
Conochitina elegans	–	–	–	–	–	89	1	–	–	9?	1?	–	–	–	–	–	–	–	–	–	–	–
Conochitina ?incerta	–	–	–	–	–	3	8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cyathochitina campanulaeformis	–	–	–	–	–	93	11	15	–	1	–	–	–	–	–	–	–	–	–	–	–	–
Desmochitina minor	–	–	–	–	–	1	13	–	3	–	–	–	–	–	–	2	2	–	–	–	–	–
Saharochitina fungiformis	–	–	–	–	–	15	5	178	17	5	–	–	1?	11	–	–	–	–	–	–	–	–
Lagenochitna prussica	–	–	–	–	–	2	6	–	–	3	–	5	–	–	–	7	–	–	–	–	–	–
Spinachitina ?coronata	–	–	–	–	–	1	133	10?	–	–	1	–	–	–	–	–	–	–	–	–	–	–
Desmochitina nodosa	–	–	–	–	–	–	8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Calpichitina sp.	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cyathochitina spp.	–	–	–	–	–	–	–	2	–	2	–	–	–	–	–	2	–	–	–	1	–	–
Lagenochitina spp.	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Rhabdochitina spp.	–	–	–	–	–	–	–	1	–	–	2	–	–	–	–	–	–	–	–	–	1	–
Tanuchitina cf. *bergstroemi*	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–
Belonechitina ?kjelstroemi	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–
Spinachitina spp.	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–	2	–	–	1	–	–	–
Belonechitina americana	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	42	–	–	–	–	–
Tanuchitina bergstroemi	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	9?	–	–	1?	–	–	–
Desmochitina erinacea	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–
Belonechitina sp. 3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1 + 3?	–	–	–	–	–
Spinachitina fossensis	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	–	–	–
Ancyrochitina sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	–	–	–	–	–	–
Belonechitina sp. 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	–	–	–	–	–	–
Hercochitina sp. 1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	30	2(?)	–	–	–	–	–
Ancyrochitina aff. *merga*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	17	–	–	–	–	–
Conochitina sp. 1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	118	–	–	–	–	–
Laufeldochitina sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–
Spinachitina sp. 2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	–	–	–
Scolecodonts	–	X	–	–	–	–	X	X	X	X	–	X	–	X	–	X	X	–	–	X	X	X
Acritarchs	–	–	–	–	–	–	X	–	X	X	–	–	–	–	–	X	–	–	–	–	–	–
Ostracods	–	–	–	–	–	X	X	X	X	–	–	–	–	–	–	–	–	–	–	–	–	–
Forams	–	–	–	–	–	X	X	–	X	X	–	X	–	–	–	–	–	–	–	–	–	–
Total number of chitinozoans	372	382	0	0	0	259	216	248	53	45	10	17	39	35	X	149	246	14	17	39	34	40
Amount of dissolved rock (g)	19.26	20.43	16.36	16.08	16.45	19.41	20.01	16.85	17.14	16.41	17.12	17.61	16.45	19.69	18.19	16.55	16.93	10.01	10.12	17.60	16.62	17.24

"P" represents specimens that are present in the sample, but remain unquantified. X – specimens present but not counted.

Table 3. Numbers of specimens recorded in samples from the Westerdale and Pickering (Loc 19) inliers

	Loc 18	Loc 17	Loc 4	Loc 26	Loc 1	Loc 6	Loc 11	02-091	Loc 19	Loc 2	Loc 16	Loc 3	02-094	Loc 13	02-093	02-096	02-095	02-100	02-089	02-088	02-099	02-097	03-033	02-087	02-086
Chitinozoa indet.	5	25	23	7	46	21	10	18	23	35	22	23	5	1	16	16	51	47	48	13	–	–	2	26	26
Belonechitina spp.	–	19	–	–	5	–	–	–	4	3	–	–	–	–	–	1	13	4	4	2	–	–	–	–	–
Conochitina spp.	4	8	–	–	7	–	2	1	–	–	–	–	–	–	–	2	7	8	2	1	–	–	–	–	–
Hercochitina spp.	1	2	3	3	–	–	–	–	2	6	1	–	–	–	–	–	3	13	8	2	–	–	–	–	–
Lagenochitina baltica	28	–	–	–	9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Euconochitina spp.	–	3	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Tanuchitina spp.	2	–	1	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Desmochitina minor	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	1	1	2	–	–	–	–	–	–	–
Lagenochitna prussica	–	–	–	–	18	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cyathochitina spp.	1	–	–	–	–	1	–	–	–	–	–	1	–	–	–	–	3	8	1	–	–	–	1	14	–
Lagenochitina spp.	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–
Rhabdochitina spp.	–	–	6	8	17	–	2	–	1	41	1	–	–	–	–	–	2	–	1	–	–	–	–	–	–
Tanuchitina cf. *bergstroemi*	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Spinachitina spp.	1	–	5	2	4	–	–	–	1	2	–	–	–	–	–	–	–	2	1	–	–	–	–	–	–
Belonechitina americana	–	63	–	–	7?	–	–	–	–	2	–	–	–	–	–	–	–	3?	15	–	–	–	–	–	–
Tanuchitina bergstroemi	1(?)	–	2(?)	1	1?	–	–	–	4(?)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Euconchitina lepta	–	–	–	–	–	–	39	–	–	15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Hercochitina aff. *seriespinosa*	2	3	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Conochitina rugata	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2? rem.	–	–	–	–	–	–
Armoricochitina sp.	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Belonechitina sp. 3	–	81	–	13	9	–	1?	1	–	4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Spinachitina fossensis	–	2?	7?	–	137	–	–	–	–	91	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Conochitina sp. 1	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Laufeldochitina sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Spinachitina sp. 2	–	–	–	16	22	–	–	–	–	30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Rhabdochitina magna	–	–	–	–	13	–	8	–	–	8	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–
Spinachitina aff. *bulmani**	–	–	–	–	29	–	–	89	–	–	6	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Hercochitina sp. 2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Bursachitina umbilicata sp. n.	–	–	–	–	–	14	12	1?	–	1?	–	141	12	13	13	–	–	–	–	–	–	–	–	–	–
Tanuchitina sp. 1	–	–	–	–	–	–	–	–	–	–	–	4	–	–	–	–	–	–	1?	–	–	–	–	–	–
Ancyrochitina merga	–	–	–	–	–	–	26	–	–	9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Belonechitina sp. 5	–	–	–	–	–	–	–	5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Kalochitina sp.	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Spinachitina sp. 3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	6	–	–	–	–	–	–
Cyathochitina aff. *caputoi*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–
Ancyrochitina sp. 1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–
Belonechitina sp. 6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	–	–	–	–	–	–	–
Euconochitina sp. 2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	–	–	–
Belonechitina postrobusta	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	423	
Scolecodonts	–	–	–	–	X	–	–	X	–	–	–	–	–	X	–	X	X	X	–	–	–	–	–	–	–
Forams	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Total number of chitinozoans	48	208	47	51	330	37	99	115	35	250	30	169	17	14	31	21	80	97	91	18	0	0	3	40	449
Amount of dissolved rock (g)	10.52	12.04	10.63	11.55	10.80	10.19	10.51	17.04	10.54	10.41	8.53	10.13	16.06	10.51	16.01	16.12	15.75	16.40	17.62	16.02	16.12	16.07	15.38	16.04	15.55

* (*sensu* Achab, 1977); X – specimens present but not counted.

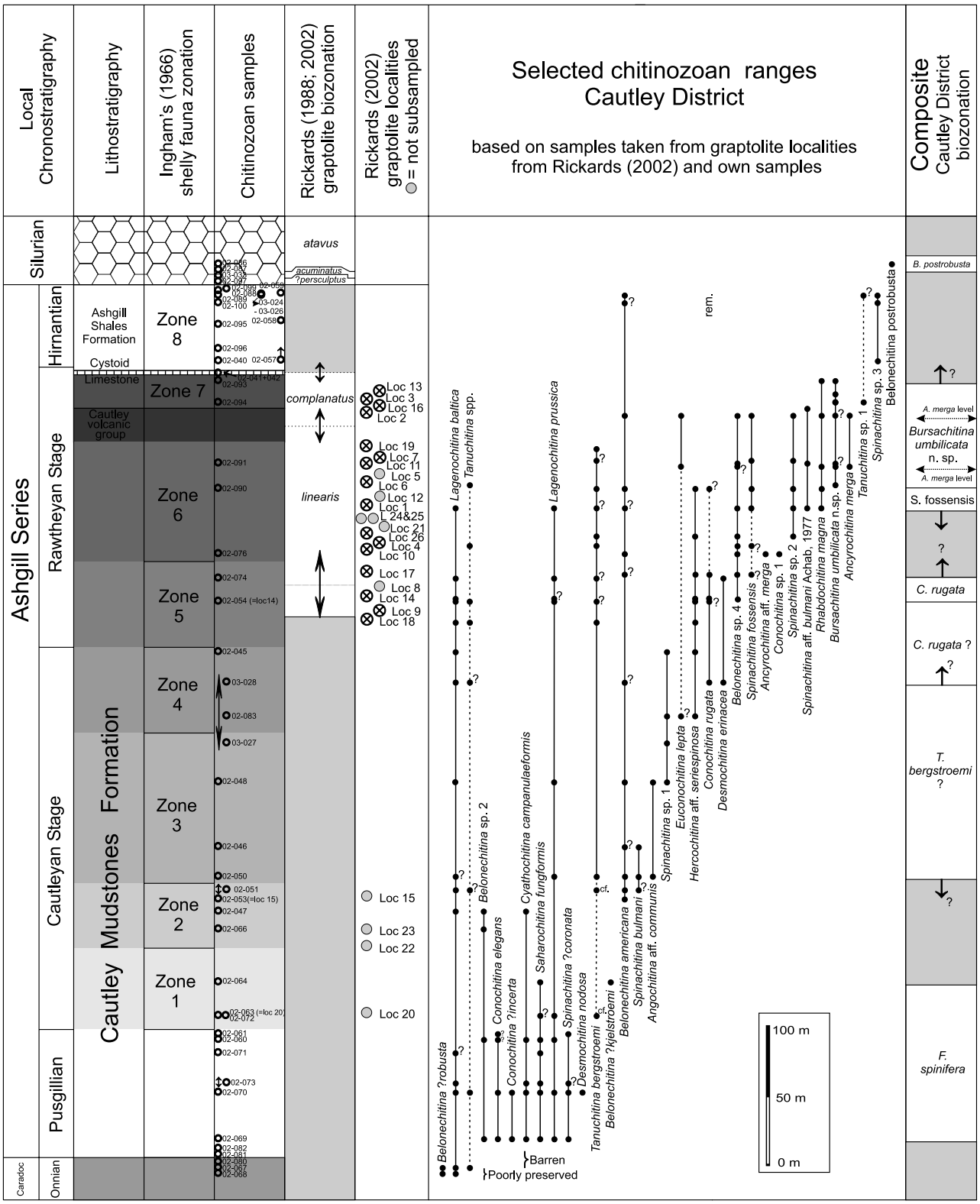

Figure 8. Range chart of selected chitinozoan species in the Cautley district. For information about the ambiguously indicated base of the *C. rugata* zone, see Section 3.a. 'rem.' are remaniated specimens.

4. Biozonation, correlation and interpretation

4.a. Cautley district biozonation

Seven biozones can be recognized in the Cautley district: four formerly known Ordovician zones, two newly defined ones and one Silurian biozone (Figs 8, 10). They are listed, discussed and defined where necessary below, from bottom to top.

The *Fungochitina spinifera* Biozone. The *Fungochitina fungiformis* Biozone was originally defined

Table 4. Numbers of specimens recorded in samples from the Cross Fell Inlier, Pus Gill section

	03-048	03-047	03-046	03-045	03-044	03-042	03-041	03-040
Chitinozoa indet.	85	22	72	96	91	43	14	65
Angochitina communis	24	10	27 + 12?	8?	7 + 12?	1?	–	–
Belonechitina robusta	48	48	28	52	–	–	–	–
Belonechitina ?robusta	51	18	17	49	–	–	–	–
Belonechitina spp.	15	4	28	17	3	5	8	3
Conochitina elegans	60	15	72	80	60	6	–	38
Conochitina sp. A	2	–	–	–	14	–	–	–
Conochitina spp.	11	9	6	3	10	1	12	12
Cyathochitina spp.	1	1	2	1	5	9	2	3
Desmochitina erinacea	1?	–	–	–	–	–	–	1
Desmochitina minor	3	1	1	1	3	8	–	5
Hercochitina spp.	1	–	–	–	–	–	–	–
Belonechitina capitata	–	4?	3 + 8?	75 + 1?	–	–	–	–
Conochitina ?incerta	–	3	1	13	–	9	8	83
Saharochitina fungiformis	–	1?	25	5	12	17	–	181
Tanuchitina spp.	–	2	–	–	–	2	–	6
Ancyrochitina sp.	–	–	3	–	–	–	–	1
B. capitata/C. elegans group	–	–	–	130	–	–	–	–
Belonechitina ?micracantha	–	–	–	8	–	–	–	–
Spinachitina ?coronata	–	–	–	2	–	–	–	–
Hercochitina ?turnbulli	–	–	–	–	2	–	–	–
Lagenochitina prussica	–	–	–	–	1?	1	1	7
Lagenochitina baltica	–	–	–	–	40	8	1	–
Rhabdochitina gracilis	–	–	–	–	5	–	–	–
Rhabdochitina spp.	–	–	–	–	5	–	–	1
Cyathochitina kuckersiana	–	–	–	–	–	98	–	–
Euconochitina spp.	–	–	–	–	–	9	–	–
Lagenochitina spp.	–	–	–	–	–	1	1	–
Spinachitina spp.	–	–	–	–	–	2	–	–
Acanthochitina sp.	–	–	–	–	–	–	–	2
Cyathochitina campanulaeformis	–	–	–	–	–	–	–	5
Lagenochitina sp. A	–	–	–	–	–	–	–	30
Conochitina aff. *incerta*	–	–	–	–	–	–	–	21
Scolecodonts	X	X	X	–	X	X	X	X
Ostracods	–	–	–	–	X	–	–	X?
Forams	–	X	X	–	X	–	–	X
Total number of chitinozoans	301	133	255	457	250	219	47	464
Amount of dissolved rock (g)	19.15	17.77	19.46	19.27**	19.57	20.39	20.15	19.13*

* – about 1/3 of the residue picked; ** – about 1/2 of the residue picked. X – specimens present but not counted.

by Nõlvak & Grahn (1993) in Baltoscandia, as corresponding to the total range of the index fossil. Nõlvak & Grahn (1993) stated that two subspecies of the zonal index species are present, namely the smooth *Fungochitina fungiformis fungiformis* and the spiny *Fungochitina fungiformis spinifera*. Paris *et al*. (1999, p. 564) elevated the latter subspecies to species rank and made *F. spinifera* the neotype for the *Fungochitina* genus, which is characterized by its spiny ornamentation. The same authors created a new genus, *Saharochitina*, for the smooth forms originally placed in the *Fungochitina* genus. The specimens from northern England are considered smooth (basically because the far from excellent preservation does not allow unambiguous recognition of ornamentation), and are placed in the *Saharochitina* genus. Nõlvak (in press) follows the revisions by Paris *et al*. (1999) and changes the name of the *Fungochitina fungiformis* Biozone to the '*Fungochitina spinifera* Biozone'. *Saharochitina fungiformis* has a slightly more extended range than *F. spinifera* in Baltoscandia.

In this paper, *Saharochitina fungiformis* is used as the indicative species for the *Fungochitina spinifera* Biozone (taking into account the state of preservation, obscuring the possible presence of test ornamentation; see above).

The *F. spinifera* Biozone is then recognized herein between samples TVDB 02-069 and 02-064, thus in the Pusgillian and Ingham's (1966) zone 1 of the Cautley Mudstone Formation. Nõlvak & Grahn (1993) report *Lagenochitina baltica* as characteristic chitinozoans from the base of the biozone upwards and their first *Spinachitina coronata* from the topmost part of the zone. If this is accepted, the interval described from the type Ashgill area might thus be restricted to the top part of the Baltoscandian *F. spinifera* Biozone. However, determinations of *S. coronata* remain provisional in the study area. The two Baltoscandian subzones, the *Cyathochitina angusta* Subzone and *Armoricochitina reticulifera* Subzone (Nõlvak & Grahn, 1993), have not been recognized, although characteristic associated fossils from the former (*Conochitina incerta*) and the latter (*Lagenochitina prussica*) are present. The appearance of *L. prussica* confirms that the top rather than the bottom part of the *F. spinifera* Biozone is present in the Cautley area.

The *Tanuchitina bergstroemi* Biozone. The biozone was defined by Nõlvak & Grahn (1993) in Baltoscandia, as corresponding to the total range of the index fossil, but is used here as a partial range zone, from the first occurrence of *T. bergstroemi*, to the first occurrence of *Conochitina rugata*, the index fossil of the overlying

https://doi.org/10.1017/S0016756805000944

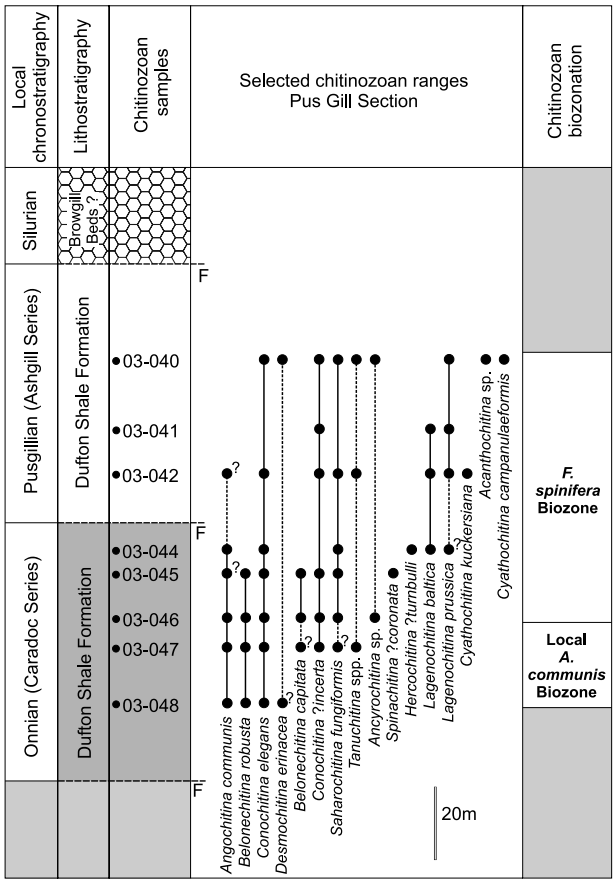

Figure 9. Range chart of chitinozoan species in the Pus Gill section.

biozone. Due to the problems in recognizing the species (see above), the base of the zone is ill-constrained in the Cautley district, and the zone is indicated with a question mark on Figures 8 and 10. *Lagenochitina baltica* and *L. prussica* are associated chitinozoans (Nõlvak & Grahn, 1993) that have also been found here. The *Acanthochitina barbata* Subzone (Nõlvak & Grahn, 1993) has not been recorded.

The *Conochitina rugata* Biozone. The biozone was defined by Nõlvak & Grahn (1993) in Baltoscandia as corresponding to the total range of the index fossil, a definition which has been applied herein as well. The biozone can thus be recognized in Ingham's (1966) zone 5 of the Cautley Mudstone Formation, and possibly in zone 4 (the lowermost sample yielding the zonal index fossil is poorly constrained stratigraphically; see discussion above) and zone 6 (only *C.* ?*rugata*), corresponding to a possible late Cautleyan and early Rawtheyan age (Figs 8, 10, 11).

The *Spinachitina fossensis* Biozone. This biozone is a partial range biozone, its base defined by the first occurrence of *S. fossensis* and its top by the first occurrence of *Bursachitina umbilicata* sp. n., the index fossil of the overlying biozone. In the Cautley district, this is between the levels of Loc 1 and Loc 6 (excluding the two doubtful lower occurrences of the index species in Loc 17 and Loc 4). This part of the Cautley Mudstone Formation (Ingham's 1966 middle part of zone 6) along the Backside Beck section in the Westerdale Inlier is also the type interval for the *S. fossensis* Biozone. The age of the interval is middle Rawtheyan (Ingham, 1966). Associated chitinozoans are *Belonechitina* sp. 3, *Spinachitina* sp. 2, and *Spinachitina* ?*bulmani sensu* Achab (1977).

The *Bursachitina umbilicata* sp. n. Biozone. The biozone is defined by the total range of *Bursachitina umbilicata* sp. n., which is between Loc 6 and Loc 13 in the type Ashgill area. This part of the Backside Beck section in the Westerdale Inlier is the type interval for the *Bursachitina umbilicata* sp. n. biozone (Ingham's 1966 middle part of zone 6 of the Cautley Mudstone Formation to the Cystoid Limestone) and is middle to late Rawtheyan in age (Ingham, 1966).

The *Ancyrochitina merga* Biozone. The biozone was defined by Paris (1990) in Northern Gondwana as corresponding to the total range of the index fossil, a definition which has been applied herein as well. However, on the composite biozonation diagram, two *A. merga* levels rather than an *A. merga* biozone were drawn, as there are only two distinct levels yielding *A. merga* in the section. Paris (1990) mentions *Euconochitina lepta* as an associated chitinozoan, also found in the Westerdale Inlier at the same levels as *A. merga*.

The *Belonechitina postrobusta* Biozone. The base of this global lower Silurian biozone was defined by Verniers *et al*. (1995) as corresponding to the first occurrence of *B. postrobusta*, low in the Llandovery. The biozone is here recognized in the highest sample from the succession, TVDB 02-086.

4.b. Pus Gill section – Cross Fell Inlier biozonation

The Baltoscandic *Fungochitina spinifera* Biozone (Nõlvak & Grahn, 1993; Nõlvak, in press; see Section 4.a) has been recognized in this section as well. Apart from *Saharochitina fungiformis*, some characteristic associated chitinozoans reported by Nõlvak & Grahn (1993) have been found, such as *Belonechitina capitata* (disappearing in the *Armoricochitina reticulifera* Subzone in Baltoscandia), *Belonechitina robusta*, *Spinachitina* ?*coronata*, *Lagenochitina baltica*, *Lagenochitina prussica* and *Conochitina* ?*incerta*. The last occurs a bit earlier in the zone than in Baltoscandia.

The Onnian part of the Dufton Shale Formation in Pus Gill, below the first occurrence of *Saharochitina fungiformis*, characterized by the occurrence of *Angochitina communis*, from sample TVDB 03-048 upwards, is provisionally referred to a local *A. communis* Biozone. Additional chitinozoans from this local biozone are *Belonechitina robusta* and *Conochitina elegans*.

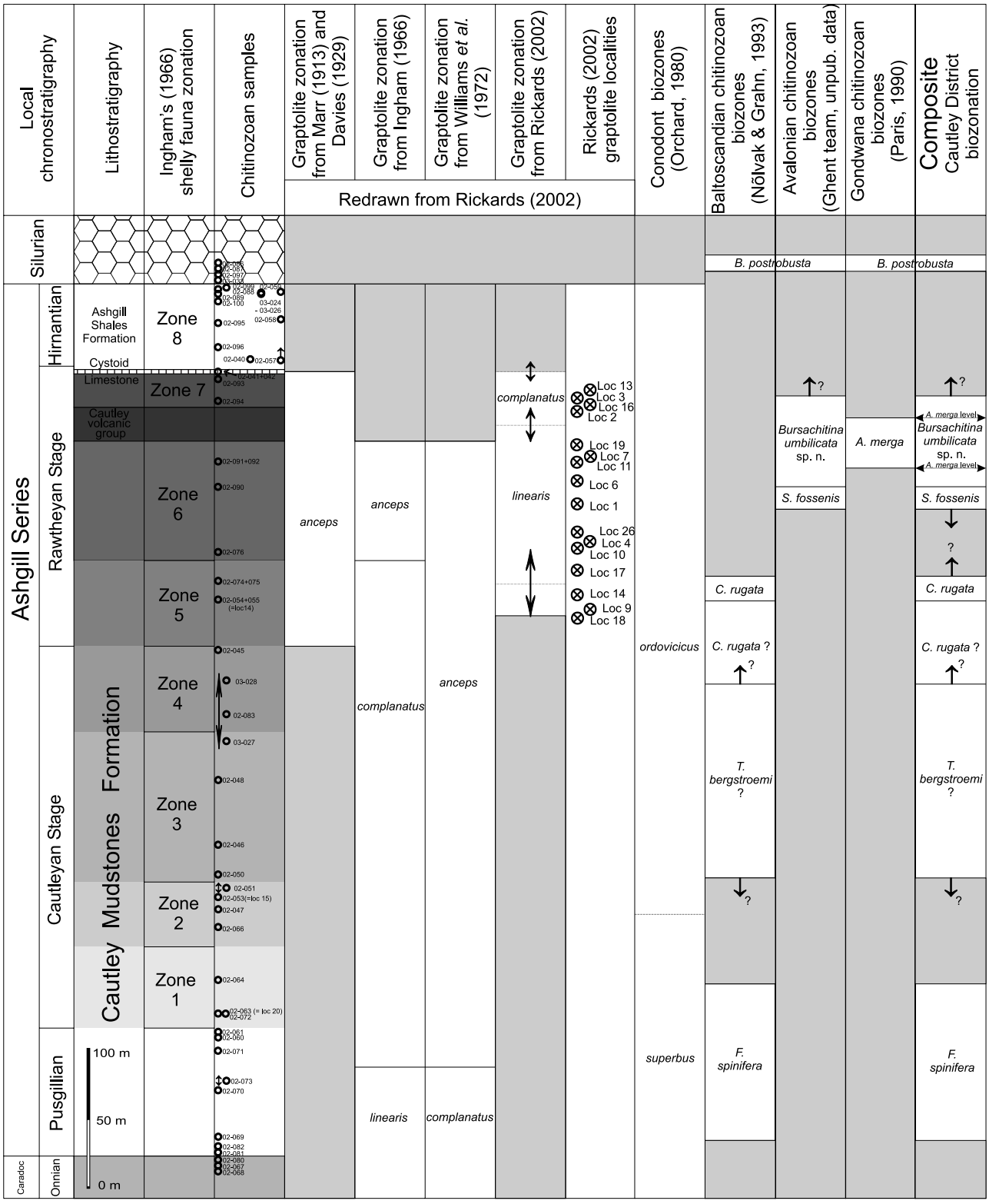

Figure 10. Biozonation in the Cautley district.

4.c. Correlation and interpretation

The Murthwaite Inlier type Ashgill sections from the Cautley district are easily correlated with the Pus Gill section, using the *Fungochitina spinifera* Biozone in both sections (Fig. 11), the former mainly yielding the upper part of the biozone and the latter also exposing the lowermost part of the biozone (with the FAD of *Saharochitina fungiformis*). Interestingly, Jenkins (1967) reported *Angochitina communis*, together with *Ancyrochitina onniensis* and *Acanthochitina barbata* from the upper Onnia Beds in Onny Valley, the

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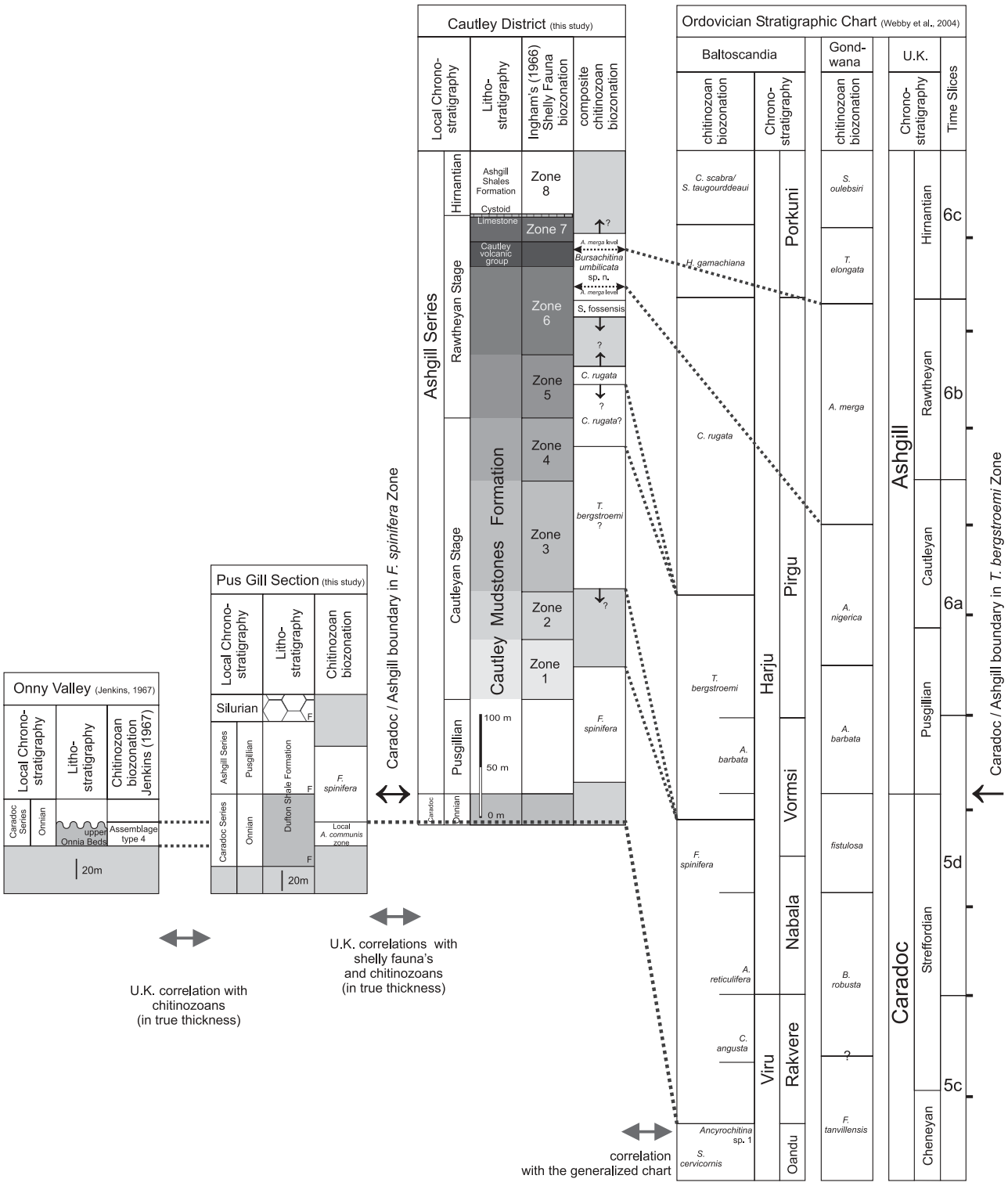

Figure 11. Correlation figure Cautley district–Pus Gill Section–Onny Valley (type Caradoc area; Jenkins, 1967; A. Ancilletta, unpub. M.Sc. thesis, Univ. Liege, 1997; T. Vandenbroucke, unpub. data) – general chitinozoan biozonation (Nõlvak & Grahn, 1993; Paris, 1990 and Webby *et al*. 2004). It shows that the correlation between the Baltoscandian and U.K. chronostratigraphic units is slightly shifted. Note that correlations between the UK section logs and the Webby *et al*. (2004) chart, according to our studies, follow the dotted lines (no horizontal correlations are inferred).

historical type Caradoc area. The latter two species were not recovered from Northern England, although there is an *Ancyrochitina* sp. from Pus Gill, and it is possible that some poorly preserved *A. onniensis* were determined as *A. communis*. Jenkins (1967) did not report *Fungochitina spinifera* nor *Saharochitina fungiformis*, however, or any species close to it. This leads to the conclusion that there is a part of the

Onnian belonging to the *F. spinifera* Biozone that is absent in the type Caradoc (or remains unreported, above Jenkins' 1967 samples) but is present in the Cross Fell Inlier. There is a (less likely) possibility that the absence of *S. fungiformis* in the Welsh Borderland has a palaeoecological rather than a stratigraphical explanation. Another problem is the appearance of *Acanthochitina barbata* in the Onny Valley section (Jenkins, 1967), which is thus inferred to be below the *F. spinifera* Biozone, while in Baltoscandia, *A. barbata* is restricted to its subzone within the *Tanuchitina bergstroemi* Biozone, above the *F. spinifera* Biozone. Prior to careful taxonomical revision (work in progress), we suggest this might be due to lumping two much alike, but separate, *Acanthochitina* species with different, restricted stratigraphical ranges (also see Nõlvak & Grahn, 1993).

The succession of three Baltoscandian biozones, the *Fungochitina spinifera*, the *Tanuchitina bergstroemi*? and the *Conochitina rugata* zones, leads to a solid correlation with Baltoscandia. Nõlvak & Grahn (1993) correlated the Caradoc/Ashgill boundary with a level in the *Acanthochitina barbata* Subzone (Vormsi age) of the *Tanuchitina bergstroemi* Biozone. This has been followed ever since, up to the most recent correlation schemes (Webby *et al*. 2004). The study of the type Ashgill area, however, clearly shows that the base of the Ashgill Series lies within the *F. spinifera* Zone, which is lower than the *T. bergstroemi* Zone in the chitinozoan biozonation scheme. Identification of the three Baltoscandian biozones also allows, for the first time, the direct dating of these biozones against the British chronostratigraphical scheme. This also implies a better correlation between the Baltoscandian and British chronostratigraphical stages.

The *Spinachitina fossensis* and the *Bursachitina umbilicata* sp. n. biozones prove to be useful (endemic) Avalonian biozones, as they have been reported from the Ashgill of Belgium, more specifically from the Fosses Formation in the Condroz Inlier (Vanmeirhaeghe & Verniers, 2004). The record of both biozones in the Cautley district enables accurate dating of the Condroz Inlier deposits.

The succession of samples yielding the index specimens is quite interesting (see Table 3, Westerdale Inlier results); Loc 26, Loc 1 and TVDB 02-090 with *Spinachitina fossensis* and/or *Spinachitina* sp. 2, *Belonechitina* sp. 3, *Spinachitina* ?*bulmani sensu* Achab (1977) are followed by Loc 6 and Loc 11, yielding *Bursachitina umbilicata* sp. n. (and *Ancyrochitina merga*, *Euconochitina lepta* in the latter), which are in turn succeeded by TVDB 02-091, Loc 7, Loc 2 and Loc 16, again yielding the *Spinachitina* and *Belonechitina* species mentioned above (and *A. merga*, *E. lepta* in Loc 2). These samples are in turn followed by four samples (Loc 3 to Loc 13) yielding a quasi-monospecific *Bursachitina umbilicata* sp. n. assemblage. At first glance, this looks like a stratigraphical repetition, possibly due to a fault or other structural disturbance between Loc 11 and TVDB 02-091. There is, however, no evidence at all in the field to support this hypothesis. Because of the morphological differences between the stout, thick-walled *Bursachitina umbilicata* sp. n. and the elegant, thin-walled, finely ornamented *Spinachitina fossensis* and associated species, different palaeoecological conditions are preferred to explain this (apparent) stratigraphical repetition of species. The only drawback to this explanation is the co-occurrence of the thin-walled *A. merga* with *B. umbilicata* sp. n.

The recognition of the *Ancyrochitina merga* Zone enables direct correlation with the Northern Gondwana realm. The first record of the zone on Avalonia, as far as we know, dates it as (late) Rawtheyan, which is in accordance with the proposed late Rawtheyan (Paris, 1990) and middle Ashgill (Cautleyan–Rawtheyan) ages (Bourahrouh, Paris & Elaouad-Debbaj, 2004; Webby *et al*. 2004).

A composite diagram of the biozones typical of the three different palaeocontinents (Fig. 10) lays the basis for a chitinozoan biozonation scheme that might be applicable throughout the rest of Avalonia.

4.d. Correlations with other fossil groups

Orchard (1980) placed the boundary between the *Amorphognathus superbus* and *Amorphognathus ordovicicus* conodont zones within Ingham's (1966) zone 2 (lower Cautleyan). This is at about the same level as the boundary between the *Fungochitina spinifera* and *Tanuchitina bergstroemi*? chitinozoan biozones in the Cautley district. The correlation between the two fossil groups is thus more or less the same as suggested by Webby *et al*. (2004, p. 44), but the former authors place this level quite low in the stratigraphy (the *superbus* and *spinifera* zones co-occur in the Caradoc), compared to this study of the type Ashgill area (where both zones co-occur up to the lower Cautleyan). The same co-occurrence of chitinozoans and conodonts has recently been reported from the nearby Lake District (Van Nieuwenhove, Vandenbroucke & Verniers, in press).

Williams *et al*. (2001) recognize three ostracod faunas: a Pusgillian–lower Cautleyan, a middle–upper Cautleyan and a Rawtheyan assemblage. Their distribution seems both stratigraphically and environmentally-palaeogeographically controlled; the low diversity of the benthonic ostracod faunas coincides with deeper marine, shelf facies at the Pusgillian and Rawtheyan horizons, while a peak of high diversity can be observed in the Cautleyan. The latter might be due to the establishment of an environment less hostile to the benthonic faunas. Fortey *et al*. (1995, p. 25) noted similar environmental changes from a shallower Cautleyan to a deeper Rawtheyan, based on shelly fauna evidence (see also Williams *et al*. 2001, p. 593). Chitinozoan diversity (species per level) does not

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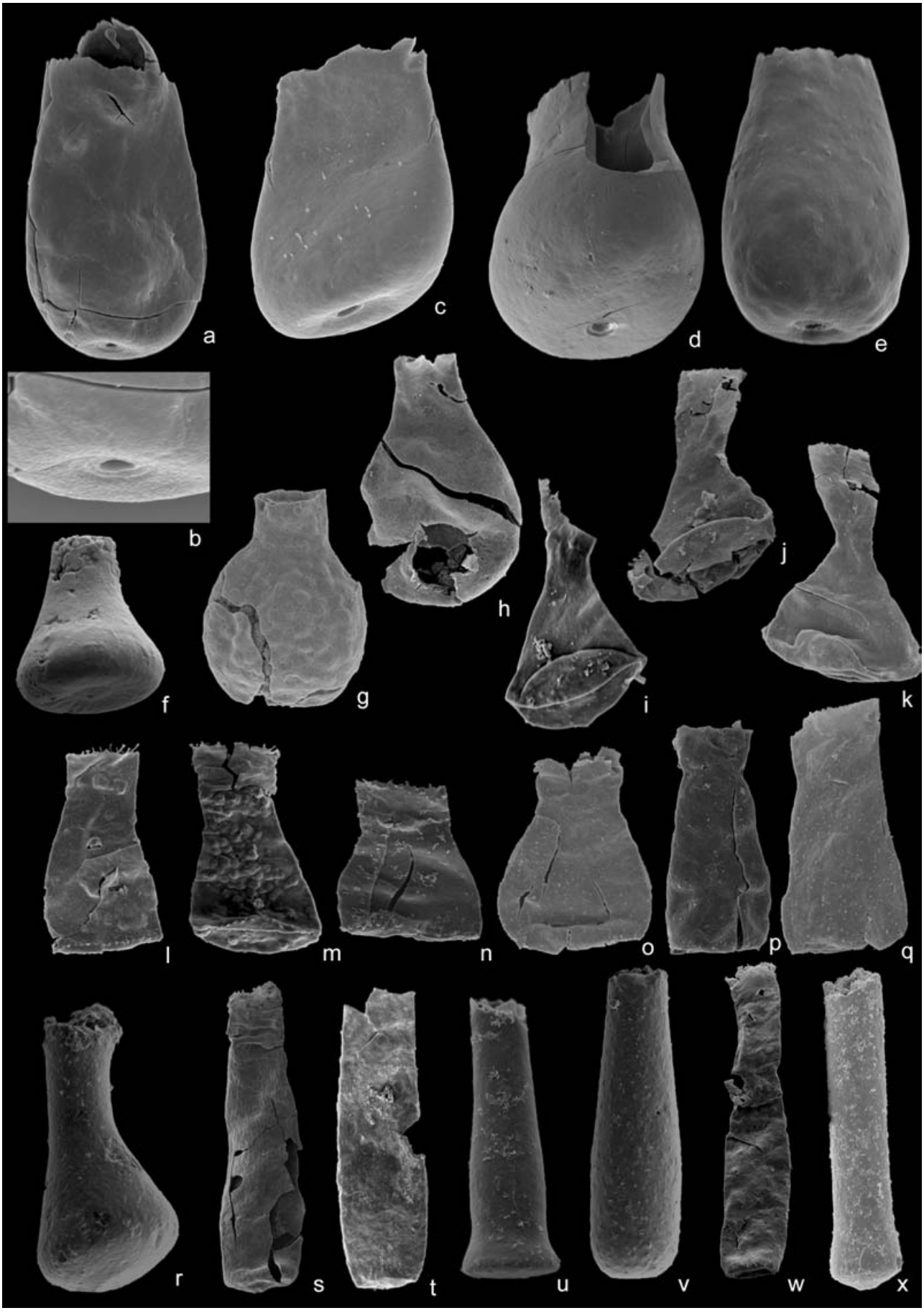

Figure 12. For legend see facing page.

change dramatically throughout this part of the section, although the samples with the maximum number of chitinozoans (in number of chitinozoans per gram dissolved rock) are situated within the suggested mainly pelagic biofacies of the lower Pusgillian and lower Rawtheyan.

From the ostracod data, Williams *et al*. (2001) interpreted the incoming of the *Amorphognathus ordovicicus* conodont fauna, at about the same level as the boundary between the two lowest ostracod assemblages, as being caused by environmental changes, thus explaining why its incoming occurred so 'high in the Ordovician'. However, the *F. spinifera* chitinozoan fauna, which is also rather high in the Ordovician (compared to all general schemes), occurs well below the level with environmental change, in an (Onnian-) Pusgillian deeper marine, shelf facies favourable for chitinozoans. Therefore, we suggest that both chitinozoan and conodont ranges and zonal boundaries are more or less where they ought to be in stratigraphy, and less controlled by environmental changes than previously thought.

For the Ordovician zones, no conclusions can be drawn in comparing the chitinozoan–graptolite relations with those from other regions, because, as far as we know, the sections studied here are the first to yield both fossil groups continuously; the cited Baltoscandian biozones are from graptolite-barren sections (Jaak Nõlvak, pers. comm. 2003), as are the records of chitinozoans from the two new Avalonian zones in the Belgian Condroz Inlier. In the definition of the Gondwana *Ancyrochitina merga* Zone, no graptolite data are mentioned (Paris, 1990).

5. Systematics

Only the new species *Bursachitina umbilicata* sp. n. is described herein. A full systematic review of the chitinozoans from the study area is undertaken in a forthcoming paper by T. Vandenbroucke. The most distinctive species are illustrated in Figures 12 and 13.

Order OPERCULATIFERA Eisenack, 1931
Family DESMOCHITININAE Eisenack, 1931, emend. Paris, 1981
Subfamily DESMOCHITININAE Paris, 1981
Genus *Bursachitina* Taugourdeau, 1966, restrict. Paris, 1981
Bursachitina umbilicata sp. n.

Material. 205 (+ 2?) specimens from Loc 6 to Loc 13; upper Rawtheyan.

Holotype. Figure 12a, b.

Holotype dimensions. L: 110; Dp: 65; Dc: 50 (for abbreviations, see Paris, 1981 and Fig. 12).

Type stratum. Cautley Mudstone Formation (Ingham's 1996 zone 7, Rawtheyan, Loc 3).

Paratypes. Figure 12c–e.

Synonymy. *Bursachitina* sp. 1 (Vanmeirhaeghe & Verniers, 2004).

Dimensions. L: 80–118–190 µm/Dp: 50–86–120 µm/Dc: 44–58–73 µm (n = 66).

Diagnosis. *Bursachitina* species with a thick vesicle wall and a typical basal scar, consisting of two concentric circles (Fig. 14).

Description. Ovoid-shaped *Bursachitina* with an inconspicuous flexure, and a rather short neck, which is often broken at the flexure level. Shoulders are absent. The vesicle wall is very thick (up to 5 µm) and the surface is usually smooth. On a few species, a weak granular ornamentation can be observed, but the ornamentation is not developed well enough for the species to be included in the genus *Eisenackitina*. At the centre of the chamber base, a typical, rather small basal scar can be observed on all specimens, consisting of two concentric circles. The basal area around the scar is often slightly dented oralwards. A simple disk shaped operculum has been observed in several specimens. It is still present in the holotype, tilted 90° (Fig. 12a).

Discussion. The three key characteristics (overall shape, thick vesicle wall and basal scar) of the species allow it to be easily identified, even from fragments. This species is quite distinct from any other (Upper

Figure 12. Chitinozoans from the Cautley district. All measurements in microns (L × Dp, or L × Dp × Dc, or L × Dp × Dc × Lc). Abbreviations, see Paris (1981): L – total length, Dp – chamber diameter, Dc – diameter of oral tube, Lc – length of oral tube. (a) *Bursachitina umbilicata* sp. n.: Holotype, Loc 3 (110 × 65 × 50), with tilted mucron; (b) *Bursachitina umbilicata* sp. n.: Holotype, Loc 3 (110 × 65 × 50), detail showing the concentric basal scar; (c) *Bursachitina umbilicata* sp. n.: Paratype, Loc 3 (120 × 95 × 70), with broken neck, as specimens are commonly recovered; (d) *Bursachitina umbilicata* sp. n.: Paratype, Loc 3 (120 × 85 × 55), part of the neck is missing, displaying the thickness of the vesicle wall; (e) *Bursachitina umbilicata* sp. n.: Paratype, Loc 3 (105 × 70), with broken neck, as the specimens are commonly recovered; (f) *Conochitina* sp. 1: TVDB 02-076 (82 × 70 × 30); (g) *Lagenochitina prussica*: Loc 1 (140 × 100 × 45 × 40); (h) *Lagenochitina baltica*: TVDB 02-047 (180 × 110 × 45); (i) *Ancyrochitina merga*: Loc 11 (130 × 80 × 20 × 55); (j) *Ancyrochitina merga*: Loc 2 (120 × 80 × 25 × 60); (k) *Euconochitina lepta*: Loc 2 (110 × 80 × 15 × 60); (l) *Spinachitina fossensis*: Loc 2 (115 × 70 × 45); (m) *Spinachitina fossensis*: Loc 1 (120 × 70 × 40 × 45); (n) *Spinachitina* sp. 2: Loc 1 (85 × 75 × 45 × 30); (o) *Belonechitina* sp. 3: Loc 17 (135 × 100 × 50); (p) *Spinachitina* sp. 1: TVDB 03-027 (150 × 60 × 35); (q) *Belonechitina americana*: Loc 17 (140 × 70 × 50); (r) *Saharochitina fungiformis*: TVDB 02-073 (105 × 65 × 28); (s) *Conochitina rugata*: Loc 14 (380 × 115 × 75); (t) *Tanuchitina bergstroemi*: TVDB 02-050 (270 × 90); (u) *Spinachitina* ?*coronata*: TVDB 02-070 (170 × 60 × 30); (v) *Belonechitina* sp. 2: TVDB 02-060 (200 × 60 × 40); (w) *Spinachitina* ?*bulmani sensu Achab* (1977a): Loc 1 (400 × 75 × 60); (x) *Conochitina incerta*: TVDB 02-070 (280 × 70 × 55).

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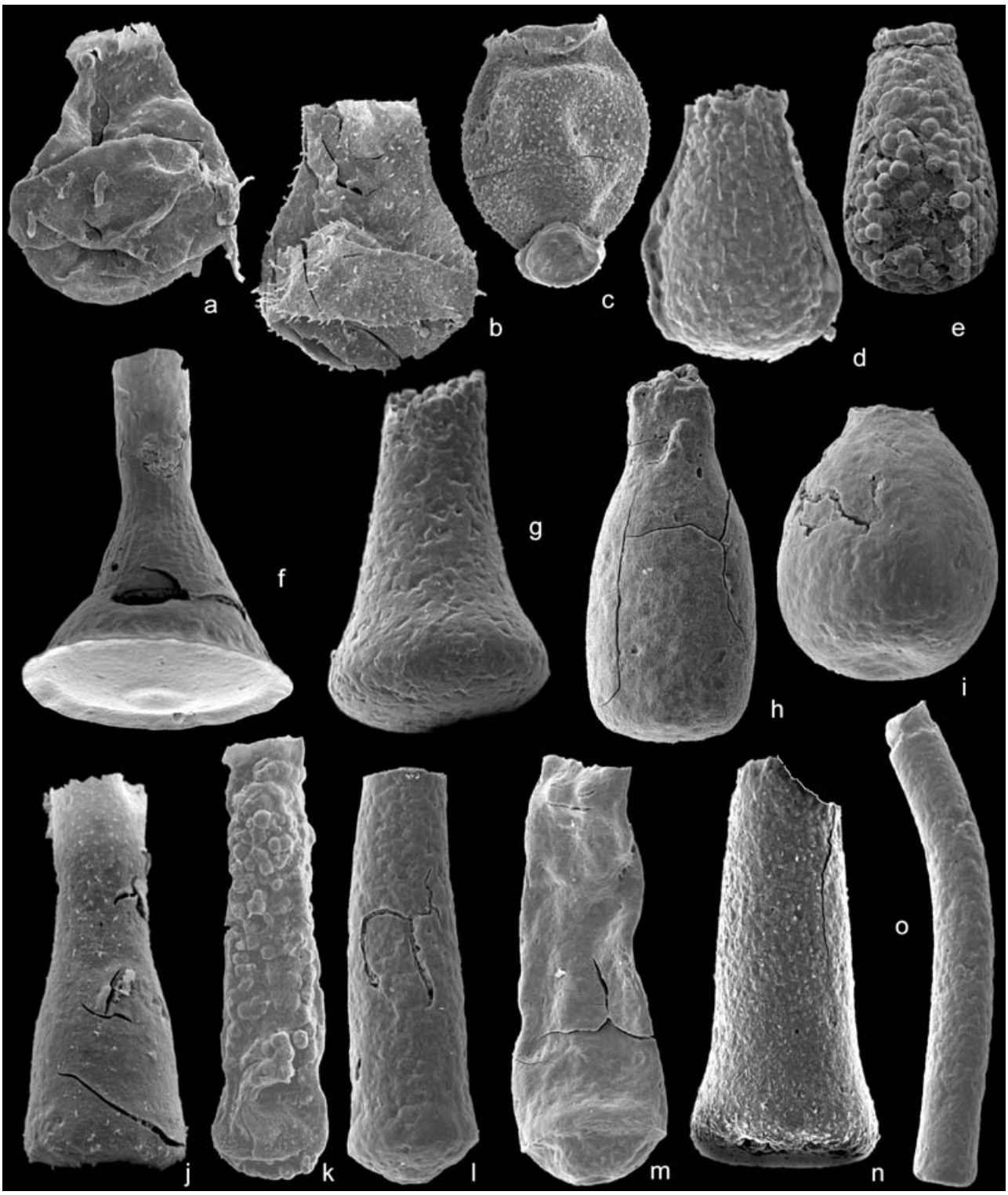

Figure 13. Chitinozoans from the Pus Gill Section. All measurements in microns (L × Dp × Dc, or L × Dp × Dc × Lc). Abbreviations, see above (Fig. 12) and Paris (1981). (a) *Ancyrochitina* sp. 1: TVDB 03-046 (85 × 70 × 30); (b) *Angochitina communis*: TVDB 03-048 (90 × 75 × 40 × 30); (c) *Desmochitina erinacea*: TVDB 03-040 (90 × 80 × 50); (d) *Hercochitina* ?*turnbulli*: TVDB 03-044 (95 × 70 × 35); (e) *Acanthochitina* sp.: TVDB 03-040; (f) *Cyathochitina kuckersiana*: TVDB 03-042 (250 × 190 × 55 × 90); (g) *Saharochitina fungiformis*: TVDB 03-046 (105 × 70 × 30); (h) *Lagenochitina baltica*: TVDB 03-042 (250 × 120 × 60 × 70); (i) *Lagenochitina prussica*: TVDB 03-040; (j) *Belonechitina* sp.: TVDB 03-042 (120 × 50 × 30 × 55); (k) *Belonechitina* capitata: TVDB 03-045 (200 × 50 × 35); (l) *Conochitina* ?incerta: TVDB 03-040 (220 × 70 × 45); (m) *Conochitina* aff. *incerta*: TVDB 03-040 (250 × 90 × 50); (n) *Belonechitina robusta*: TVDB 03-045 (200 × 90 × 50); (o) *Conochitina elegans*: TVDB 03-044 (470 × 55 × 50).

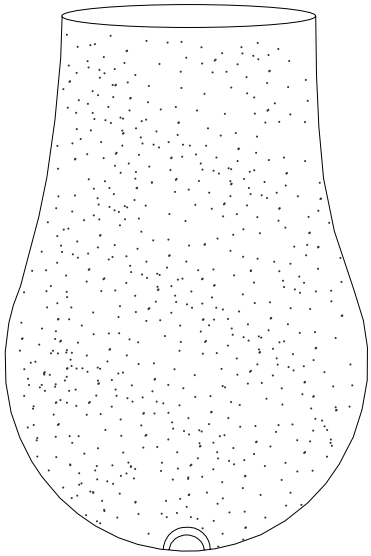

Figure 14. *Bursachitina umbilicata* sp. n. reconstruction drawing.

Ordovician) chitinozoan. Shortly after the first description of the species, Vanmeirhaeghe & Verniers (2004; pers. comm. 2003) reported *Bursachitina umbilicata* sp. n. (as *Bursachitina* sp. 1) from the Fosses Formation (Condroz Inlier, Belgium).

6. Conclusions

The recognition of three Baltoscandian (*Fungochitina spinifera*, *Tanuchitina bergstroemi*?, and *Conochitina rugata*) biozones in the type Ashgill area enables direct correlation with Baltica. From this study, it is clear that the base of the Ashgill Series lies within the *F. spinifera* Zone, rather than in the *T. bergstroemi* zone as previously believed, and is lower in the chitinozoan biozonation scheme. The observation of the same *F. spinifera* Zone in the Onnian and Pusgillian of the Pus Gill section enables direct correlation with the Cautley district. In addition, the occurrence of *A. communis* in the Pus Gill section below the FAD of *S. fungiformis*, indicates correlation with the topmost Onnian beds of Onny Valley (Shropshire), leaving the *S. fungiformis*-bearing part of the Pus Gill Onnian undescribed from the type Caradoc area (see Jenkins, 1967). The three Baltoscandian zones are now much better correlated with the British series and stages. The *F. spinifera* Zone (late Oandu-early Vormsi time: Nõlvak & Grahn, 1993; Nõlvak, in press) is of late Onnian to early Cautleyan age; the *T. bergstroemi*? Zone (late Vormsi and early Pirgu time: Nõlvak & Grahn, 1993) is of Cautleyan age and the *C. rugata* Zone (late Pirgu: Nõlvak & Grahn, 1993) possibly corresponds to a late Cautleyan age and definitely to an early Rawtheyan age.

Higher up the section, the (middle to late) Rawtheyan *Spinachitina fossensis* and *Bursachitina umbilicata* sp. n. zones have been defined, allowing correlation with the Belgian part of Avalonia and dating of some of the chitinozoan-bearing Condroz Inlier formations.

Recognition of the Rawtheyan *Ancyrochitina merga* and the Silurian *Belonechitina postrobusta* zones enables correlation with the Northern Gondwana biozonation scheme of Paris (1990) and with the global chitinozoan biozonation scheme for the Silurian (Verniers *et al*. 1995).

Acknowledgements. Careful reviewers Florentin Paris and Stewart Molyneux helped to improve the paper with their constructive remarks. This paper is a contribution to FWO project G.0094.01 (Tectonics of the Early Palaeozoic basin development in NW Europe: basin analysis and magnetic fabric analysis in the Belgian Caledonides) and to IGCP project 503 (Ordovician Palaeogeography and Palaeoclimate). We would like to thank the following colleagues: Florentin Paris (for help with the systematics and sharing data), Jaak Nõlvak and Jan Vanmeirhaeghe (for help with systematics), Nigel Woodcock (for help in the field), Sabine Vancauwenberghe (for help with processing), Mark Williams and Stewart Molyneux (for discussion) and Stig Bergström (for conodont discussions).

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Appendix. Sample localities

For sample localities (1 to 26) from Rickards (2002), we refer to the appendix of the cited paper. The GPS measurements below are in the standard WGS84 reference system and the bedding is given as dip direction/dip readings.

Sample localities Cautley district, 2002.

TVDB 02-040: Ashgill Shales Formation; Taythes Inlier; W bank of Taythes Gill, outcrop immediately above water level; 8 paces S of the TVDB 02-041 locality, measured along the W bank of the stream.

TVDB 02-041: Cystoid Limestone; Taythes Inlier; W bank Taythes Gill; 12 paces S of the TVDB 02-042 locality, measured along the E bank of the stream.

TVDB 02-042: Cystoid Limestone; Taythes Inlier; E bank of Taythes Gill; 10 paces S of the southern boundary of a felsite outcrop on the E bank, measured along the E bank of the stream.

TVDB 02-045: Cautley Mudstone Formation; Ingham's (1966) zone 4; Taythes Inlier; E bank Taythes Gill; 10 paces downstream (N) of the TVDB 02-043 locality, or 5.5 paces downstream of the Lamprophyre dyke, lying within a felsite, the latter not shown on the Ingham (1966) map. Both limestone and mudstones were collected for this sample.

TVDB 02-046: Cautley Mudstone Formation; Ingham's (1966) zone 3; N 54°21.163′ W 002°27.048′; Taythes Inlier; E bank Taythes Gill; 8 paces downstream (N) of the northern boundary a felsite outcrop, measured along the E bank of Taythes Gill; bedding 294/84.

TVDB 02-047: Cautley Mudstone Formation; Ingham's (1966) zone 2; N 54°21.187′ W 002°27.093′; Taythes Inlier; W bank Taythes Gill.

TVDB 02-048: Cautley Mudstone Formation; Ingham's (1966) zone 3; N 54°21.205′ W 002°27.116′; Taythes Inlier; W bank Taythes Gill; 11 paces downstream from the confluence of a little gill with Taythes Gill on the W bank, measured along the W bank of the stream; bedding 60/104; limestone nodule; about 20 cm above water level.

TVDB 02-050: Cautley Mudstone Formation; Ingham's (1966) basal zone 3; N 54°21.236′ W 002°27.163′; Taythes Inlier; E bank Taythes Gill; 34 paces upstream (S) of a little

wall crossing the burn, measured along the W bank of the gill; 90 cm above water level.

TVDB 02-051: Cautley Mudstone Formation; Ingham's (1966) top zone 2; N 54°21.255′ W 002°27.175′; Taythes Inlier; W bank Taythes Gill; 15 paces upstream (S) of a little wall crossing the burn, measured along the W bank of the gill; 90 cm above water level; sample taken in the gill.

TVDB 02-053: Cautley Mudstone Formation; Ingham's (1966) zone 2: N 54°21.428′ W 002°27.231′; Poor GPS coverage; Taythes Inlier; Rickards' (2002) locality 15; a few metres W from the place where the 'calcareous grit' (Fig. 2) crosses the track; in a little gill, 110 cm upstream from the where the gill crosses the track.

TVDB 02-054: Cautley Mudstone Formation; Ingham's (1966) zone 5; Taythes Inlier; Splinter Gill, Rickards' (2002) locality 14, very small outcrop (about 1m^2); mudstone sample (weathered).

TVDB 02-057: Ashgill Shales Formation; N 54°22.405′ W 002°26.450′; Murthwaite Inlier; River Rawthey; S bank; 6.50 to 6.60 m downstream from a lamprophyre dyke, indicated on Figure 5.

TVDB 02-058: Ashgill Shales Formation; N 54°22.392′ W 002°26.403′; Murthwaite Inlier; River Rawthey; S bank; 25 paces upstream from the middle of a bridge and 3 paces downstream from the place where a little burn and a small wall ends in the Rawthey River, also on the S bank; sandy mudstones from the upper part of the Ashgill Shales Formation.

TVDB 02-059: Top Ashgill Shales Formation; N 54°22.381′ W 002°26.365′; Murthwaite Inlier; River Rawthey; small outcrop in the S bank; 39 paces upstream from the TVDB 02-058 locality.

TVDB 02-060: Cautley Mudstone Formation; Pusgillian; Murthwaite Inlier; Sally Brow Section; first large outcrop climbing up along the overgrown Sally Brow Section, starting from the road to Sedbergh; 11 paces upwards along the stream, from the place where a little side track from the 'public footpath to Murthwaite' crosses the stream, this at 36 paces from the fence on the footpath; 1.5 m upstream from the lower edge of the outcrop; Pusgillian.

TVDB 02-061: Cautley Mudstone Formation; Pusgillian; Murthwaite Inlier; Sally Brow Section; 8 paces upstream from TVDB 02-060, paced through the stream.

TVDB 02-063: Cautley Mudstone Formation; Ingham's (1966) zone 1; Murthwaite Inlier; Sally Brow Section; outcrop featuring a fault (Ingham, 1966, pl. 25); stratigraphically 1.70 m below the fault; immediately above the water level; left bank.

TVDB 02-064: Cautley Mudstone Formation; Ingham's (1966) zone 1; Murthwaite Inlier; Sally Brow Section; 5 paces upstream from the place where the 'public footpath to Murthwaite' rejoins and touches the stream; left bank; 0.5 m above the water level.

TVDB 02-066: Cautley Mudstone Formation; Ingham's (1966) zone 2; Murthwaite Inlier; Sally Brow Section; 2 m downstream from TVDB 02-065; unweathered sample within the stream.

TVDB 02-067: Cautley Mudstone Formation; Uppermost Onnian; N 54°22.869′ W 002°25.975′; Murthwaite Inlier; Foggy Gill; hillside outcrop along the upper reaches of Foggy Gill, a little upstream from where the wall turns away from the gill; at 13 paces (NNE) from the corner of the wall; weathered; see detail map (Fig. 6).

TVDB 02-068: Cautley Mudstone Formation; Uppermost Onnian; Murthwaite Inlier; Foggy Gill; hillside outcrop along the upper reaches of Foggy Gill, 6 paces due N and uphill from the TVDB 02-067 locality; weathered; see detail map (Fig. 6).

TVDB 02-069: Cautley Mudstone Formation; Uppermost Onnian; N 54°22.841′ W 002°25.995′; Murthwaite Inlier; Foggy Gill; small cliff (45 by 30 cm) in a hillside outcrop along the upper reaches of Foggy Gill, 31 paces downstream from the corner of the wall, described in TVDB 02-067; 10 to 17 cm below the top of the small cliff; bedding 251/35; unweathered; see detail map (Fig. 6).

TVDB 02-070: Cautley Mudstone Formation; Pusgillian; Murthwaite Inlier; Foggy Gill; left bank; at water level; 1.60 m downstream from the place where a wall (fence), running downhill from a little barn, ends at the stream; see map (Fig. 5).

TVDB 02-071: Cautley Mudstone Formation; Pusgillian; Murthwaite Inlier; Foggy Gill; left bank; at water level; 80 paces downstream from the little wall described in TVDB 02-070 and 80 paces upstream from the wall along the road to Sedbergh.

TVDB 02-072: Cautley Mudstone Formation; Ingham's (1966) zone 1; Murthwaite Inlier; Foggy Gill; 69 to 85 cm upstream from where the gill disappears in two concrete pipes, under the road to Sedbergh; middle of the small stream, at water level.

TVDB 02-073: Cautley Mudstone Formation; Pusgillian; Murthwaite Inlier; Sally Beck; middle of the stream; 6.20 m upstream from the most upstream pillar of the Sedbergh Road Bridge over Sally Beck

TVDB 02-074: Cautley Mudstone Formation; Ingham's (1966) top zone 5; N 54°22.559′ W 002°26.615′; Murthwaite Inlier; River Rawthey; downstream from Rawthey Bridge, left bank, 5 paces upstream from the place where a fence ends perpendicular to the river, on the right bank, measured on the left bank, and 33 paces downstream from the confluence of the River Rawthey and Sally Beck; mudstone.

TVDB 02-076: Cautley Mudstone Formation; Ingham's (1966) basal zone 6; Murthwaite Inlier; River Rawthey; downstream from Rawthey Bridge; centre of the river, exactly at the spot where a side stream flows into the river (see map); 5.5 paces from the steep left bank.

TVDB 02-080: Cautley Mudstone Formation; Uppermost Onnian; Murthwaite Inlier; Foggy Gill; see detailed map of the upper reaches of Foggy Gill (Ingham *et al*. *in* Fortey *et al*. 1991; outcrop situation slightly changed through time): 9.35 m from tree 'A' (on the corner of the wall); 6.10 m from tree 'B' and 1.30 m from tree 'C'; just N of a 'prepared path'; weathered sample (see Fig. 6).

TVDB 02-081: Cautley Mudstone Formation; Uppermost Onnian or lowermost Pusgillian; Murthwaite Inlier; Foggy Gill; see detailed map of the upper reaches of Foggy Gill (Ingham *et al*. in Fortey *et al*. 1991; outcrop situation slightly changed through time): 270 to 280 cm from tree 'C' and 630 cm from tree 'D'; weathered sample (see Fig. 6).

TVDB 02-082: Cautley Mudstone Formation; Pusgillian; Murthwaite Inlier; Foggy Gill; same outcrop as TVDB 02-081; see detailed map of the upper reaches of Foggy Gill (Ingham *et al*. in Fortey *et al*. 1991; outcrop situation slightly changed through time): 320 to 330 cm from tree 'C' and 660 cm from tree 'D'; stratigraphically 33 cm above TVDB 02-081; weathered sample (see Fig. 6).

TVDB 02-083: Cautley Mudstone Formation; Ingham's (1966) zone 4; N 54°20.913′ W 002°28.287′ Taythes Inlier, southern part; somewhat more upstream along Birkfields Beck from Ingham's (1966) T38 locality; in a straight section of the stream; big outcrop on the right bank; 1.5 m above the water level; 24 paces upstream from a fence and

https://doi.org/10.1017/S0016756805000944

62 paces upstream from an abandoned shed on the right bank; limestone (with a lot of pyrite).

TVDB 02-086: Skelgill Formation; Silurian; Westerdale Inlier; Spengill; left bank; 50 m upstream from the confluence of Stockless Gill and Spengill, measured along the right bank; Stratigraphically 1.89 to 1.95 cm above a limy sandstone bed (= basal beds of the Silurian System); Bedding 011/51; black graptolitic shale.

TVDB 02-087: Skelgill Formation; Silurian; Westerdale Inlier; Spengill; right bank; 47.05 m upstream from the confluence of Stockless Gill and Spengill, measured along the right bank; Stratigraphically 45 to 50 cm above a limy sandstone bed (= basal beds of the Silurian System); in a uniform outcrop with pencil cleavage.

TVDB 02-088: Ashgill Shales Formation; Westerdale Inlier; Spengill; left bank; 40.90 m upstream from the confluence of Stockless Gill and Spengill, measured along the right bank; in an outcrop stretching from 41.30 to 40.50 m from the same confluence; 20 to 40 cm above water level.

TVDB 02-089: Top Ashgill Shales Formation; Westerdale Inlier; Backside Beck; right bank; 1.94 to 2.11 m downstream from the confluence of Stockless Gill and Spengill (centre of the stream), Ashgill shales with sandy intercalations; bedding 007/34.

TVDB 02-090: Cautley Mudstone Formation; Ingham's (1966) top zone 6; Westerdale Inlier; Backside Beck; left bank; 27 paces upstream from the 90°corner of the wall running downhill from Mountain View Farm with a fence along Backside Beck; outcrop with three levels: sample in the second level; most pronounced in the banks; 2 cm sample 32 cm above the base of the level and 68 cm below the top; bedding 001/15.

TVDB 02-091: Cautley Mudstone Formation; Ingham's (1966) top zone 6; N 54°23.212′ W 002°28.207′; Westerdale Inlier; Backside Beck; left bank; 31 paces upstream from the TVDB 02-090 locality; 21.50 m downstream from the contact with the overlying volcanic rocks; bedding 308/01; laminated mudstone.

TVDB 02-093: Cautley Mudstone Formation; Ingham's (1966) top zone 7; N 54°23.450′ W 002°28.070′; Westerdale Inlier; Backside Beck; left bank; 68.20 m downstream from the base of the lamprophyre dyke shown on the map (Ingham, 1966); about 1 m above the base of the outcrop.

TVDB 02-094: Cautley Mudstone Formation; Ingham's (1966) top zone 7; N 54°23.439′ W 002°28.095′; Westerdale Inlier; Backside Beck; left bank; 43 paces downstream from the TVDB 02-093 locality and 6 paces upstream from the highest clear outcrop of the underlying pink volcanic rocks.

TVDB 02-095: Ashgill Shales Formation; Westerdale Inlier; Backside Beck; right bank; 90 m downstream from the confluence of Stockless Gill and Spengill, measured along the right bank; 10 cm above water level; mudstone.

TVDB 02-096: Ashgill Shales Formation; N 54°23.496′ W 002°28.058′; Westerdale Inlier; Backside Beck; right bank; 33 m downstream from the base of the lamprophyre dyke shown on the map (Ingham, 1966).

TVDB 02-097: Basal Silurian Beds (Rickards, 1988); Westerdale Inlier; Spengill; left bank; in the middle part of the limy sandstone bed (= basal beds of the Silurian System).

TVDB 02-099: Ashgill Shales Formation; Westerdale Inlier; Spengill; right bank; 46.80 m upstream from the confluence of Stockless Gill and Spengill, measured along the right bank; 3 paces downstream from the TVDB 02-098 locality; northernmost (= most upstream) outcrop of the Ashgill Shales in Spengill.

TVDB 02-100: Ashgill Shales Formation; N 54°23.538′ W 002°28.991′; Westerdale Inlier; Backside Beck; right bank; 30 m downstream from the confluence of Stockless Gill and Spengill, measured along the right bank.

Sample localities Cautley district, 2003.

TVDB 03-024: Ashgill Shales Formation; N 54°21.331′ W 002°28.066′; Taythes Inlier; Ecker Secker Beck; Wharfe Member outcrop; stratigraphically 18 to 25 cm below the base of the lowest of two conglomerate levels (Wharfe Member) within the Ashgill Shale Formation.

TVDB 03-025: Ashgill Shales Formation-Wharfe Member; N 54°21.331′ W 002°28.066′; Taythes Inlier; Ecker Secker Beck; Wharfe Member outcrop; shales between the two conglomerate levels (Wharf Member) within the Ashgill Shale Formation; stratigraphically 20 to 30 cm above the top of the lowest and 55 to 65 cm below the base of the upper conglomerate level.

TVDB 03-026: Ashgill Shales Formation; N 54°21.331′ W 002°28.066′; Taythes Inlier; Ecker Secker Beck; Wharfe Member outcrop; stratigraphically 90 to 100 cm above the top of the highest of two conglomerate levels (Wharfe Member) within the Ashgill Shale Formation.

TVDB 03-027: Cautley Mudstone Formation; Ingham's (1966) top zone 3; N 54°20.908′ W 002°28.250′; Taythes Inlier, southern part; Birkfields Beck; Ingham's (1966) T39 locality or slightly higher in section; 0.5 m above the water level; bedding 255/58.

TVDB 03-028: Cautley Mudstone Formation; Ingham's (1966) zone 4; N 54°20.917′ W 002°28.316′; Taythes Inlier, southern part; Birkfields Beck; 12 paces E from where a fence crosses the beck, higher than Ingham's (1966) T38 locality; water level; bedding 240/40.

TVDB 03-033: Skelgill Formation; Silurian; N 54°23.566′ W 002°27.943′; Westerdale Inlier; Spengill; left bank; Stratigraphically 0 to 6 cm above a 2 cm thick bentonite level which in turn is resting upon the limy sandstone bed (= basal beds of the Silurian; Rickards, 1988).

Sample localities Pus Gill section, 2003.

Some fences have been replaced and moved compared to older maps, but it is still quite easy to recognize the localities from former studies.

TVDB 03-040: Dufton Shale Formation; Pusgillian; N 54°37.536′ W 002°28.209′; Cross Fell Inlier; Pus Gill section; taken at water level, in the left bank of the gill; 18 paces upstream from where the fence shown on Figure 7 crosses the gill, paced along the right bank of the gill.

TVDB 03-041: Dufton Shale Formation; Pusgillian; N 54°37.562′ W 002°28.168′; Cross Fell Inlier; Pus Gill section; taken at water level, in the middle of the stream, immediately below the northern edge of the new bridge crossing Pus Gill, about 35 paces downstream of the centre of the bend in the gill at P 18 (in Burgess & Holliday, 1979).

TVDB 03-042: Dufton Shale Formation; Pusgillian; N 54°37.582′ W 002°28.150′; Cross Fell Inlier; Pus Gill section; in the left bank of the gill; 70 paces upstream of the TVDB 03-041 locality, and about 85 paces downstream of the waterfall at the P 16 locality (in Burgess & Holliday, 1979).

TVDB 03-044: Dufton Shale Formation; Onnian; GPS 8,5 m upstream Pus Gill = N 54°37.617′ W 002°28.101′; Cross Fell Inlier; Pus Gill section; low in an about 1 m high outcrop in the left bank of the gill; 29.5 m downstream of clearest (1.10 m high), and northernmost step of the waterfall at the P 16 locality (in Burgess & Holliday, 1979), measured along the left bank of the gill.

https://doi.org/10.1017/S0016756805000944

TVDB 03-045: Dufton Shale Formation; Onnian; Cross Fell Inlier; Pus Gill section; in an about 2 m high outcrop in the left bank of Pus Gill, 42 paces downstream from where the new fence (which is about 3 m N of the old wall, which in turn is most probably the one figured on former maps) crosses the gill; taken at 4.5 m W of the eastern edge of the outcrop, 55 cm above the base of the outcrop; stratigraphically in a 42 cm thick shaly layer, in between two massive 30 cm thick layers, from 26 to 34 cm above the top of the lower massive layer.

TVDB 03-046: Dufton Shale Formation; Onnian; N 54°37.634′ W 002°28.067′; Cross Fell Inlier; Pus Gill section; immediately N of where the old wall crossed the stream and S of the new fence (see above); measured along the right bank of Pus Gill: 5 m upstream from the old wall and 8.8 m downstream of the new fence.

TVDB 03-047: Dufton Shale Formation; Onnian; N 54°37.645′ W 002°28.004′; Cross Fell Inlier; Pus Gill section; 59 paces upstream from the new fence (see above), paced along the left bank of Pus Gill; sample in the stream.

TVDB 03-048: Dufton Shale Formation; Onnian; N 54°37.663′ W 002°27.961′; Cross Fell Inlier; Pus Gill section; 70 paces upstream from the TVDB 03-074 locality, paced along the left bank of Pus Gill; about the northernmost decent outcrop; at about the same locality of P 11 (in Burgess & Holliday, 1979); sample in right bank, at water level.

https://doi.org/10.1017/S0016756805000944