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Integrated stratigraphical study of the Rhuddanian-Aeronian (Llandovery, Silurian) boundary succession in the Rheidol Gorge, Wales: a proposed Global Stratotype Section and Point for the base of the Aeronian Stage

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LETHAIA

The Rheidol Gorge section, approximately 17 km east of Aberystwyth, mid Wales, exposes a ca. 20 m-thick succession of Llandovery (Silurian) strata from the upper Rhuddanian *Pernerograptus revolutus* Biozone through the lower Aeronian *Demirastrites triangulatus* Biozone and basal *Neodiplograptus magnus* Biozone. The section records deposition under a range of bottom-water oxygenation states. The Rhuddanian-Aeronian boundary is located 0.8 m above an abrupt lithological change from predominantly organic-poor, bioturbated 'oxic' mudrocks to an interval of black, richly graptolitic 'anoxic' shales. The graptolite fauna through the boundary interval, including the local lowest occurrence of *D. triangulatus*, allows precise correlation with other parts of the world. Graptolite assemblages indicative of separate divisions in the underlying *revolutus* Biozone and of the lower and upper parts of the *triangulatus* Biozone are also present. Chitinozoans are relatively well preserved in the section and indicate the *Spinachitina maennili* Biozone throughout the boundary interval, as is widely the case. The results of carbon isotope analyses from organic matter indistinctly show the weak interval of positive shift in $\delta^{13}C_{org}$ values through the Rhuddanian-Aeronian boundary interval, as observed globally, though local or regional processes appear largely to overprint the global signal. Overall, the excellent biostratigraphical record, well-documented local and regional stratigraphical context, historical significance, as well as easy access and assured long-term preservation, mean that the Rheidol Gorge section can be proposed as a strong candidate for a new Global Stratotype Section and Point for the base of the Aeronian Stage. ☐ *Silurian, Llandovery, Rhuddanian, Aeronian, Global Stratotype Section and Point, Graptolites, Chitinozoa, Carbon Isotopes*

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The current Global Stratotype Section and Point (GSSP) for the base of the Aeronian Stage, located near the town of Llandovery in south-central Wales (Fig. 1), is defined as follows: '… 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 et al. (1984, p. 165, figs 60, 61, 62, 62). This point correlated with the base of the *Monograptus triangulatus* graptolite Biozone in the section' (Bassett 1985). However, it has since been pointed out by a number of authors (e.g. Melchin *et al.* 2004, 2020; Davies *et al.* 2011, 2013) that, at the GSSP, the *D. triangulatus* Biozone was recognized only in one sample by the occurrence of only one taxon, *Monograptus austerus sequens* (Hutt, 1974) (now assigned to *Pernerograptus sequens*, Štorch *et al.* 2018), and that species is elsewhere known to occur only in the middle of the *D. triangulatus* Biozone. Additionally, recently studied specimens questionably identified as *Pernerograptus sequens* were reported from a level only 2 cm above the base of the *D. triangulatus* Biozone at the Hlásná Třebaň section in Central Bohemia (Štorch *et al.* 2018). Therefore, there is significant ambiguity as to whether the GSSP correlates with the base of the *D. triangulatus* Biozone as recognized either regionally or globally.

For this reason, and also the lack of other available data from the current GSSP 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, and carbon isotope chemostratigraphy of the upper Rhuddanian-lower Aeronian portion of the Rheidol Gorge succession, located in west-central Wales (Figs 1, 2), to assess its potential as a new candidate section for this GSSP. This paper reports the results of this restudy and proposes Rheidol Gorge as a candidate section for consideration as a new GSSP for the base of the Aeronian Stage. The preliminary results of much of this work were presented by Melchin *et al.* (2018) and the text and illustrations in this paper draw extensively from that report. A separate paper, describing the chitinozoan fauna, was published by De Weirdt *et al.* (2019).

The first comprehensive geological and palaeontological study of the Rheidol Gorge area was published by Jones (1909) who recognized that the well-exposed riverine section provided a key transect through the local lower to mid Llandovery succession. 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. Jones showed that the Rheidol Gorge section exposed an almost continuous succession of strata through much of the interval that is now known as the Rhuddanian and Aeronian stages, and 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 palaeontological studies (e.g. Elles & Wood 1901–18; Challinor 1928, 1945; Packham 1962; Jones & Rickards 1967; Cullum & Loydell 1996; Zalasiewicz *et al.* 2011). However, the importance of the section was most clearly established, both from a graptolite systematic and biostratigraphical perspective, by the monograph of Sudbury (1958), which provided a detailed analysis of the lower 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 biozonation of the lower Aeronian (e.g. Rickards 1976; Zalasiewicz *et al.* 2009). In addition, Packham (1962), employing material collected from many of

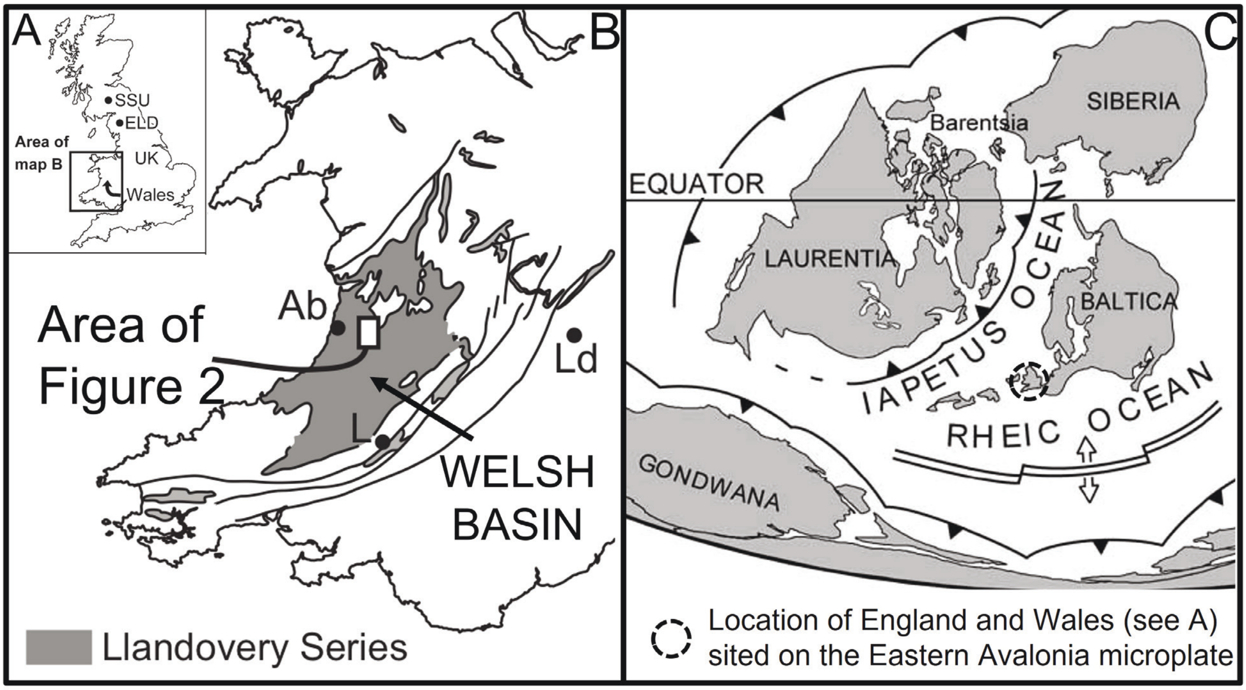

Fig. 1. A, location of Wales and the Welsh Basin relative to other major sites of Llandovery age rocks in the UK (ELD, English Lake District; SU, Southern Uplands). B, distribution of Llandovery rocks deposited in and along the faulted margins of Welsh Basin including location of the Rheidol Gorge area shown in Figure 2 (Ab, Aberystwyth; L, Llandovery, Ld, Ludlow). C, simplified plate tectonic map for the early Silurian (440 Ma) showing location of England and Wales on Eastern Avalonia (but see text) (adapted from Scotese 2003).

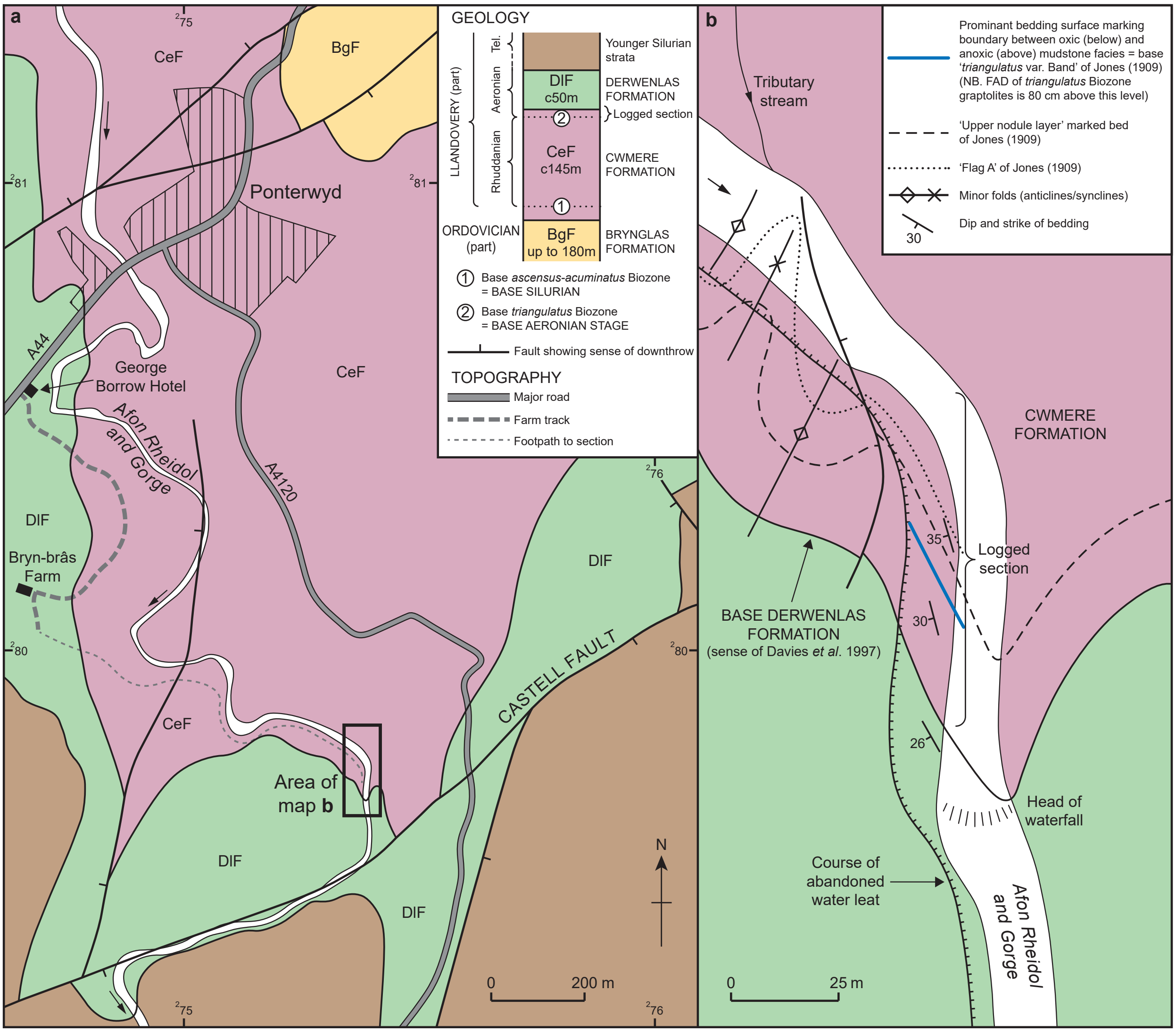

Fig. 2. Location map and geology of the Ponterwyd area and study section. Modified and updated from Jones (1909) and British Geological Survey (1984). Numbers along the margins of (a) refer to the UK National Grid. Note that the base of the Derwenlas Formation, based on the criteria introduced by Davies *et al.* (1997) and used subsequently throughout mid Wales, differs from that shown on the published British Geological Survey map of the Rheidol Gorge (see text and Figure 4).

Sudbury's sample levels, in addition to material from other localities, undertook detailed systematic study of the species of *Glyptograptus*. More recently, Cullum & Loydell (2011) provided a new lithological log of the upper Rhuddanian and lower Aeronian portions of the section, which showed that graptolites occur at many more stratigraphical levels in the section than had been documented previously, and that graptolites occur throughout the immediate interval that spans the base of the *triangulatus* Biozone.

Since the fieldwork of Jones (1909) and Sudbury (1958) was conducted, portions of the Rhuddanian-Aeronian succession have become partially or completely overgrown with vegetation. Nevertheless, among the currently exposed outcrops at this locality there is a continuous and readily accessible succession of strata from the middle part of the Rhuddanian *revolutus* Biozone at least into the mid-Aeronian *leptotheca* Biozone (Fig. 3). For this study, we have resampled, in detail, the graptolite faunas of the middle-upper *revolutus* Biozone and the lower half of the *triangulatus* Biozone, allowing precise placement of the base of the latter biozone, which is widely regarded as the preferred level for correlation of the base of the Aeronian (Štorch *et al.* 2018; Melchin *et al.* 2020). In addition, we have re-evaluated the systematic status of the very well-preserved and diverse faunas reported by Sudbury (1958) and Packham (1962) and incorporated their data with ours into a composite graptolite biostratigraphical succession.

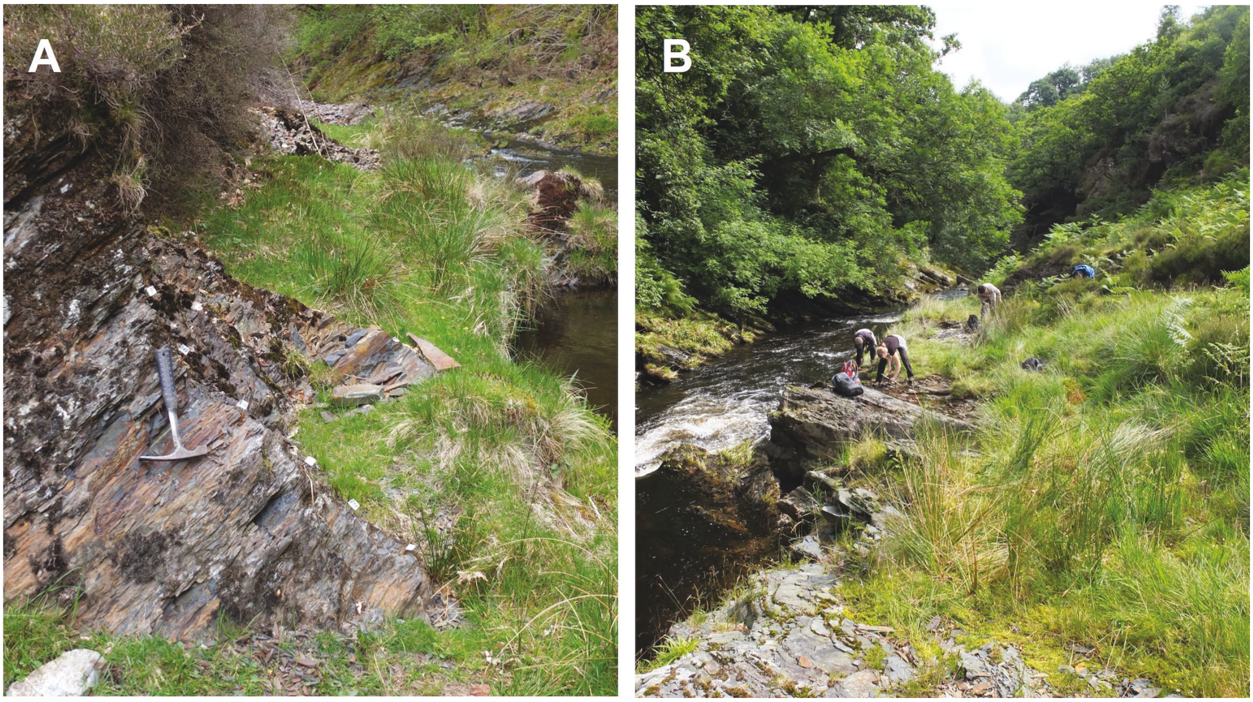

Fig. 3. General views of the Rheidol Gorge section. A, looking up-river at upper to mid Rhuddanian strata comprising the lower part of the section (hammer for scale in foreground is 0.28 m). B, looking down-river at upper Rhuddanian and lower Aeronian strata comprising the upper part of the studied section (note the prominent bedding surface below the nearest person at a level 0.8 m below the first appearance of *triangulatus* Biozone graptolites, see also Figures 3D, 4, 5D, 15). It is important to note that whereas many of the images of the Rheidol Gorge section suggest the presence of a locally extensive vegetation cover, the riverbanks and adjacent rock platforms provide unbroken exposure through the studied section including the boundary interval and demonstrate minimal synsedimentary and tectonic dislocation, as shown in Figure 4.

In order to develop an integrated understanding of the Rheidol Gorge succession, we have also undertaken the following studies through the Rhuddanian-Aeronian boundary interval, from the mid-*revolutus* Biozone into the *magnus* Biozone:

1) detailed description of the lithological succession, particularly focusing on sedimentological evidence of occurrence of intervals of gravity-driven sediment transport, and combined sedimentological/ichnological evidence of the changing redox state of the bottom waters at the time of deposition;
2) systematics and biostratigraphy of the chitinozoan faunas, summarized here and published by De Weirdt *et al.* (2019); and
3) the carbon isotope chemostratigraphy based on analysis of the whole-rock organic matter.

Geological setting

The succession of Rhuddanian to Aeronian sedimentary rocks in the Rheidol Gorge region forms part of the contiguous Ordovician to Silurian marine succession that forms the fill of the lower Palaeozoic Welsh Basin. During the early Silurian the basin occupied mid-southern palaeolatitudes (Woodcock & Strachan 2012; Davies *et al.* 2016). Although traditionally viewed as sited on the Eastern Avalonia microcraton, Waldron *et al.* (2011) suggested that the Welsh Basin has more complex crustal foundations. Nevertheless, by Hirnantian times, following their late Katian collision with Baltica and the associated ‘Shelveian’ deformation of rocks in and around Wales (Toghill 1992), these once separate crustal elements appear to have formed part of a unified tectonic plate and faunal province (e.g. Cocks & Fortey 1990). The latter, prior to its subsequent collision, remained separated from the more northerly Laurentian Supercontinent by the narrowing Iapetus Ocean (Fig. 1).

The Welsh Basin was a region of enhanced subsidence through the Rhuddanian-early Aeronian stages. Large-scale patterns of sedimentation reflect the influence and interaction of both global (eustatic and climatic) and regional (tectonic and epeirogenic) forcing factors (Davies *et al.* 1997, 2013, 2016; Brenchley *et al.* 2006). Palinspastic reconstructions of the basin fill that focus particularly on its Silurian evolution were provided by Woodcock *et al.* (1996), Davies *et al.* (1997, 2006) and Cherns *et al.* (2006). The impacts of back-arc extensional tectonics and associated volcanism characterized much of the Ordovician. Later, during the Telychian, intra-basinal faulting and the deposition of thick sand-rich turbidite systems were a response to the onset of docking with Laurentia. In contrast, the intervening Late Ordovician to Aeronian succession formed during a period of relative tectonic quiescence. The widespread slumping displayed by Hirnantian rocks in the basin records the impact of that interval's well-documented environmental and sea level changes (e.g. Cave & Hains 1986; James 2014), whereas deposition during the ensuing Rhuddanian and Aeronian was characterized principally by the slow accumulation of turbiditic and hemipelagic muds as part of an aggrading westwards-thinning slope-apron system (Davies *et al.* 1997). The Rheidol Gorge section records deposition on the distal part of this system, the few thin turbidite sandstones seen in its lower part testifying to a location between sandy lobes that were located to the north and south (Davies and Waters 1995; Wilson *et al.* 2016).

The Welsh Basin succession accumulated beneath bottom waters that varied from well oxygenated (oxic) to fully starved of oxygen (anoxic) (see below) (e.g. Cave & Hains 1986; Davies *et al.* 1997). The oxic conditions promoted early diagenetic changes in the uppermost layer of sea bed sediment as well as colonization by soft-bodied burrowing benthos (see Cave 1979; Smith 1987; Challands *et al.* 2009). Hence, the deposits that accumulated during such periods are characterized by pale, oxidized hemipelagites that display the effects of bioturbation, notably burrow-mottling. Distinctive white-weathering phosphatized mudstone lenses commonly mark the location of former redox boundaries within the sediment. In contrast, when anoxic conditions prevailed and burrowing organisms were excluded from the sea bed, dark, organic and pyrite-rich sediments accumulated and hemipelagic layers preserve suspension lamination. In detail, as the Rheidol Gorge section well exemplifies (see below), the spectrum of preserved facies is far more nuanced. Yet it remains convenient to label intervals of strata dominated by the products of these intervals of contrasting chemical conditions as either 'oxic' or 'anoxic', and such gross designations have proved useful in the lithostratigraphical subdivision of the basin's mud-prone slope-apron successions (Davies *et al.* 1997). Thus, their predominantly anoxic features underpin the recognition and definition of the mainly Rhuddanian Cwmere Formation, whereas predominantly oxic indicators are used to recognize and define the overlying lower-mid-Aeronian Derwenlas Formation (see Lithostratigraphy, below). The Rheidol Gorge section offers important insights into the use of these chemical facies in defining the Cwmere-Derwenlas formational boundary.

The remains of graptolites are rarely preserved in the lighter coloured, mottled 'oxic' facies, but their abundance in the Welsh Basin's darker coloured 'anoxic' facies has underpinned a long history of taxonomic and biostratigraphical research (e.g. Zalasiewicz *et al.* 2009 and references therein). This work has demonstrated that many of the well-dated, graptolite-bearing units are widely recognisable throughout the basin. Davies *et al.* (2016) contend that the alternating pattern of light, mottled 'oxic' rocks with dark graptolitic 'anoxic' units, that characterize the late Hirnantian to Aeronian Welsh Basin slope-apron succession (see Davies *et al.* 1997), reveals a chemical stratigraphy linked principally to global sea level fluctuations and, in turn, to the expansion and contraction of a contemporary Gondwanan-based ice sheet (Page *et al.* 2007).

Structurally, the Rheidol Gorge section is sited on the flanks of the Plynlimon Dome, one of a series of large periclines present in the region that are cored by outcrops of Ordovician (upper Katian and Hirnantian) rocks (British Geological Survey 1984). Lead-zinc mineralization along the area's numerous ENE-WSW trending cross faults, including the Castell Fault (Fig. 3), supported a thriving 19th century mining industry. Small-scale, open anticlines and synclines with NNE-SSW trending axes traverse the site as do a number of smaller-scale faults (Fig. 2). The strata have undergone low-grade (anchizone) metamorphism (Merriman 2006). They show a weak, axial planar cleavage at a high angle to bedding. The folding and cleavage displayed by the Welsh Basin's fill testify to a regional mid-Devonian compressive deformation. Although previously seen as marking the destruction of Iapetus and collision with Laurentia and, hence, as a final phase of the Caledonian orogenic cycle, Woodcock & Soper (2006) and Woodcock *et al.* (2007) suggested instead that this deformation resulted from collision to the south and was an early expression of Variscan tectonics.

Despite the impacts of later metamorphic and tectonic events, primary sedimentary features are readily identifiable in all of the strata through the section studied, throughout much of which graptolites are abundant. The latter show varying degrees of deformation depending on the lithology, and whether they are preserved as pyrite infills or as flattened films. In the latter case, the specimens are commonly accompanied by sheet silicate mineral overgrowths, as described by Underwood (1992) and Page *et al.* (2008). In the case of pyrite moulds, the specimens may be either undeformed or show some brittle deformation, in the form of lateral offset, extensional breakage, or compressive shingling of stipe fragments, depending on their orientation relative to cleavage.

Methods

Field sampling

Much of the sampling for this study took place in August 2016, during which time new graptolite assemblages and samples for chitinozoan and isotope analysis were collected. To facilitate this sampling programme, a detailed new sedimentary log of the section was compiled (by JRD) to supersede the earlier logs of Jones (1909), Cave & Hains (1986) and Cullum & Loydell (2011). A particular focus during logging was on the spectrum of, and transitions between, oxic and anoxic facies, as well as the location of the regional lithostratigraphical boundary between the Cwmere and Derwenlas formations. The new log is shown as Figure 4 and provides the template for all of the location levels given below.

Graptolite sampling, focusing mainly on the lower ca. 12.5 m of the section (the exposed portion of the *revolutus* Biozone and the lower part of the *triangulatus* Biozone), took place at every level that we found identifiable graptolites. The graptolite biostratigraphy of the interval above the 12.5 m level is that described in detail by Sudbury (1958). We collected some samples through the rest of the section, primarily to verify the correspondence with Sudbury's collections. One exception was that we found a graptolite-bearing level at our 17.5–17.7 m level that was not reported by Sudbury (1958) or Cullum & Loydell (2011). This graptolitic interval is laterally truncated by a fault/slide surface and not exposed along the riverbank, but is exposed in crags located a few metres to the west.

Graptolite study

Graptolites collected as part of this project were studied mainly by MJM using a Nikon SMZ 1270 microscope with a co-axial illuminator and a λ/4 plate to maximize reflective contrast between the graptolite specimens and host rock. Drawings were made using a camera lucida, which were then digitized by tracing in Adobe Illustrator. All graptolites illustrated in this paper are identified in the figure captions with Zx numbers and are housed at the British Geological Survey in Keyworth, except for one specimen, marked SM, which is housed at the Sedgwick Museum, University of Cambridge, UK.

In addition to our new graptolite collections, we have integrated the data from Sudbury (1958, fig. 4), who provided a detailed, sample-by-sample graptolite faunal list for the section above our 9.37 m level, although most of her samples came from above the 12.5 m mark. The correlation between our section log and that of Sudbury (1958) was achieved using a combination of lithological marker units, particularly the concretion-bearing horizons at our 7.3 and 15.0 m levels (Fig. 4), as well as some key graptolite faunal occurrence levels.

The identifications of Sudbury (1958) have been reassessed: 1, in the light of more recent systematic work on similarly aged faunas at other localities (e.g. Štorch 2015; Štorch and Melchin 2018); and 2, following a re-examination of Sudbury's illustrations and some of the illustrated specimens housed in the Sedgwick Museum, Cambridge University. We have also taken account of the observations on material from Rheidol Gorge made by Packham (1962). Our reassessment of each of the taxa in Sudbury's table 1, as well as Packham's data, is given in our Table 1.

The chitinozoan work done as part of this study was fully documented by De Weirdt *et al.* (2019) and the illustrated specimens are housed in the collections of the Department of Geology, Ghent University.

Isotope analyses

The carbon isotope and total organic carbon analyses were conducted in the Environmental Stable Isotope laboratory at University of Leicester. Powdered samples were treated with 10% HCl, subsequently washed, dried and homogenized, sub-sampled and encapsulated in tinfoil cups. Total organic carbon (TOC) and $\delta^{13}C_{org}$ were determined using a SerCon ANCA GSL elemental analyser interfaced to a SerCon Hydra 20–20 continuous flow isotope ratio mass spectrometer. Typical measurement reproducibility was better than ±0.1‰ for $\delta^{13}C$.

Results and discussion

Sedimentology and lithostratigraphy

Although the Rheidol Gorge section is more heavily vegetation-covered than when it was studied by Jones (1909) and Sudbury (1958), a stratigraphical interval of approximately 20 m thick is continuously exposed through the upper Rhuddanian and lower Aeronian strata (Figs 2, 4, 5). The succession comprises thinly interbedded hemipelagic and turbidite mudstones. Subordinate siltstone and fine sandstone turbidites are thickest and most abundant in the lower half of the section. These are the 'sandy flags' of Jones (1909) and, together with two conspicuous nodule horizons, provide important marker horizons when logging the section. The 'prominent bedding surface' shown on Figures 4 and 5 at the 9.13 m level between light

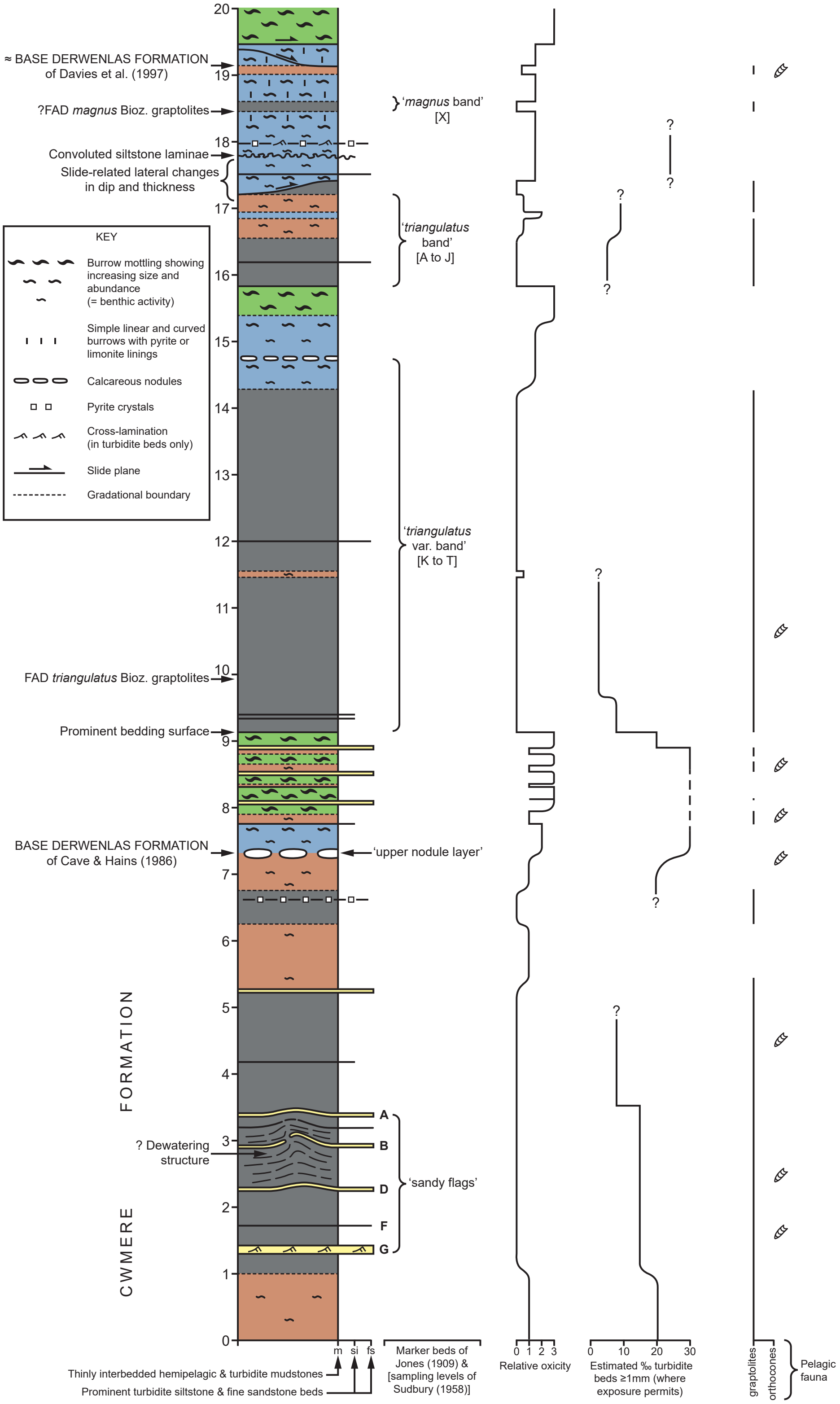

Fig. 4. Lithological log of the studied section (produced by JRD) showing the most conspicuous and persistent marker horizons identified by Jones (1909), sample intervals of Sudbury (1958) (note that aside from her sample X, Sudbury's alphabetical intervals A to T are in descending order – A being the highest/youngest and T the lowest/oldest), as well as features indicative of relative oxicity (see Table 2 for key to colours and values), estimated % turbidite beds, and intervals of occurrence of graptolite faunas. See text for explanation of the different levels used for the boundary between the Cwmere and Derwenlas formations. The level based on the criteria of Davies *et al.* (1997), as adopted on Figure 2, is the most widely utilized on BGS geological maps of mid Wales.

Table 1. Comparative table of taxonomic names employed by Sudbury (1958) and Packham (1962) with those employed in this study for the same taxa. References refer to first and/or recent usage of the revised taxon names

Sudbury 1958, Packham 1962*	This study	References
Climacograptus extremus	*Metaclimacograpus undulatus*	Bulman & Rickards 1968; Melchin 1998
Climacograptus hughesi	*Metaclimacograptus slalom*	Zalasiewicz 1996
Climacograptus rectangularis	*Normalograptus rectangularis*	Melchin 1998
*Climacograptus tamariscoides**	*Glyptograptus tamariscoides*	Melchin 1998
Rhaphidograptus toernquisti	*Rhaphidograptus toernquisti*	n/a
Orthograptus bellulus	uncertain, not included in our study	n/a
Glyptograptus sinuatus	*Rickardsograptus sinuatus*	Melchin *et al.* 2011
Glyptograptus tamariscus	*Glyptograptus tamariscus*	n/a
*Glyptograptus tamariscus tamariscus**	*Glyptograptus tamariscus tamariscus**	n/a
*Glyptograptus tamariscus acutus**	*Glyptograptus tamariscus acutus**	n/a
*Glyptograptus tamariscus angulatus**	*Glyptograptus tamariscus angulatus**	n/a
*Glyptograptus tamariscus distans**	*Glyptograptus tamariscus distans**	n/a
*Glyptograptus tamariscus linearis**	*Glyptograptus perneri*	Štorch 2015
*Glyptograptus tamariscus varians**	*Glyptograptus tamariscus varians**	n/a
*Glyptograptus enodis enodis**	*Glyptograptus enodis enodis**	n/a
*Glyptograptus enodis latus**	*Glyptograptus enodis latus**	n/a
*Glyptograptus alternis**	*Glyptograptus alternis**	n/a
Glyptograptus tamariscus incertus	*Glyptograptus incertus*	Packham 1962
Diplograptus magnus	*Neodiplograptus magnus*	Legrand 1987
Petalograptus minor	*Petalolithus minor*	Bouček & Přibyl 1941
Petalograptus palmus latus	uncertain, not included in our study	n/a
Petalograptus palmeus ovato-elongatus	*Petalolithus ovatoelongatus*	Bouček & Přibyl 1941; Štorch 2015
Petalograptus sp.	*Petalograptus sp.*	n/a
Monograptus atavus	*Atavograptus atavus*	Rickards 1974
Monograptus communis communis	*Campograptus communis*	Obut 1949; Štorch *et al.* 2018
Monograptus communis rostratus	*Campograptus rostratus*	Štorch *et al.* 2018
Monograptus concinnus	*Pristiograptus concinnus*	Obut 1965
Monograptus cyphus	*Coronograptus cyphus*	Obut *et al.* 1968
Monograptus cyphus var.	uncertain, not included in our study	n/a
Monograptus cf. gemmatus	uncertain, not included in our study	n/a
Monograptus gregarius	*Coronograptus gregarius*	Obut *et al.* 1968
Monograptus intermedius	*"Monograptus" intermedius*	n/a
Monograptus ?leptotheca	uncertain, not included in our study	n/a
Monograptus pseudoplanus	*Campograptus pseudoplanus*	Štorch *et al.* 2018
Monograptus revolutus B	*Pernerograptus austerus*	Hutt 1974; Štorch 2015
Monograptus revolutus C	*Pernerograptus sudburiae*	Hutt 1974; Štorch *et al.* 2018
Monograptus revolutus D	*Pernerograptus sequens*	Hutt 1974; Štorch *et al.* 2018
Monograptus separatus separatus	*Demirastrites triangulatus*	Štorch *et al.* 2018, this study
Monograptus separatus extremus	*Demirastrites extremus*	this study
Monograptus separatus fimbriatus	*Demirastrites pectinatus*	Přibyl & Münch 1941; Štorch *et al.* 2018
Monograptus separatus praedecipiens	*Demirastrites praedecipiens*	Štorch *et al.* 2018
Monograptus separatus triangulatus	*Demirastrites triangulatus*	Eisel 1912; Štorch 2015
Monograptus toernquisti toernquisti	*Demirastrites? walkerae walkerae*	Rickards *et al.* 1977; Štorch *et al.* 2018
Monograptus toernquisti elongatus	*Demirastrites? walkerae rheidolensis*	Rickards *et al.* 1977; Štorch *et al.* 2018
Monograptus toernquisti brevis	*Demirastrites? brevis*	Štorch *et al.* 2018
Monograptus sp. 1	uncertain, not included in our study	n/a
Monograptus (Diversograptus) ?capillaris	*Diversograptus capillaris*	n/a
Monograptus (Diversograptus) sandersoni	*Pribylograptus sandersoni*	Obut *et al.* 1968
Rastrites longispinus	*Rastrites longispinus*	n/a
Rastrites peregrinus	uncertain, not included in our study	n/a

Fig. 5. Selected views of the studied section (the specified levels refer to Fig. 4). A, Mid Rhuddanian strata in the lower part of the section (prominent fine sandstones in lower left at ends of 0.5 m scale bar are sandy flags A and B). B, Upper Rhuddanian strata below boundary level, geniculation of 1 m long (total) measure is at the level of 'upper nodule layer'. C, base Aeronian boundary level showing the 'prominent bedding surface' at lower tip of 1 m long (total) measure (see also Figs 3, 15); D, Lower Aeronian (lower to mid *triangulatus* Biozone) strata in middle part of section, hammer for scale in foreground is 0.28 m, arrow shows level of nodules at 15 m. E, slide surface affecting upper *triangulatus* Biozone strata in the upper part of the section, hammer for scale is 0.28 m.

grey bioturbated mudstones below and black, richly graptolitic mudstones above is a further critical level within the section.

Detailed sedimentary logging has permitted recognition not only of obviously light-coloured, mottled rocks interpreted as 'oxic' and dark graptolitic rocks interpreted as 'anoxic' mudstone facies, but also four distinct subfacies based on gross colour, the preservation of lithogical contacts and suspension lamination, a local Bioturbation Index that factors in the abundance and variety of ichnotaxa present, as well as maximum burrow diameters (Table 2, Figs 6, 7). Following the work of Challands *et al.* (2009) on Welsh Basin Katian rocks, these subfacies can be interpreted in terms of the relative oxicity (RO) of the basin floor conditions at the time of deposition. Because of the subtle nature of their differences, and the small size and disparate nature of RO 1 bioturbation features, RO 0 and RO 1 subfacies are commonly indistinguishable in many field locations. Their differences typically fail to meet the criteria for mappable boundaries between the interpreted 'anoxic' and 'oxic' Welsh Basin divisions. Many divisions labelled as 'anoxic' (e.g. Cave & Hains 1986; Davies *et al.* 1997) likely include possibly significant portions that were deposited under suboxic as opposed to fully oxygen-deficient conditions. Conversely, it is subfacies with RO indices of ≥2 that are dominant in their oxic counterparts. However, it is important to note in the Rheidol Gorge site, and elsewhere in the Welsh Basin, facies viewed in relative terms as even strongly oxic likely accumulated under conditions that, technically, likely always remained within the dysoxic range (see Arthur and Sageman 1994; Challands *et al.* 2009) (Table 2; Fig. 6).

Table 2. 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 Cave & Hains 1986; Davies *et al.* 1997) and allow the recognition of four slope apron mudstone subfacies (see also Figs 4, 6 and 7). *In absolute terms, basin floor 'oxic' conditions likely always remained within the dysoxic range (see text and Fig. 6).

Gradational indicators 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)

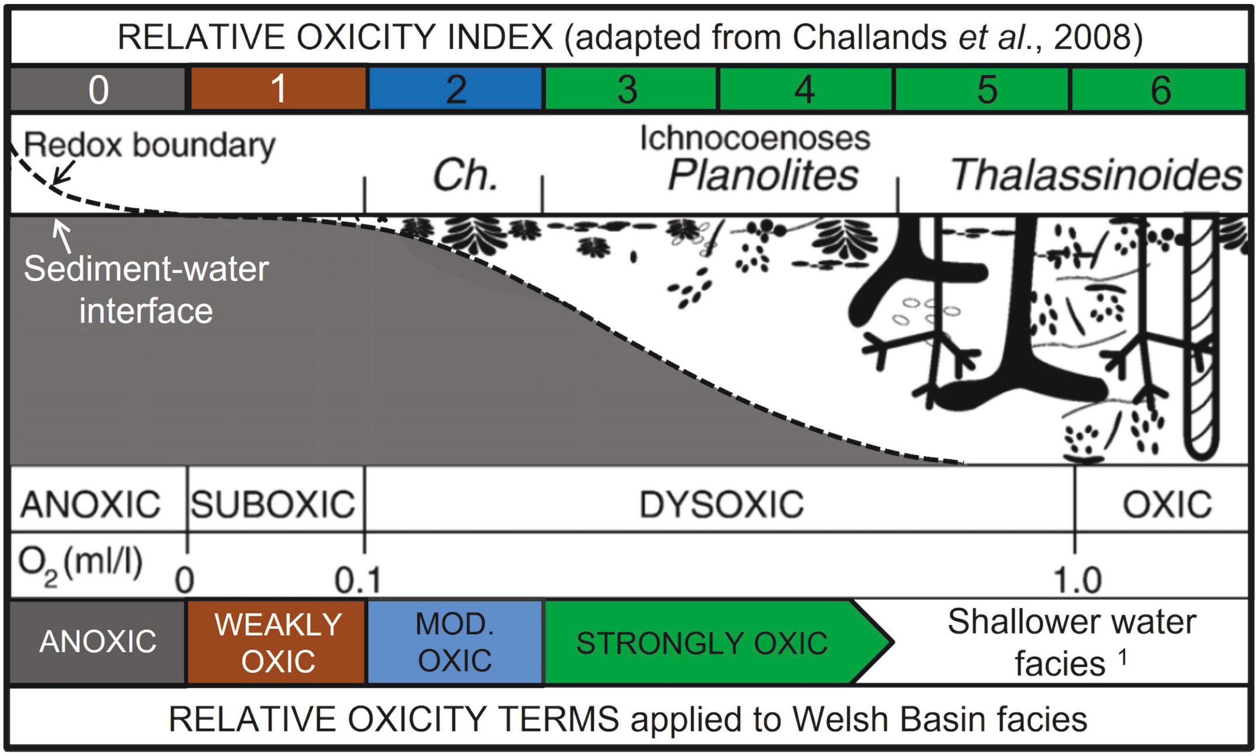

Fig. 6. Schematic illustration showing the relationship of relative oxicity states (RO 1 to 6) to the putative redox boundary, oxygenation levels and size, depth and diversity of burrow systems; and the relative oxicity terms in use in the Welsh Basin (see Table 2; Figs 4, 7).[1] The size and diversity of trace fossils indicative of RO 4 to 6 feature predominantly in non-turbiditic shallower water facies associated with basin margin and platformal settings (see Davies *et al.* 2013). Abbreviations: Ch, *Chondrites*; MOD, moderately.

The recognition and logging of these subfacies in the Rheidol Gorge section reveals a cyclical distribution (Fig. 4) in which anoxic, graptolitic black mudstones grade upwards through weakly bioturbated (RO = 1) into moderately to strongly bioturbated oxic mudstones (RO = 2–3). A lower order of cyclicity is implied by the smaller-scale alternation of weak and more strongly oxic facies evident below the proposed stratotype level and in the upper part of the section. Variations in the ratio of turbiditic to hemipelagic mudstone appear broadly to complement these chemical variations.

Davies *et al.* (2016) correlated anoxic levels within the Rhuddanian and Aeronian Welsh Basin succession with marine transgressions affecting the basin margin. In showing that these can also be correlated more widely, they advocated a glacioeustatic origin. Oxic intervals, by contrast, coincide with periods of regression and progradation and, in the basin, of increased levels of turbidite supply. These mark periods, Davies *et al.* (2016) suggested, when regional isostasy and epeirogenesis were influential forcing factors.

The distribution of oxic and anoxic subfacies in the Rheidol Gorge section also inform lithostratigraphical analysis. The exposed succession is widely acknowledged to span the upper part of the mainly anoxic Cwmere Formation and the lower part of the overlying Derwenlas Formation. Cave & Hains (1986) placed the boundary between these formations at the layer of prominent calcareous nodules (the 'upper nodule layer' of Jones 1909) that underlies the lowest, strongly bioturbated interval in the section (Fig. 5B); below the 'prominent bedding plane' (Figs 4, 5C). Thus, they included the thick overlying unit of graptolitic mudstone, which includes the first appearance datum (FAD) of *triangulatus* Biozone graptolites, in their Derwenlas Formation (see below). In contrast, during their regional mapping campaign, Davies *et al.* (1997) found it practical to locate the base of the Derwenlas Formation at the base of a much thicker, crag-forming packet of oxic facies mudstones below which they consistently found *magnus* Biozone graptolites. In the Rheidol section, this level occurs just below the top of our measured section, above the '*magnus* Band' of Sudbury (1958) (Fig. 4). Use of this regional definition, and its implication that thin units of strongly bioturbated mudstone are present in the Cwmere Formation, is advocated here.

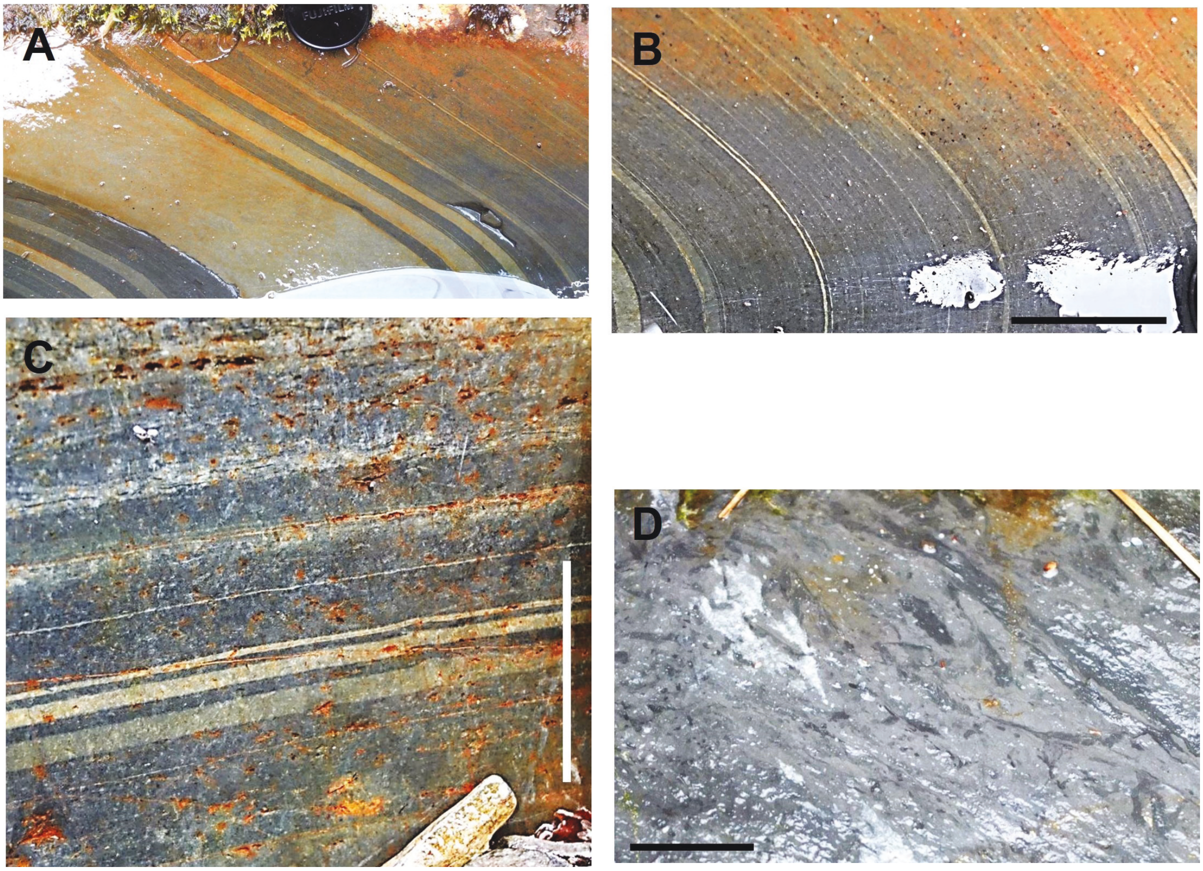

Fig. 7. Impacts of differing levels of oxicity during deposition and early diagenesis; location references refer to Figure 4 and RO values to Table 2 (see also Fig. 6). A, delicately laminated, anoxic hemipelagic mudstones (dark grey-black) with fine-grained sandstone and siltstone turbidite beds and laminae (pale grey/brown) (RO = 0), c 1.32 m, lens cap is 5 cm in diameter (note thickest turbidite bed is sandy flag G of Jones (1909). B, enhanced close-up of hemipelagic lamination in A (note well preserved varve-like alternation of dark, organic-rich and lighter silt-rich laminae), scale bar is 5 cm. C, upwards transition from dark grey, diffusely laminated hemipelagic mudstones with paler turbidite beds and laminae and sparse burrows (RO = 1) into increasingly burrow-mottled equivalents (RO = 2 to 3), c 8.9 m, scale bar is 3 cm (note more diffuse nature of the lithological contacts and more poorly preserved hemipelagic lamination in the lower facies compared with A and B and increasing levels of disruption and loss of definition upwards; D, Strongly burrow-mottled mudstone (RO = 3) at c 8.25 m, scale bar is 20 mm (note range of burrow sizes including large diameter varieties and presence of branching burrow systems).

Graptolite Biostratigraphy

The general graptolite biozonation 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 Zone of *M. communis* as occurring at the horizon of the large calcareous concretions, which, in our lithological log (Fig. 4), occurs at the 7.3–7.4 m level.

Sudbury (1958) employed essentially the same biozonation 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 9.13 m.

Our study employs the graptolite biozonation of Zalasiewicz *et al.* (2009) and discussion of the correlation with the graptolite biozonations of other parts of the world can be found below. For this study we resampled, in detail, the faunas of the *revolutus* Biozone (≈ *cyphus* Biozone) and the lower part of the *triangulatus* Biozone. Although we also made some collections in higher strata, much of our current interpretation of the graptolite biostratigraphy of the overlying strata is based on a taxonomic reassessment of the work of Sudbury (1958) (see Table 1). The graptolite occurrence data, integrating our own work and that of Sudbury, is shown in Figure 8.

Pernerograptus revolutus *Biozone*.– The lower 10.17 m of our measured section contains graptolite faunas representative of the *Pernerograptus revolutus* Biozone. The most indicative species of this biozone is *P. revolutus* (Kurck, 1882) (Fig. 10, L, P, Q), together with *Normalograptus*? *wyensis* Zalasiewicz & Tunnicliff, 1994 (Fig. 9L-O), *Pernerograptus sudburiae* (Hutt, 1974) (Fig. 10R, S, Z) and *Metaclimacograptus undulatus* (Kurck, 1882) (Fig. 9I, J), which extend into the overlying strata. This biozone also contains the only occurrences of *Coronograptus cyphus* (Lapworth, 1876) (Fig. 10W-Y) and *Cystograptus penna* (Hopkinson, 1869) (Fig. 9Y). The occurrence of *Glyptograptus perneri* Štorch, 2015 (= *Glyptograptus tamariscus linearis* Perner, 1897 *sensu* Packham, 1962) (Fig. 9U) in our lowest sample indicates that this level is within the middle part of the *revolutus* Biozone, as recognized by Zalasiewicz *et al.* (2009).

Graptolite samples are sparse and rather poorly preserved in the ~5.5 – ~8.5 m interval. Between 8.77 and 9.99 m there is a relatively rich and, in

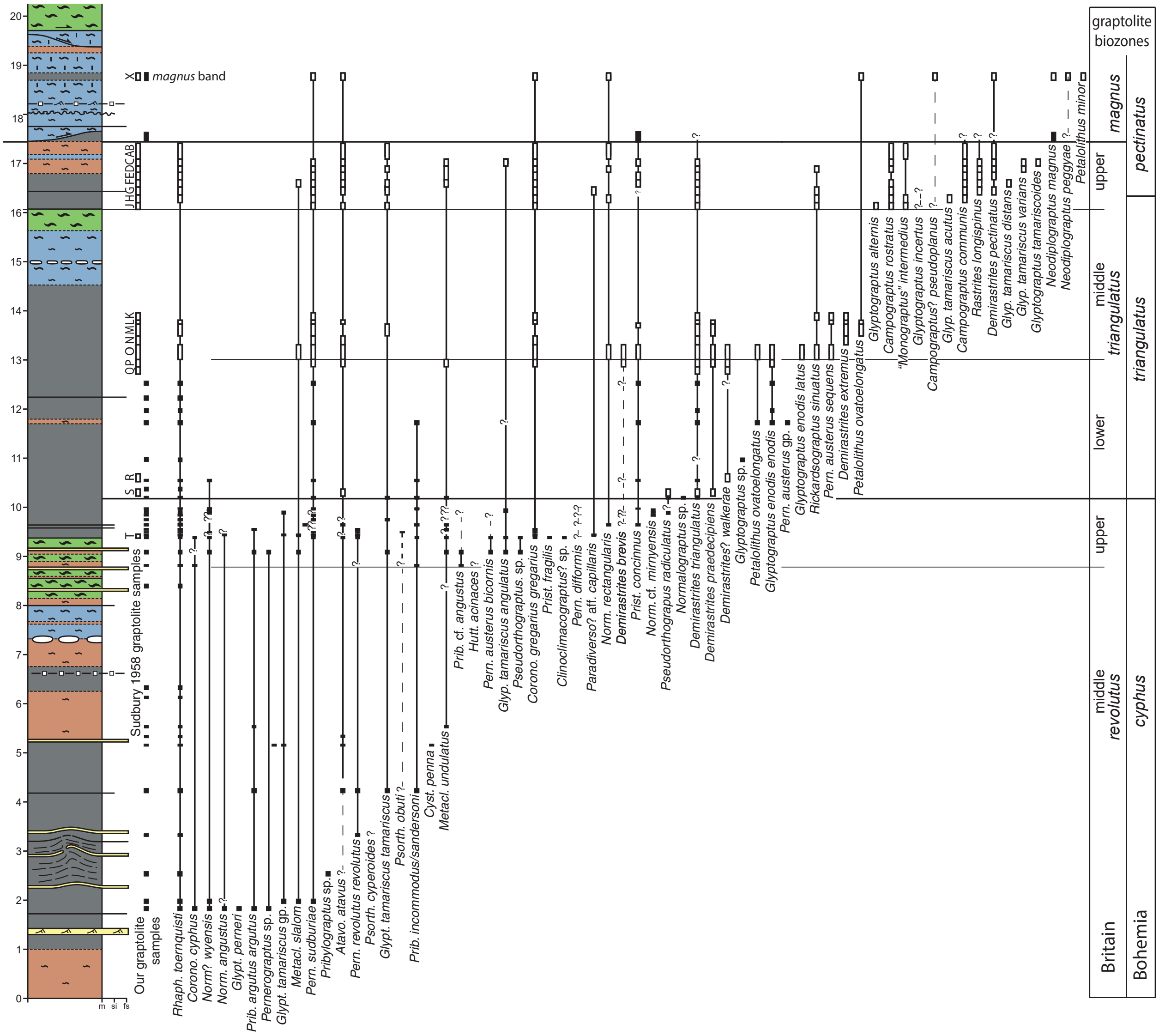

Fig. 8. Graptolite biozonation and ranges of selected graptolite taxa for the lower-mid portion of the section sampled by the authors. Black boxes – samples from this study; white boxes – samples from Sudbury (1958). The *magnus* band is as recognized by Jones (1909), Sudbury (1958) and Cullum & Loydell (2011).

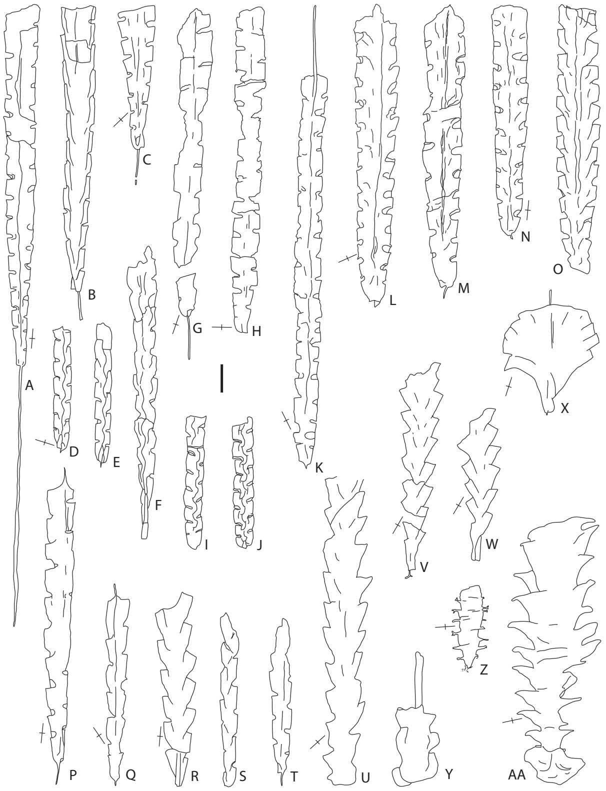

Fig. 9. Selected biserial and unibiserial graptolites from the upper Rhuddanian – lower Aeronian in the Rheidol Gorge section. A–C, *Rhaphidograptus toernquisti* (Elles & Wood, 1906). A, Zx14028, 10.52-10.57 m. B, full relief, Zx12393, 9.37-9.39 m. C, Zx12273, 4.18-4.28 m. D, E, *Metaclimacograptus slalom* Zalasiewicz, 1996. D, full relief, Zx12372, 9.17 m. E, full relief, Zx12146, 9.11-9.14 m. F, *Clinoclimacograptus*? sp., full relief, note the unusual, apparently protracted proximal end, Zx12395, 9.37-9.39 m. G, H, *Normalograptus angustus* (Perner, 1895). G, Zx12163, 1.78-1.88 m. H, Zx12476, 9.4-9.45 m. I, J, *Metaclimacograptus undulatus* (Kurck, 1882). I, full relief, Zx12125, 9.11-9.14 m. J, full relief, Zx12333, 5.53 m. K, *Normalograptus* cf. *mirnyensis* (Obut & Sobolevskaya, 1967), Zx13911, 9.87 m. L-O, *Normalograptus*? *wyensis* Zalasiewicz & Tunnicliff, 1994. L, Zx14039, 10.52-10.57 m. M, partial relief, Zx12188, 1.93-2.03 m. N, Zx13863, 9.47-9.5 m. O, partial relief, Zx12379, 9.17 m. P, Q, *Glyptograptus tamariscus tamariscus* Nicholson, 1868. P, Zx12271, 4.18-4.28 m. Q, Zx13970, 10.17-10.22 m. R, *Glyptograptus enodis enodis* Packham, 1962, Zx14108, 12.47-12.57 m. S, T, *Glyptograptus tamariscus angulatus* Packham, 1962. S, full relief, Zx12125, 9.11-9.14 m. T, Zx13934, 9.9-9.94 m. U, *Glyptograptus perneri* Štorch, 2015. V, W, *Pseudorthograptus radiculatus* (Manck, 1918). V, Zx13991, 9.82-9.87 m. W, Zx13958, 10.17-10.22 m. X, *Petalolithus ovatoelongatus* (Kurck, 1882), Zx14057, 11.67-11.77 m. Y, *Cystograptus penna* (Hopkinson, 1869), full relief, Zx12324, 5.13-5.18 m. Z, *Pseudorthograptus* sp., severely deformed, Zx12376, 9.17 m. AA, *Pseudorthograptus obuti* (Rickards & Koreň, 1974), Zx13859, 9.47-9.5 m. All specimens preserved in compressed form unless otherwise stated. Elongate cross symbols indicate direction of tectonic lineation (bedding-cleavage intersection and/or mineral lineation) on bedding surfaces, shown for those samples where it was clearly evident. Scale bar represents 1 mm.

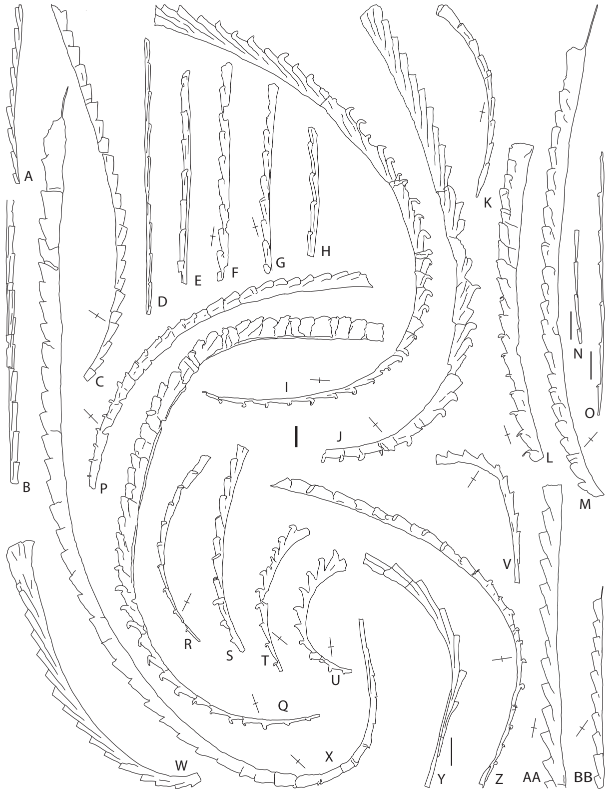

Fig. 10. Selected monograptid graptolites from the upper Rhuddanian – lower Aeronian in the Rheidol Gorge section. A, C, *Atavograptus atavus* (Jones, 1909). A, full relief, Zx12321, 5.13-5.18 m. C, partial relief, shows some brittle deformation, Zx12256, 4.18-4.28 m. B, *Huttagraptus acinaces* (Törnquist, 1899)?, full relief, Zx12113, 8.77-8.82 m. D, *Pribylograptus angustus* (Rickards, 1970), full relief, Zx12122, 8.77-8.82 m. E-H, *Pribylograptus incommodus* (Törnquist, 1899) or *Pribylograptus sandersoni* (Lapworth, 1876), due to the fragmentary and sometimes deformed nature of the specimens, it was not possible to reliably distinguish these two species. E, Zx12124, 8.77-8.82 m. F, Zx13992, 9.82-9.87 m., G, Zx12256, 4.18-4.28 m. H, full relief, Zx12430, 9.37-9.39 m. I, J, *Pernerograptus austerus bicornis* (Hutt, 1974). I, partial to full relief, some brittle deformation in the mesial region, Zx12365, 9.17 m. J, partial to full relief, some brittle deformation mesially, Zx12424, 9.37-9.39 m. K, M, *Pribylograptus argutus argutus* (Lapworth, 1876). K, Zx12253, 4.18-4.28. M, flattened to partial relief, deformed in proximal part of preserved specimen, Zx12288, 4.18-4.28 m. L, P, Q, *Pernerograptus revolutus revolutus* (Kurck, 1882). L, partial relief, deformed distally, Zx12475, 9.4-9.45 m. P, flattened to partial relief, deformed mesially, Zx12227, 3.29-3.35 m. Q, flattened to partial relief, brittle deformation mesially to distally, Zx13863, 9.47-9.5 m. N, *Pristiograptus fragilis* (Rickards, 1970), Zx12419, 9.37-9.39 m. O, *Paradiversograptus capillaris* (Carruthers, 1867)?, Zx12476, 9.40-9.45 m. R, S, Z, *Pernerograptus sudburiae* (Hutt, 1974). R, Zx14077, 1.67-11.77 m. S, flattened to partial relief, Zx12432, 9.37-9.39 m. Z, partial relief, some brittle deformation mesially, Zx12189, 1.93-2.03 m. T, U, *Pernerograptus difformis* (Törnquist, 1899)?. T, partial relief, some deformation near distal end, Zx12136, 9.11-9.14 m. U, Zx13994, 9.82-9.87 m. V, *Coronograptus gregarius gregarius* (Lapworth, 1876), Zx12475, 9.4-9.45 m. W-Y *Coronograptus cyphus* (Lapworth, 1876). W, partial relief, Zx12120, 8.77-8.82 m. X, some brittle deformation in proximal-mesial region, Zx12165, 1.78-1.88 m. Y, full relief, Zx12398, 9.37-9.39 m. AA, BB, *Pristiograptus concinnus* (Lapworth, 1876). AA, full relief, Zx14096, 12.47-12.57 m. BB, partial to full relief, Zx14061, 11.67-11.77 m. All specimens preserved in compressed form unless otherwise stated. Elongate cross symbols indicate direction of tectonic lineation (bedding-cleavage intersection and/or mineral lineation) on bedding surfaces, shown for those samples where it was clearly evident. Scale bars represent 1 mm: bold scale in the centre of the figure applies to all images except N, O, and Y.

some samples, well-preserved fauna indicative of the upper *revolutus* Biozone. This subzone is marked by the incoming of *Pernerograptus bicornis* (Hutt, 1974) (= *Monograptus austerus bicornis*) (Fig. 10I, J) and *Glyptograptus tamariscus angulatus* Packham, 1962 (Fig. 9S, T). Taxa that first appear in our collections in this interval and extend into the overlying *triangulatus* Biozone include *Coronograptus gregarius gregarius* (Lapworth, 1876) (Fig. 10V), *Pristiograptus concinnus* (Lapworth, 1876) (Fig. 10AA, BB), and *Pseudorthograptus radiculatus* (Manck, 1918) (recently shown to be a senior synonym of *P. finneyi* by Maletz *et al.* 2021) (Fig. 9V, W). The last species is characteristic of the Rhuddanian-Aeronian boundary interval in the Prague Basin (Štorch 2015; Štorch *et al.* 2018) and this is the first report of this species in the UK. In addition, fragmentary specimens that we questionably identify as *Demirastrites*? *brevis* (Sudbury, 1958) (= *Monograptus toernquisti brevis*) (Fig. 11J-L) 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, changing to strongly triangulate thecae mesially and distally, may represent a transitional form between pernerograptids with elongate to triangulate proximal-mesial thecae, and species of *Demirastrites*, which have rastritid thecae proximally and triangulate thecae mesially and distally.

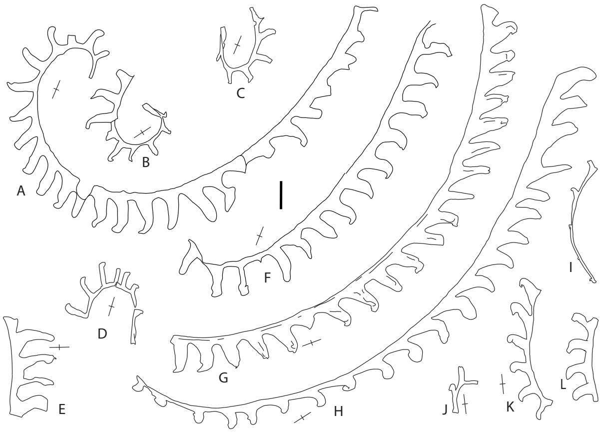

Fig. 11. Selected specimens of *Demirastrites* and *Demirastrites*? from the uppermost Rhuddanian – lower Aeronian in the Rheidol Gorge section. A–G, *Demirastrites triangulatus* (Harkness, 1851). A, specimen collected by Sudbury (1958), identified as *Monograptus triangulatus separatus*, flattened to partial relief, SM A24849, Sudbury's Horizon S (approx. 10.25–10.45 m). B, partial relief, minor brittle deformation, Zx14016, 10.17-10.22 m. C, partial relief, Zx13970, 10.17-10.22 m. D, partial relief, some brittle deformation mesially, Zx14056, 11.67-11.77 m. E, Zx14039, 10.52-10.57 m. F, partial relief, Zx13976, 10.17-10.22 m. G, partial relief, Zx14071, 11.67-11.77 m. H, I, *Demirastrites*? *walkerae* (Rickards, Hutt & Berry, 1977), all partial relief, Zx14105a, b, 12.47-12.57 m. J-L, *Demirastrites*? *brevis* (Sudbury, 1958). J, partial relief, Zx14004a, 9.82-9.87 m. K, partial relief, Zx14004b, 9.82-9.87 m. L, partial relief, Zx13983, 9.67 m. Elongate cross symbols indicate direction of tectonic lineation (bedding-cleavage intersection and/or mineral lineation) on bedding surfaces, shown for those samples where it was clearly evident. Scale bar represents 1 mm.

Demirastrites triangulatus *Biozone*.– Our lowest sample containing *D. triangulatus* (Harkness, 1851) occurs at the 10.17 m level, 0.8 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* (which she assigned to *Monograptus separatus separatus*, see Figure 11A, and has more recently been referred to as *Demirastrites triangulatus separatus*, e.g. Zalasiewicz *et al.* 2009). The data presented by Sudbury, and our re-examination of some of her material, has showed that *D. t. separatus* and *D. t. triangulatus* co-occur in many samples and are also intergradational in form. We therefore follow Štorch & Melchin (2018) and do not regard these two subspecies as distinct taxa. More quantitative morphometric work is required on this species group, particularly forms identified as *D. triangulatus* from China, Siberia, and northern North America (see Štorch & Melchin 2018).

Sudbury's (1958) data also indicate that two other triangulate monograptid species, *Demirastrites praedecipiens* (Sudbury, 1958) and *'Monograptus' walkerae* Rickards, Hutt & Berry, 1977 (named *Monograptus toernquisti toernquisti* by Sudbury), also occur in the lower part of the *triangulatus* Biozone. Although we have not found *D. praedecipiens* in our collections, we have found specimens questionably identifiable as *D.*? *walkerae* (Fig. 11H, I). We have also found the first occurrence of *Petalolithus ovatoelongatus* (Kurck, 1882) (Fig, 9X) and *Glyptograptus enodis enodis* Packham, 1962 (Fig. 9R) in the lower *triangulatus* Biozone.

Based on the data presented by Sudbury (1958), the base of the middle *triangulatus* Biozone of Zalasiewicz *et al.* (2009) can be recognized at the 13.0 m level by the appearance of *Pernerograptus sequens* (Hutt, 1974). *Glyptograptus enodis latus* Packham, 1962 and *Rickardsograptus sinuatus* (Nicholson, 1869) also make their first appearance at this level. *Demirastrites extremus* (Sudbury, 1958) first occurs higher within this subzone.

Of the species considered to be indicative of the upper *triangulatus* Biozone in Britain (Zalasiewicz *et al.* 2009), *Campograptus rostratus* (Elles & Wood, 1913), *Campograptus communis* (Lapworth, 1876), *Glyptograptus acutus* Packham, 1962, *Rastrites* *longispinus* Perner, 1897, *Demirastrites pectinatus* (Richter, 1853), and *Glyptograptus tamariscoides* (Packham, 1962) all occur in the Rheidol Gorge (Sudbury, 1958). Therefore, we mark the base of the upper *triangulatus* Biozone at the 16.1 m level, with the first appearance of the lowest-occurring of these species, *C. rostratus*. Of particular importance for international correlation is that *Demirastrites pectinatus* first appears 30 cm higher (see further discussion below).

Neodiplograptus magnus Biozone.– The interval identified by Sudbury (1958) as representing the *magnus* Biozone (her horizon X) occurs at a level of approximately 18.7–18.9 m in our measured section. This is also the interval that provided the specimens of *Neodiplograptus magnus* and *N. peggyae* described by Cullum & Loydell (1996). During our sampling we discovered another level of black shales below this, at 17.45–17.65 m, which is laterally terminated by a fault/slide plane and is not exposed on the bank of the river. This interval has also yielded specimens of *Neodiplograptus magnus*. Full documentation of this fauna is planned as a future study.

Chitinozoan Biostratigraphy

Chitinozoans are increasingly considered useful stratigraphical tools in the historic Ordovician (e.g. Vandenbroucke 2008) and Silurian (e.g. Steeman *et al.* 2016) successions of the Welsh basin. The chitinozoan biostratigraphy of the upper Rhuddanian-lower Aeronian interval of the Rheidol Gorge section was fully documented by De Weirdt *et al.* (2019). The 28 samples that were collected as part of that study were integrated with the lithological and graptolite biostratigraphical data documented here. The 28 samples yielded more than 2300 chitinozoan specimens assigned to 16 different taxa, 12 of which were left in open nomenclature (Figs 12, 13). The occurrences of *Spinachitina maennili* (Nestor, 1980a) and *Conochitina iklaensis* Nestor, 1980a through most of the interval studied indicate that the whole succession, from the mid-*revolutus* to the upper *triangulatus* graptolite biozones, can be assigned to the *S. maennili* Chitinozoan Biozone. The short stratigraphical range of *Conochitina electa* Nestor, 1980b in the lower half of the *S. maennili* Biozone, within the *revolutus* graptolite Biozone of the Rheidol Gorge section, is a signature that was previously recognized in other sections (e.g. the East Baltic, Loydell et al. 2003, 2010). The *S. maennili* Biozone has been widely recognized in Rhuddanian-Aeronian boundary successions in other parts of the world, and has been considered a globally recognizable biostratigraphical interval (e.g. Verniers *et al.* 1995; Melchin *et al.* 2020).

Carbon Isotope Chemostratigraphy

The results of our carbon isotope analyses are shown in Figure 14. Although these data do show the trend of slightly increasing $\delta^{13}C_{org}$ values through the Rhuddanian-Aeronian boundary interval, identified as the Early Aeronian Carbon Isotope Excursion (EACIE) in some other regions (e.g. Štorch *et al.* 2018; Hammarlund et al. 2019; Melchin *et al.* 2020; Braun et al. 2021), the overall pattern of variation is dominated by relatively strong fluctuations between samples and also relatively heavy values in the bioturbated mudstone-dominated intervals between 5.3 m and 9.37 m and a sharp drop to more strongly negative values at the level of the 'prominent bedding plane', 0.8 m below the base of the Aeronian. Although some other sections show a slight drop in $\delta^{13}C_{org}$ values just below the onset of the EACIE (see Hammarlund et al. 2019, fig. 4), the magnitude of that negative shift is 0.5‰ or less in those other sections, whereas the negative shift in the uppermost Rhuddanian at Rheidol Gorge is greater than 2‰, occurring at the level of a pronounced facies change. A pattern of strongly fluctuating $\delta^{13}C_{org}$ values, with generally higher values in oxic mudstones and lower in black shales, was observed in other studies of Upper Ordovician and lower Silurian Welsh Basin strata (Challands *et al.* 2009; Snelling *et al.* 2011). In both cases, the patterns of variation were interpreted to be the result of local to regional carbon cycling processes rather than a global signal and that may also be the explanation for the patterns seen in the Rheidol Gorge section.

Global correlation

As noted above, all of the graptolite biozones and subzones of the upper Rhuddanian and lower Aeronian recognizable in Britain as a whole (Zalasiewicz *et al.* 2009) can be readily distinguished in the Rheidol Gorge section, and this biozonation is easily correlated with the more generalized global graptolite biozonation of Melchin *et al.* (2020). Among the other regions of the world the most refined and precise graptolite biozonation through this interval was recently described by Štorch *et al.* (2018) from the Hlásná Třebaň section in the Prague Synform, Bohemia. The Rheidol Gorge succession shares many key taxa with the Bohemian succession through the boundary interval that help constrain correlation between these regions. Most important is the first appearance datum

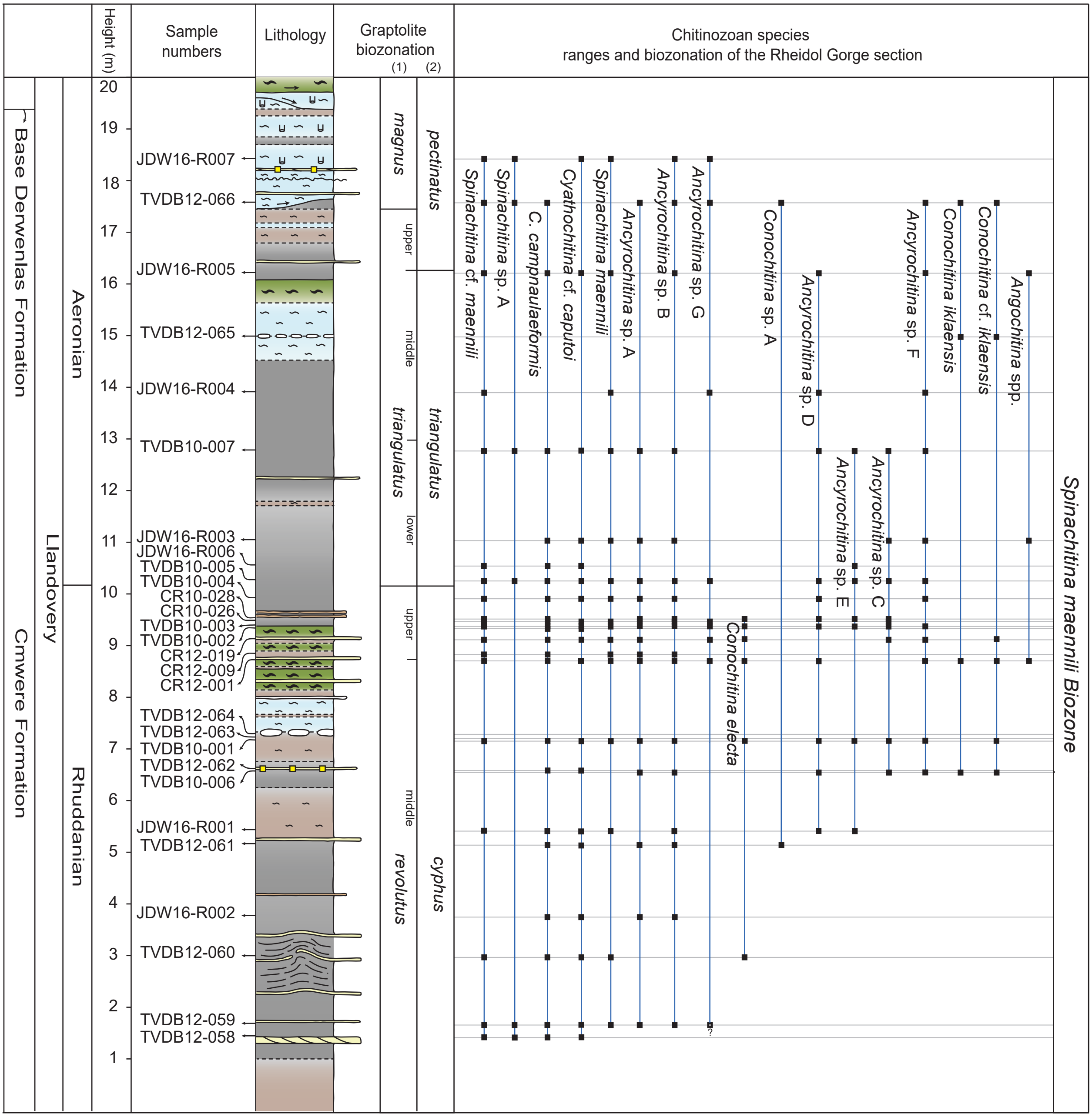

Fig. 12. Range chart of chitinozoan taxa encountered in this study, adapted from De Weirdt *et al.* (2019). For lithological symbols see Figure 4. Note that the level of the base of the Derwenlas Formation is as defined by Davies et al. (1997).

(FAD) of *Demirastrites triangulatus*. However, several other taxon range ends, including the last appearance of *Coronograptus cyphus* and first appearances of *Pseudorthograptus radiculatus* and *Pristiograptus concinnus* just below the FAD of *D. triangulatus*, and the FADs of *Demirastrites*? *walkerae* and *Petalolithus ovatoelongatus* just above, demonstrate the confidence with which the biozonal boundary can be correlated precisely between these two sections. In contrast with the Bohemian succession, the FADs of species of *Rastrites* and *Campograptus* occur relatively higher in the Rheidol Gorge succession, based on our presently available data.

Štorch *et al.* (2018) extensively discussed the correlation of the Prague Synform succession through this interval with those known from other parts of the world. Given the biostratigraphical similarities of the Rheidol Gorge and Prague Synform successions, we

Fig. 13. Images of selected chitinozoan taxa. 1, *Spinachitina maennili* (Nestor, 1980a), 2338_001; sample TVDB12-001; *revolutus* graptolite Biozone. 2, *Spinachitina maennili* (Nestor, 1980a), 2338_060; sample TVDB12-001; *revolutus* graptolite Biozone. 3, *Spinachitina maennili* (Nestor, 1980a), 2338_015; detail showing the nature of the basal processes; sample TVDB12-001; *revolutus* graptolite Biozone. 4, *Spinachitina* cf. *maennili* (Nestor 1980a), TVDB10-007_027; sample TVDB10-007; *triangulatus* graptolite Biozone. 5, *Spinachitina* sp. A., TVB12-066_089; sample TVB12-066; *magnus* graptolite Biozone. 6, *Ancyrochitina* sp. A., TVDB12-061_34; sample TVDB12-061; *revolutus* graptolite Biozone. 7, *Ancyrochitina* sp. B., TVDB12-059_041; sample TVDB12-059; *revolutus* graptolite Biozone. 8, *Ancyrochitina* sp. C. CR10-019_024; sample CR10-019; *revolutus* graptolite Biozone. 9, *Ancyrochitina* sp. D., TVDB10-006_027; sample TVDB10-006; *revolutus* graptolite Biozone. 10, *Ancyrochitina* sp. E., CR10-028_154; sample CR10-028_154; *revolutus* graptolite Biozone. 11, *Ancyrochitina* sp. F., TVD10-001_326; sample TVD10-001; *revolutus* graptolite Biozone. 12, *Ancyrochitina* sp. G., CR10-001_013; sample CR10-001; *revolutus* graptolite Biozone. 13, *Cyathochitina* cf. *caputoi* Da Costa, 1971, CR10-026_028; sample CR10-026; *revolutus* graptolite Biozone. 14, *Cyathochitina campanulaeformis* (Eisenack, 1931), TVDB12-061_004; sample TVDB12-061; *revolutus* graptolite Biozone. 15, *Conochitina iklaensis* Nestor, 1980a. TVDB12-066_015; sample TVDB12-066; *magnus* graptolite Biozone. 16, *Conochitina electa* Nestor, 1980b, CR10-019_012; sample CR10-019; *revolutus* graptolite Biozone. Scale bar represents 50 μm for all figures, unless indicated otherwise.

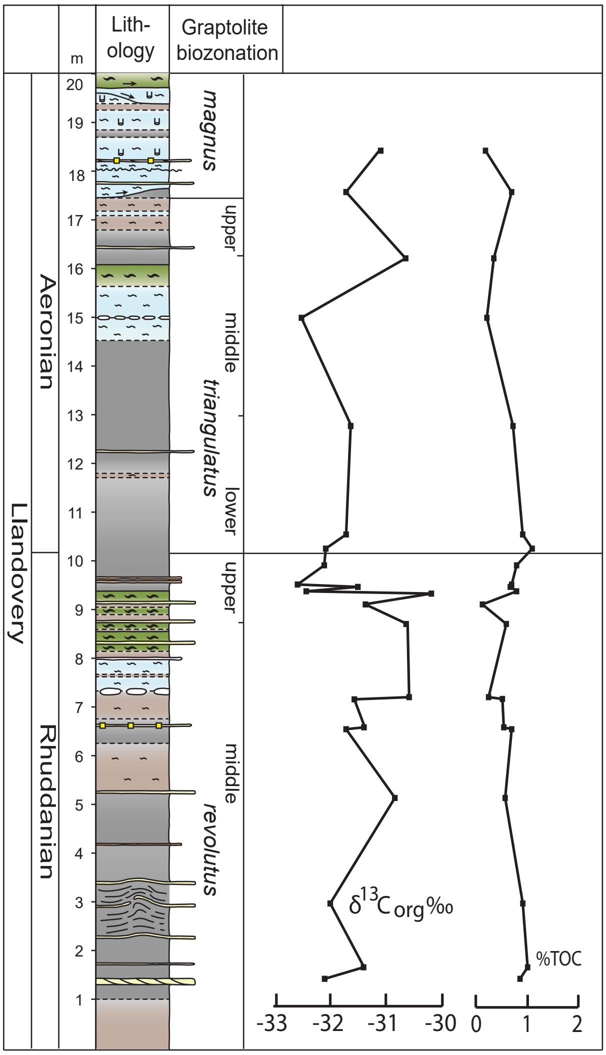

Fig. 14. Results of analysis of carbon isotopes from whole-rock organic matter $\delta^{13}C_{org}$ and percent total organic carbon (%TOC). For lithological symbols see Figure 4.

feel it is not necessary to repeat this whole discussion here. In summary, the first appearance of *Demirastrites triangulatus* (or very closely similar forms that require taxonomic restudy) and its first occurrence relative to the FADs of other taxa, including *Pristiograptus concinnus* and the genera *Rastrites* and *Petalolithus*, together with the last appearance of *Coronograptus cyphus*, appear to show consistent patterns in many parts of the world, including north Africa and Saudi Arabia, northeastern Europe (including Baltica), and parts of Siberia (Štorch *et al*. 2018). Recent data from Arctic Canada (Melchin *et al*. 2017a) show that *D. triangulatus* can be used to define a biostratigraphical interval defined by this taxon, and Melchin (in Strauss *et al*. 2020) recognized the base of this biozone in northern Yukon by the first appearance of the genus *Demirastrites*. Štorch *et al*. (2018) also noted that the base of the *D. triangulatus* Biozone in several regions of Siberia can be recognized by the first appearance of species of *Demirastrites*, petalolithids, and rastritids. The biostratigraphical work on this interval in China has a long and complex history, reviewed by Štorch *et al*. (2018). However, the most recent work by Maletz *et al*. (2021) from a section in the Shennongjia region of the Hubei Province shows a well-defined base of the *D. triangulatus* Biozone marked by the coincident first appearances of *D. triangulatus*, *P. concinnus*, and species of *Petalolithus* and *Rastrites*. The fact that all of these taxa first appear at the same level suggests the presence of a short hiatus or condensed section at this level in the Shennongjia section, but that the pattern is otherwise generally consistent with those seen in other parts of the world, including Wales and Bohemia. Štorch *et al*. (2018) also emphasized the fact that the successions and faunas in many other parts of the world are in need of much more detailed biostratigraphical and systematic work to confirm the details of their species distributions. As a result of these considerations, it can be concluded that the graptolite succession at Rheidol Gorge provides a detailed and precise set of graptolite biostratigraphical data that is useful for high-resolution global correlation of graptolitic sections in this interval within the constraints of the resolution of the biostratigraphical data available in several other parts of the world.

Correlation of the base of the Aeronian with this section, or any well-documented section based on graptolite biostratigraphy, outside of the deep-water graptolitic facies, is hampered by the lack of information about the precise biostratigraphical relationship between the graptolite biozonation and the biozonations based on chitinozoan and conodont taxa that commonly occur in more shallow-water facies. Our data demonstrate, as was also shown by Melchin *et al*. (2020), that the *maennili* Chitinozoan Biozone spans much of the upper Rhuddanian *revolutus* Graptolite Biozone, well into the lower Aeronian. Likewise, the *Pseudobelodina expansa* Conodont Biozone spans a similar interval and the correlation of its lower and upper boundaries with the graptolite biozonation is not well constrained (Loydell *et al*. 2003; Melchin *et al*. 2020). On the other hand many sections that are rich in conodonts and shelly fossils, such as those on Anticosti Island, have only very sparse graptolite data (or none) through this interval (e.g. Riva & Petryk 1981). A notable exception is the study of the Aizpute-41 core in Latvia by Loydell *et al*. (2003), which documented well-preserved and rich graptolite, conodont and chitinozoan faunas.

The problem of the cross-facies correlation of the base of the Aeronian may be aided by data from stable carbon isotope chemostratigraphy. Melchin & Holmden (2006) showed that there was a weak positive shift in both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ values at or near the level of the base of the Aeronian in Arctic Canada with the potential for global correlative significance. Several more recent studies have shown that the time of onset of this weak positive excursion in $\delta^{13}C_{org}$ values correlates very closely with the base of the *D. triangulatus* Biozone (e.g. Frýda & Štorch 2014; Štorch *et al*. 2018; Hammarlund et al. 2019), and Braun *et al*. (2021) showed that it can now be recognized to occur in both the $\delta^{13}C_{org}$ and $\delta^{13}C_{carb}$ records in at least 12 sections worldwide, although in many instances the timing of the positive shift is not precisely constrained. Unfortunately, the Rheidol Gorge $\delta^{13}C_{org}$ data suggest that its pattern of carbon isotope change is controlled primarily by local or regional factors, limiting the potential use of carbon isotope data from Rheidol Gorge for global correlation. Nevertheless, the global event of weak positive shift at or near the base of the Aeronian may be evident in our section and the very precise graptolite correlation of the base of the Aeronian at Rheidol Gorge with the Hlásná Třebaň section indicates that the base of the Aeronian, as proposed here, correlates very closely with the time of onset of the weak positive $\delta^{13}C$ excursion (the EACIE) as recognized elsewhere.

Level of the proposed Global Stratotype Section and Point

One of the key objectives of this study was to provide documentation of the Rheidol Gorge section as a possible candidate for a new Global Stratotype Section and Point (GSSP) for the base of the Aeronian Stage. For consideration of a section as a GSSP, it should, ideally, possess the following attributes (Remane *et al*. 1996):

1. Exposure over an adequate thickness;
2. Continuous sedimentation;
3. Adequate rate of sedimentation to distinguish successive events;
4. Absence of synsedimentary and tectonic disturbances;
5. Absence of metamorphism and strong diagenetic alteration;
6. Abundance and diversity of well-preserved fossils;
7. Absence of vertical facies changes at or near the boundary;
8. Favourable facies for long-range biostratigraphical correlation.

In addition, other potential favourable characteristics may include:

9. Potential for radioisotopic dating;

10. Potential for magnetostratigraphical study;
11. Potential for chemostratigraphical study;
12. Knowledge of regional palaeogeographical context, facies relationships, and sequence stratigraphical framework;
13. Relatively easy, international accessibility and potential for permanent protection.

More recent studies have further highlighted the importance of non-biostratigraphical criteria and also the potential for use of quantitative stratigraphical correlation methods in the process of GSSP selection (e.g. Smith *et al.* 2014; Melchin *et al.* 2017b).

Our data show that the Rheidol Gorge section spans an approximately 20 m interval, with no evidence of a break in sedimentation, which spans two graptolite subzones below the proposed GSSP and two biozones (one with three subzones) above. Thus, there is adequate thickness to clearly discern a highly resolved biostratigraphy, even in the portions of the *revolutus* Biozone where graptolite-bearing strata are not continuously present. The section is offset by only very minor faults and potential slide surfaces that are readily recognizable and can be accounted for in documentation of the full section. The interval in the immediate vicinity of the proposed GSSP level is tectonically undisturbed. Likewise, the relatively low level of metamorphism has not been sufficient to obscure either the fine depositional features necessary to reconstruct the sedimentology, or to render a significant proportion of the graptolites and chitinozoans unidentifiable, despite some deformation. Graptolites are abundant at many levels, particularly in the interval spanning the level of the proposed GSSP and in the overlying strata. The underlying strata have sufficiently diverse faunas for well-resolved biostratigraphical subdivision. Although there are facies changes between anoxic and variably oxic intervals, as noted above, these variations have not prevented recognition of a well-resolved graptolite biostratigraphy, especially in the GSSP interval. All of the standard British upper Rhuddanian and lower Aeronian graptolite biozones and subzones are recognizable, and these biozones can be correlated internationally with high resolution (e.g. Loydell 2012). The same is true for the chitinozoan biostratigraphy.

No readily isotopically datable ash beds were found in the study section. However, the black shale units do have potential for Re-Os dating. The level of metamorphism suggests that the strata may have been too heated to resolve a primary magnetostratigraphical record. The most recently published data suggests that all or most of the *revolutus* Biozone and all of the early-mid-Aeronian occur within an interval of reversed polarity (Hounslow *et al.* 2021).

Although the weak interval of positive shift in $\delta^{13}C_{org}$ values seen globally may be discernible in our section, the overall pattern of strongly fluctuating carbon isotope values suggests that the dominance of local or regional processes largely overprints any global signal.

As described above, the geological, stratigraphical and palaeoenvironmental context of the Rheidol Gorge section is particularly well understood. The sequence stratigraphy and facies relationships within the Welsh Basin have been recently very thoroughly documented by Davies *et al.* (1997, 2011, 2013, 2016). In addition, this succession has considerable historical significance, both in its own right as a key reference section for early Aeronian graptolite biostratigraphy, and in its palaeographical relationship with the classic successions of the Llandovery region, including the current GSSP for the Aeronian Stage.

The Rheidol Gorge section is easy to access by foot from the the A44 road in the village of Ponterwyd. The site forms part of the Coed Rheidol National Nature Reserve and is already designated a Site of Special Scientific Interest (SSSI). As such, it is protected by law from any form of habitat-damaging future development. In addition, the flow in the Afon Rheidol is regulated, and the site protected from extensive flood damage, by the up-river dam to the Nant-y-moch Reservoir.

We propose that the GSSP for the Base of the Aeronian Stage should be in the Rheidol Gorge section, as documented herein, 10.17 m above the base of our measured section, which is marked by the first appearance of *Demirastrites triangulatus*, 0.8 m above the level of the prominent bedding surface, as shown in Figures 4 and 15.

Conclusions

The Rheidol Gorge river section has been re-logged and resampled in a study to establish its credentials as a replacement GSSP for the Aeronian Stage of the Llandovery Series. The sedimentology and biostratigraphy of the section have been thoroughly investigated and the first carbon isotope analysis of the succession undertaken. Well-preserved graptolites enable the recognition of the *revolutus, triangulatus* and *magnus* graptolite biozones and several subzones. Chitinozoa of the *S. maennili* Biozone are present throughout the section. The findings of the carbon isotope work suggest that although a weak interval of positive shift in $\delta^{13}C_{org}$ values through the Rhuddanian-Aeronian

Fig. 15. A. General view of the Rheidol Gorge as approached from the north-west from Bryn-brâs Farm (arrow shows the relative down river location of the proposed base Aeronian Stage GSSP, c. 50 m-high cliff on right is in Derwenlas Formation); B. host section for proposed new base Aeronian Stage GSSP (arrowed) taken at the first appearance of *Demirastrites triangulatus* Biozone graptolites within the local Cwmere Formation, located 0.8 m above the prominent bedding surface (left end of hammer) at 9.37 on the measured section (Fig. 4) that marks the contact between oxic (below) and anoxic (above) mudstone facies within the upper *Pernerograptus revolutus* Biozone (see Figs 2B, 8 and text); C. close-up of proposed base Aeronian Stage GSSP level (arrowed), 15.5 cm pencil is aligned parallel to bedding (head of hammer in same position as in B).

boundary interval seen globally may be discernible in our section, the overall pattern of strongly fluctuating carbon isotope values suggests that a dominance of local or regional processes largely overprints any global signal. The stage-defining, base *triangulatus* Biozone level has been identified precisely within an interval of continuously fossiliferous and structurally intact strata, marked by the first appearance of *Demirastrites triangulatus*. The well-exposed section is easily accessed and is located in a protected nature reserve within the historical type region. Hence, it meets the criteria required of a GSSP and is a strong candidate for selection as the new base Aeronian Stage type locality.

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