

The Furongian (late Cambrian) Steptoean Positive Carbon Isotope Excursion (SPICE) in Avalonia

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The Steptoean Positive Carbon Isotope Excursion (SPICE) of earliest late Cambrian (Furongian) age is identified in England. The excursion is found within a *ca* 145 m thick siliciclastic succession within the middle and higher part of the Outwoods Shale Formation of Warwickshire, and reaches a maximum $\delta^{13}\text{C}_{\text{org}}$ amplitude of 4.1‰ at values of -25.6‰ . Biostratigraphical data show that the excursion occupies the greater part of the *Olenus* trilobite biozone, an equivalent of the *Glyptagnostus reticulatus* biozone that marks the base of the Furongian and coeval base of the Steptoean in North America. The amplitude of the excursion approaches that recorded in limestone-dominated Laurentian successions, and is greater than that recently documented for organic-rich mudstones of palaeocontinental Baltica in southern Sweden. A minor positive excursion above the SPICE may equate with a similar excursion recognised in Siberia. The SPICE in the Outwoods Shale Formation seems closely linked to the widely recognised early Furongian eustatic sea level rise. There is no evidence in the English succession for slightly later regression, elsewhere considered coincident with the peak of the excursion and pivotal to some previous models explaining the SPICE.

Keywords: Cambrian, Furongian, carbon isotope excursion, England, Avalonia

Late Cambrian (Furongian) carbonate successions in many parts of the world (North America, Argentina, Siberia, Kazakhstan, China, Australia) contain an interval of markedly positive $\delta^{13}\text{C}_{\text{carb}}$ values, peaking at $+5\text{‰}$ (Saltzman *et al.*, 2000; Kouchinsky *et al.*, 2008). More recently, the same positive Carbon Isotope Excursion (CIE) has been identified in organic-rich mudstones of the Alum Shale Formation in southern Sweden, where $\delta^{13}\text{C}_{\text{org}}$ peak values are around -28‰ (with a maximum amplitude of around 2‰) (Ahlberg *et al.*, 2009). This CIE, first recognised in the late Cambrian of North America by Brasier (1993) and confirmed as a global CIE by Saltzman *et al.* (1995), is termed the Steptoean Positive Carbon Isotope Excursion (SPICE) (Saltzman *et al.*, 1998). We report here the occurrence of the SPICE in the Cambrian of central England, the first record in an Avalonian succession. The palaeogeographic setting of these mid-shelf clastic deposits contrasts with

areas where the SPICE has previously been identified (e.g. shallow carbonate shelf in North America; shallow, dysoxic-anoxic shelf in southern Sweden). This contrasting setting provides an opportunity to critically assess the likely driving mechanism(s) that created this global isotopic excursion.

The SPICE is believed to have had a duration of about 4 Ma (Saltzman *et al.*, 1998), although 3 Ma is probably a better estimate based on dates recently published by Peng and Babcock (2008). In common with other positive CIEs in the geological record, one interpretation of the SPICE is attributed to increased burial of organic carbon, that is enriched in isotopically light ^{12}C thus increasing the ^{13}C pool in the oceans. However, terrestrial weathering impacts related to sea level and/or climate change have also been considered as explanations (Saltzman *et al.*, 2000, 2004; Gill *et al.*, 2007b).

A link between the SPICE and high organic carbon burial is suggested by data from Nevada that show the event to be associated with a positive sulphur isotope ($\delta^{34}\text{S}$) excursion. This is interpreted to reflect large-scale diagenetic pyrite development and burial under reducing sedimentary conditions (Gill *et al.*, 2007b). This relationship is less clear in western Newfoundland, where SPICE is not positively correlated with $\delta^{34}\text{S}$. It may show that the relationship of SPICE and $\delta^{34}\text{S}$ is significantly affected by local environmental restrictions, heterogeneity of $\delta^{34}\text{S}$ in Cambrian sea water, or ocean redox fluctuations (Hurtgen *et al.*, 2009). There is also no evidence for widespread black shales coinciding with the positive CIE, although these may have been restricted to deep ocean basins rather than the relatively shallow shelf margins that are inferred to be the depositional setting of most of the studied late Cambrian successions (Cramer & Saltzman, 2007; Álvaro *et al.*, 2008). An exception is the Alum Shale Formation of Sweden. Here, thick black shales formed across a broad, poorly oxygenated shelf of no great depth, and span a much greater interval of time than represented by the SPICE alone (perhaps 25 Ma) (Thickpenny, 1984, 1987). Glumac and Walker (1998) and Saltzman *et al.* (1998) suggested that ocean stratification and black shale formation might have been widespread in the late Cambrian, with the SPICE representing a short-lived pulse of enhanced ^{13}C burial controlled by weathering or biological productivity. Cowan *et al.* (2003) suggested that very high sea-levels immediately prior to the SPICE could have fertilised the oceans through remobilising nutrients previously concentrated by protracted continental weathering of un-vegetated cratons. This nutrient pulse could have resulted in a surge of biological productivity, creating the SPICE.

Saltzman *et al.* (2000, 2004) discussed the potential role of globally enhanced weathering of isotopically heavy marine carbonates linked to a glacial event as a driver for the SPICE. Although supporting evidence for this appears to be provided by a purported widespread sea level fall (of about 25 m; Saltzman *et al.*, 2000) that coincides with the peak of the SPICE, there is no unambiguous evidence for a high latitude ice sheet in the late Cambrian (Saltzman *et al.*, 2000). There are also geochemical data from Siberia suggesting that the SPICE broadly coincides with very high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in sea water, implying high rates of continental chemical weathering for the late Cambrian (Kouchinsky *et al.*, 2008). Whilst enhanced chemical weathering may lead to

global cooling through draw-down of atmospheric carbon dioxide, some data suggest that rates of chemical weathering are relatively low in modern-day cold environments (Raymo, 1991); perhaps the geochemical data are symptomatic of global greenhouse conditions during the SPICE. There is a further problem with the interpretation of relative sea level changes with respect to the SPICE. Although there appears to be a general consensus that the peak of the SPICE coincided with a global sea level lowstand, this scenario requires differing palaeoenvironmental interpretations for lithologically similar units; shale/wackestone-dominated sediments deposited at the onset of the SPICE in North America reflect drowning of the carbonate shelf, whilst similar lithofacies at the peak of the SPICE are believed to represent lowstand deposits, the latter based largely on the presence of an inferred coeval hiatus in trilobite faunas and missing $\delta^{13}\text{C}$ SPICE in North American cratonic successions (Saltzman *et al.*, 1998). Other evidence cited in favour of global late Cambrian regression includes carbonate platform exposure in Queensland and seamount-margin collapse in Kazakhstan (Cook *et al.*, 1991; Saltzman *et al.*, 2004).

Whatever theory is advanced to explain the SPICE, it needs to take account of strong circumstantial evidence for a link with changes of diversity in trilobite populations (Saltzman *et al.*, 1998; Zhu *et al.*, 2006). After an initial extinction event, at the onset of the SPICE, some studies have recorded a diversification of trilobite faunas through the overlying succession occupied by the excursion, with peak diversity coinciding with the peak of the excursion (Saltzman *et al.*, 2000). An exception to this pattern occurs in shallow marine carbonates of the northwestern Siberian platform, where the mostly endemic trilobite fauna declines in diversity below the onset of SPICE, and continues to decline through the event (Kouchinsky *et al.*, 2008).

With so many uncertainties remaining about the interpretation of the SPICE, its wider recognition in a variety of contrasting palaeogeographical and palaeoenvironmental settings appears to offer the best hope for future understanding.

Geological setting

In the late Cambrian, southern Britain occupied a high latitude (*ca* 60°) location in the southern hemisphere, on the south-east margin of the Iapetus Ocean (Cocks & Torsvik, 2002; Fig. 1). The region formed part of Eastern Avalonia, a small palaeocontinent that also comprised crustal fragments of North America, Belgium and Germany, that may have been attached to the western edge of Gondwana throughout the Cambrian (Brenchley *et al.*, 2006), or which may have been separated from it (Landing & MacGabhann, 2010). Within this broader framework, three main depositional settings can be recognised in the Cambrian of southern Britain: the Welsh Basin to the west, the Midland Platform covering central England, and a conjectural Anglian Basin to the east (Fig. 2). The Welsh succession is structurally complex and the Anglian succession unproven. In North Wales, Furongian (late Cambrian) rocks that are coeval with the SPICE are mainly represented by parts of the turbiditic Maentwrog and Ffestiniog Flags formations (Mawddach Group)

(Allen & Jackson, 1985; Pratt *et al.*, 1995; Howells & Smith, 1997; Young *et al.*, 2002) or, locally, by the partial laterally equivalent Marchlyn Formation (Howells & Smith; Howells, 2007); in South Wales they form part of the Lingula Flags Formation. These units comprise mudstones, siltstones and sandstones. Correlative Furongian mudstones are absent from Shropshire and poorly known at Malvern (Cowie *et al.*, 1972; Rushton, 1999).

Across the Midland Platform, Furongian strata are relatively complete and undisturbed. The region formed a stable, but gently subsiding, intra-cratonic shelf (Bridge *et al.*, 1998; Brenchley *et al.*, 2006; Rushton *et al.*, 1999), across which there was near-continuous deposition throughout most of the later Cambrian, and limited post-depositional deformation. This geological setting, combined with the availability of borehole material with comprehensive biostratigraphical data, make the succession of the Midland Platform the optimum area in the southern UK for investigation of the SPICE. The 950 m thick Cambrian succession partly crops out within a narrow, south-westward dipping inlier near Nuneaton, Warwickshire (Fig. 3), and consists of the sand-rich early Cambrian Hartshill Sandstone Formation, overlain by the mudrock-dominated Stockingford Shale Group, of mid Cambrian to earliest Ordovician age. Although marine depositional environments across the Midland Shelf are thought to have been relatively shallow throughout the Cambrian, the finer-grained sediments of the Stockingford Shale Group probably represent comparatively deeper water conditions. The group comprises a number of mudstone formations, and a thin sandstone unit (Moor Wood Sandstone Formation; 15 m thick) of limited geographical development (Bridge *et al.*, 1998). One of these mudstone units, named the Outwoods Shale Formation, is coeval with strata in North America recording the SPICE (Fig. 4).

The Outwoods Shale Formation comprises interbedded dark grey and pale grey mudstones, and rare, very thin (typically 25 mm) sandstones with wavy or current bedding (Taylor & Rushton, 1971, pp. 9 – 22). Whilst deposition probably occurred under poorly oxygenated conditions, alternation of dark, pyritic mudstones with grey, burrowed mudstones suggests frequent fluctuation between relatively reducing and oxidizing marine environments (Taylor & Rushton, 1971). This is consistent with high frequency fluctuations in total organic carbon (TOC) data obtained from the Outwoods Shale Formation during this study (Appendix 1) The Outwoods Shale Formation is intruded by spessartite lamprophyre sills (forming part of the Midlands Minor Intrusive Suite) dated as Late Ordovician (Bridge *et al.*, 1998), making accurate assessment of the formation's true thickness problematic. Including intrusive rocks, Taylor and Rushton (1971) calculated it as about 300 m thick; Bridge *et al.* (1998) estimated it to be 250 m excluding the igneous rocks.

The fauna of the Outwoods Shale Formation includes 36 species of trilobite (+ agnostoids), indicating assignment to the *Agnostus pisiformis*, *Olenus* and *Parabolina spinulosa* biozones (Taylor & Rushton, 1971; Rushton, 1978, 1983; Bridge *et al.*, 1998; Fig. 4). The fauna includes cosmopolitan genera that Taylor and Rushton (1971) equated with the Dresbachian and lowest Franconian stages of North America; stages that equate with the Marjuman and Steptoean of Ludvigsen and Westrop (1985).

In the late 1960s the British Geological Survey (BGS) drilled a number of boreholes in the Nuneaton area of Warwickshire, two of which penetrated the Outwoods Shale Formation (Fig. 3). Cores from these boreholes form the basis of the current investigation into the development of the SPICE in Avalonia. The base and lower part of the formation were proved by Merevale Borehole No. 3 [National Grid Reference SP 3071 9574; depth interval 0 – 157.96 m], and the top and higher part of the formation were proved by Merevale Borehole No. 1 [SP 2994 9608; depth interval 130.28 – 217.63 m] (Fig. 5). Between the base of Merevale No. 1 and the top of Merevale No. 3 there is an un-cored interval, approximately 50 m thick, which is represented in outcrops and was sampled at Oldbury Quarry [SP 310 950, 305 960].

Material and methods

Curated borehole material from the Outwoods Shale Formation in Merevale boreholes 1 and 3 includes bulk rock samples from every 1ft (ca 0.3 m) core interval. This material was sub-sampled for organic carbon isotope analysis ($\delta^{13}\text{C}_{\text{org}}$) at 1.22 m (4 ft) intervals, between 89 m (292 ft) and ca 1.8 m (6 ft) depth in Merevale Borehole 3, and 217.6 m (714 ft) and 130.75 m (429 ft) in Merevale Borehole 1. Based on an average dip of 26° for the strata in Merevale 1 and 35° for Merevale 3, the true vertical depth frequency for sampling of these boreholes is 1.09 m and 0.97 m respectively. Some irregularities in sample frequency result from small intervals of core loss or absence of bulk material for sampling at particular depths in the archived samples. The borehole sampling included intervals adjacent to igneous intrusions, so that the impact of these on isotopic values could be assessed.

The detailed biostratigraphy of the Merevale boreholes was described by Taylor & Rushton (1971) and Rushton (1978, 1983). These Furongian trilobite faunas resemble coeval successions in Scandinavia, characterised by the olenid biofacies. This facies is generally considered to reflect poorly oxygenated marine environments, as also indicated by the presence of phosphatocopid arthropods (Williams *et al.* 1994; Williams & Siveter, 1998). The interval we sampled ranges from the upper part of the *Agnostus pisiformis* Biozone, through the *Olenus* Biozone (= *Glyptagnostus reticulatus* Biozone of Terfelt *et al.*, 2008), to the base of the *Parabolina spinulosa* Biozone, a biostratigraphical interval that spans strata coeval with the North American Steptoean succession (Fig. 4). Direct correlatives of the subzones in the lower part of the Scandinavian *Olenus* Biozone are recognisable in the Outwoods Shale Formation, the base of the zone being taken at the first appearance of *Glyptagnostus reticulatus* (Angelin) and *Olenus gibbosus* (Wahlenberg), at 55 m depth in Merevale Borehole 3. The latter differs from the usage of Rushton (1978), which was based on the appearance of *Homagnostus obesus* (Belt) at 61 m depth. The upper part of the *Olenus* Biozone, represented in the outcropping succession in Oldbury Quarry and in Merevale Borehole 1 (Fig. 5), was designated the *O. cataractes* Subzone by Rushton (1983), because the homotaxial Scandinavian subzones of *O. attenuatus*, *O. dentatus* and *O. scanicus* could not be recognised in detail. In Sweden, the presence of *Irvingella major* Ulrich & Resser in the base of the *P.*

spinulosa Biozone (Rushton & Weidner, 2010) suggests that the top of the Steptoean and the top of the *Olenus* Biozone are practically coincident.

Supplementary bulk rock sampling was undertaken on the exposed succession at Oldbury Quarry [SP 30965 94922], covering the stratigraphical gap in the cored succession between the base of Merevale Borehole 1 and the top of Merevale Borehole 3 (drilled in the bottom of the quarry). Most of the outcrop sampling was at 1 m intervals (true vertical depth), and spans a total stratigraphical interval of ca 47 m, including a 5 m thick igneous intrusion (Fig. 6). These samples also provided additional faunal data for the outcropping succession.

The samples were initially treated with 5% hydrochloric acid (HCl) to remove any carbonate material. To achieve this, approximately 1g of sample material was placed in a 500 ml beaker and 100 ml of 5% HCl acid reagent added and left for 24 hours. Depending on the carbonate content additional acid was added to maintain an acidic solution. After 24 hours, the beaker was topped up to 500 ml with deionised water and the sample material allowed to settle for a further 24 hours. Once settled, the supernatant was decanted, ensuring minimal disturbance of the sediment, and the beaker then topped up again to 500 ml with deionised water. Dilution was repeated 3 times in total with an overall minimum of 1200 ml of deionised water used. After the final decanting, the excess water (50 – 100 ml) was allowed to evaporate off in a drying oven at ~50°C. Once dry, the sample was loosened from the base of the beaker with a clean plastic spatula and transferred to an agate pestle and mortar, ground, and a known quantity (~500 µg C) weighed into a tin capsule.

$^{13}\text{C}/^{12}\text{C}$ analyses were performed using a Carlo Erba 1500 on-line to a VG TripleTrap (plus secondary cryogenic trap in the mass spectrometer for these very low carbon content samples) and Optima dual-inlet mass spectrometer, with $\delta^{13}\text{C}$ values calculated to the VPDB scale using a within-run laboratory standard (BROC1) calibrated against NBS-19 and NBS-22. Replicate analysis of well-mixed samples indicated a precision of about 0.2‰ (1 SD).

Analytical Results

Figure 5 shows bulk rock $\delta^{13}\text{C}_{\text{org}}$ for the sampled interval in Merevale boreholes 1 and 3 and the outcropping succession at Oldbury Quarry. A table of analytical results is given in Appendix 1, including total organic carbon (TOC) values for each sample.

$\delta^{13}\text{C}_{\text{org}}$ shows the development of a broad positive CIE (Excursion1) within the *Olenus* Biozone of the Outwoods Shale Formation, with maximum amplitude of around 4.1‰. A smaller positive excursion (Excursion 2), with amplitude of about 1.1‰, occurs in the top of the *Olenus* Biozone and basal *P. spinulosa* Biozone. Excursion 1 occupies an estimated (dip corrected) composite stratigraphical thickness of about 145 m, whilst Excursion 2 spans a 25 m thick interval.

The base of Excursion 1 begins at around 54 m depth in Merevale Borehole 3, approximately 7 m above the base of the *Olenus* Biozone, where there is a distinct inflection in $\delta^{13}\text{C}_{\text{org}}$ and the start of an upward trend to more positive $\delta^{13}\text{C}_{\text{org}}$. Values of $\delta^{13}\text{C}_{\text{org}}$ peak at -27.2‰ in the upper part of Merevale Borehole 3, increase further to -25.6‰ in the outcrop succession at Oldbury Quarry (Figs 5, 6), and then progressively decline to -29.7‰ at the top of the excursion in the Merevale 1 succession, measured as occurring at approximately 174 m depth.

From 85 m to 54 m depth in Merevale Borehole 3, and between 162.5 m and 173.5 m in Merevale Borehole 1, values of $\delta^{13}\text{C}_{\text{org}}$ are relatively stable within the range -29.7 to -29.1‰ (Fig. 5), and are taken to represent typical background values against which to assess the development of excursions. Below 85 m depth in Merevale Borehole 3, $\delta^{13}\text{C}_{\text{org}}$ is significantly lower, falling to a minimum of -31.6‰ in the 7 m interval above a thick sill (with its top at 91.75 m; Fig. 5). This sharp decline is attributed to the impact of the sill on the carbon isotope values of the immediately adjacent mudstones. The fact that this lowering of $\delta^{13}\text{C}_{\text{org}}$ is stratigraphically confined to a narrow (*ca* 7 m) interval above the sill strongly suggests that the igneous intrusions in the Outwoods Shale Formation have not significantly compromised the primary carbon isotope composition of the formation as a whole. A similar local effect is seen in mudstones adjacent to a sill intruding the sampled outcrop succession in Oldbury Quarry (Fig. 6). In general, the effect of diagenesis on $\delta^{13}\text{C}$ values is relatively limited (Sharp, 2007), as demonstrated by the survival of the SPICE signature in highly altered, dolomitised and ore-bearing rocks (He, 1995; Saltzman *et al.*, 2000). The consistent trend and biostratigraphical correlation of the SPICE in the Nuneaton succession (Fig. 5, 7) with SPICE signatures from elsewhere strongly indicate the general robustness of our $\delta^{13}\text{C}$ values.

TOC values for the sampled succession are low, averaging around 2%, with high frequency oscillations through much of the succession probably reflecting primary alternations in the sedimentary environment (see above). Within a few metres of igneous intrusions TOC values are generally lower and less variable, consistent with these bodies having a localised geochemical impact.

Global Comparison

The development of a significant positive CIE, spanning the bulk of the *Olenus* Biozone (Excursion 1) in the Outwoods Shale Formation, clearly correlates with the late Cambrian SPICE. Published biostratigraphical data provide strong evidence for independent correlation of the *Olenus* Biozone of the English late Cambrian with the basal Furongian and coeval North American Steptoean succession, including the presence of the global index trilobite species *Glyptagnostus reticulatus* (Taylor & Rushton, 1971; Rushton, 1983; Fig. 7). Whilst acknowledging that $\delta^{13}\text{C}$ values derived from organic and carbonate sources can vary (Young *et al.*, 2008), it is interesting to note that the amplitude of the excursion in the Outwoods Shale Formation (4.1‰) is only slightly lower than the maximum (5‰) documented for the SPICE in the carbonate-dominated successions ($\delta^{13}\text{C}_{\text{carb}}$) in North America, and is

substantially greater than that determined for organic-rich mudstones ($\delta^{13}\text{C}_{\text{org}}$) of southern Sweden (1.5 to 2.0‰) (Saltzman *et al.*, 2004; Ahlberg *et al.*, 2009).

Figure 7 shows a comparison of the Outwoods Shale Formation $\delta^{13}\text{C}_{\text{org}}$ curve with worldwide signatures (both $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{carb}}$) documented for the SPICE, using the first appearance of the cosmopolitan agnostoid *Glyptagnostus reticulatus* as a common datum. Although similarity of $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{carb}}$ signatures is not necessarily to be expected even from the same succession (Young *et al.*, 2008), there is a striking general correspondence of these global curves. The Avalonian ($\delta^{13}\text{C}_{\text{org}}$) and Siberian ($\delta^{13}\text{C}_{\text{carb}}$) signatures match in the general form of the SPICE peak and in the development of a higher secondary peak, although independent evidence for correlation of the Siberian 'post SPICE' peak and Excursion 2 is lacking. Differences between $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{carb}}$ are usually caused by fractionation effects (especially photosynthetic fractionation) that are largely controlled by water temperature, concentration of dissolved carbon dioxide and nutrient supply (Young *et al.*, 2008). Decreased isotopic difference between $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{carb}}$ signatures in the Ordovician has previously been attributed to critically high or low concentrations of atmospheric carbon dioxide (Young *et al.*, 2008, and references therein); perhaps the general similarity of the Avalonian and Siberian curves on Figure 7, which occupy distinctly different palaeolatitudes (Fig. 1), might be similarly interpreted. Although high carbon dioxide is favoured by established views of the late Cambrian palaeoenvironment, evidence for at least periodically low atmospheric carbon dioxide has recently been inferred from latest Furongian equatorial beach deposits, allegedly showing evidence of freeze-thaw effects (Runkel *et al.*, 2010).

It is notable that the SPICE in England, and to a lesser extent in Siberia, is characterised by a long and gradual upward decline in $\delta^{13}\text{C}_{\text{org}}$ above the peak CIE. In some other successions the decline in values above the peak of the SPICE is more abrupt, which may be influenced by sampling density and/or stratigraphical completeness. In the case of the Nevada succession, this may be caused by erosion associated with a proposed drop in sea level near the peak of the SPICE (Saltzman *et al.*, 2004; Peng *et al.*, 2004).

Lithofacies and sea level

To investigate if there is any significant relationship between the development of the positive $\delta^{13}\text{C}_{\text{org}}$ excursion and lithofacies in the English succession, graphic outline lithological logs have been generated from the published descriptions of the Merevale boreholes (Taylor & Rushton, 1971; Fig. 5). These logs do not show an *exact* relationship between the onset of the SPICE and lithofacies changes. However, the relatively sudden appearance of phosphatic nodules a few metres above the base of the SPICE, closely associated with a concentration of thin 'glaucopitic' sandstone lenses, may indicate a sharp reduction in rates of deposition. This is most consistent with a marine transgression and subsequent highstand, where rapid deepening starves the shelf of sediment (Huggett & Gale, 1997). Burrowing and the frequency of thin sandstones both gradually decline as $\delta^{13}\text{C}_{\text{org}}$ values

continue to rise in the upper part of the Merevale 3 Borehole (Fig. 5). These features could also indicate marine deepening, leading to reduced circulation and the more frequent establishment of seabed anoxia. If the sandstones represent intermittent high-density gravity flows, as suggested by Bridge *et al.* (1998), then the creation of extra accommodation space at the basin margins would reduce their development and extent in shelf successions, and further promote the establishment of oxygen-poor environments.

There are no major lithofacies changes associated with the development of the peak of the SPICE in the Outwoods Shale Formation, nor any evidence of a eustatic fall in sea level (Fig. 6). The estimated magnitude of the eustatic change in North America is modest (*ca* 25 m; Saltzman *et al.*, 2000), and may have been compensated for by more active basin subsidence affecting the English succession, or masked by the relatively greater depth of the basin. The record of phosphatic nodules in the relatively narrow interval spanning the upper part of the Oldbury Quarry and basal 13 m of Outwoods Shale Formation in Merevale Borehole 1 (Fig. 5, 6), might suggest a brief period of reduced sedimentation rates and/or current winnowing.

Published data for southern Britain show a pulsed rise in sea level throughout the Cambrian, culminating in a late Cambrian highstand during which there were three cycles of fall and rise in sea level associated with faunal changes (Woodcock, 2000). Little has been published on the detailed sequence stratigraphy of the Cambrian in southern Britain. However, data for the Welsh Basin suggests that relatively few of the Cambrian sequences recognised in this area are likely to be purely eustatic in origin (Woodcock, 1990).

Faunal Diversity & Extinction

Major trilobite faunal changes accompany the development of the SPICE in North America, Kazakhstan and China (Saltzman *et al.*, 2000), but in the Outwoods Shale Formation the relationship appears more subtle. Furongian trilobite faunas of Avalonia and Baltica belong to the Olenid Biofacies that developed in response to oxygen-deficient marine environments characterised by mudstone deposition. In contrast, coeval faunas in Laurentia inhabited carbonate-dominated marine shelves, and show much higher overall diversity. Despite these difficulties of comparison, the sporadic faunal evidence from the Outwoods Shale Formation is that there is no direct analogue of the trilobite extinction event that heralds the onset of the SPICE elsewhere. This might simply be explained by the fact that the Avalonian trilobites already occupied challenging palaeoenvironments, and that the SPICE, and its environmental consequences, simply had a lower impact on these faunas. In Baltica, where the trilobite fauna is broadly comparable to Avalonia, the replacement of trilobites by phosphatocopids in the top of the *A. pisiformis* Biozone suggests that palaeoenvironmental conditions were already inhospitable immediately prior to the development of the SPICE and the appearance of *Olenus* (Williams *et al.*, 1994).

Although faunal data from the Outwoods Shale Formation are based on collecting from limited diameter borehole core and sampling of discontinuous

outcrops, there is some evidence for slightly more diverse trilobite faunas in the higher part of the *Olenus* Biozone (Rushton, 1983). Some 15 trilobite taxa occur in the *O. cataractes* Subzone (spanning the peak and falling limb of the CIE) compared to 9 taxa in the lower part of the *Olenus* Biozone. This pattern is somewhat analogous to trilobite diversity trends reported for North America (Saltzman *et al.*, 2000). The *O. cataractes* Subzone fauna includes non-olenid forms, such as agnostoids, *Proceratopyge*, *Irvingella* and *Cliffia?* (Rushton, 1983). Based on the horizon of the trilobite inceptions recorded by Rushton (1983), the bulk of the taxa in the *O. cataractes* Subzone appear just above the peak of the SPICE (i.e. above the peak of Excursion 1 on Fig. 5). Of the 4 taxa that appear around the peak of the CIE, 3 have, so far as is known, very limited ranges, and may reflect niche exploitation by a trilobite fauna that was adapted to adverse palaeoenvironments. The remainder of the *O. cataractes* Subzone fauna could, at least in part, reflect faunal recovery following the extreme environmental perturbation recorded by the SPICE. In more condensed successions and/or where a drop in sea level and possible erosion are coincident with the peak of the SPICE, faunas in the overlying succession might appear to be artificially close to the CIE peak, making an assessment of the impact of the CIE on diversification trends less straightforward.

New palaeontological data for the Oldbury Quarry succession show that the biota is dominated by algal remains, described by Taylor and Rushton (1971) as resembling such Cambrian algae as *Morainia*, *Bosworthia* and *Yuknessia*. There are also infrequent specimens of the possibly worm-like “Problematicum A” described by Taylor and Rushton (1971, p. 25). Calcareous fossils are very rare, comprising a single indeterminate agnostoid. Phosphatic fossils include two small lingulate brachiopods and three phosphatocopids; a possible specimen of *Veldotron* suggests correlation with the *O. cataractes* Subzone, based on records by Williams and Siveter (1998). The sparseness of fauna is consistent with the general faunal character of the higher part of the Outwoods Shale Formation (despite the slightly greater diversity over this interval), and with the coeval higher part of the Alum Shale Formation in Sweden. Schovsbo (2007) attributed the lack of fauna in the Swedish succession to reduced preservation of calcareous faunas; there, times of increased bottom-water aeration caused generation of corrosive pore waters through oxidation of sulphides, reducing the preservation potential of calcareous remains. The same process may be applicable to the Nuneaton succession, reflecting oxygen recovery of the marine environment following the peak of the SPICE near the base of the Oldbury Quarry succession.

Driving mechanisms for SPICE

Previous attempts to understand the mechanism(s) controlling the development of SPICE have focussed on the relationship of the positive CIE to inferred sea level change and to patterns of biotic change in trilobite populations (Saltzman *et al.*, 2004; Zhu *et al.*, 2006). Lithological evidence, tentatively suggesting that the onset of the SPICE in the Outwoods Shale Formation coincides with a reduction in sedimentation triggered by a relative

rise in sea level, is consistent with a widely inferred eustatic rise at the base of the Furongian (Peng *et al.*, 2004). The association of a eustatic rise in sea level with positive CIEs is also a feature developed in Mesozoic successions (Jones & Jenkyns, 2001). Some previous research has suggested that the SPICE was caused by a slightly later Furongian regression event that appears to be coincident with the CIE peak in Laurentia (Saltzman *et al.*, 2004). Evidence from the $\delta^{13}\text{C}_{\text{org}}$ data from the Outwoods Shale Formation suggests that a positive trend in $\delta^{13}\text{C}$ values was already well established below the peak of SPICE. Apparent diachroneity of the onset and peak of the SPICE, discussed by Ahlberg *et al.* (2009), is attributed to uncertainties in biostratigraphical resolution and variable sampling techniques. Consequently, this later marine regression does not appear to be strongly implicated in triggering the SPICE, and possible scenarios linked to regression (Glumac & Walker, 1998; Saltzman *et al.*, 2004) involving increased sediment deposition and enhanced burial of carbon, or changes in the weathering patterns induced by exposure of shelf margins, seem less plausible explanations. In fact, evidence suggests that there is likely to be a stronger correlation between regression and lowering of $\delta^{13}\text{C}$ (Ripperdan, 2002).

The global record for the Cambrian shows that CIEs occurred with remarkable frequency in the earliest Palaeozoic (Zhu *et al.*, 2006, fig. 1) compared to the Mesozoic and Cenozoic, suggesting that features of the Cambrian made the carbon cycle inherently more sensitive to perturbation. The evidence from the Alum Shale Formation in southern Sweden (Thickpenny, 1987) indicates that parts of the marine ecosystem remained poorly oxygenated for long periods of the early Palaeozoic, beyond those times characterised by positive $\delta^{13}\text{C}$ excursions. This may suggest that large parts of the late Cambrian marine realm were relatively closer to tipping points, and therefore more strongly influenced by smaller degrees of change to critical parameters. More generally, Gill *et al.* (2007b) suggested that the Palaeozoic was a transitional interval between rapid isotopic variability in Proterozoic oceans, to more gradual change in the Mesozoic and Cenozoic. In this context, it might not be necessary to invoke geologically infrequent large-scale changes in ocean circulation pattern (Saltzman *et al.*, 2000) to explain significant shifts in the ^{13}C pool.

The combination of environmental circumstances that led to the SPICE remains enigmatic. Enhanced organic productivity and its burial in an expanded marine oxygen minimum zone seem the most likely processes, as evidenced by some data showing a positive sulphur isotope excursion that parallels SPICE (Gill *et al.*, 2007a, b). In this context, the strongly symmetrical topology of SPICE seen in the high-resolution data for the Nuneaton succession (Figs 5, 7), and in particular its gradual build-up and decline, is speculative evidence for the CIE being a biotic response to biolimiting resources. A basal Furongian eustatic sea level rise could have delivered a powerful nutrient pulse to the oceans, as suggested by Cowan *et al.* (2003). Given the evidence for generally poor ocean ventilation in the mid and late Cambrian, the resulting increase in surface water productivity would have favoured enhanced burial of organic matter, and a trend to more positive $\delta^{13}\text{C}$ values. In this scenario, peak SPICE would reflect maximum biotic response

to the nutrient bonanza, and declining SPICE and return to background $\delta^{13}\text{C}$ values a response to progressive exhaustion of this resource. Subsequent widespread sea level fall and erosion, apparently coincident with peak SPICE in North America (Saltzman *et al.*, 2000), but possibly post-dating this horizon (see Faunal Diversity & Extinction), could have recycled basin-margin sediments enriched in $\delta^{13}\text{C}$, and led to the formation of the 'Post-SPICE Peak' (Fig. 7). The absence of widespread late Cambrian black shale deposits remains a problem for this and other productivity-centred hypotheses. In some parts of the world, these deposits might survive as Cambrian graphite-rich units in metamorphic complexes (B. Windley, oral communication, 2010).

In the late Cambrian, continental masses were concentrated in the southern hemisphere and Gondwana was undergoing extreme levels of chemical weathering producing vast deposits of quartz-rich sandstone and thick offshore marine fan deposits (Álvarez *et al.*, 2008, fig. 2; Avigad *et al.*, 2005; Fig. 1). This may have profoundly affected marine geochemistry, and data from strontium isotopes appear to confirm the unique importance of chemical weathering on ocean geochemistry in the late Cambrian compared to submarine hydrothermal circulation (Kouchinsky *et al.*, 2008). Goddérís *et al.* (2001) have suggested that the early Palaeozoic carbon cycle was significantly influenced by the progressive oxidation of a large reduced carbon reservoir exhumed during the Pan-African Orogeny.

Fuller explanation of the SPICE may depend on a more complete understanding of the role of these factors, rather than relying solely on traditional assumptions about the biotic response to changes in sea level and ocean circulation.

Conclusions

The late Cambrian (Furongian) Outwoods Shale Formation seen in boreholes and outcrop in Warwickshire, England, preserve a relatively expanded positive $\delta^{13}\text{C}_{\text{org}}$ excursion occupying the greater part of the *Olenus* Biozone (= *G. reticulatus* Biozone of Terfelt *et al.*, 2008). This excursion is identified as the SPICE, a globally developed positive $\delta^{13}\text{C}$ excursion not previously recognised in Avalonia. The excursion spans an interval of 145 m, with maximum amplitude of 4.1‰, and is largely unaffected by the presence of Ordovician igneous intrusions. The SPICE signature in the Outwoods Shale Formation appears to have a particularly protracted upper limb, perhaps partly unrepresented in North American successions because of erosion associated with a lowstand. The Outwoods Shale Formation also shows the development of a smaller positive $\delta^{13}\text{C}_{\text{org}}$ excursion, spanning an interval of ca 25 m in the topmost *Olenus* Biozone and basal *P. spinulosa* Biozone, with a maximum amplitude of 1.1‰. This smaller CIE is superficially very similar to the 'Post-SPICE' feature recognised in Siberia.

The relatively shallow, mid-shelf environment with intermittently anoxic and sub-oxic conditions, in which the siliciclastic sediment of the Outwoods Shale Formation was deposited, contrasts with the shallow, well-aerated, basin-

margin, carbonate-dominated succession of North America, and with the shallow, sediment-starved, poorly oxygenated epicontinental sea in which the organic-rich mudstones of the Alum Shale Formation accumulated.

Recognition of the SPICE in the English late Cambrian succession is valuable for global correlation, and may also point to the greater importance of the basal Furongian marine transgression, and possible associated nutrient and productivity pulses, in creating the CIE. The base of the SPICE in the Outwoods Shale Formation is represented by a very distinct positive shift in $\delta^{13}\text{C}_{\text{org}}$ values, significantly below the CIE peak. This suggests that a slightly later regressive event, that has been linked with the positive CIE peak in North America and elsewhere, might not be directly related to the cause of the excursion as has been postulated by some previous research.

The relatively high frequency of carbon isotope excursions in the Cambrian suggests that processes that drove changes in the Mesozoic $\delta^{13}\text{C}$ profile might not fully explain events like the SPICE. Geological processes specific to the Cambrian, such as extreme chemical weathering of Gondwana, palaeogeographic configuration, or ecosystem simplicity could have had a significant role in making this interval of geological time more prone to perturbations of the carbon cycle.

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Appendix 1 – Stable isotope analysis and total organic carbon (%C) of bulk rock samples from the Outwoods Shale Formation in Merevale boreholes 1 and 3 and the Oldbury Quarry outcrop succession. Sample values likely to be affected by proximity to igneous intrusions are shown in bold.

BGS Sample No.	Borehole / Outcrop	Borehole depth (ft / m)	Biozone	$\delta^{13}\text{C}$	%C
SSK3155	Merevale Borehole 1	714 / 217.63	<i>O. cataractes</i>	-27.7	0.4
SSK3156	Merevale Borehole 1	710 / 216.40	<i>O. cataractes</i>	-28.3	2.9
SSK3157	Merevale Borehole 1	706 / 215.19	<i>O. cataractes</i>	-27.7	0.5
SSK3158	Merevale Borehole 1	702 / 213.97	<i>O. cataractes</i>	-27.7	0.3
SSK3159	Merevale Borehole 1	698 / 212.75	<i>O. cataractes</i>	-28.3	1.5
SSK3160	Merevale Borehole 1	694 / 211.53	<i>O. cataractes</i>	-28.3	0.9
SSK3161	Merevale Borehole 1	690 / 210.31	<i>O. cataractes</i>	-28.2	0.6
SSK3163	Merevale Borehole 1	682 / 207.87	<i>O. cataractes</i>	-28.5	1.3
SSK3164	Merevale Borehole 1	678 / 206.65	<i>O. cataractes</i>	-28.3	1.0
SSK3165	Merevale Borehole 1	674 / 205.44	<i>O. cataractes</i>	-28.5	1.3
SSK3166	Merevale Borehole 1	670 / 204.22	<i>O. cataractes</i>	-28.3	0.4
SSK3167	Merevale Borehole 1	666 / 203.00	<i>O. cataractes</i>	-28.7	1.1
SSK3168	Merevale Borehole 1	662 / 201.78	<i>O. cataractes</i>	-28.5	0.3
SSK3169	Merevale Borehole 1	658 / 200.56	<i>O. cataractes</i>	-28.7	1.7
SSK3170	Merevale Borehole 1	654 / 199.34	<i>O. cataractes</i>	-28.7	0.7
SSK3171	Merevale Borehole 1	650 / 198.12	<i>O. cataractes</i>	-28.8	0.8
SSK3172	Merevale Borehole 1	646 / 196.90	<i>O. cataractes</i>	-28.6	0.5
SSK3173	Merevale Borehole 1	642 / 195.68	<i>O. cataractes</i>	-28.8	0.9
SSK3175	Merevale Borehole 1	634 / 193.24	<i>O. cataractes</i>	-29.1	1.8
SSK3176	Merevale Borehole 1	630 / 192.02	<i>O. cataractes</i>	-29.0	0.6
SSK3177	Merevale Borehole 1	626 / 190.80	<i>O. cataractes</i>	-29.1	1.7
SSK3178	Merevale Borehole 1	622 / 189.59	<i>O. cataractes</i>	-29.0	1.1
SSK3179	Merevale Borehole 1	618 / 188.37	<i>O. cataractes</i>	-29.1	0.6
SSK3180	Merevale Borehole 1	614 / 187.15	<i>O. cataractes</i>	-29.0	0.6
SSK3181	Merevale Borehole 1	610 / 185.93	<i>O. cataractes</i>	-29.2	2.0
SSK3182	Merevale Borehole 1	606 / 184.71	<i>O. cataractes</i>	-28.9	0.2
SSK3183	Merevale Borehole 1	602 / 183.49	<i>O. cataractes</i>	-29.2	1.6
SSK3184	Merevale Borehole 1	598 / 182.27	<i>O. cataractes</i>	-29.2	1.1
SSK3185	Merevale Borehole 1	594 / 181.05	<i>O. cataractes</i>	-29.4	2.9
SSK3186	Merevale Borehole 1	590 / 179.83	<i>O. cataractes</i>	-29.4	2.6
SSK3187	Merevale Borehole 1	586 / 178.61	<i>O. cataractes</i>	-29.2	1.6
SSK3188	Merevale Borehole 1	582 / 177.40	<i>O. cataractes</i>	-29.3	3.7
SSK3189	Merevale Borehole 1	578 / 176.17	<i>O. cataractes</i>	-29.6	3.7
SSK3190	Merevale Borehole 1	574 / 174.96	<i>O. cataractes</i>	-29.5	2.0
SSK3191	Merevale Borehole 1	570 / 173.74	<i>O. cataractes</i>	-29.7	3.2
SSK3192	Merevale Borehole 1	566 / 172.52	<i>O. cataractes</i>	-29.4	1.7
SSK3193	Merevale Borehole 1	562 / 171.30	<i>O. cataractes</i>	-29.5	3.4
SSK3194	Merevale Borehole 1	557 / 169.77	<i>O. cataractes</i>	-29.6	2.3
SSK3195	Merevale Borehole 1	554 / 168.86	<i>O. cataractes</i>	-29.4	0.7
SSK3196	Merevale Borehole 1	550 / 167.64	<i>O. cataractes</i>	-29.7	2.2
SSK3197	Merevale Borehole 1	546 / 166.42	<i>O. cataractes</i>	-29.8	2.7
SSK3198	Merevale Borehole 1	542 / 165.20	<i>O. cataractes</i>	-29.6	1.9
SSK3199	Merevale Borehole 1	539 / 164.29	<i>O. cataractes</i>	-29.5	2.0
SSK3200	Merevale Borehole 1	533 / 162.46	<i>O. cataractes</i>	-29.7	2.4

SSK3201	Merevale Borehole 1	530 / 161.54	<i>O. cataractes</i>	-28.8	0.3
SSK3202	Merevale Borehole 1	526 / 160.32	<i>O. cataractes</i>	-29.4	3.0
SSK3203	Merevale Borehole 1	522 / 159.10	<i>O. cataractes</i>	-29.1	1.8
SSK3204	Merevale Borehole 1	518 / 157.89	<i>O. cataractes</i>	-29.1	2.5
SSK3205	Merevale Borehole 1	514 / 156.67	<i>O. cataractes</i>	-29.4	2.3
SSK3206	Merevale Borehole 1	510 / 155.45	<i>O. cataractes</i>	-28.8	0.2
SSK3207	Merevale Borehole 1	507 / 154.53	<i>O. cataractes</i>	-29.1	2.1
SSK3208	Merevale Borehole 1	502 / 153.00	<i>O. cataractes</i>	-29.2	2.7
SSK3209	Merevale Borehole 1	498 / 151.79	<i>O. cataractes</i>	-28.8	1.2
SSK3210	Merevale Borehole 1	494 / 150.57	<i>O. cataractes</i>	-29.3	2.1
SSK3211	Merevale Borehole 1	490 / 149.35	<i>O. cataractes</i>	-29.1	2.3
SSK3212	Merevale Borehole 1	486 / 148.13	<i>O. cataractes</i>	-28.8	0.6
SSK3213	Merevale Borehole 1	482 / 146.91	<i>O. cataractes</i>	-29.2	2.9
SSK3214	Merevale Borehole 1	478 / 145.69	<i>O. cataractes</i>	-29.2	2.0
SSK3215	Merevale Borehole 1	475 / 144.78	<i>O. cataractes</i>	-29.0	3.1
SSK3216	Merevale Borehole 1	470 / 143.26	<i>P. spinulosa</i>	-29.0	1.0
SSK3217	Merevale Borehole 1	466 / 142.04	<i>P. spinulosa</i>	-29.4	1.0
SSK3218	Merevale Borehole 1	462 / 140.82	<i>P. spinulosa</i>	-29.6	1.2
SSK3219	Merevale Borehole 1	458 / 139.60	<i>P. spinulosa</i>	-29.5	1.1
SSK3220	Merevale Borehole 1	454 / 138.38	<i>P. spinulosa</i>	-29.2	1.1
SSK3221	Merevale Borehole 1	450 / 137.16	<i>P. spinulosa</i>	-29.6	0.9
SSK3222	Merevale Borehole 1	446 / 135.94	<i>P. spinulosa</i>	-29.9	1.6
SSK3223	Merevale Borehole 1	442 / 134.72	<i>P. spinulosa</i>	-29.8	1.6
SSK3224	Merevale Borehole 1	438 / 133.50	<i>P. spinulosa</i>	-29.5	0.9
SSK3225	Merevale Borehole 1	434 / 132.28	<i>P. spinulosa</i>	-29.9	2.1
SSK3226	Merevale Borehole 1	429 / 130.76	<i>P. spinulosa</i>	-29.6	1.7
SSK2793	Merevale Borehole 3	292 / 89.00	<i>A. pisiformis</i>	-31.6	1.0
SSK2794	Merevale Borehole 3	290 / 88.39	<i>A. pisiformis</i>	-30.7	0.3
SSK2795	Merevale Borehole 3	286 / 87.17	<i>A. pisiformis</i>	-30.3	0.3
SSK2796	Merevale Borehole 3	278 / 84.73	<i>A. pisiformis</i>	-29.9	1.1
SSK2797	Merevale Borehole 3	262 / 79.86	<i>A. pisiformis</i>	-29.5	0.5
SSK2798	Merevale Borehole 3	240 / 73.15	<i>A. pisiformis</i>	-29.6	1.4
SSK2799	Merevale Borehole 3	236 / 71.93	<i>A. pisiformis</i>	-29.4	1.1
SSK2800	Merevale Borehole 3	232 / 70.71	<i>A. pisiformis</i>	-29.5	1.4
SSK2801	Merevale Borehole 3	228 / 69.49	<i>A. pisiformis</i>	-29.3	0.4
SSK2802	Merevale Borehole 3	224 / 68.28	<i>A. pisiformis</i>	-29.3	1.6
SSK2803	Merevale Borehole 3	220 / 67.06	<i>A. pisiformis</i>	-29.7	2.1
SSK2804	Merevale Borehole 3	216 / 65.84	<i>A. pisiformis</i>	-29.5	1.6
SSK2805	Merevale Borehole 3	212 / 64.62	<i>A. pisiformis</i>	-29.2	1.5
SSK2806	Merevale Borehole 3	208 / 63.40	<i>A. pisiformis</i>	-29.5	0.7
SSK2807	Merevale Borehole 3	204 / 62.18	<i>A. pisiformis</i>	-29.2	0.5
SSK2808	Merevale Borehole 3	200 / 60.96	<i>O. gibbosus</i>	-29.4	1.0
SSK2809	Merevale Borehole 3	198 / 60.35	<i>O. gibbosus</i>	-29.4	2.4
SSK2810	Merevale Borehole 3	194 / 59.13	<i>O. gibbosus</i>	-29.3	0.7
SSK2811	Merevale Borehole 3	190 / 57.91	<i>O. gibbosus</i>	-29.5	1.0
SSK2812	Merevale Borehole 3	186 / 56.69	<i>O. gibbosus</i>	-29.2	0.5
SSK2813	Merevale Borehole 3	182 / 55.47	<i>O. gibbosus</i>	-29.1	2.0
SSK2814	Merevale Borehole 3	178 / 54.25	<i>O. gibbosus</i>	-29.6	1.2
SSK2815	Merevale Borehole 3	176 / 53.64	<i>O. gibbosus</i>	-29.2	0.8
SSK2816	Merevale Borehole 3	170 / 51.82	<i>O. gibbosus</i>	-28.7	1.1
SSK2817	Merevale Borehole 3	166 / 50.60	<i>O. gibbosus</i>	-28.5	1.0
SSK2818	Merevale Borehole 3	162 / 49.38	<i>O. gibbosus</i>	-28.7	1.2
SSK2819	Merevale Borehole 3	158 / 48.16	<i>O. gibbosus</i>	-28.8	2.1
SSK2820	Merevale Borehole 3	154 / 46.94	<i>O. gibbosus</i>	-28.6	1.4
SSK2821	Merevale Borehole 3	150 / 45.72	<i>O. gibbosus</i>	-28.5	2.6
SSK2822	Merevale Borehole 3	146 / 44.50	<i>O. gibbosus</i>	-28.1	1.9

SSK2823	Merevale Borehole 3	142 / 43.28	<i>O. gibbosus</i>	-28.2	2.4
SSK2824	Merevale Borehole 3	138 / 42.06	<i>O. gibbosus</i>	-28.4	3.8
SSK2825	Merevale Borehole 3	134 / 40.84	<i>O. gibbosus</i>	-28.1	1.1
SSK2826	Merevale Borehole 3	130 / 39.62	<i>O. truncatus</i>	-28.0	1.9
SSK2827	Merevale Borehole 3	126 / 38.40	<i>O. truncatus</i>	-27.7	0.3
SSK2828	Merevale Borehole 3	122 / 37.19	<i>O. truncatus</i>	-27.6	0.5
SSK2829	Merevale Borehole 3	118 / 35.97	<i>O. truncatus</i>	-27.7	1.3
SSK3043	Merevale Borehole 3	114 / 34.75	<i>O. truncatus</i>	-28.0	2.3
SSK3044	Merevale Borehole 3	110 / 33.53	<i>O. truncatus</i>	-27.9	2.0
SSK3045	Merevale Borehole 3	106 / 32.31	<i>O. truncatus</i>	-27.9	2.0
SSK3046	Merevale Borehole 3	102 / 31.09	<i>O. truncatus</i>	-28.0	2.6
SSK3047	Merevale Borehole 3	97 8" – 99 / 29.77 – 30.18	<i>O. truncatus</i>	-28.2	2.5
SSK3048	Merevale Borehole 3	89 – 91 / 27.13 – 27.74	<i>O. truncatus</i>	-27.7	1.5
SSK3049	Merevale Borehole 3	88 / 26.82	<i>O. wahlenbergi</i>	-28.2	1.9
SSK3050	Merevale Borehole 3	84 / 25.60	<i>O. wahlenbergi</i>	-27.4	0.4
SSK3051	Merevale Borehole 3	80 / 24.38	<i>O. wahlenbergi</i>	-27.4	1.0
SSK3052	Merevale Borehole 3	78 / 23.77	<i>O. wahlenbergi</i>	-27.6	1.6
SSK3053	Merevale Borehole 3	74 / 22.56	<i>O. wahlenbergi</i>	-27.8	2.3
SSK3054	Merevale Borehole 3	72 / 21.95	<i>O. wahlenbergi</i>	-27.7	1.9
SSK3055	Merevale Borehole 3	68 / 20.73	<i>O. wahlenbergi</i>	-27.2	0.4
SSK3056	Merevale Borehole 3	59 – 63 / 17.98 – 19.20	<i>O. wahlenbergi</i>	-28.3	2.1
SSK3057	Merevale Borehole 3	55 6" – 58 6" / 16.92 – 17.83	<i>O. wahlenbergi</i>	-28.3	2.8
SSK3058	Merevale Borehole 3	52 / 15.85	<i>O. wahlenbergi</i>	-28.3	1.5
SSK3059	Merevale Borehole 3	48 / 14.63	<i>O. wahlenbergi</i>	-28.9	2.0
SSK3060	Merevale Borehole 3	44 / 13.41	<i>O. wahlenbergi</i>	-27.4	0.2
SSK3061	Merevale Borehole 3	40 / 12.19	<i>O. wahlenbergi</i>	-27.5	0.3
SSK3062	Merevale Borehole 3	36 / 10.97	<i>O. wahlenbergi</i>	-27.8	1.4
SSK3063	Merevale Borehole 3	32 / 9.75	<i>O. wahlenbergi</i>	-27.8	0.2
SSK3064	Merevale Borehole 3	28 / 8.53	<i>O. wahlenbergi</i>	-27.5	1.2
SSK3065	Merevale Borehole 3	24 / 7.32	<i>O. wahlenbergi</i>	-27.9	0.8
SSK3066	Merevale Borehole 3	20 / 6.10	<i>O. wahlenbergi</i>	-27.9	0.7
SSK3067	Merevale Borehole 3	16 / 4.88	<i>O. wahlenbergi</i>	-28.5	1.4
SSK3068	Merevale Borehole 3	12 / 3.66	<i>O. wahlenbergi</i>	-28.8	0.7
SSK3069	Merevale Borehole 3	8 / 2.44	<i>O. wahlenbergi</i>	-27.2	0.2
SSK3070	Merevale Borehole 3	6 / 1.83	<i>O. wahlenbergi</i>	-27.2	0.2
		Height above outcrop datum (m)			
MR 42369	Oldbury Quarry	0	<i>O. cataractes</i>	-26.6	0.2
MR 42370	Oldbury Quarry	1	<i>O. cataractes</i>	-25.7	0.1
MR 42371	Oldbury Quarry	2	<i>O. cataractes</i>	-25.6	0.1
MR 42372	Oldbury Quarry	3	<i>O. cataractes</i>	-27.4	0.4
MR 42373	Oldbury Quarry	4	<i>O. cataractes</i>	-26.5	0.4
MR 42374	Oldbury Quarry	5	<i>O. cataractes</i>	-26.5	0.3
MR 42375	Oldbury Quarry	6	<i>O. cataractes</i>	-27.2	0.6
MR 42376	Oldbury Quarry	7	<i>O. cataractes</i>	-27.8	1.4
MR 42377	Oldbury Quarry	8	<i>O. cataractes</i>	-27.8	1.4
MR 42378	Oldbury Quarry	9	<i>O. cataractes</i>	-26.4	0.2
MR 42379	Oldbury Quarry	10	<i>O. cataractes</i>	-27.6	1.7
MR 42380	Oldbury Quarry	11	<i>O. cataractes</i>	-26.7	0.3
MR 42381	Oldbury Quarry	12	<i>O. cataractes</i>	-26.8	1.9
MR 42382	Oldbury Quarry	13	<i>O. cataractes</i>	-27.1	2.7

MR 42383	Oldbury Quarry	14	<i>O. cataractes</i>	-27.3	2.9
MR 42384	Oldbury Quarry	15	<i>O. cataractes</i>	-27.4	2.6
MR 42385	Oldbury Quarry	16	<i>O. cataractes</i>	-27.5	2.8
MR 42386	Oldbury Quarry	17	<i>O. cataractes</i>	-26.7	1.5
MR 42387	Oldbury Quarry	18	<i>O. cataractes</i>	-26.8	1.8
MR 42388	Oldbury Quarry	19	<i>O. cataractes</i>	-27.1	1.6
MR 42389	Oldbury Quarry	20	<i>O. cataractes</i>	-27.4	2.6
MR 42390	Oldbury Quarry	21	<i>O. cataractes</i>	-27.1	2.9
MR 42391	Oldbury Quarry	22	<i>O. cataractes</i>	-27.4	3.4
MR 42392	Oldbury Quarry	23	<i>O. cataractes</i>	-27.2	1.4
MR 42393	Oldbury Quarry	24	<i>O. cataractes</i>	-27.2	2.9
MR 42394	Oldbury Quarry	25	<i>O. cataractes</i>	-27.2	2.4
MR 42395	Oldbury Quarry	26	<i>O. cataractes</i>	-27.7	3.2
MR 42396	Oldbury Quarry	27	<i>O. cataractes</i>	-27.2	1.4
MR 42397	Oldbury Quarry	28	<i>O. cataractes</i>	-27.7	3.1
MR 42398	Oldbury Quarry	29	<i>O. cataractes</i>	-27.5	2.0
MR 42399	Oldbury Quarry	30	<i>O. cataractes</i>	-29.5	1.6
MR 42400	Oldbury Quarry	38	<i>O. cataractes</i>	-27.3	0.5
MR 42401	Oldbury Quarry	39	<i>O. cataractes</i>	-27.3	0.8
MR 42402	Oldbury Quarry	40	<i>O. cataractes</i>	-27.4	0.2
MR 42403	Oldbury Quarry	41	<i>O. cataractes</i>	-27.6	0.5
MR 42404	Oldbury Quarry	42	<i>O. cataractes</i>	-27.8	1.7
MR 42405	Oldbury Quarry	43	<i>O. cataractes</i>	-27.8	0.8
MR 42406	Oldbury Quarry	44	<i>O. cataractes</i>	-27.7	0.6
MR 42407	Oldbury Quarry	45	<i>O. cataractes</i>	-27.5	0.6
MR 42408	Oldbury Quarry	46	<i>O. cataractes</i>	-28.0	1.2
MR 42409	Oldbury Quarry	47	<i>O. cataractes</i>	-27.8	0.6

FIGURE CAPTIONS

Figure 1. Global late Cambrian palaeogeography, showing position of the Avalonia terrane with respect to major contemporary palaeocontinents (Laurentia, Baltica & Gondwana) and ocean basins. Based on Cocks and Torsvik (2002, fig. 3).

Figure 2. Palaeogeography of England and Wales during the late Cambrian (*Olenus* Biozone), showing main land areas, depo-centres and areas of marine shelf deposition. Based on Map C2a in Cope *et al.* (1992).

Figure 3. Regional location (a), geological setting (b), and simplified geological cross section (c) of the study area. Based on Plate 12 of Taylor & Rushton (1971).

Figure 4. Cambrian and Early Ordovician stratigraphy of the Nuneaton area, and its relationship to the Cambrian of North America.

Figure 5. Integrated stratigraphy of the Outwoods Shale Formation in the Merevale boreholes and Oldbury Quarry. Position of the Oldbury Quarry curve and section with respect to logs and signatures from the Merevale boreholes is based on the shape and magnitude of the quarry signature and regional

geological structure. The quarry signature and section (sampled at true vertical depth) is expanded by about 13% to provide consistency with the dipping succession sampled in the boreholes.

Figure 6. The Oldbury Quarry succession [SP 30965 94922]: (a) general view showing relationship to logged section and major igneous intrusions; (b) typical Outwoods Shale Formation lithology (length of hammer ca 0.3 m).

Figure 7. Global comparison of the SPICE with that recorded at Nuneaton. Correlative datum is the base of the *Glyptagnostus reticulatus* Biozone or its lateral equivalent. The thickness of the Nuneaton signature has been adjusted for dip. NB: the horizon of *Irvingella* in the Nuneaton succession is based on extrapolation of an occurrence in nearby outcrops (see Rushton, 1983, fig. 3), and appears to represent a level close to the top of its range. carb. = carbonate; org. = organic.

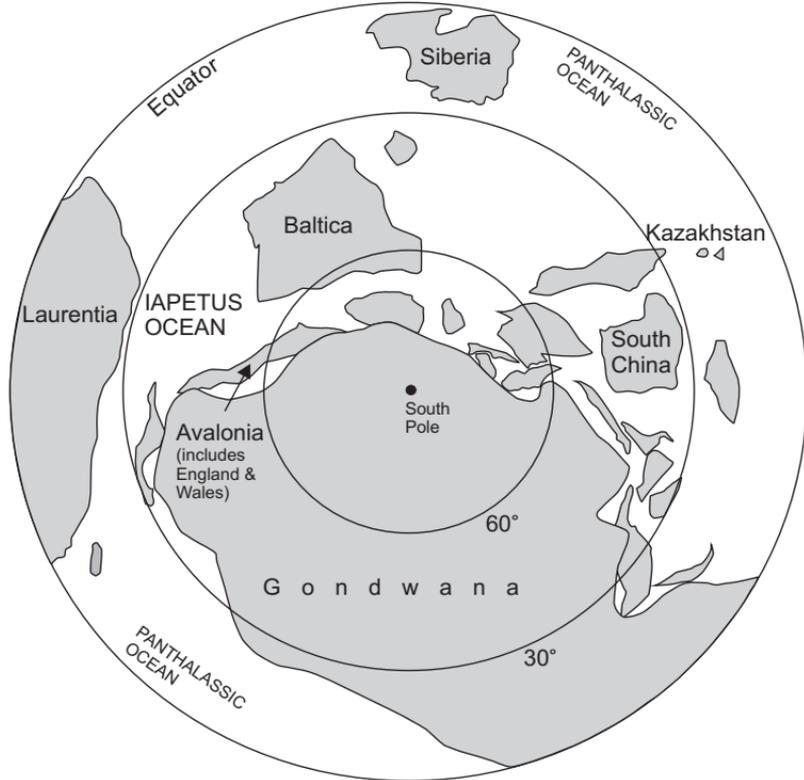


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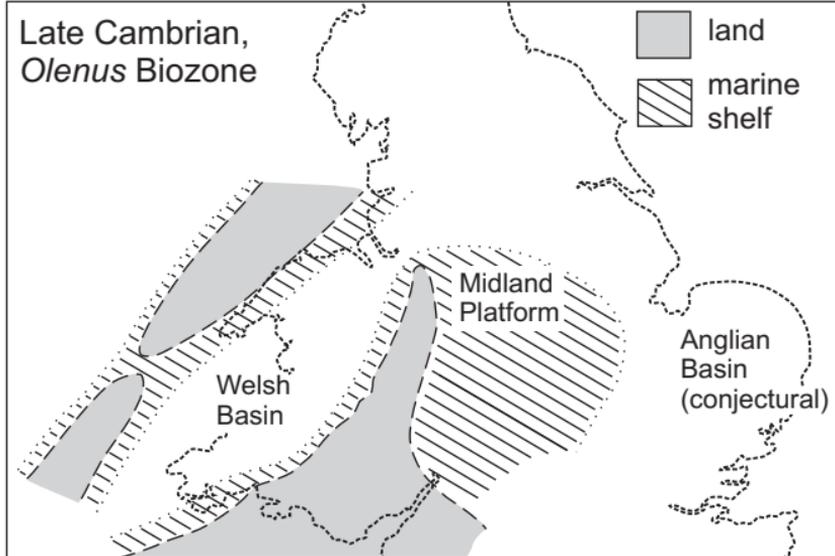


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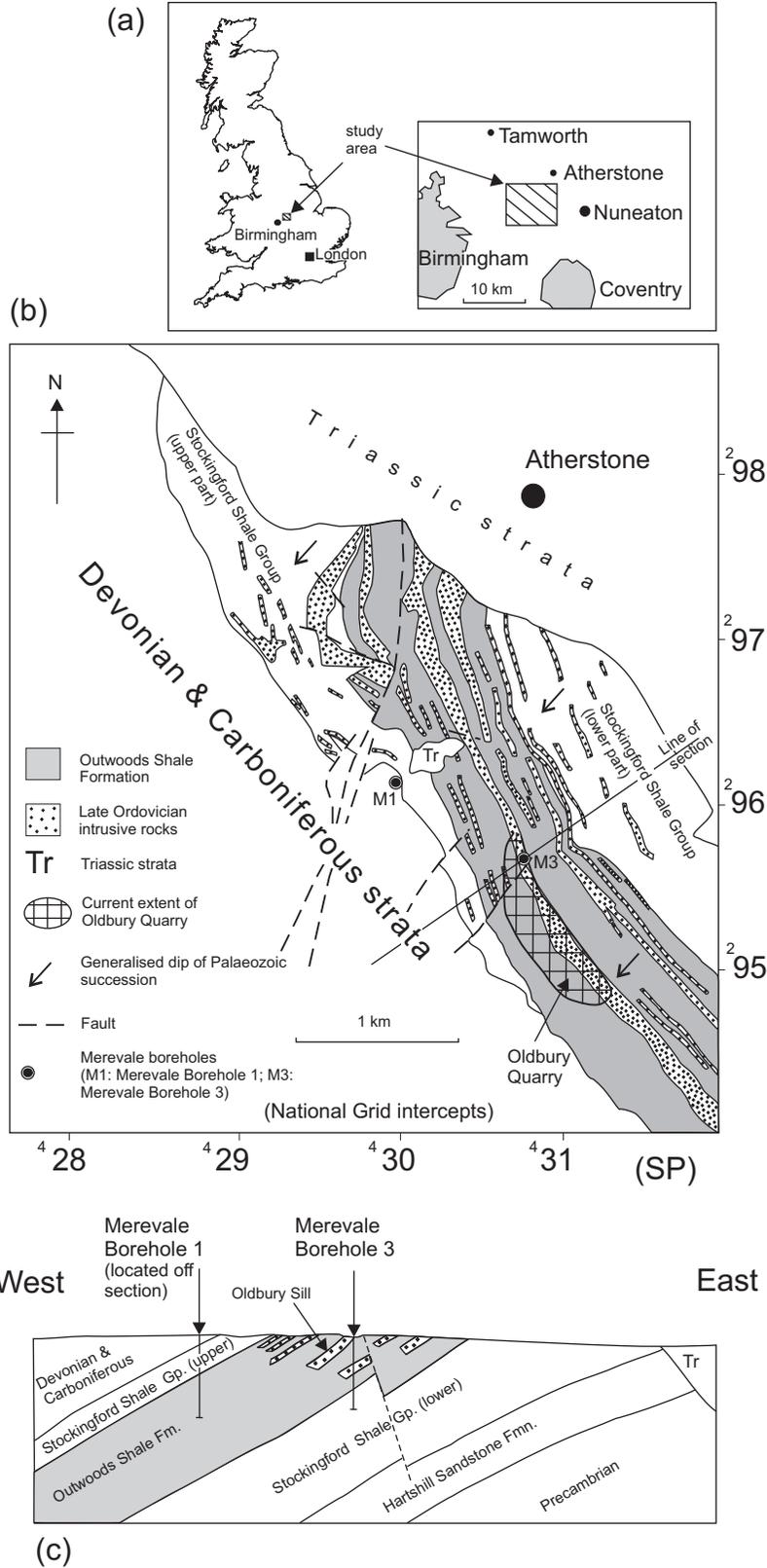


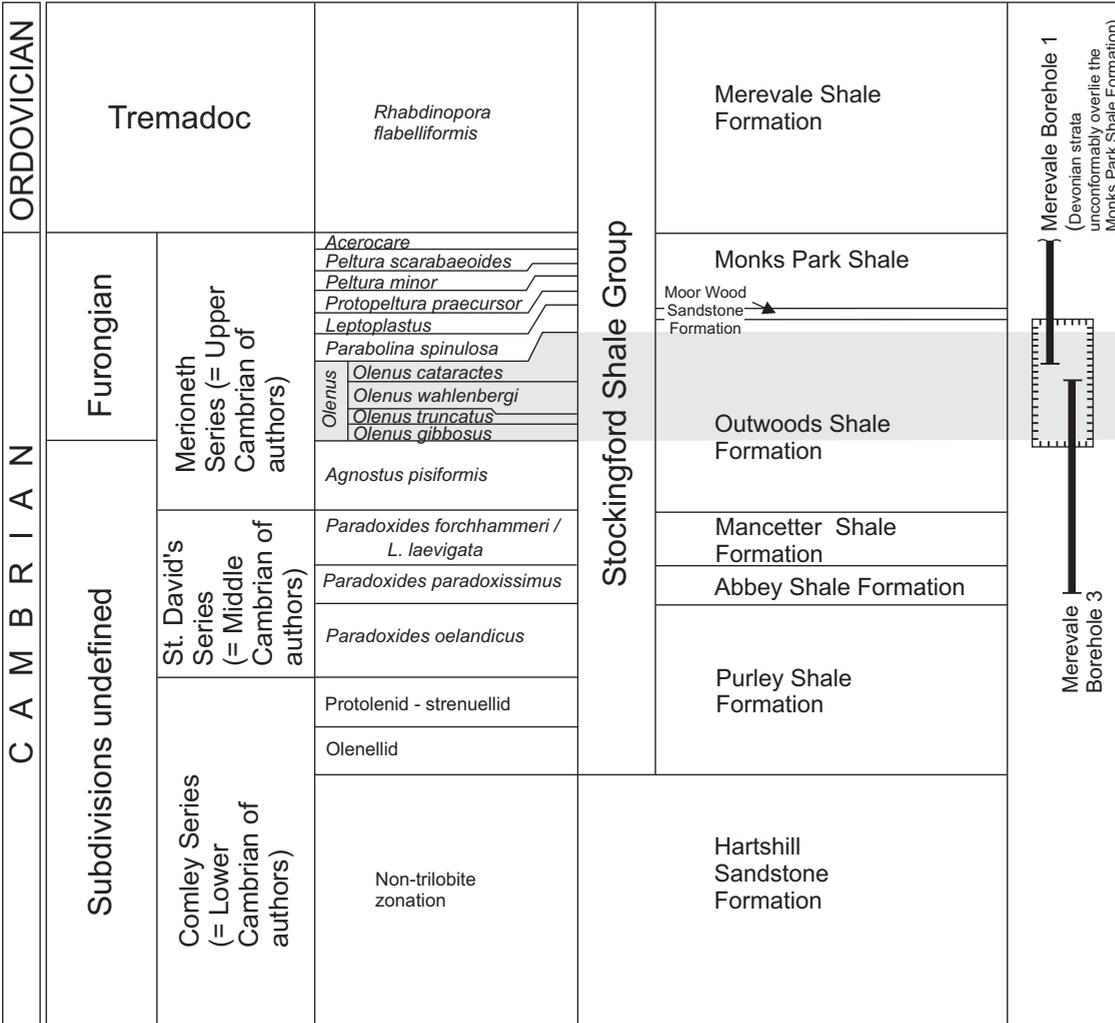
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England and Wales

SERIES		TRILOBITE BIOZONATION	LITHOSTRATIGRAPHY (Nuneaton area)	BOREHOLE RANGES
GLOBAL (Peng et al., 2004)	REGIONAL			

North America

STAGE		TRILOBITE BIOZONATION
(Howell <i>et al.</i> , 1944)	(Ludvigsen & Westrop, 1985)	



Trempealeuan	Sunwaptan	<i>Saukia</i>
Franconian		<i>Saratogia</i> <i>Taenicephalus</i>
Dresbachian	Steptoean	<i>Elvinia</i> <i>Dunderbergia</i> <i>Prehousia</i> <i>Dicanthopyge</i> <i>Aphelaspis</i>
	Marjuman	<i>Crepicephalus</i> <i>Cedaria</i>

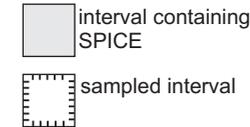


Figure 4. Cambrian and Early Ordovician stratigraphy of the Nuneaton area, and its relationship to the Cambrian of North America.

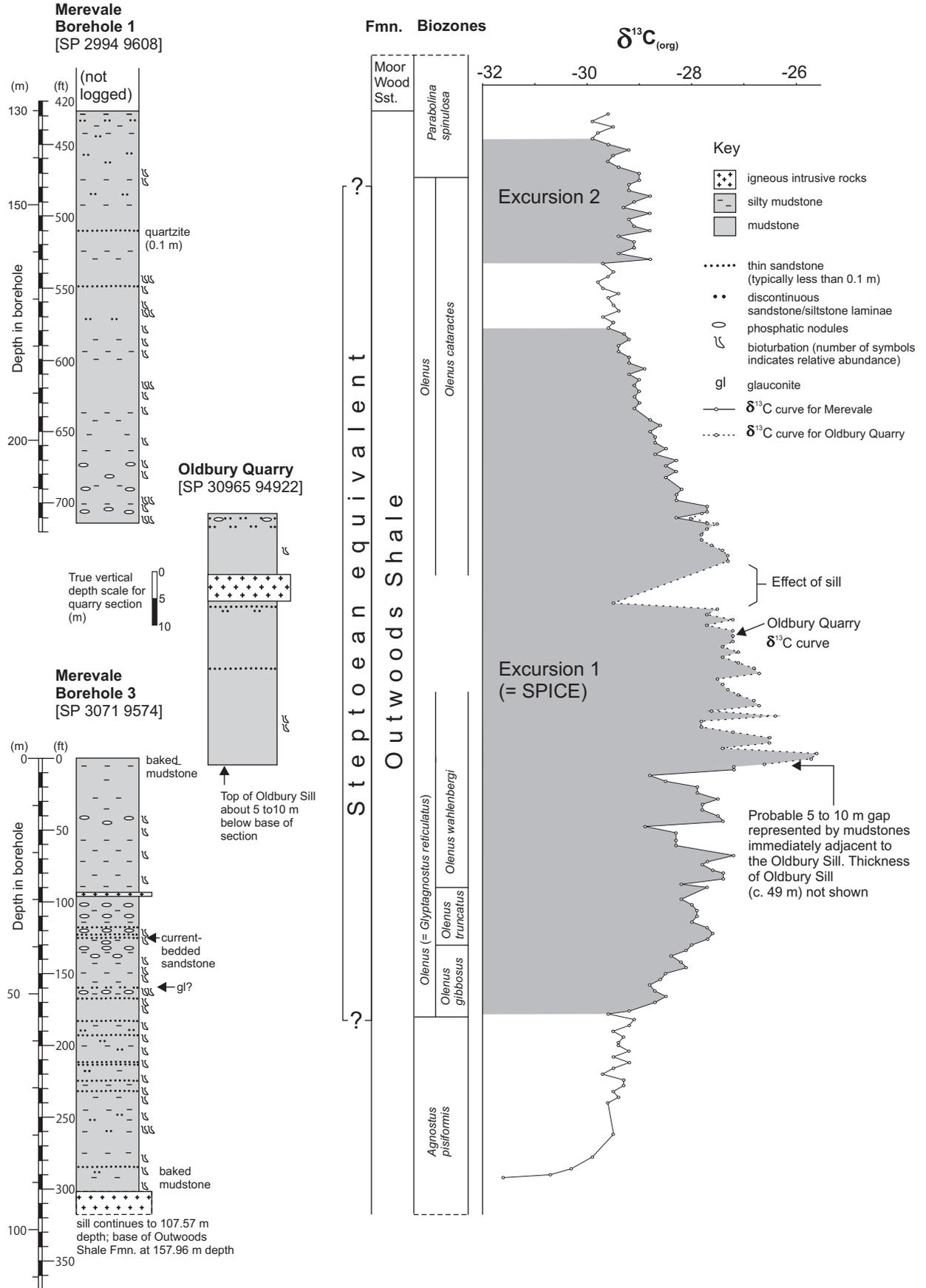


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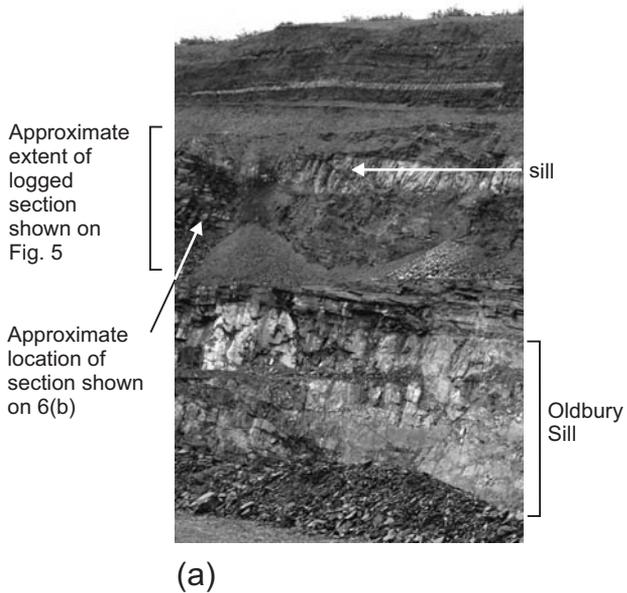


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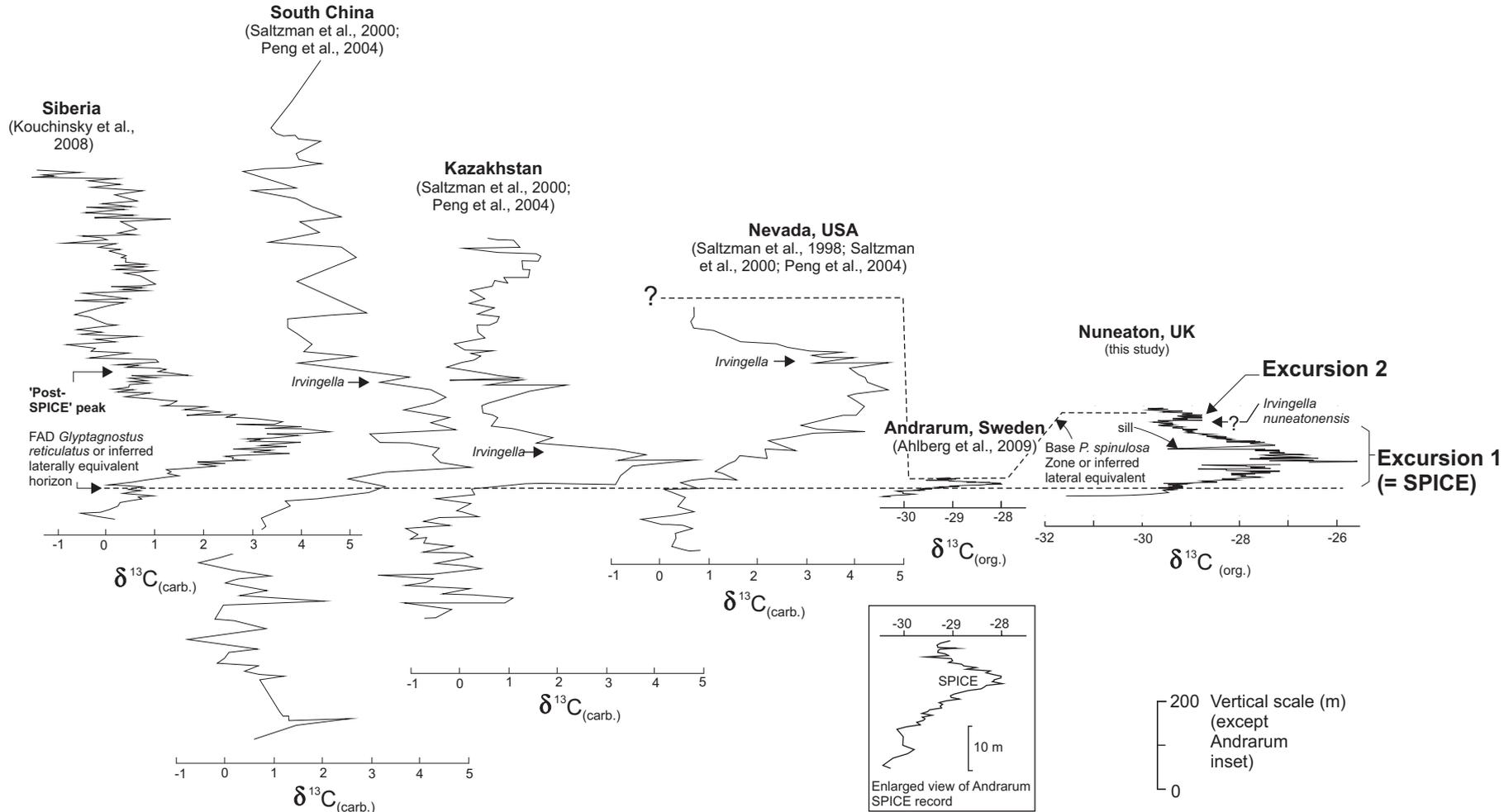


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