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Front cover
Rheidol Gorge section; note prominent bedding surface (by rucksack) 0.8 m below the first appearance of *triangulatus* Biozone graptolites.

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OPEN REPORT OR/18/139

Integrated stratigraphic study of the Rhuddanian-Aeronian (Llandovery, Silurian) boundary succession at Rheidol Gorge, Wales: a preliminary report

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Acknowledgements

Melchin *et al.* (2016), at the International Geoscience Programme Project 591 – Closing Meeting ‘The Early to Mid Palaeozoic Revolution’ (Ghent University, 2016), presented the preliminary results of an ongoing study to assess the candidacy of the famous Rheidol Gorge section (mid Wales, UK) as a replacement GSSP for the base Aeronian Stage. A group of conference participants were shown the section as part of the post-conference field trip to the Welsh Basin. This report represents an updated and revised version of the field guide compiled for that visit.

The land owners at Bryn-brâs Farm and the George Borrow Hotel are warmly thanked for facilitating vehicular access both for the post-conference visit and during the course of our study. Mark Williams assisted with the field logistics and sample collection and Rosemary Melchin and James Wilkinson also assisted in the collection of the graptolite and isotope samples. Several of the figures in this account bear testimony to the excellent drafting skills of Antony Smith (Aberystwyth University). Support staff at Ghent and Leicester universities are also warmly thanked for their assistance in the preparation of samples. Financial assistance to MJM for this project was provided by a Natural Sciences and Engineering Research Council of Canada Discovery Grant. As an Honorary Research Associate, JRD also acknowledges the support of staff at BGS notably Rhian Kendall (BGS Cardiff Office) for her review of the submitted manuscript and for facilitating its approval and release.

Abstract:

Rheidol Gorge, approximately 17 km west of Aberystwyth, mid Wales, exposes a continuous succession of strata from the middle part of the upper Rhuddanian *Coronograptus cyphus* Biozone through the lower Aeronian *Demirastrites triangulatus* (= *Monograptus triangulatus*) Biozone. Parts of the Aeronian succession are well known for their beautiful lower Aeronian graptolites preserved as pyrite internal moulds. We measured this section and sampled for graptolites, palynomorphs, and for lithological and geochemical analyses. One of our objectives was to assess the section for its suitability as a candidate for a new Global Stratotype Section and Point for the base of the mid-Llandovery Aeronian Stage.

The succession alternates between bioturbated grey mudstones lacking in graptolites and laminated, graptolitic black shales. The black shales commonly show thin, interbedded siltstones. The grey mudstones are interpreted to represent deposition under oxic to dysoxic conditions, the black shales an anoxic seafloor environment. The strata have undergone low-grade metamorphism, commonly with a weakly to moderately developed cleavage, and the graptolites often show ductile and/or brittle deformation.

Strata of the middle to upper *cyphus* Biozone are c 10.2 m thick and yield graptolite faunas of varying diversity and preservation quality. 0.8 m below the base of the *D. triangulatus* Biozone there is a change from predominantly organic-poor mudrocks with interbeds of darker shales with sparse graptolites to an interval of predominantly black shales with a relatively rich graptolite fauna. The graptolites in the black shale interval, which spans the zonal boundary, are flattened or in partial relief, commonly deformed, and the strata tend to break along cleavage rather than bedding planes. Nevertheless, a distinctive graptolite fauna occurs through the boundary interval that allows good correlation with successions in other parts of the world. The base of the *D. triangulatus* Biozone is marked by the first appearance of *D. triangulatus*. Other species first appearing just below the base of the *D. triangulatus* Biozone that are useful for international correlation include *Pristiograptus concinnus* and *Pseudorthograptus finneyi*. Strata rich in well-preserved, pyritic graptolites become common about 2.3 m above the base of the *triangulatus* Biozone.

Chitinozoans are poorly to moderately well preserved in the section and indicate the *Spinachitina maennili* Biozone through the boundary interval, without any significant faunal changes, as is the case in many other parts of the world.

1. Introduction

The first comprehensive geological and palaeontological study of the Rheidol Gorge area was published by Jones (1909). That paper summarized the previous geological studies in the region and thoroughly documented the stratigraphy, structure and graptolite biostratigraphy of the Plynlimon and Ponterwyd areas, including a detailed geological map and description of the Rheidol Gorge section, just south of Ponterwyd (Figs 1 and 2). Jones showed that the Rheidol Gorge section exposes an almost continuous succession of strata through much of the interval that is now known as the Rhuddanian and Aeronian stages. He also documented the succession of graptolite faunas and biozones through the section. Since that time, a number of papers have included material from Rheidol Gorge in paleontological studies (e.g., Elles and Wood, 1901-18; Challinor, 1928, 1945; Packham, 1962; Jones and Rickards, 1967; Cullum and Loydell, 1996; Zalasiewicz *et al.*, 2009). However, the importance of the section was most clearly established, both from a graptolite systematic and biostratigraphic perspective, by the monograph of Sudbury (1958), which provided a detailed analysis of the early Aeronian triangulate monograptids that has since formed the basis for the classification of these taxa, and has also provided a key framework for the regional and global graptolite zonation of the lower Aeronian (e.g., Rickards, 1976; Zalasiewicz *et al.*, 2009). Most recently, Cullum and Loydell (2011) provided a new lithological log of the upper Rhuddanian and lower Aeronian portions of the section and Russell *et al.* (2013) undertook a very detailed study of the sedimentology of the strata at and just below the Rhuddanian-Aeronian boundary interval. One of the most important points of the Cullum and Loydell (2011) paper was that they showed that graptolites occur at many more stratigraphic levels in the section than had been documented previously, and that graptolites occur throughout the immediate interval that spans the base of the *Demirastrites triangulatus* (= *Monograptus triangulatus*) Biozone.

In the definition of the Global Stratotype Section and Point for the base of the Aeronian Stage, it is stated "… the marker point for the base is within a continuous lithological section through part of the Trefawr Formation at the base of locality 72 in transect h as described by Cocks and others (1984, p. 165, figs 60, 61, 62, 62). This point correlated with the base of the base of the *Monograptus triangulatus* graptolite Biozone in the section" (Bassett, 1985). It has since been pointed out by a number of authors (e.g. Melchin *et al.*, 2004, 2012; Davies *et al.*, 2011, 2013), however, that at the GSSP, the *D. triangulatus* Biozone was only recognized in one sample by the occurrence of one taxon, *Monograptus austerus sequens*, and that species is elsewhere known only to occur in the middle of the *D. triangulatus* Biozone. Therefore, the GSSP does not appear to correlate with the base of the *D. triangulatus* Biozone as recognized regionally or globally. For this reason, and also the lack of other available data from this section that may be useful for global correlation, a working group was created within the International Subcommission on Silurian Stratigraphy in 2011, to restudy this boundary with the aim of finding a GSSP that permits precise global correlation of the base of the Aeronian. Following from the work of Russell *et al.* (2013), our research group has undertaken a thorough restudy of the lithological succession, graptolite and chitinozoan biostratigraphy, as well carbon isotope chemostratigraphy (currently under study) of the upper Rhuddanian-lower Aeronian portion of the Rheidol Gorge succession to assess its potential as a new candidate section for this GSSP. The purpose of this informal field guide is to report on our current progress in this work.

2. Lithostratigraphy and sedimentology

Although the Rheidol Gorge section is more heavily covered in vegetation than it was at the time it was studied by Jones (1909) and Sudbury (1958), a stratigraphic interval of 20 m in thickness is almost continuously exposed through the upper Rhuddanian and lower Aeronian strata (Figure 2). Our detailed new log of this part of section (Figure 3) supersedes the earlier logs of Jones (1909) and Cullum and Loydell (2011) (all levels referred to elsewhere in this report refer to this figure). The strata in this succession are assigned to the upper part of the Cwmere Formation and the lower part of the overlying Derwenlas Formation. The boundary between these two formations (or there earlier equivalents; see Davies et al., 1997) has been variously placed at either: 1) a layer of prominent calcareous nodules (the "upper nodule layer" of Jones, 1909) (e.g. Cave and Hains, 1986); or 2) at the base of a succession more continuously dominated by massive mottled mudstones just below the top of our measured section, above the "*magnus* Band" of Sudbury (1958) (Davies *et al.*, 1997).

Our studied stratigraphic interval consists of at least three cycles of laminated, graptolitic black shales, grading upward through weakly bioturbated into moderately to strongly bioturbated mudstones. The base of the second of these cycles is a sharp contact of black shales overlying light grey mudstones at the 9.37 m level (marked as the "prominent bedding surface", Figs 2 and 3). This contact, interpreted as a flooding surface (see Davies *et al.*, 2016), produces a prominent bedding plane that, together with the "sandy flags" of Jones (1909) and two conspicuous nodule horizons, provides an important reference marker for the section. Siltstone to fine sandstone laminae and beds (interpreted as turbidites) occur interbedded with the mudstones and these are thickest and most abundant in the lower half of the section.

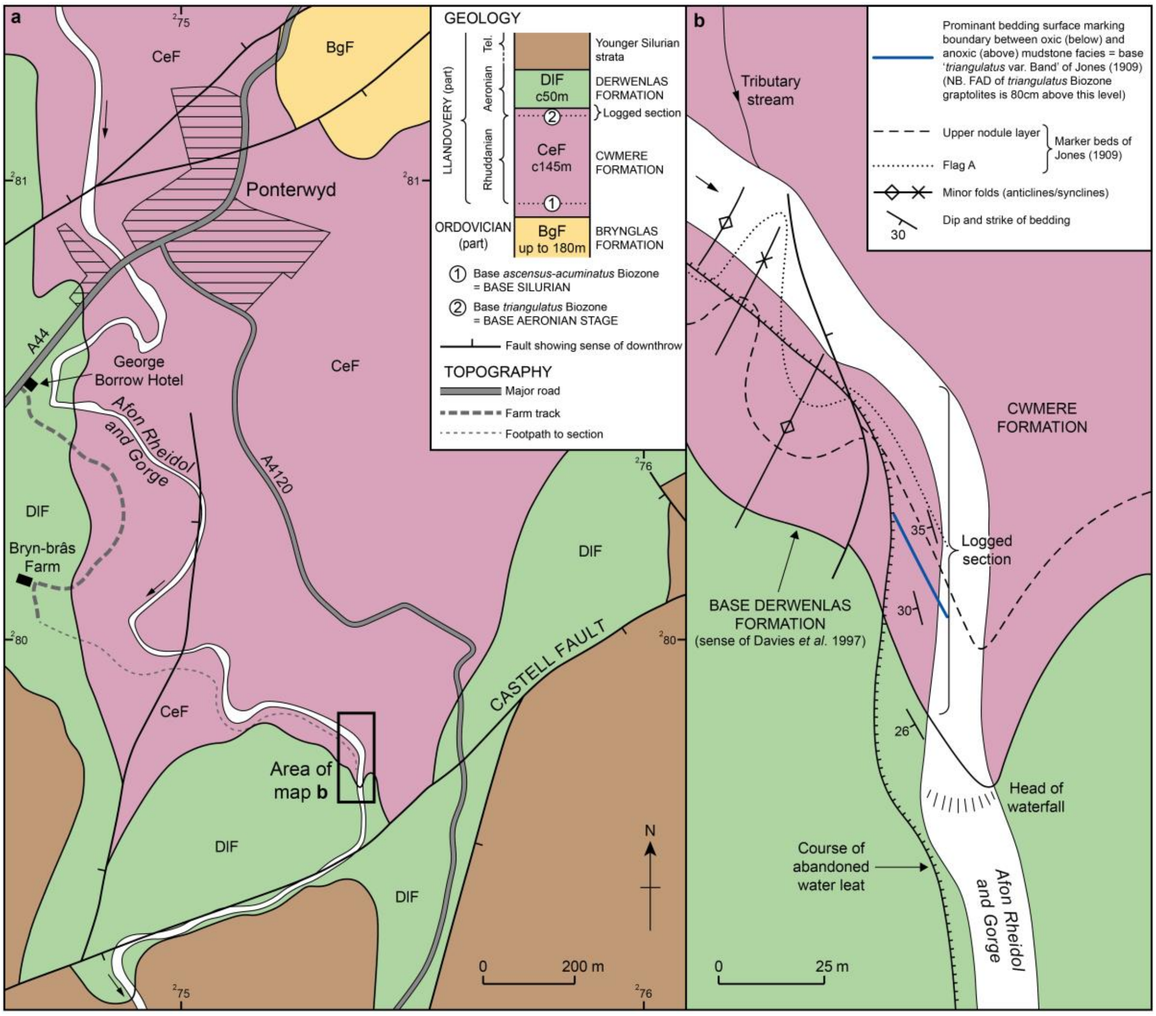

Figure 1. Location map and geology of the Ponterwyd area and study section. Modified and updated from Jones (1909) and BGS (1984). Numbers along the margins of **(a)** refer to the UK National Grid.

Detailed lithological logging (by JRD) has permitted recognition of four distinct facies within the mudstone, based on their style and intensity of bioturbation, colour, and degree of preservation of lamination (Table 1, Fig. 4). These can be interpreted in terms of the relative oxicity (RO) of the basin floor conditions at the time of deposition and the distribution of these facies through the section is shown in Figure 3.

Figure 2. View of the upper part of the Rheidol Gorge section; note the prominent bedding surface (by rucksack) 0.8 m below the first appearance of *D. triangulatus* Biozone graptolites.

Gradational indictors of oxicity / RELATIVE OXICITY / Inferred basin floor bottom conditions		Colour of hemipelagic mudstone	Preservation of hemipelagic lamination	Turbidite-hemipelagite contacts (range of uncertainty in mm)	Welsh Basin bioturbation index (BI) (inc. form & abundance of burrow-mottling)	Max. burrow diameter (mm)
0	Anoxic (anaerobic)	Dark grey-black	Well preserved	Distinct/sharp (0)	0 (none visible)	0
1	Weakly oxic (suboxic)	Dark-medium grey	Minor loss of definition	Minor loss of clarity (<0.25)	1 (simple, sparse)	≤1 (micro-bioturbation)
2	Moderately oxic*	Medium-pale grey	Significant loss of definition	Diffuse; significant loss of clarity (0.5-1)	2-3 (simple, common)	≤2
3	Strongly oxic*	Pale grey	Largely destroyed	Indefinite, difficult to recognise (1-2)	4-5 (pervasive, varied, complex)	≤4 (wide size range)

Table 1. Relative Oxicity (RO): Features displayed by deep-water Rhuddanian and Aeronian slope apron mudstone facies in the Welsh Basin that are inferred to record the impact of differing levels of basin floor oxicity (see also Figures 3 and 4; compare with Cave & Hains, 1986; Davies *et al.*, 1997). *Note that bottom conditions in the Welsh Basin were likely never fully oxic, but remained dysoxic (dysaerobic) at best.

3. Graptolite Biostratigraphy

The general graptolite zonation of the Rheidol Gorge succession was documented by Jones (1909). For the interval of interest in this study, Jones recognized the Zone of *Monograptus cyphus* overlain by the Zone of *Monograptus communis*. The latter was subdivided into a *triangulatus*-var band, *triangulatus* band, *magnus* band, and *leptotheca* band, in ascending order. Jones (1909) regarded the base of the *M. communis* Zone as occurring at the horizon of the large calcareous concretions, which, in our lithological log (Fig. 3), occurs at the 7.3-7.4 m level.

Sudbury (1958) employed essentially the same zonation in her detailed study of triangulate monograptids from this section, although she referred the strata above the *cyphus* Zone as belonging to the *gregarius* Zone, rather than the *communis* Zone. Sudbury also recognized that the stratigraphically lowest graptolites indicative of the *triangulatus*-var band occur approximately 2 m above the top of the level of the large concretions. Sudbury documented only one graptolite-bearing horizon between the concretion layer and the first appearance of triangulate monograptids (her horizon T), and this horizon immediately overlies the prominent level of change from light grey mudstones to black shales in our log at 9.37 m.

Our study employs the graptolite zonation of Zalasiewicz *et al*. (2009). Graptolites were collected mainly by MJM, JAZ and Professor Mark Williams (Leicester University), with assistance from CR, Rosemary Melchin, and James Wilkinson. For this report we focus mainly on the faunas of the *revolutus* Biozone (≈ *cyphus* Biozone) and the lower part of the *triangulatus* Biozone, which we sampled for graptolites in detail (Figure 5). Most of our current interpretation of the graptolite biostratigraphy of the overlying strata is based on the work of Sudbury (1958). To date we have relatively few new collections from these higher strata. The ranges of the most common and biostratigraphically significant graptolites from the *revolutus* and lower *triangulatus* biozones are shown in Figure 5 and specimens of these taxa are illustrated in Figure 6.

Pernerograptus revolutus Biozone

The lower 10.13 m of our measured section contains graptolite faunas indicative of the *Pernerograptus revolutus* Biozone. Some of the indicative species of this biozone are *P. revolutus*, *Normalograptus*? *wyensis*, as well as *Pernerograptus sudburiae* and *Metaclimacograptus undulatus*, which extend into the overlying strata. This biozone also contains the highest occurrences of *Coronograptus cyphus* and *Cystograptus penna*.

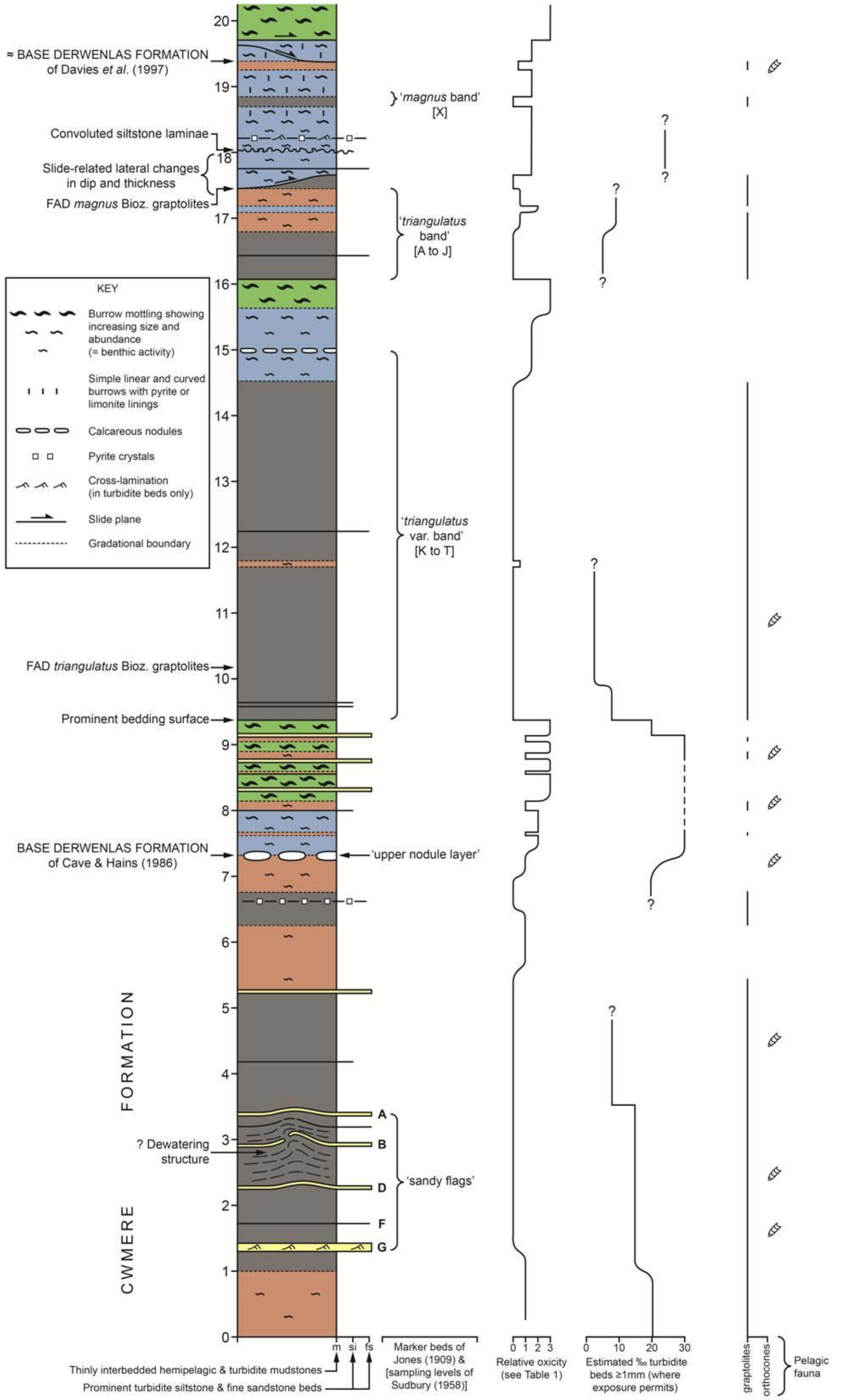

Figure 3. Lithologic log of the studied section showing key graptolite horizons recognized by this study, marker horizons identified by Jones (1909) and sample intervals of Sudbury (1958), as well as features indicative of relative oxicity (see Table 1), estimated % turbidite beds, and intervals of occurrence of pelagic faunas.

Figure 4A. Delicately laminated, anoxic hemipelagic mudstones (dark grey-black) with fine-grained sandstone and siltstone turbidite beds and laminae (pale grey/brown) (RO = 0; see Table 1) at c 1.32 m (see Figure 3). Lens cap is 5 cm in diameter. The thickest turbidite bed is ‘flag G’ of Jones (1909; see also Cullum & Loydell, 2011).

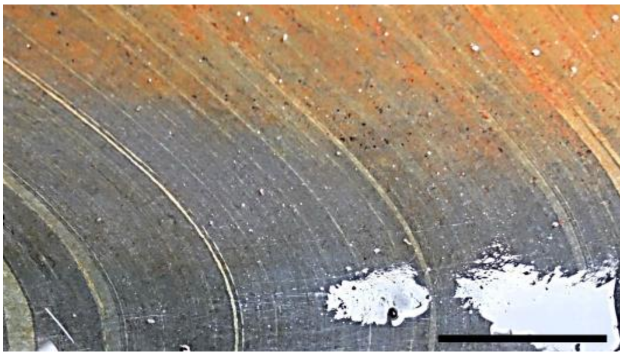

Figure 4B. Enhanced close-up of hemipelagic lamination, location as Fig. 4A. Note well preserved varve-like alternation of dark, organic-rich and lighter silt-rich laminae. Scale bar is 5 cm.

Figure 4C. Upwards transition from dark grey, diffusely laminated hemipelagic mustones with paler turbidite beds and laminae and sparse burrows (RO = 1) into increasingly burrow-mottled equivalents (RO = 2 to 3), at c 9.15 m (see Figure 3). Scale bar is 3 cm. Note the more diffuse nature of the lithological contacts and more poorly preserved hemipelagic lamination in the lower facies the compared with Figs 4A and 4B and the increasing levels of disruption and loss of definition upwards (see Table 1).

Figure 4D. Strongly burrow-mottled mudstone (RO = 3; see Table 1) at c 8.50 m (see Figure 3). Scale bar is 21 mm. Note range of burrow sizes including large diameter varieties and presence of branching burrow systems.

The occurrence of *Glypograptus tamariscus linearis* in our lowest sample indicates that level is within the middle *revolutus* Biozone, as recognized by Zalasiewicz *et al.* (2009).

Graptolite samples are sparse and rather poorly preserved in the ~5.5 – ~8.75 m interval. Between 8.75 and 10.05 m there is a relatively rich and, in some samples, well preserved fauna indicative of the upper *revolutus* Biozone. This subzone is marked by the incoming of *Pernerograptus austerus bicornis* and *Glyptograptus tamariscus angulatus*. Taxa that appear in our collections in this interval and extend into the overlying *triangulatus* Biozone include *Coronograptus gregarius*, *Pristiograptus concinnus*, and *Pseudorthograptus finneyi*. The last species is characteristic of the Rhuddanian-Aeronian boundary interval in the Prague Basin (Štorch, 2015) and this is the first report of this species in the UK. In addition, fragmentary specimens that we questionably identify as *Demirastrites brevis* first appear in the upper part of the *revolutus* Biozone. This is significant because it suggests that this species, which is characterized by having a few axially elongate proximal thecae, may represent a transitional form between pernerograptids with strongly triangulate proximal-mesial thecae and other species of *Demitrastrites*.

Demirastrites triangulatus Biozone

Our lowest sample containing *D. triangulatus* occurs 0.8-0.85 m above the level of the prominent lithological change at 9.37 m. Our correlation with the sample level records of Sudbury (1958) suggests that this sample occurs immediately below her horizon S, which is also her lowest level yielding *D. triangulatus* (specimens she assigned to *Monograptus separatus separatus,* which has more recently been referred to as *Demirastrites triangulatus separatus*). The data presented by Sudbury showed that *D. t. separatus* and *D. t. triangulatus* co-occur in many samples and are also intergradational in form. We, therefore, have not regarded these as distinct subspecies for the purpose of this study and note that more quantitative morphometric work is required on this species group.

Sudbury's (1958) data also indicate that two other species assigned *Demirastrites*, *D. praedecipiens* and *D*? *walkerae* (named *Monograptus toernquisti toernquisti* by Sudbury) also occur in the lower part of the *triangulatus* Biozone. We have also found the first occurrence of *Petalolithus* sp. and *Glyptograptus enodis enodis* as taxa first appearing in the lower *triangulatus* Biozone.

In the data presented by Sudbury, the base of the middle *triangulatus* Biozone of Zalasiewicz *et al.* (2009) can be recognized by the appearance of *Pernerograptus austerus sequens.* The base of the upper *triangulatus* Biozone of Zalasiewicz *et al.* (2009) can be identified at the ~16.35 m level in our Rheidol Gorge section by the first appearance of a species most commonly known in Britain as *Demirastrites triangulatus fimbriatus*. Many authors have regarded this form as being a junior synonym of *Demirastrites pectinatus.* If this interpretation is correct, then the base of the upper *triangulatus* Biozone of Zalasiewicz *et al.* (2009) can be regarded as correlative with the base of the *pectinatus* Biozone as recognized in some other parts of Europe (e.g. Štorch *et al*., 2017).

Neodiplograptus magnus Biozone

The interval identified by Sudbury (1958) as representing the *magnus* Biozone (her horizon X) occurs at a level of approximately 18.65-18.85 m in our measured section. Another level of black shales below this, at 17.45-17.65 m, which is laterally terminated by a fault/slide plane, may also yield specimens of *Neodiplograptus magnus*. This material is currently under study.

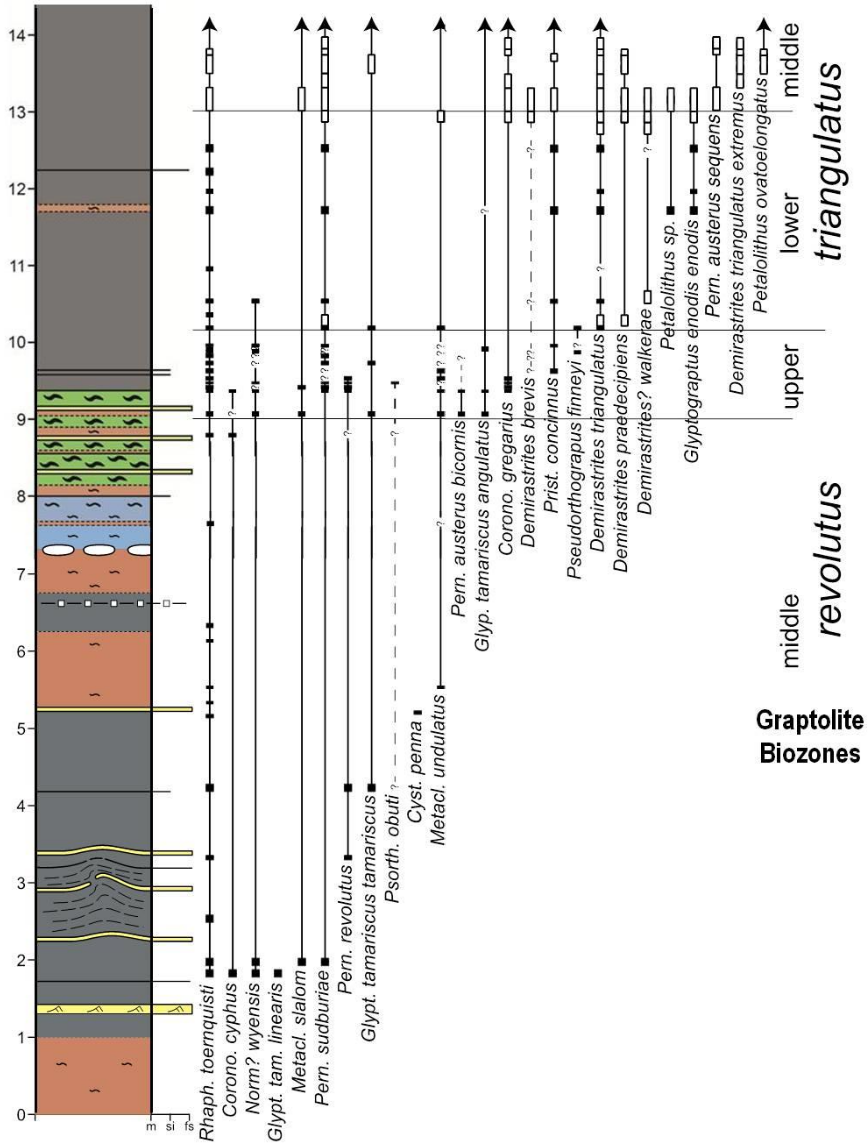

Figure 5. Graptolite biozonation and ranges of selected graptolite taxa for the lower-mid portion of the Rheidol Gorge section sampled by the authors. Black boxes – samples from this study; white boxes – samples from Sudbury (1958).

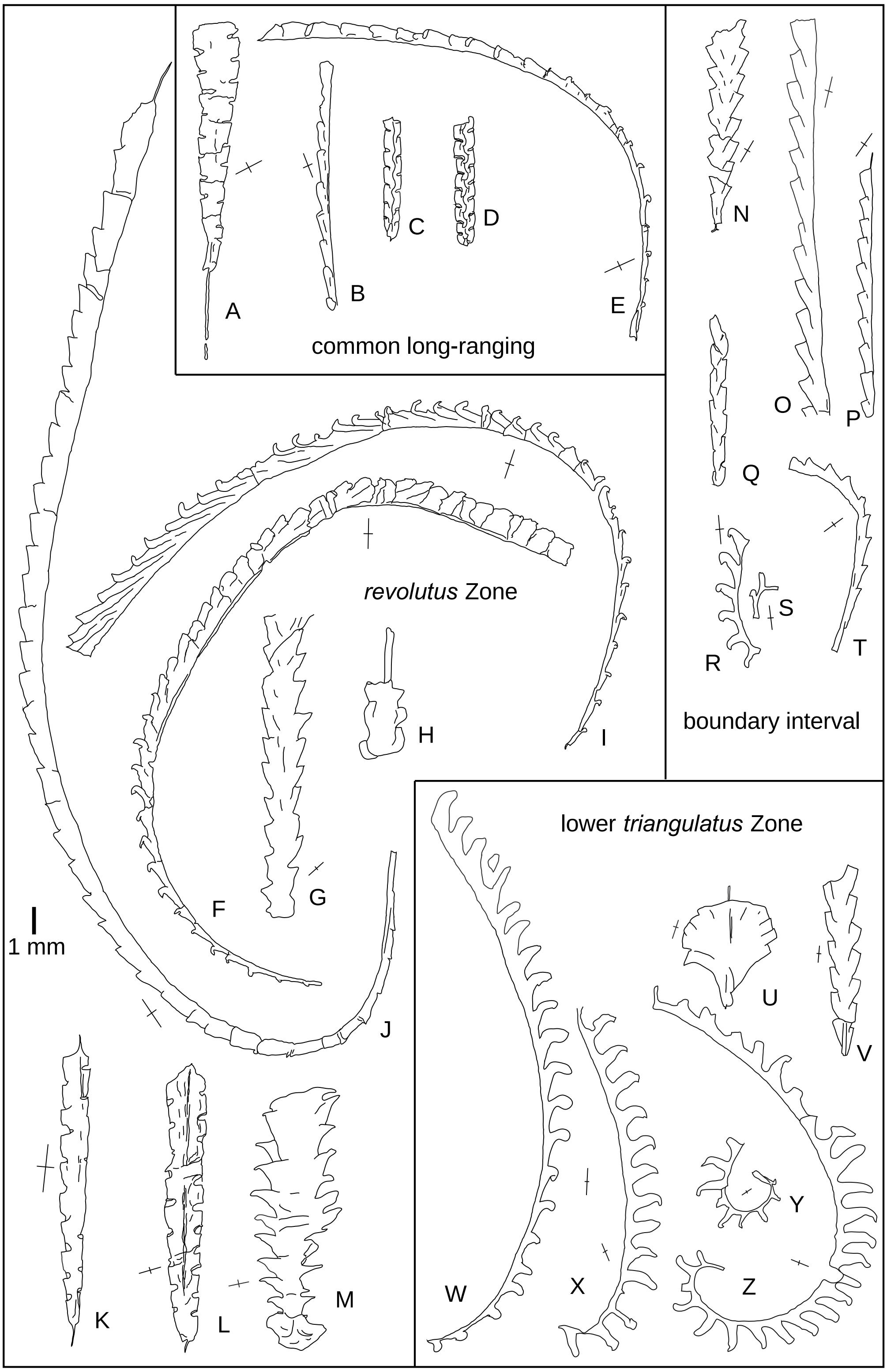

Figure 6. Biostratigraphically important and common graptolites from the *revolutus* and lower *triangulatus* Zones. A – *Rhaphidograptus toernquisti*; B – *Pribylograptus sandersoni/incommodus*; C – *Metaclimacograptus slalom*; D – *Metaclimacograptus undulatus*; E – *Pernerograptus sudburiae*; F – *Pernerograptus revolutus*; G – *Glyptograptus tamariscus linearis*; H – *Cystograptus penna*; I – *Pernerograptus austerus bicornis*; J – *Coronograptus cyphus*; K – *Glyptograptus tamariscus tamariscus*; L – *Normalograptus*? *wyensis*; M – *Pseudorthograptus obuti*; N – *Pseudorthograptus finneyi*; O, P – *Pristiograptus concinnus*; Q – *Glyptograptus tamariscus angulatus*; R, S – *Demirastrites brevis*?; T – *Coronograptus gregarius*; U – *Petalolithus* sp.; V – *Glyptograptus enodis enodis*; W – *Demirastrites*? *walkerae*; X, Y, Z – *Demirastrites triangulatus*.

4. Chitinozoan Biostratigraphy

The chitinozoans from the Rheidol Gorge section are being studied by TRAV and JDW. Twenty-one samples spanning most of our measured interval were collected for chitinozoans, almost all of which have yielded identifiable, often fairly well-preserved specimens (Fig. 7). Nine species can be identified, four of which are currently in open nomenclature. All species occur essentially through the whole study interval and are representative of the *Spinchitina maennili* Biozone, which is characteristic of late Rhuddanian-early Aeronian strata in many regions.

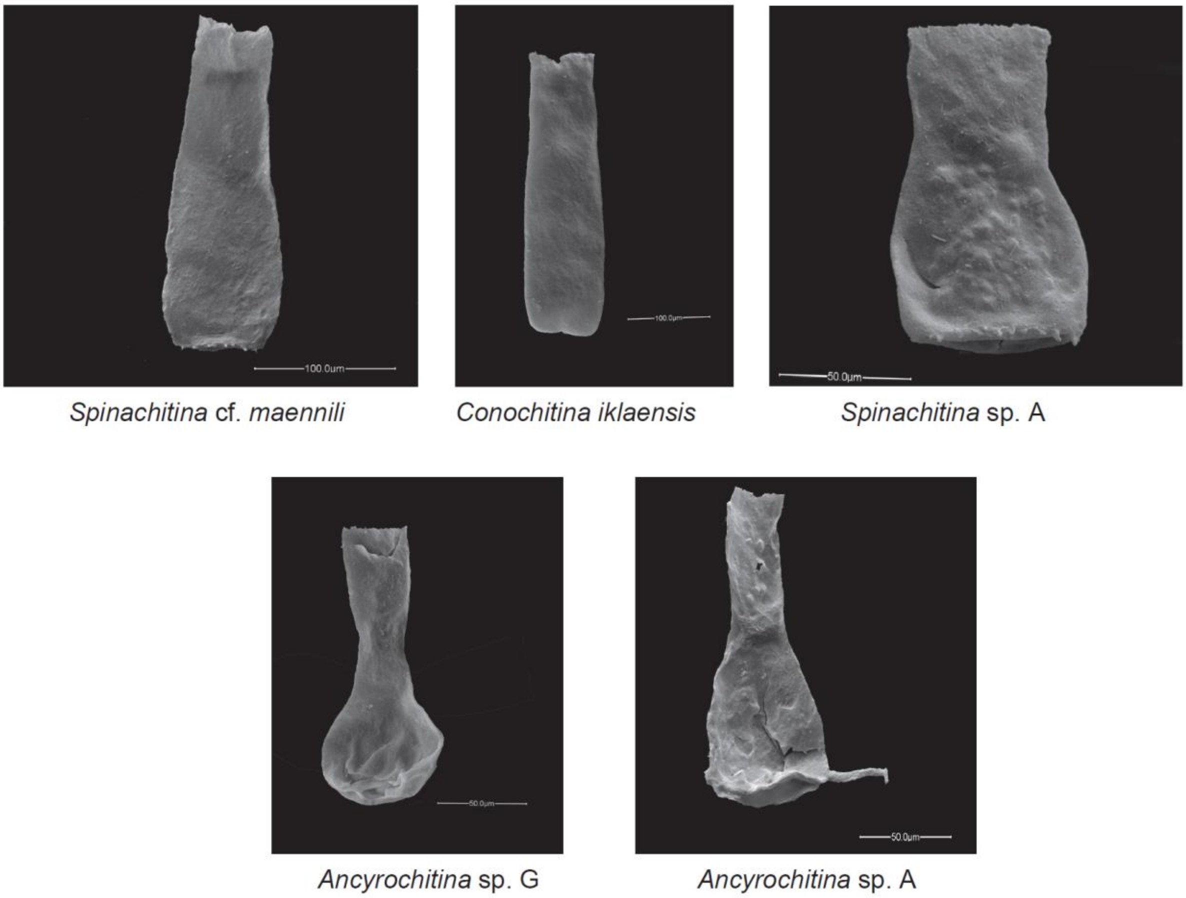

Figure 7. Representative chitinozoan taxa.

5. Level of the Proposed Global Stratotype Section and Point

For consideration of this section as a possible global stratotype for the Base of Aeronian Stage, we propose that the GSSP should be 10.17 m above the base of our measured section, shown by the dashed white line on Figure 8, which is marks the first appearance of the graptolite *Demirastrites triangulatus*, 0.8 m above the level of the prominent bedding surface, as shown in Figures 2, 3 and 5.

Figure 8. Level (dashed white line) of first appearance of *triangulatus* Biozone graptolites, 0.8 m above prominent bedding surface (dashed blue line) at level 9.37 that marks the contact between oxic (below) and anoxic (above) mudstone facies within the upper *Pernerograptus revolutus* Biozone (see Figures 1, 2 and 3; and text)

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