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Fry, Charlotte; Wheeley, James; Boomer, Ian; Ray, David

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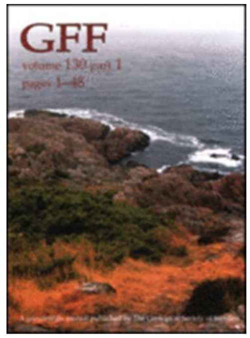

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Complete List of Authors:	Fry, Charlotte; University of Birmingham, School of Geography, Earth & Environmental Sciences Ray, David; University of Birmingham, School of Geography, Earth & Environmental Sciences Wheeley, James; University of Birmingham, School of Geography, Earth & Environmental Sciences Boomer, Ian; University of Birmingham, School of Geography, Earth & Environmental Sciences Jarochowska, Emilia; Universität Erlangen-Nürnberg, GeoZentrum Nordbayern, Fachgruppe Paläoumwelt Loydell, David; University of Portsmouth, School of Earth and Environmental Sciences
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The Homerian carbon isotope excursion (Silurian) within graptolitic successions on the Midland Platform (Avalonia), UK: implications for regional and global comparisons and correlations

Charlotte R. Fry[a], David C. Ray[a*], James R. Wheeley[a], Ian Boomer[a], Emilia Jarochowska[b] and David K. Loydell[c]
[*]Corresponding author: daveray01@yahoo.com

[a]School of Geography, Earth & Environmental Sciences, University of Birmingham, Edgbaston, B15 2TT, United Kingdom

[b]GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstr. 28, 91054 Erlangen, Germany

[c]School of Earth and Environmental Sciences, University of Portsmouth, Burnaby Road, Portsmouth, PO1 3QL, United Kingdom

Abstract: New $\delta^{13}C_{carb}$ data from the most stratigraphically extensive graptolitic sections of Homerian age in the study area are reported from Wenlock Edge and the Ludlow Anticline (UK). These sections, situated upon the Midland Platform (Avalonia), were key in establishing the Homerian graptolite biozonation used within the type Wenlock Series, and are consequently of international importance. Based upon 162 $\delta^{13}C_{carb}$ samples from four outcrops (Eaton Track, Longville-Stanway Road Cutting, Burrington Section and Mortimer Forest Stop 1), new graptolite collections and a re-evaluation of the original graptolite collections, the onset of both lower (older) and upper (younger) peaks of the Homerian Carbon Isotope Excursion have been calibrated to a revised graptolite biozonation (*lundgreni - nassa - praedeubeli-deubeli - ludensis* biozones). In addition, high resolution correlation between the Ludlow Anticline and Wenlock Edge has been achieved by bio-, chemo- and sequence stratigraphic techniques. These correlations suggest a uniformity of depositional rates across the study area and indicate minor diachroneity at the base of the Much Wenlock Limestone Formation. Finally, correlations of the Midland Platform Homerian Carbon Isotope Excursion have allowed for better comparisons with other sections from which high-resolution graptolite and carbon isotope data are available. Such comparisons highlight the pan-regional synchronicity of the Homerian Carbon Isotope Excursion.

Key Words: Avalonia, Homerian carbon isotope excursion, Midland Platform, revised graptolite biozonation, Silurian.

Introduction

The Silurian is characterized by a highly dynamic, glacially mediated climate, associated with strong eustatic sea-level fluctuations, marine biodiversity crises and carbon isotope excursions (Loydell 2007; Calner 2008; Munnecke et al. 2010; Melchin et al. 2012). There are five prominent Silurian carbon isotope excursions that are well studied and widely recognised (the sedgwickii Zone excursion of Štorch & Frýda 2012; and the Ireviken, Mulde, Lau and Klonk carbon isotope excursions of

Cramer et al. 2011; Saltzman & Thomas 2012). The "Mulde" or Homerian carbon isotope excursion (CIE) occurs within the Homerian Stage of the Wenlock Series (Silurian) and is a double-peaked positive CIE. The Homerian CIE has been recognised from a range of marine depositional settings and from multiple palaeogeographic regions including Avalonia, Baltica, Laurentia and peri-Gondwana (Corfield et al. 1992; Porębska et al. 2004; Noble et al. 2005; Cramer et al. 2006; Calner 2012; Frýda & Frýdová 2014). The lower (older) peak of the Homerian CIE is associated with marked extinction events ("Big Crisis" or *lundgreni* event impacting graptolites; and the preceding Mulde Event impacting conodonts) and is well biostratigraphically constrained by graptolite and conodont occurrences (Cramer et al. 2012). Above, the upper (younger) peak is less well age constrained, but appears to occupy much of the remainder of the Homerian and ends close to the Homerian-Gorstian (Wenlock-Ludlow) boundary (Blain et al. 2016).

In spite of the Homerian CIE being among the better age constrained of the Silurian carbon isotope excursions, it has not been fully documented within the key graptolitic successions of the Midland Platform of England. Furthermore, the Homerian of the Midland Platform is of global significance because it was instrumental in the establishment of the Wenlock Series (Murchison 1872; Holland et al. 1963; Holland et al. 1969; Bassett et al. 1975; Bassett 1989; Lawson & White, 1989; Aldridge et al. 2000; Davies et al. 2011) and contains the Global boundary Stratotype Sections and Points (GSSPs) (Melchin et al. 2012). The aim of this article is to document the presence of the Homerian CIE within the most stratigraphically extensive graptolitic sections of the Midland Platform, which are developed along Wenlock Edge (Shropshire) and within the Ludlow Anticline (Shropshire and Herefordshire). This documentation allows for a comparison of the Homerian CIE with a revised graptolite biozonation recognised within the type Wenlock succession, as well as with other graptolite-constrained carbon isotopic records upon other palaeocontinents.

Regional lithostratigraphy and biostratigraphy

The Homerian Stage as developed along Wenlock Edge and the Ludlow Anticline consists of the Coalbrookdale and Much Wenlock Limestone formations. Broadly these formations show an upward shallowing from shales and nodular limestones of the Coalbrookdale Formation, to the skeletal limestones of the Much Wenlock Limestone Formation; representing shallowing from Benthic Assemblage 5 to outer Benthic Assemblage 1 (Brett et al. 1993), within the north-eastern part of Wenlock Edge (Ray & Butcher 2010). Variations in relative water-depth are also observable laterally along the outcrop belt, with the north-eastern part of Wenlock Edge being relatively shallower than the south-western part of Wenlock Edge and the Ludlow Anticline. This variation in relative water-depth is most obvious in the Much Wenlock Limestone Formation along Wenlock Edge. Here the formation may be divided into reef and off-reef tracts, based upon the presence or absence of coral-stromatoporoid reefs (Bassett 1989; Ray et al. 2010). Of particular significance is the restriction of graptolites within the Much Wenlock Limestone Formation to the relatively deeper-waters of the off-reef tract (Figure 1). Similarly the Coalbrookdale Formation appears more graptolitic within the south-western part of the outcrop-belt, indicating a deepening of the platform towards its margin with the Welsh Basin in the west.

FIGURE 1 HEREABOUTS

Figure 1. An outcrop map of the Much Wenlock Limestone Formation (thick black band) and Coalbrookdale (CF) Formation showing the location of key sections and facies belts along Wenlock Edge and the Ludlow Anticline. BEQ, Benthall Edge Quarry (SJ 664 034); LQS, Lea South Quarry (SO 594 982); MF, Mortimer Forest stops 1 to 3 (SO 471 730 to SO 472 730); GR, Goggin Road (SO 472 719).

The Eaton Track (SO 5016 8999), Longville-Stanway Road Cutting (SO 5397 9270) and Burrington Section (SO 4439 7241 to SO 4417 7257) are of importance as a result of them being stratigraphically extensive, containing important lithostratigraphic boundaries and key graptolite occurrences (Figures 1 and 2); features instrumental in the establishment of the upper Wenlock Series (Homerian). In particular, the graptolite occurrences documented in Holland et al. (1969) and Bassett et al. (1975) originally allowed for the classic tripartite graptolite subdivision of the Homerian into the *lundgreni*, *nassa* and *ludensis* biozones (Bassett 1989; Zalasiewicz et al. 2009) and now, based upon a reassessment of the same graptolites, enable a revised subdivision into the *lundgreni*, *nassa*, *praedeubeli-deubeli* and *ludensis* biozones. Such features make these sections ideal for the identification and biostratigraphic calibration of the Homerian CIE within the type Wenlock area, and allow for comparison with other successions across Avalonia and beyond.

FIGURE 2 HEREABOUTS

Figure 2. Location maps for Eaton Track (A), the Longville-Stanway Road Cutting (B) and Burrington Section (C) identifying key geologic features, carbon isotopic sampling intervals (thick grey line) and the biostratigraphy locations (Loc.) from Holland et al. (1963) and Bassett et al. (1975). TP46 and TP47 correspond to numbered telegraph poles at the Burrington Section.

A reassessment of the middle to upper Homerian graptolite biozonation

The middle to upper Homerian graptolites of the Ludlow district were described and illustrated by Holland et al. (1969), whilst those of the type Wenlock area (which includes the Eaton track and Longville-Stanway road sections discussed herein) were listed in Bassett et al. (1975). At the time of these publications there was a tripartite graptolite biozonal division of the Homerian, with the *Cyrtograptus lundgreni* Biozone succeeded by the *Gothograptus nassa* Biozone and this in turn by the *Colonograptus ludensis* Biozone. Subsequently, Jaeger (in Barca & Jaeger 1990) erected a new species *Colonograptus praedeubeli,* which can be distinguished from *C. ludensis* by its lesser dorso-ventral width and generally longer sicula. The first appearance of *C. praedeubeli* precedes that of *C. ludensis* and, as a result, the upper Homerian (post-*nassa* Biozone) is now routinely divided into a lower *praedeubeli-deubeli* Biozone overlain by the *ludensis* Biozone (Loydell 2012).

For the present work additional graptolite material has been collected from the Burrington area and the figures in Holland et al. (1969) re-assessed. In addition, the Wenlock Edge specimens of Bassett et al. (1975), housed in the Sedgwick Museum of Earth Sciences, Cambridge, have been re-examined.

Gothograptus nassa was recorded from a surprisingly low stratigraphical level (within the Apedale Member of the Coalbrookdale Formation) from the Eaton track section by Bassett et al. (1975). The specimens concerned are small fragments, lacking the dense reticulum and apertural hoods characteristic of *G. nassa*. They are indeterminable, but presumably belong instead to one of the numerous retiolitid species recorded from the *lundgreni* Biozone. *Gothograptus nassa* is present in the section (Figure 3A), however, from Location 25, close to the base of the Farley Member (Coalbrookdale Formation) at the highest level to yield graptolites from this section.

Bassett et al. (1975) recorded *Colonograptus ludensis* (and cf. *ludensis*) from four localities along the Longville-Stanway road cutting, one high in the Farley Member, the other three within the Much Wenlock Limestone Formation. *C. ludensis* is not, however, present in the collections, with the identifiable specimens being *C. praedeubeli* (Figure 3B, D). This is accompanied by *C. deubeli* (Figure 3C) in the lower two collections. These four collections can be assigned to the *praedeubeli-deubeli* Biozone.

Holland et al. (1969, text-fig. 4) recorded *C. ludensis* from localities assigned to the "Wenlock Shale" (= Coalbrookdale Formation) in the Burrington area, west of Ludlow. All *Colonograptus* specimens collected from localities 114B and 61 (the latter in the Burrington section discussed herein) can be assigned to *C. praedeubeli* (which is common) or *C. deubeli* (which is less common). The specimen illustrated by Holland et al. (1969, pl. 130, fig. 2, text-fig. 2a) from Location 61 is also, based on its narrow, slowly widening rhabdosome, clearly *C. praedeubeli*. Location 62 yielded a new species, *Holoretiolites lawsoni*, to Holland et al. (1969). Now assigned to *Spinograptus*, the species is shown as restricted to the lower part of the *praedeubeli-deubeli* Biozone by Kozłowska et al. (2013). A broader *Colonograptus* proximal end (Holland et al. 1969, text-fig. 2g, h), which can be assigned to *C. ludensis*, is from Location 41, at the base of the Much Wenlock Limestone Formation, which is shown by Holland et al. (1969, text-fig. 4) to be stratigraphically just below the level of Burrington Location 63. The presence of *C. deubeli* at Location 114D, slightly higher in the formation, indicates a level no higher than the middle of the *ludensis* Biozone (Koren' & Urbanek 1994; Lenz 1995).

FIGURE 3 HEREABOUTS

Figure 3. Biostratigraphically important graptolites from the Eaton track and Longville-Stanway road sections. Locality numbers are those of Bassett et al. (1975) as used also on figures 2 and 4. All specimens are housed in the Sedgwick Museum of Earth Sciences, Cambridge. Scale bar represents 1 mm. A. *Gothograptus nassa* (Holm), SM A. 80195, Location 25. B, D. *Colonograptus praedeubeli* (Jaeger, in Barca & Jaeger): B. SM A. 80063, Location 50; D. SM A. 80067a, Location 49. C. *Colonograptus praedeubeli* (Jaeger), SM A. 80073, Location 47.

Eaton Track lithostratigraphy and biostratigraphy

The Eaton Track section in the hamlet of Eaton is near the base of the Wenlock Edge escarpment. The section contains the upper Coalbrookdale Formation, the boundary between its constituent members (Apedale and Farley members) and the boundary between the *lundgreni* and *nassa* biozones. In total Eaton Track contains c. 54 m of the Coalbrookdale Formation, but vegetation and soil cover obscure much of the succession and make accurate estimates of thickness difficult. As a result of such difficulties, carbon isotopic sampling has focused upon the upper part of the track (c. 20.5 m) which contains the key biozone and lithostratigraphic boundaries

(Figure 4); the lower half of the succession has been sampled less extensively. The carbon isotopic results described herein are derived from graptolite sampling locations 19 to 25 of Bassett et al. (1975), and a large cliff section between locations 20 and 21. The succession is of international significance in that it was put forward as the stratotype for the base of the Gleedon Chronozone of the Homerian Stage, at a position coincident with boundary between the *lundgreni* and *nassa* biozones (Bassett et al. 1975; Bassett 1989; Aldridge et al. 2000). Here the base of the *nassa* Biozone is marked by the disappearance of *Monograptus flemingii* within sampling location 24 (Bassett et al. 1975). Above, the boundary between the Apedale and Farley members occurs within sampling location 25 (Bassett et al. 1975) and is associated with the appearance of frequent nodular limestone (carbonate mudstone) beds separated by shales; gradational over a few metres. The first appearance of *Gothograptus nassa* is within location 25. The top of the current exposure is within the lower Farley Member and contains the lower of the two thin bentonites noted by Ray et al. (2010, p. 132).

FIGURE 4 HEREABOUTS

Figure 4. Eaton Track (SO 5016 8999) and Longville-Stanway Road Cutting (SO 5397 9270) sections showing the likely position of graptolite collections (from Bassett et al. 1975), graptolite and conodont biozonation, lithostratigraphy, general sedimentology including marker bentonites (MB), and carbon isotopic sampling locations and values. PS9 and PS10 relates to the position of the boundary between the parasequences of Ray et al. (2010). a. graptolite biozones; b. conodont biozones; c. formations; d. members.

Longville-Stanway Road Cutting lithostratigraphy and biostratigraphy

The Longville-Stanway Road Cutting, near the hamlet of Longville in the Dale, occurs along the lower part of the Wenlock Edge escarpment and contains a succession that begins approximately 20 m above that exposed at the top of the Eaton Track Section (c. 4.6 km to the southwest). The succession consists of the uppermost part of the Coalbrookdale Formation (Farley Member) and the Longville and Edgton members of the Much Wenlock Limestone Formation (Aldridge et al. 2000; Ray et al. 2010). Within this succession graptolite occurrences are restricted to 0.9 m below, and 0.6 m, 3.9 m and 5.7 m above the base of the Much Wenlock Limestone Formation (Figure 4) and correspond to sampling locations 46, 47, 49 and 50 of Bassett et al. (1975). The stratigraphic distribution of graptolite occurrences broadly corresponds to the extent of good continuous roadside exposure (c. 7.1 m) and forms the focus of the carbon isotopic sampling described herein. Based upon the presence of *Colonograptus praedeubeli* and *Colonograptus deubeli*, the uppermost Farley Member and Longville Member may be attributed to the late Homerian *praedeubeli-deubeli* Biozone. In addition, the Longville Member has also yielded *Ozarkodina bohemica bohemica* (Aldridge et al. 2000), a conodont broadly indicative of the middle to late Homerian (Slavík 2014).

Burrington lithostratigraphy and biostratigraphy

The hamlet of Burrington is located on the northern limb of the Ludlow Anticline, some 8 km west-south-west of the town of Ludlow. The Burrington Section contains c. 26 m of strata, within a number of discontinuous exposures within sunken lanes and disused quarries. These exposures begin within the hamlet itself and extend north-westwards up the hillside for c. 300 m. The succession consists of the upper

Coalbrookdale and Much Wenlock Limestone formations and is considered representative of the Ludlow area. Unlike at Wenlock Edge a subdivision of the Coalbrookdale and Much Wenlock Limestone formations into constituent members has not been made here, owing to more gradational and relatively subtle lithological changes. Indeed during our fieldwork the precise position of the boundary between Coalbrookdale and Much Wenlock Limestone formations was difficult to establish with confidence; a situation not helped by poor exposure. This transitional interval may be partly equivalent to the Farley Member (the Tickwood Beds of Bassett, 1974) as developed along Wenlock Edge. Graptolites have been collected from localities 60 to 64 of Holland et al. (1963) (also see Holland et al. 1969; Aldridge et al. 2000). However, in comparison to the Longville-Stanway Road Cutting and Eaton Track these biostratigraphic collections are more difficult to locate accurately and have consequently been shown as occurring over broader stratigraphic intervals than was probably the original case (Figure 5). Of particular biostratigraphic significance is the occurrence of *Gothograptus nassa* from location 60 indicating the *nassa* Biozone, *Colonograptus praedeubeli*, *C. deubeli* and *Spinograptus lawsoni* from the overlying Coalbrookdale Formation (locations 61 and 62) indicating the *praedeubeli-deubeli* Biozone, and *C. ludensis* from the Much Wenlock Limestone Formation indicating the *ludensis* Biozone (locations 63 and 64). In addition, location 64 is the highest record of graptolites within the Much Wenlock Limestone Formation of this area and the section as a whole is key in demonstrating the graptolite biozonation of the uppermost Wenlock (Holland et al. 1969).

FIGURE 5 HEREABOUTS

Figure 5. The Burrington Section (SO 4439 7241 to SO 4417 7257) showing the likely position of graptolite collections (Holland et al. 1963; 1969), graptolite biozonation, lithostratigraphy, general sedimentology including marker bentonites (MB), and carbon isotopic sampling locations and values. a. graptolite biozones; b. formations. See figure 4 for lithology key.

Carbon Isotope Stratigraphy

Each section was logged and sampled at a range of intervals depending upon accessibility (Table 1). Up to 2 mg of carbonate rock powder, per sample, was analysed at the University of Birmingham's SILLA laboratory facility. This method of analysing bulk rock for stable isotopes, which inevitably does contain some skeletal material, has been shown to provide reliable results in other Silurian studies (e.g. Cramer *et al*. 2006; Hughes & Ray 2016). The powdered carbonate was placed in a vial in a heated sample rack (90^{o}C), where the vial head space was replaced by pure helium via an automated needle system as part of an Isoprime Multiflow preparation system. Samples were then manually injected with approximately 200 µl of phosphoric acid and left to react for at least 1 hour before the headspace gas was sampled by an automated needle and introduced into a continuous-flow Isoprime mass-spectrometer. Duplicate samples were extracted from each vial and a mean value obtained for both $\delta^{13}C$ and $\delta^{18}O$. Samples were calibrated using IAEA standards NBS-18 and NBS-19 and reported as ‰ on the VPDB scale. An external precision of better than 0.1‰ is typically achieved for both $\delta^{13}C$ and $\delta^{18}O$. In total, 162 samples provided results.

TABLE 1 HEREABOUTS

Table 1. $\delta^{13}C_{carb}$ and $\delta^{18}O$ data from Eaton Track, Longville-Stanway Road Cutting, Burrington Section and Mortimer Forest Stop 1.

Eaton Track carbon isotope stratigraphy

The Eaton Track section contains the oldest investigated succession and, based upon the identification of the *lundgreni* and *nassa* biozones, it should contain the lower positive peak of the Homerian CIE (Figures 2 and 4). As a means of assessing the isotopic variability within the *lundgreni* Biozone, samples were taken from below the main measured section (between 12.5 and 33.0 m below location 21 of Bassett et al. 1975). These samples (Figure 2; Table 1) range between -1.75 ‰ and -0.40 ‰ $\delta^{13}C_{carb}$ (mean -1.13 ‰) and are typical of that biozone and the Apedale Member more generally, when compared with records from the nearby Lower Hill Farm Borehole (SO 5817 9788) (Hughes & Ray 2016). Within the main measured section and the uppermost 12.15 m of the *lundgreni* Biozone, $\delta^{13}C_{carb}$ values fluctuate between -0.39 ‰ and +1.43 ‰ (mean +0.23 ‰). Immediately above the *lundgreni* Biozone is an interval of no exposure approximating to 3.5 m of missing section. The overlying outcrop corresponds to the lowest graptolite collection of the *nassa* Biozone (Location 24 of Bassett et al. 1975) and yields an initial $\delta^{13}C_{carb}$ value of +2.64 ‰. This positive shift in values is considered to indicate that the onset of the Homerian CIE is at a stratigraphic position somewhere between the last graptolite collection of the *lundgreni* Biozone and the first of the *nassa* Biozone. From this initial peak, values decline over three closely spaced isotopic measurements to a low of +1.08 ‰. Above, the succession contains the transition from the Apedale Member, into the lowest part of the Farley Member (Coalbrookdale Formation) (Location 25 of Bassett et al. 1975). Here $\delta^{13}C_{carb}$ values show a broad rise, over multiple samples, with a peak value of +2.79 ‰ (mean +2.37 ‰). Such values are considered to reflect the rising limb of the lower peak of the Homerian CIE, which has been previously reported from the Farley Member (Schmidt et al. 2002).

Longville-Stanway Road Cutting carbon isotope stratigraphy

The succession at the Longville-Stanway Road Cutting is exclusively within the *praedeubeli-deubeli* Biozone and contains a succession that begins approximately 20 m above that exposed at the top of the Eaton Track Section. The basal few metres of the succession contain the transition between the Farley Member (Coalbrookdale Formation) and Longville Member (Much Wenlock Limestone Formation), and are accompanied by a progressive rise in $\delta^{13}C_{carb}$ values from +1.35 ‰ to +2.25 ‰. Above, values broadly plateau (mean +2.20 ‰), albeit with notable fluctuations between 2.98 m and 4.69 m (+1.66 ‰ to +2.44 ‰). This rise and plateau in values are considered to reflect the lower part of the upper peak of the Homerian CIE.

Burrington carbon isotope stratigraphy

The Burrington Section is representative of the *nassa, praedeubeli-deubeli* and *ludensis* biozones and therefore is partly synchronous with the Eaton Track and Longville-Stanway Road Cutting sections. Location 60 (Holland et al. 1963) is the oldest part of the succession (*nassa* Biozone) and contains $\delta^{13}C_{carb}$ values between +0.60 ‰ to +1.21 ‰ (mean +0.99 ‰). Above, the sunken lane-side section contains the uppermost Coalbrookdale Formation and its gradational transition with the overlying Much Wenlock Limestone Formation. Within the Coalbrookdale Formation (between marker telegraph poles 46 and 47) $\delta^{13}C_{carb}$ values range from - 0.83 ‰ to

+0.85 ‰ (mean +0.24 ‰), and based upon the slight lowering of values, in comparison with those below and above, may reflect the trough in values between the dual peaks of the Homerian CIE (*praedeubeli-deubeli* Biozone). The transition interval with the Much Wenlock Limestone Formation shows initially similar values to those observed below, before values rise sharply to +4.04 ‰. While this marked positive shift is only identified in a single sample within the lane-side section, distinctly higher values are reported from the Much Wenlock Limestone Formation, which is exposed within a small disused quarry stratigraphically above. Here, $\delta^{13}C_{carb}$ values range from +1.24 ‰ to +3.80 ‰ (mean +2.17 ‰), and are likely characteristic of the upper peak of the Homerian CIE (*ludensis* Biozone). Particularly notable features of this interval are the positive spikes in values at 26.60 m, 36.36 m and 39.36 m. While these appear to be part of a broader positive shift in values between the Coalbrookdale and Much Wenlock Limestone formations, they are clearly anomalous and may reflect a diagenetic effect or pulses of platform-derived carbonate deposited during storm events, as described by Blain et al. (2016) for the uppermost Much Wenlock Limestone Formation of the Ludlow Anticline. The youngest part of the succession occurs back on the lane at a marked bend (Location 64 of Holland et al. 1963) and gives values between +1.79 ‰ and +1.99 ‰ (mean +1.89 ‰). The minor fall in values between the underlying quarry and this section may reflect the onset of the declining values within the upper peak of the Homerian CIE, which is observed elsewhere near the top Much Wenlock Limestone Formation; such values are only marginally higher than those obtained from c. 6.5 m below the top of the Much Wenlock Limestone Formation at the nearby Goggin Road section (Blain et al. 2016) and may represent the fall in values between Mortimer Forest stops 1 and 2, c. 7 m to 9 m below the top of the Much Wenlock Limestone Formation (Figure 6).

Regional and pan-regional correlation

Upon the Midland Platform the best documented and most stratigraphically extensive records of the Homerian CIE are derived from the Silurian inliers of the West Midlands (Wren's Nest Hill, Dudley (SO 937 920)) (Cramer et al. 2012; Marshall et al. 2012), and it is from these inliers that the initial documentation of a double-peaked late Homerian CIE was made (Corfield et al. 1992). In addition, the upper peak of the Homerian CIE has been documented within the reef tract along Wenlock Edge, and the declining limb of the upper peak further documented from Ledbury and the Ludlow Anticline (Corfield et al. 1992; Thomas & Ray, 2011; Marshall et al. 2012; Blain et al. 2016). While these sections are, for the most part, well correlated via bentonites and sequence stratigraphy (Ray et al. 2010; 2011; 2013), direct graptolite biostratigraphic control is poor; owing to a very limited number of graptolite finds. Accordingly, the establishment of the Homerian CIE within the graptolitic sections described herein, and the correlation of these sections with the established carbon isotopic and sequence stratigraphic records should help to improve chronostratigraphic constraints across the Midland Platform (Figure 6), and further enable improved correlation with successions outside of the Midland Platform for which detailed graptolite and carbon isotopic determinations have been obtained.

FIGURE 6 HEREABOUTS

Figure 6. A correlation of key sections along Wenlock Edge and the Ludlow Anticline based upon biozones and carbon isotopic curves. The generalised carbon isotopic curve is derived from the inner platform area situated within the West Midlands

(Corfield et al. 1992; Cramer et al. 2012; Marshall et al. 2012). Carbon isotopic curves for Benthall Edge, Lea South and Goggin Road are taken from Blain et al. (2016) and Mortimer Forest stops 2 and 3 are from Thomas & Ray (2011). Thick grey lines indicate the correlation of lithostratigraphic boundaries. Dashed thin grey lines indicate the correlation of biozonal boundaries. S1, start of lower peak of the Homerian CIE; P1, peak of lower CIE; E1/S2, end of lower CIE and the start of the upper; P2, peak of upper CIE; E2, end of upper CIE. a. Stage; b. Stage Slices (Cramer et al. 2011); c. graptolite biozones; d. lithostratigraphic formations within the West Midlands (inner platform); e. lithostratigraphic members within the West Midlands (inner platform). Gor., Gorstian; L. E. Fm., Lower Elton Formation; LQL Mb., Lower Quarried Limestone Member; UQL Mb. Upper Quarried Limestone Member. Scale bar is applicable only to the sections.

The onset of the lower peak of the Homerian CIE is associated with the base of the Much Wenlock Limestone Formation within the West Midlands from which there are reports of *Monograptus flemingii* (Butler, 1939; Bassett, 1976; Ray et al. 2010). At Eaton Track a similar situation occurs with the onset of the Homerian CIE approximating to the last appearance of *M. flemingii* and a marked lithological change marking the transition between the Apedale and Farley members (of the Coalbrookdale Formation). Unfortunately, the poor exposure and limited lithological variability within the Eaton Track succession precludes the clear identification of the parasequences attributed to this stratigraphic interval within the West Midlands (Ray et al. 2010). However, it is notable that in both of the successions the onset of the Homerian CIE is approximately synchronous with the replacement of distal shales with a shallower limestone-rich succession. This synchronous appearance of limestones may be explained by a basinward shift of proximal facies during a marine regression, and this sea-level fall, in association with the onset of the lower peak of the Homerian CIE, has been reported from multiple palaeo-continents (Johnson, 2006; Calner, 2008) and is considered likely to be glacio-eustatic in origin (Loydell 1998; Trotter et al. 2016).

Outside of the Midland Platform and Avalonia the close association of the last appearance of *M. flemingii* and the onset of the lower peak of the Homerian CIE is well established. Upon Baltica the Bartoszyce IG 1 (north-eastern Poland), Grötlingbo-1 (Gotland, Sweden) and Viduklė-61 (Lithuania) boreholes record the last appearance of *M. flemingii* immediately prior to pronounced positive shifts in $\delta^{13}C$ values (Porębska et al. 2004; Calner et al. 2006; Radzevičius et al. 2014). Similarly upon Laurentia the Simpson Park I section (Nevada, USA) documents the same series of events (Cramer et al. 2006). A further similarity between these four successions is the first appearance of *Gothograptus nassa* within the lower peak of the Homerian CIE. Based upon the reassessment of the Eaton Track graptolite biozonation this same relationship can be observed upon the Midland Platform.

The subdivision of the former *ludensis* Biozone (Bassett et al. 1975) on the Midland Platform into the *praedeubeli-deubeli* and *ludensis* biozones allows for the trough and upper peak of the Homerian CIE to be correlated and compared in detail. Broadly the trough and upper rising limb of the Homerian CIE occur within the *praedeubeli-deubeli* Biozone, with peak isotopic values likely occurring high in the same biozone (+4.04 ‰ within the Burrington Section) or within the lowermost part of the overlying *ludensis* Biozone. Above, values typically plateau before declining towards the top of the Homerian Stage. In terms of regional correlation and age constraints, the establishment of the *praedeubeli-deubeli* Biozone and the rising limb of the upper peak of the Homerian CIE within the Longville-Stanway Road Cutting are particularly helpful, in that they are associated with the widely traceable flooding surface between parasequences 9 and 10 of Ray et al. (2010) (Figure 4). In particular, the correlation of these parasequences along Wenlock Edge and to the West Midlands allows for comparison with more extensive carbon isotope records (Marshall et al. 2012) and reveals that the upper peak of the Homerian CIE is restricted to an interval encompassing Parasequence 9 and the lower part of Parasequence 10, above which carbon isotopic values broadly plateau and then decline towards the top of Parasequence 10. Such an arrangement suggests that the maximum isotopic values of the upper peak of the Homerian CIE may be very close to the studied interval at the Longville-Stanway Road Cutting and therefore within the *praedeubeli-deubeli* Biozone. Comparison with the Burrington Section also reveals a change from the rising limb of the upper peak of the Homerian CIE to a plateau in carbon isotopic values, which corresponds to the transition between *praedeubeli-deubeli* and *ludensis* biozones. Based upon this section the peak values of the upper peak of the Homerian CIE likely occur close to the boundary between the *praedeubeli-deubeli* and *ludensis* biozones. This same relationship may also be observed outside of the Midland Platform and Avalonia with both the Bartoszyce IG 1 (north-eastern Poland) and Viduklė-61 (Lithuania) boreholes (Porębska et al. 2004; Radzevičius et al. 2014) revealing a minimum in isotopic values within the lower part of the *praedeubeli-deubeli* Biozone, above which values rise towards the upper part of the biozone, with peak values achieved close to the boundary between the *praedeubeli-deubeli* and *ludensis* biozones.

A further correlative feature of Parasequence 10 is that it represents a significant marine regression resulting in the progradation of shallow limestone-rich facies across much of the Midland Platform (Ray et al. 2010). This sea-level fall, in association with the upper peak of the Homerian CIE, has been reported from multiple palaeo-continents (Johnson, 2006) and is considered likely to be glacio-eustatic in origin (Loydell 1998; Trotter et al. 2016). Within the Ludlow area the progradation of shallow limestone-rich facies has resulted in the replacement of the deep-marine shales of the Coalbrookdale Formation with the Much Wenlock Limestone Formation. However, graptolite age constraints indicate that the base of the Much Wenlock Limestone Formation is diachronous between Wenlock Edge (*praedeubeli-deubeli* Biozone) and the Ludlow Anticline (*ludensis* Biozone). This south-westward younging reflects the time taken for shallow-marine limestone facies, typical of the off-reef tract of the Much Wenlock Limestone Formation, to prograde out into the somewhat deeper platform setting present at Ludlow. According to Thomas & Ray (2011) the flooding surface between parasequences 9 and 10 can be observed in the Ludlow area near the base of Mortimer Forest Stop 1. Based upon the diachroneity described herein, this is erroneous, and the parasequence 9-10 boundary should occur stratigraphically below, within the *praedeubeli-deubeli* Biozone and in association with the plateau in carbon isotopic values. This would correspond to the transition interval between the Coalbrookdale and Much Wenlock Limestone Formation at the Burrington Section, and fits well with the progradational nature of Parasequence 10 resulting in the deposition of the Much Wenlock Limestone Formation.

Mortimer Forest stops 1 to 3 are of particular significance for the stratigraphy of the Homerian Stage and Ludlow area, in that they represent near continuous exposure of the upper 15 m of the Much Wenlock Limestone Formation and contain the GSSP for the overlying Gorstian Stage and Ludlow Series (Mortimer Forest Stop

3, Pitch Coppice Quarry (Melchin et al. 2012)). While carbon isotope values are available for stops 2 and 3 (Thomas & Ray 2011) these do not display values that could definitely be attributed to the upper peak of the Homerian CIE (+0.44 ‰ to +1.25 ‰). As a means of improving our understanding of the upper part of the Much Wenlock Limestone Formation, carbon isotope values have been established for all but the inaccessible upper 2 m of the Mortimer Forest Stop 1 quarry face. Here carbon isotope values range between +0.88 ‰ and +2.33 ‰ (mean +1.89 ‰; Table 1) and are considered representative of the plateau in values associated with the upper peak of the Homerian CIE (Figure 6). By combining the carbon isotopic record for the Burrington Section and Mortimer Forest stops 1 to 3 the upper peak of the Homerian CIE can now be better resolved within the Ludlow area. As with the off-reef tract along Wenlock Edge the upper peak of the Homerian CIE appears to occupy the majority of the Much Wenlock Limestone Formation. However, while the thickness of the Much Wenlock Limestone Formation at the south-western end of Wenlock Edge (River Onny Section, south of Craven Arms) is reported as 21 m (Bassett et al. 1975), Cocks et al. (1992) considered the Much Wenlock Limestone Formation to be much thicker within the Ludlow area (55 m to 144 m). The apparent thickening of the Much Wenlock Limestone Formation might, in part, reflect the transition from shelf to basin, which takes place to the immediate west of the Ludlow Anticline. However, a combination of poor exposure, faulting and the transitional nature of the base of the formation are also important and may have led to an overestimate of thickness. Indeed within the nearby Wigmore Rolls area of the Ludlow Anticline the difficulties in unequivocally distinguishing the Much Wenlock Limestone Formation from the shales and limestones of the upper Coalbrookdale Formation led Whitaker (1994) to combine all the shale-limestone sequences into a new formation, the Wigmore Rolls Formation. The Wigmore Rolls Formation ranges in thickness from 30 m to 163 m and corresponds to successions previously attributed to the Much Wenlock Limestone Formation.

Considerations of the thickness of the Much Wenlock Limestone Formation between Mortimer Forest Stop 3 and the Burrington Section are of significance in that the Burrington Section contains the highest record of Homerian graptolites (Location 64) below the Gorstian GSSP (Mortimer Forest Stop 3). According to Lawson & White (1989) Location 64 within Burrington Section is within the lower third of the Much Wenlock Limestone Formation and occurs 40 m below the top of the formation, indicating a significant stratigraphic thickness between the last graptolites of the Homerian and the first graptolites of the Gorstian. However, the River Onny Section with a reported thickness of 21 m for the Much Wenlock Limestone Formation is only 8.5 km north of the Burrington Section and is representative of a gradual thinning of the formation (33 m to 21 m) along Wenlock Edge and towards the Ludlow area. Furthermore, 220 m to the northeast of the top of the Burrington section (Location 64), and across a minor fault, is Burrington Common Quarry (SO 4438 7266; Location 65 of Holland et al. 1963). This small disused quarry contains 5.9 m of Much Wenlock Limestone Formation with features indicative of the very highest part of the succession. In particular, a highly distinctive 0.18 m thick shale horizon, within fine comminuted crinoidal grainstones, is present and almost certainly corresponds to the widely traceable flooding surface at the base of Parasequence 11 (Lawson & White 1989; Thomas & Ray 2011; Blain et al. 2016). In addition, below the flooding surface are *Favosites* corals, which are generally rare within all but the uppermost Much Wenlock Limestone Formation within the Ludlow Anticline. Based upon these considerations it seems likely that the thickness of the Much Wenlock

Limestone Formation between Mortimer Forest Stop 3 and the Burrington Section is likely to be similar to that reported along Wenlock Edge (21 m to 33 m) and Location 64 and the highest records of Homerian graptolites may therefore be stratigraphically higher within the formation than previously thought.

Conclusions

New $\delta^{13}C_{carb}$ data from the most stratigraphically extensive graptolitic sections of late Homerian age are reported from Wenlock Edge and the Ludlow Anticline, thereby encompassing the type Homerian succession. The establishment of the Homerian CIE within graptolitic successions increases our understanding of the scale and timing of carbon isotopic variations and improves both regional and global correlation. The main conclusions are summarized below:

1. The 162 $\delta^{13}C_{carb}$ samples from four outcrops (Eaton Track, Longville-Stanway Road Cutting, Burrington Section and Mortimer Forest Stop 1) provide evidence for the onset of both lower and upper peaks of the Homerian CIE in association with graptolite records. Based upon this data the lower excursion begins in association with the last appearance of *Monograptus flemingii* and appears restricted to the overlying *nassa* Biozone. Above, the trough between excursions and the upper rising limb of the Homerian CIE occur within the *praedeubeli-deubeli* Biozone, with peak values corresponding to the boundary between the *praedeubeli-deubeli* and *ludensis* biozones. The declining limb of the upper excursion is within upper part of the Much Wenlock Limestone Formation and is likely restricted to the *ludensis* Biozone.
2. Based on a biostratigraphical re-assessment, the base of the Much Wenlock Limestone Formation is diachronous, lying within the *praedeubeli-deubeli* Biozone in the off-reef tract along Wenlock Edge, but at a higher level, close to the base of the *ludensis* Biozone, within the Ludlow Anticline.
3. Based upon carbon isotopic, lithological and sequence stratigraphic considerations, the Burrington Section, Mortimer Forest Stop 1 and Longville-Stanway Road Cutting allow for high resolution correlation between the Ludlow Anticline and Wenlock Edge. These correlations suggest a uniformity of depositional rates across the study area and suggest that the thickness of the Much Wenlock Limestone Formation between its top at Mortimer Forest Stop 3 and base in the Burrington Section is similar to that reported along Wenlock Edge (21 m to 33 m).
4. The application of $\delta^{13}C_{carb}$ chemostratigraphy to graptolitic successions has allowed for better comparisons with other sections outside of Avalonia from which high-resolution graptolite and carbon isotope data are available. Such comparisons highlight the apparent synchronicity of the Homerian CIE with respect to the *lundgreni*, *nassa*, *praedeubeli-deubeli* and *ludensis* biozones.

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References

Aldridge, R.J., Siveter, David J., Siveter, Derek J., Lane, P.D., Palmer, D. & Woodcock, N.H., 2000: British Silurian stratigraphy, Geological Conservation Review Series, No. 19, Joint Nature Conservation Committee, Peterborough, 542 pp.

Barca, S. & Jaeger, H., 1990: New geological and biostratigraphical data on the Silurian in SE-Sardinia. Close affinity with Thuringia. *Bollettino della Società Geologica Italiana* 108, 565-580.

Bassett, M.G., 1974: Review of the stratigraphy of the Wenlock Series in the Welsh Borderland and South Wales. *Palaeontology* 17, 145-177.

Bassett, M.G., 1976: A critique of diachronism, community distributions and correlation of the Wenlock–Ludlow boundary. *Lethaia* 9, 207-218.

Bassett, M.G., 1989: The Wenlock Series in the Wenlock area. In: Holland, C. H. & Bassett, M.G. (Eds.), A Global Standard for the Silurian System. National Museum of Wales, Geological Series No. 9, Cardiff, pp. 51-73.

Bassett, M.G., Cocks, L.R.M., Holland, C.H., Rickards, R.B. & Warren, P.T., 1975: The type Wenlock Series. Report of the Institute of Geological Sciences. 75, pp. 1-19.

Blain, J.A., Ray, D.C. & Wheeley, J.R., 2016: Carbon isotope ($\delta^{13}C_{carb}$) and facies variability at the Wenlock-Ludlow boundary (Silurian) of the Midland Platform, UK. *Canadian Journal of Earth Sciences* 53, 1-6.

Brett C.E., Boucot A.J. & Jones B., 1993: Absolute depths of Silurian benthic assemblages. *Lethaia* 26, 25-40.

Butler, A.J., 1939: The stratigraphy of the Wenlock Limestone at Dudley. *Quarterly Journal of the Geological Society of London* 95, 34-74.

Calner, M., 2008: Silurian global events – at the tipping point of climate change. In Mass extinctions. Edited by A.M.T. Elewa. Springer-Verlag, Berlin and Heidelberg. pp. 21-58.

Calner, M., 2012: New chemostratigraphic data through the Mulde Event interval (Silurian, Wenlock), Gotland, Sweden. *GFF* 134, 65-67.

Calner, M., Kozłowska, A., Masiak, M. & Schmitz, B., 2006: A shoreline to deep basin correlation chart for the middle Silurian coupled extinction-stable isotopic event. *GFF* 128, 79-84.

Cocks, L.R.M., Holland, C.H. & Rickards, R.B., 1992: A revised correlation of Silurian rocks in the British Isles: Geological Society of London, Special Report, 21, 32 pp.

Cramer, B.D., Kleffner, M.A. & Saltzman, M.R., 2006: The Late Wenlock Mulde positive carbon isotope ($d^{13}C_{carb}$) excursion in North America. *GFF* 128, 85–90.

Cramer, B.D., Brett, C.E., Melchin, M.A., Männik, P., Kleffner, M.A., McLaughlin, P. I., Loydell, D.K., Munnecke, A., Jeppsson, L., Corradini, C., Brunton, F.R. & Saltzman, M.R., 2011: Revised chronostratigraphic correlation of the Silurian System of North America with global and regional chronostratigraphic units and $\delta^{13}C_{carb}$ chemostratigraphy. *Lethaia* 44, 185-202.

Cramer, B.D., Condon, D.J., Söderlund, U., Marshall, C., Worton, G.W., Thomas, A.T., Calner, M., Ray, D.C., Perrier, V., Boomer, I., Patchett, P.J. & Jeppsson, L., 2012: U-Pb (zircon) age constraints on the timing and duration of Wenlock (Silurian) paleocommunity collapse and recovery during the 'Big Crisis'. The *Geological Society of America Bulletin* 124 (11/12), 1841-1857.

Corfield, R.M., Siveter, D.J., Cartlidge, J.E. & McKerrow, W.S., 1992: Carbon isotope excursion near the Wenlock-Ludlow, (Silurian) boundary in the Anglo-Welsh area. *Geology* 20, 371-374.

Davies, J.R., Ray, D.C., Thomas, A.T., Loydell, D.K., Cherns, L., Cramer, B.D., Veevers, S.J., Worton, G.J., Marshall, C., Molyneux, S.G., Vandenbroucke, T.R.A., Verniers, J., Waters, R.A., Williams M. & Zalasiewicz, J. A., 2011: Siluria revisited: A field guide. International Subcommission on Silurian Stratigraphy, Field Meeting 2011 (ed. D.C. Ray), 1-170.

Frýda, J, & Frýdová, B., 2014: First evidence for the Homerian (late Wenlock, Silurian) positive carbon isotope excursion from peri-Gondwana: new data from the Barrandian (Perunica). *Bulletin of Geosciences* 89, 617-634

Holland, C.H., Lawson, J.D. & Walmsley, V.G., 1963: The Silurian rocks of the Ludlow District, Shropshire. Bulletin of the British Museum (Natural History), Geology Series 8, 93-171.

Holland, C.H., Rickards, R.B. & Warren, P.T., 1969: The Wenlock graptolites of the Ludlow district, Shropshire, and their stratigraphical significance. *Palaeontology* 12, 663-683.

Hughes, H.E. & Ray, D.C., 2016: The carbon isotope and sequence stratigraphic record of the Sheinwoodian and lower Homerian stages (Silurian) of the Midland Platform, UK. *Palaeogeography, Palaeoclimatology, Palaeoecology* 445, 97-114.

Johnson, M.E., 2006: Relationship of Silurian sea-level fluctuations to oceanic episodes and events. *GFF* 128, 115-121.

Koren', T.N. & Urbanek, A., 1994: Adaptive radiation of monograptids after the Late Wenlock crisis. *Acta Palaeontologica Polonica* 39, 137-167.

Kozłowska, A., Dobrowolska, K., & Bates, D.E.B., 2013: A new type of colony in Silurian (upper Wenlock) retiolitid graptolite Spinograptus from Poland. *Acta Palaeontologica Polonica* 58, 85-92.

Lawson, J.D. & White, D.E., 1989: The Ludlow Series in the Ludlow area. In: Holland, C.H. & Bassett, M.G. (Eds.), A Global Standard for the Silurian System. National Museum of Wales, Geological Series No. 9, Cardiff, pp. 73-90.

Lenz, A.C., 1995: Upper Homerian (Wenlock, Silurian) graptolites and graptolite biostratigraphy, Arctic Archipelago, Canada. *Canadian Journal of Earth Sciences* 32, 1378-1392.

Loydell, D.K., 1998: Early Silurian sea-level changes. *Geological Magazine* 135 (4), 447-471.

Loydell, D.K., 2007: Early Silurian positive $\delta^{13}C$ excursions and their relationship to glaciations, sea-level changes and extinction events. *Geological Journal* 42, 531-546.

Loydell, D.K., 2012: Graptolite biozone correlation charts. *Geological Magazine* 149, 124-132.

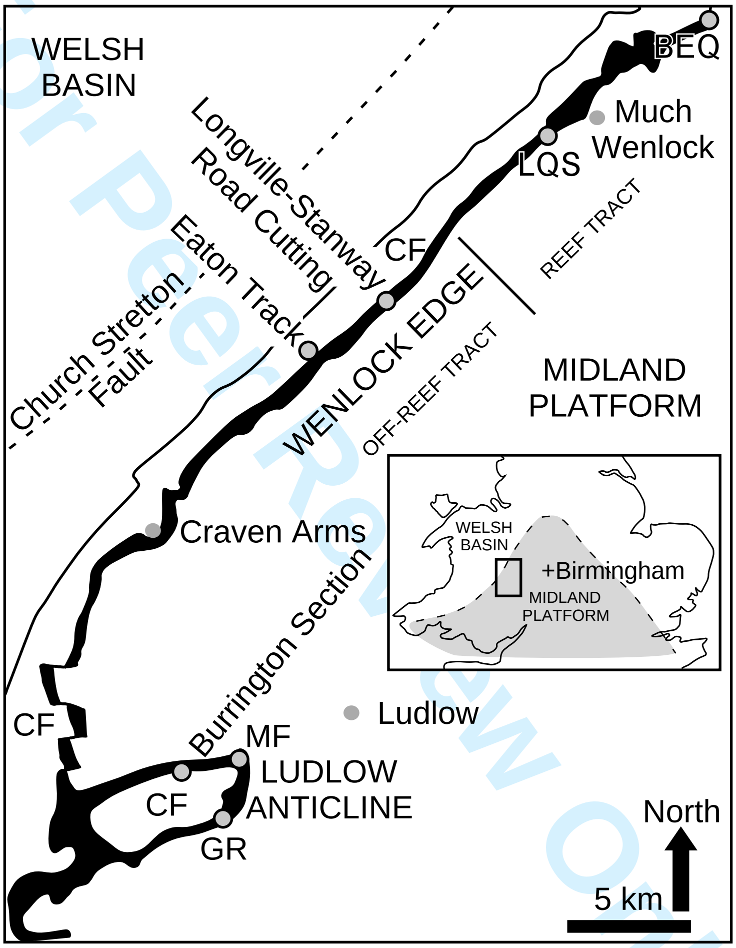
Marshall, C., Thomas, A.T., Boomer, I. & Ray, D.C., 2012: High resolution $\delta^{13}C$ stratigraphy of the Homerian (Wenlock) of the English Midlands and Wenlock Edge. *Bulletin of Geosciences* 87, 669-679.

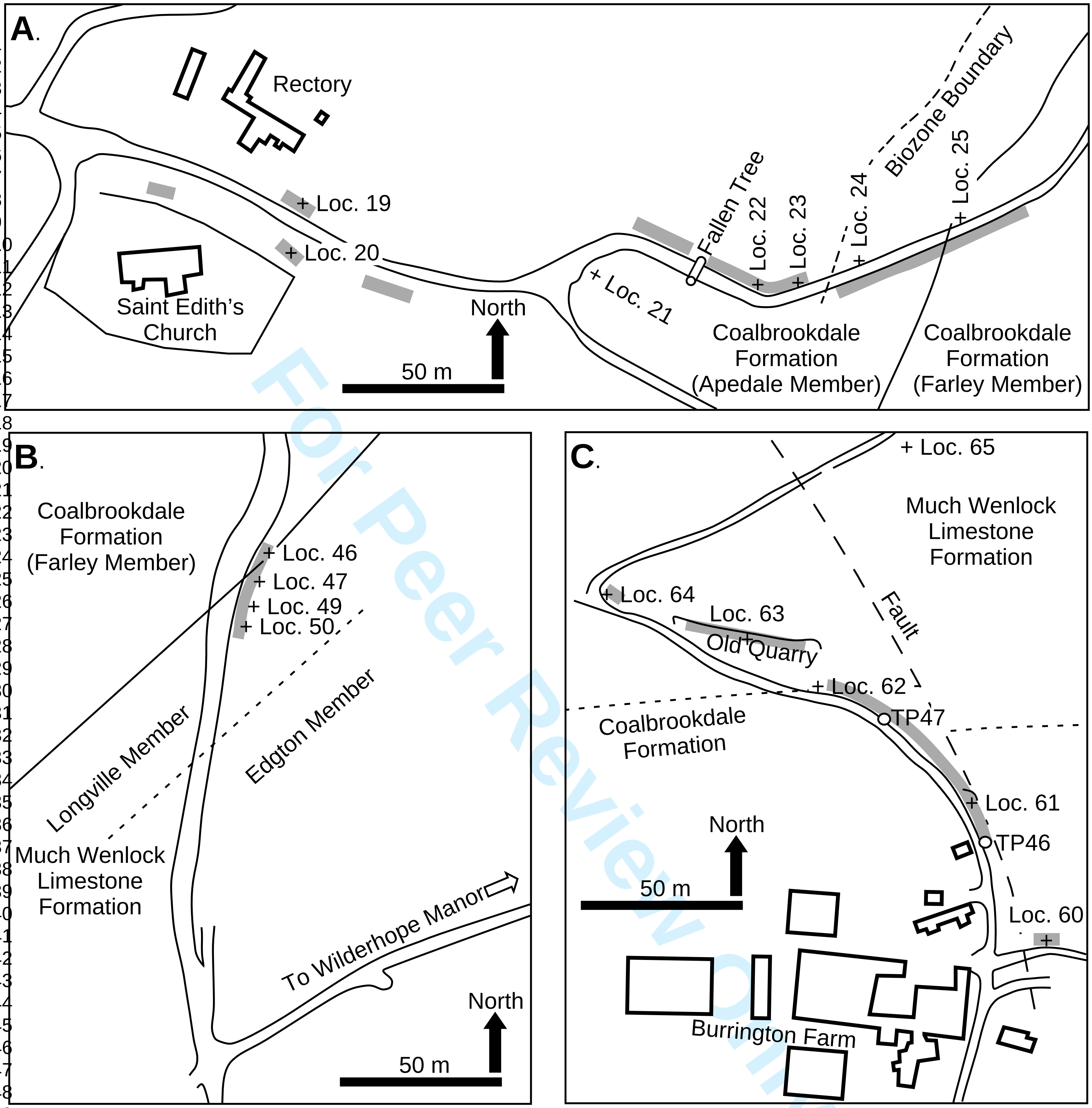
Melchin, M.J., Sadler, P.M. & Cramer, B.D., 2012: The Silurian Period. In: The Geologic Time Scale 2012. Edited by F.M. Gradstein, J.G. Ogg, M. Schmitz & G. Ogg. Elsevier, New York. pp. 525-558.

Munnecke, A., Calner, M., Harper, D.A.T. & Servais, T., 2010: Ordovician and Silurian sea-water chemistry, sea level, and climate: A synopsis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 296, 389-413.

Murchison, R. I., 1872: Siluria. The history of the oldest rocks in the British Isles and other countries; with sketches of the origin and distribution of native gold, the general succession of geological formations, and changes of the Earth's surface. 5th Edition. John Murray, London, xvii + 566 pp

Noble, P.J., Zimmerman, M.K., Holmden, C. & Lenz, A. C., 2005: Early Silurian (Wenlockian) $\delta^{13}C$ profiles from the Cape Phillips Formation, Arctic Canada and their relation to biotic events. *Canadian Journal of Earth Sciences* 42, 1419-1430.
Porębska, E., Kozłowska-Dawidziuk, A. & Masiak, M., 2004: The *lundgreni* event in the Silurian of the East European Platform, Poland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 213, 271-294.
Radzevičius S., Spiridonov, A. & Brazauskas, A., 2014: Integrated middle–upper Homerian (Silurian) stratigraphy of the Viduklė-61 well, Lithuania. *GFF* 136, 218-222.
Ray, D.C., Brett, C.E., Thomas, A.T. & Collins, A.V.J., 2010: Late Wenlock sequence stratigraphy in central England. *Geological Magazine* 147, 123-144.
Ray, D.C. & Butcher, A., 2010: Sequence stratigraphy of the type Wenlock area (Silurian), England. *Bollettino della Società Paleontologica Italiana* 49, 47-54.
Ray, D.C., Collings, A.V.J., Worton, G.J. & Jones G., 2011: Upper Wenlock bentonites from Wren's Nest Hill, Dudley; comparisons with prominent bentonites along Wenlock Edge, Shropshire, England. *Geological Magazine* 148, 670-681.
Ray, D.C., Richards, T.D., Brett, C.D., Morton, A. & Brown, A.M., 2013: Late Wenlock sequence and bentonite stratigraphy in the Malvern, Suckley and Abberley Hills, England. *Palaeogeography, Palaeoclimatology, Palaeoecology* 389, 115-127.
Saltzman, M.R. & Thomas, E., 2012: Carbon isotope stratigraphy. In: The geologic time scale 2012. Edited by F.M. Gradstein, J.G. Ogg, M. Schmitz & G. Ogg. Elsevier, New York. pp. 207-232.
Schmidt, S.-J., Corfield, R.M. & Siveter, D. J., 2002: Whole-rock stable carbon and oxygen isotope stratigraphy of the type Wenlock Series (Silurian), Welsh Borderland, UK. VI Isotope Workshop, Abstracts, Tallinn, Estonia. pp. 92-93.
Slavík, L., 2014: Revision of the conodont zonation of the Wenlock-Ludlow boundary in the Prague Synform. *Estonian Journal of Earth Sciences* 63, 305-311.
Štorch, P. & Frýda, J., 2012: The late Aeronian graptolite *sedgwickii* Event, associated positive carbon isotope excursion and facies changes in the Prague Synform (Barrandian area, Bohemia). *Geological Magazine* 149, 1089-1106.
Thomas, A.T. & Ray, D.C., 2011: Pitch Coppice: GSSP for the base of the Ludlow Series and Gorstian Stage, Whitwell Coppice. In: Ray, D.C. (Ed.), Siluria Revisited, a Field Guide, International Subcommission on Silurian Stratigraphy Field Meeting 2011, pp. 80-84.
Trotter, J.A., Williams, I.S., Barnes, C.R., Männik, P. & Simpson, A., 2016: New conodont $\delta^{18}O$ records of Silurian climate change: implications for environmental and biological events. *Palaeogeography, Palaeoclimatology, Palaeoecology* 443, 34-48
Whitaker, J. H. McD., 1994: Silurian basin slope sedimentation and mass movement in the Wigmore Rolls area, central Welsh Borderland. *Journal of the Geological Society* 151, 27-40.
Zalasiewicz, J.A., Taylor, L., Rushton, A.W.A., Loydell, D.K., Rickards, R.B. & Williams, M., 2009: Graptolites in British stratigraphy. *Geological Magazine* 146, 785-850.


WELSH BASIN
Longville-Stanway Road Cutting
Eaton Track
Church Stretton Fault
CF
BEQ
Much Wenlock
LQS
REEF TRACT
WENLOCK EDGE
OFF-REEF TRACT
MIDLAND PLATFORM
Craven Arms
Burrington Section
WELSH BASIN
+Birmingham
MIDLAND PLATFORM
Ludlow
CF
MF
LUDLOW ANTICLINE
CF
GR
North
5 km


A.
Rectory
Saint Edith's Church
+ Loc. 19
+ Loc. 20
+ Loc. 21
Fallen Tree
Loc. 22
Loc. 23
Loc. 24
Loc. 25
Biozone Boundary
North
50 m
Coalbrookdale Formation (Apedale Member)
Coalbrookdale Formation (Farley Member)
B.
Coalbrookdale Formation (Farley Member)
+ Loc. 46
+ Loc. 47
+ Loc. 49
+ Loc. 50
Longville Member
Edgton Member
Much Wenlock Limestone Formation
To Wilderhope Manor
North
50 m
C.
+ Loc. 65
Much Wenlock Limestone Formation
+ Loc. 64
Loc. 63
Old Quarry
Fault
+ Loc. 62
TP47
Coalbrookdale Formation
Loc. 61
TP46
North
50 m
Loc. 60
Burrington Farm

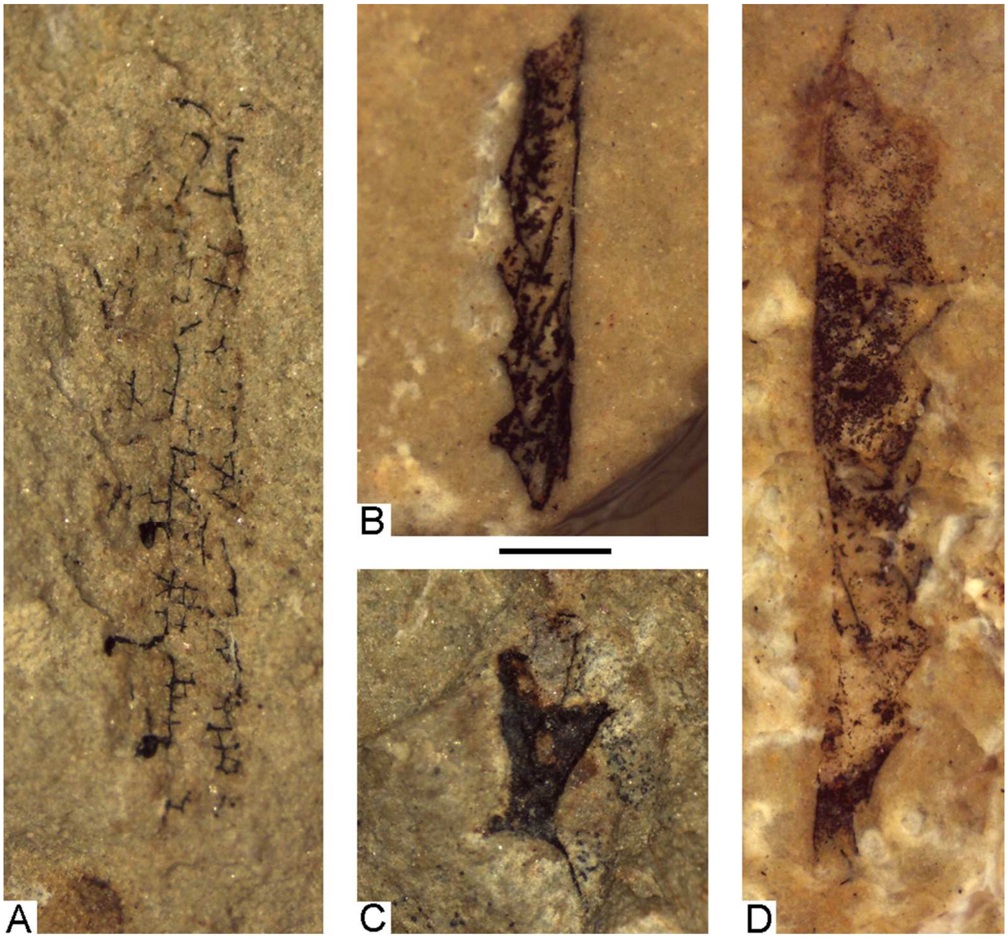
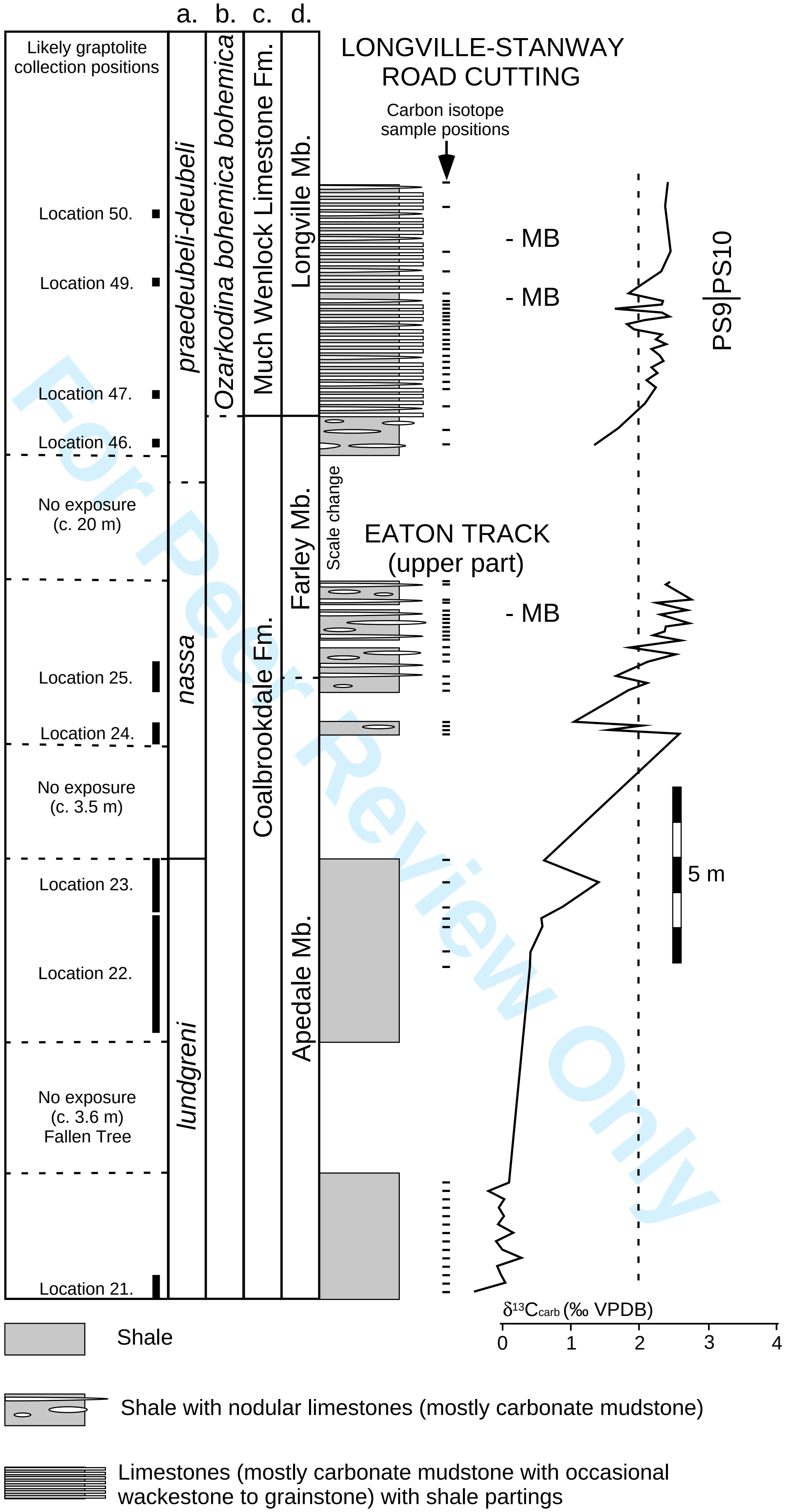
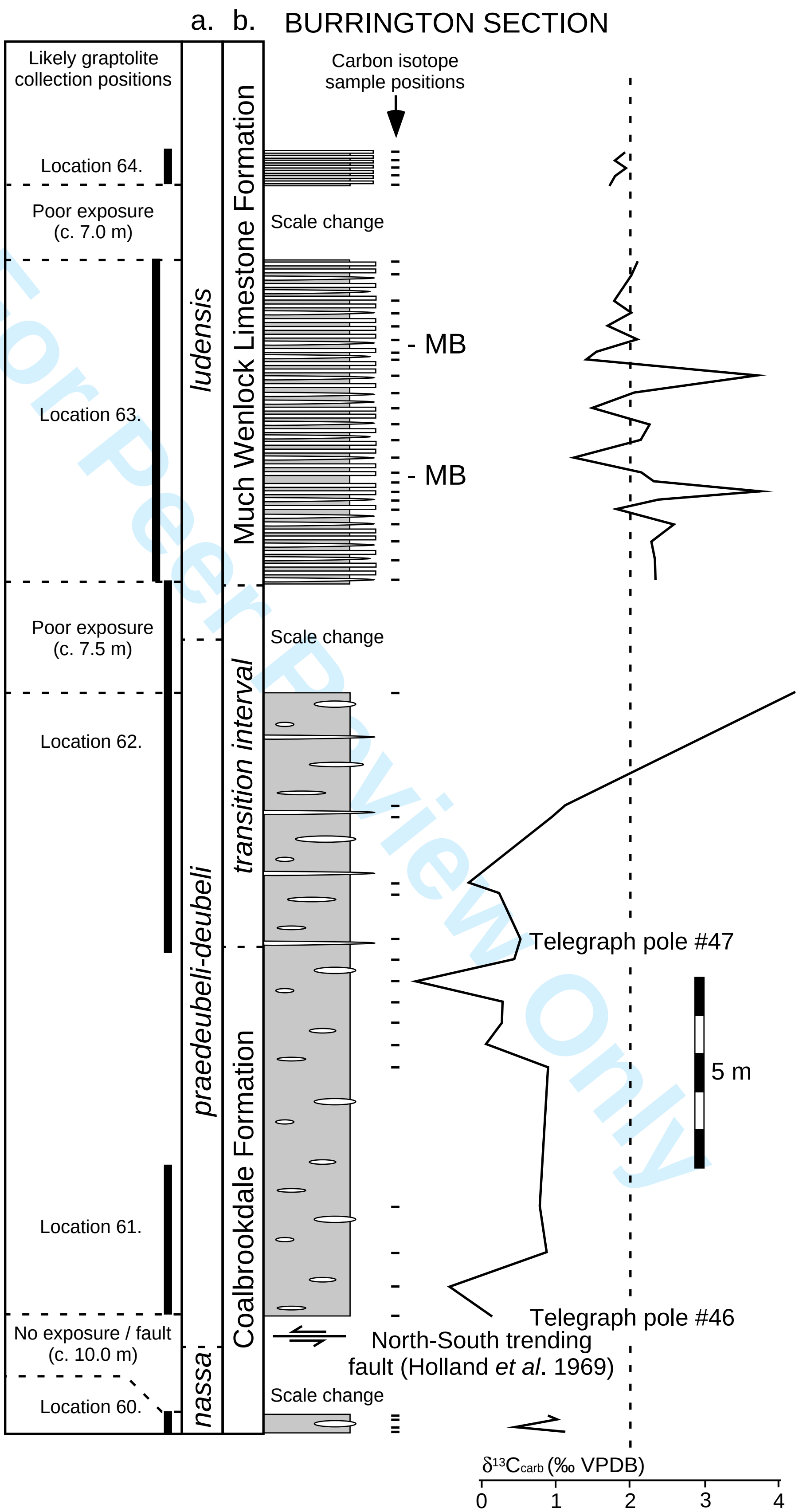


Figure 3. Biostratigraphically important graptolites from the Eaton track and Longville-Stanway road sections. Locality numbers are those of Bassett et al. (1975) as used also on figures 2 and 4. All specimens are housed in the Sedgwick Museum of Earth Sciences, Cambridge. Scale bar represents 1 mm. A. Gothograptus nassa (Holm), SM A. 80195, Location 25. B, D. Colonograptus praedeubeli (Jaeger, in Barca & Jaeger): B. SM A. 80063, Location 50; D. SM A. 80067a, Location 49. C. Colonograptus praedeubeli (Jaeger), SM A. 80073, Location 47.

90x83mm (300 x 300 DPI)


a. b. c. d.
Likely graptolite collection positions
praedeubeli-deubeli
Ozarkodina bohemica bohemica
Much Wenlock Limestone Fm.
Longville Mb.
LONGVILLE-STANWAY ROAD CUTTING
Carbon isotope sample positions
Location 50.
Location 49.
Location 47.
Location 46.
- MB
- MB
PS9|PS10
No exposure (c. 20 m)
nassa
Coalbrookdale Fm.
Farley Mb.
Scale change
EATON TRACK (upper part)
- MB
Location 25.
Location 24.
No exposure (c. 3.5 m)
Location 23.
Location 22.
5 m
Apedale Mb.
lundgreni
No exposure (c. 3.6 m) Fallen Tree
Location 21.
δ13Ccarb (‰ VPDB)
0 1 2 3 4
Shale
Shale with nodular limestones (mostly carbonate mudstone)
Limestones (mostly carbonate mudstone with occasional wackestone to grainstone) with shale partings

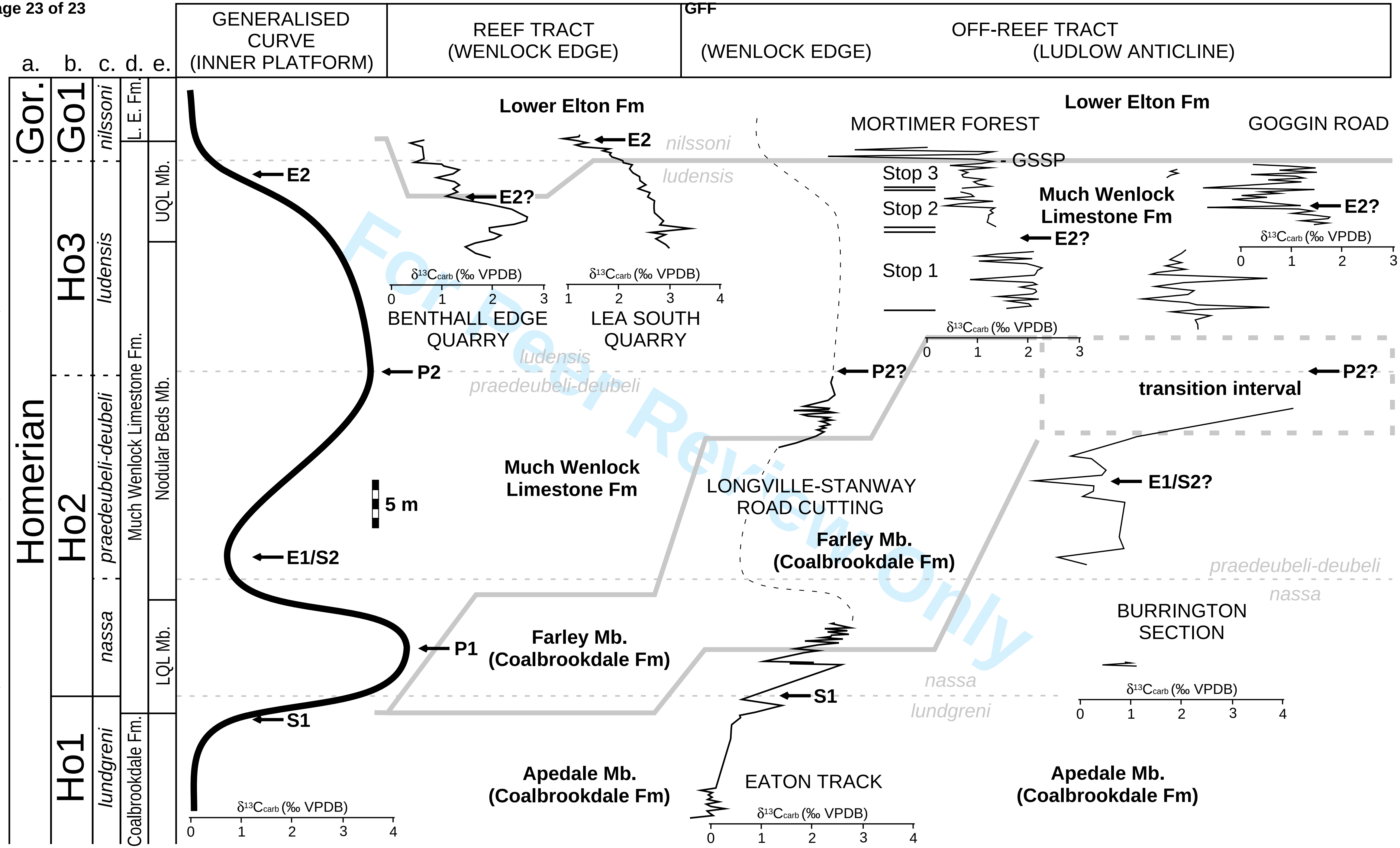

a. b. BURRINGTON SECTION
Likely graptolite collection positions
Carbon isotope sample positions
Location 64.
Poor exposure (c. 7.0 m)
Scale change
Location 63.
Much Wenlock Limestone Formation
ludensis
- MB
- MB
Poor exposure (c. 7.5 m)
Scale change
Location 62.
transition interval
praedeubeli-deubeli
Telegraph pole #47
5 m
Coalbrookdale Formation
Location 61.
Telegraph pole #46
No exposure / fault (c. 10.0 m)
North-South trending fault (Holland et al. 1969)
nassa
Location 60.
Scale change
δ13Ccarb (‰ VPDB)
0 1 2 3 4

Sample Code	Position from lowest sample (m)	$\delta^{13}C$	$\delta^{18}O$
Eaton Track (EAT)			
EAT001	c. -33.00	-0.97	-9.5
Location 19			
EAT002	c. -29.0	-1.14	-8.5
EAT003	c. -28.8	-1.03	-8.8
EAT004	c. -28.6	-1.75	-8.5
EAT005	c. -28.4	-1.19	-8.9
EAT006	c. -28.2	-1.23	-8.8
EAT007	c. -28.0	-1.15	-8.9
EAT008	c. -27.8	-1.25	-8.7
EAT009	c. -27.6	-1.11	-8.8
EAT010	c. -27.4	-1.14	-9.7
Location 20			
EAT011	c. -27.0	-0.97	-8.3
EAT012	c. -26.8	-1.42	-8.5
EAT013	c. -26.6	-1.55	-8.4
EAT014	c. -26.4	-1.50	-8.0
Between locations 20 and 21			
EAT015	c. -15.0	-0.89	-8.3
EAT016	c. -14.5	-1.44	-8.6
EAT017	c. -14.0	-0.71	-8.4
EAT018	c. -13.5	-0.83	-8.7
EAT019	c. -13.0	-0.92	-8.2
EAT020	c. -12.5	-0.40	-8.7
Locations 21 to 25			
EAT021	0.00	-0.39	-7.5
EAT022	0.25	0.06	-7.2
EAT023	0.50	-0.01	-7.5
EAT024	0.75	-0.07	-8.0
EAT025	1.00	0.28	-7.9
EAT026	1.25	0.01	-8.0
EAT027	1.50	-0.09	-8.2
EAT028	1.75	0.17	-9.0
EAT029	2.00	-0.06	-8.3
EAT030	2.25	0.03	-7.8
EAT031	2.50	-0.06	-7.6
EAT032	2.75	0.04	-7.6
EAT033	3.00	-0.18	-8.3
EAT034	3.25	0.12	-7.6
EAT035	8.95	0.41	-6.8
EAT036	9.40	0.42	-6.5
EAT037	10.14	0.60	-6.0
EAT038	10.41	0.58	-7.2
EAT039	10.77	0.89	-7.0
EAT040	11.47	1.43	-7.9
EAT041	12.15	0.62	-8.3
EAT042	15.93	2.64	-6.1
EAT043	16.06	1.59	-7.7
EAT044	16.17	2.08	-7.8
EAT045	16.29	1.08	-4.3
EAT046	17.24	1.87	-7.8
EAT047	17.45	2.15	-7.5
EAT048	17.69	1.69	-4.6
EAT049	18.11	2.17	-7.3
EAT050	18.33	2.57	-5.2
EAT051	18.52	1.90	-5.2
EAT052	18.73	2.66	-6.3
EAT053	18.91	2.25	-8.0
EAT054	19.03	2.42	-6.8
EAT055	19.16	2.44	-6.3
EAT056	19.27	2.79	-4.5
EAT057	19.41	2.55	-6.3
EAT058	19.53	2.37	-6.8
EAT059	19.66	2.75	-4.7
EAT060	19.89	2.31	-6.4
EAT061	19.98	2.82	-5.1
EAT062	20.43	2.44	-6.2
EAT063	20.51	2.51	-4.9

Sample Code	Position from lowest sample (m)	$\delta^{13}C$	$\delta^{18}O$
Longville-Stanway Road Cutting (LON)			
LON001	0.00	1.35	-3.8
LON002	0.47	1.69	-3.7
LON003	1.13	2.09	-5.8
LON004	1.56	2.25	-5.9
LON005	1.76	2.11	-5.9
LON006	1.93	2.28	-5.7
LON007	2.11	2.20	-6.0
LON008	2.28	2.36	-5.1
LON009	2.41	2.31	-6.7
LON010	2.58	2.19	-6.2
LON011	2.72	2.41	-5.7
LON012	2.83	2.25	-6.1
LON013	2.98	2.34	-6.1
LON014	3.12	1.93	-7.4
LON015	3.24	1.83	-6.4
LON016	3.37	2.08	-5.8
LON017	3.45	2.44	-6.0
LON018	3.58	2.35	-6.1
LON019	3.66	1.66	-8.0
LON020	3.77	2.34	-6.1
LON021	3.89	2.35	-5.7
LON022	4.08	1.86	-6.5
LON023	4.69	2.33	-5.8
LON024	5.22	2.47	-5.8
LON025	6.45	2.39	-5.5
LON026	7.09	2.43	-5.6

Sample Code	Position from lowest sample (m)	$\delta^{13}C$	$\delta^{18}O$
Burrington Section (BUR)			
BUR001	0.00	1.21	-6.5
BUR002	0.10	0.60	-7.0
BUR003	0.30	1.13	-7.8
BUR004	0.40	1.01	-7.5
c. 10 m gap in section, plus fault			
BUR005	10.40	0.15	-6.9
BUR006	11.18	-0.40	-6.7
BUR007	12.08	0.84	-6.7
BUR008	13.27	0.75	-7.9
BUR009	16.87	0.85	-6.9
BUR010	17.47	0.07	-7.5
BUR011	18.00	0.27	-7.3
BUR012	18.58	0.28	-7.6
BUR013	19.10	-0.83	-7.2
BUR014	19.67	0.43	-6.9
BUR015	20.17	0.51	-6.6
BUR016	21.40	0.23	-7.1
BUR017	21.66	-0.15	-7.4
BUR018	23.37	0.92	-7.5
BUR019	23.67	1.09	-6.6
BUR020	26.60	4.04	-6.7
c. 7.5 m gap in section			
BUR021	34.06	2.36	-5.4
BUR022	34.61	2.34	-5.3
BUR023	35.02	2.30	-5.3
BUR024	35.49	2.60	-5.4
BUR025	35.93	1.84	-7.4
BUR026	36.14	2.42	-6.1
BUR027	36.36	3.80	-0.9
BUR028	36.61	2.34	-6.1
BUR029	36.86	2.17	-6.1
BUR030	37.22	1.24	-6.5
BUR031	37.72	2.16	-6.0
BUR032	38.09	2.27	-6.0
BUR033	38.52	1.51	-6.9
BUR034	38.91	2.08	-6.1
BUR035	39.36	3.74	-0.8
BUR036	39.80	1.42	-5.5
BUR037	39.97	1.56	-5.7
BUR038	40.30	2.11	-5.7
BUR039	40.63	1.72	-5.5
BUR040	41.01	2.04	-5.6
BUR041	41.30	1.81	-5.0
BUR042	41.94	2.02	-5.3
BUR043	42.33	2.12	-5.7
c. 7.0 m gap in section			
BUR044	49.33	1.79	-7.3
BUR045	49.53	1.85	-6.4
BUR046	49.73	1.99	-5.5
BUR047	49.93	1.85	-5.5
BUR048	50.13	1.97	-5.3

Sample Code	Position from lowest sample (m)	$\delta^{13}C$	$\delta^{18}O$
Mortimer Forest Stop 1 (MOR)			
MOR001	0.00	1.61	-7.9
MOR002	0.25	2.11	-5.9
MOR003	0.50	2.07	-6.1
MOR004	0.75	1.64	-6.2
MOR005	1.00	2.26	-6.4
MOR006	1.25	1.45	-7.1
MOR007	1.50	2.15	-6.1
MOR008	1.75	2.22	-5.8
MOR009	2.00	2.19	-6.3
MOR010	2.25	1.89	-6.1
MOR011	2.50	2.22	-6.2
MOR012	2.75	2.14	-6.0
MOR013	3.00	0.88	-7.9
MOR014	3.25	1.47	-8.0
MOR015	3.50	2.18	-6.0
MOR016	3.75	2.21	-6.0
MOR017	4.00	2.24	-5.9
MOR018	4.25	2.33	-6.0
MOR019	4.50	2.17	-5.8
MOR020	4.75	2.02	-6.2
MOR021	5.00	1.06	-8.2
MOR022	5.25	2.14	-6.5
MOR023	5.50	1.05	-8.4
MOR024	5.75	1.42	-8.4
MOR025	6.00	2.16	-6.5


GFF
GENERALISED CURVE (INNER PLATFORM)
REEF TRACT (WENLOCK EDGE)
OFF-REEF TRACT
(WENLOCK EDGE)
(LUDLOW ANTICLINE)
a. b. c. d. e.
Gor. Go1 nilssoni L. E. Fm.
Homerian
Ho3 ludensis
Ho2 praedeubeli-deubeli
Ho1 lundgreni
nassa
Much Wenlock Limestone Fm.
Coalbrookdale Fm.
UQL Mb.
Nodular Beds Mb.
LQL Mb.
Lower Elton Fm
E2
E2?
P2
P2?
E1/S2
E1/S2?
P1
S1
5 m
δ13Ccarb (‰ VPDB)
BENTHALL EDGE QUARRY
LEA SOUTH QUARRY
MORTIMER FOREST
GOGGIN ROAD
GSSP
Stop 3
Stop 2
Stop 1
Much Wenlock Limestone Fm
transition interval
Much Wenlock Limestone Fm
LONGVILLE-STANWAY ROAD CUTTING
Farley Mb. (Coalbrookdale Fm)
BURRINGTON SECTION
EATON TRACK
Apedale Mb. (Coalbrookdale Fm)
nilssoni
ludensis
praedeubeli-deubeli
nassa
lundgreni