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The Sommerodde (Telychian, Silurian) positive carbon isotope excursion: why is its magnitude so variable?

Sommerodde carbon isotope excursion

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Abstract: The Sommerodde positive organic carbon isotope excursion (SOCIE), within the *Oktavites spiralis* graptolite Biozone (Telychian, Silurian), was first identified in the Sommerodde-1 core, Bornholm, Denmark, where it is the largest positive excursion within the Upper Ordovician–lower Silurian part of the core. Other published occurrences of the SOCIE are discussed here, together with new $\delta^{13}C_{org}$ data from the Jabalón River section, Corral de Calatrava, central Spain where the SOCIE is only a very minor positive excursion. Very unusually, the SOCIE is best developed in deeper water settings, contrary to the typical pattern of declining excursion magnitude offshore. In the Sommerodde-1 core (Bornholm), and where it has been tentatively identified in the Vežaičiai-2 core (Lithuania), the SOCIE is developed in pale, organic-poor mudstones. It is considered likely that the SOCIE's magnitude has been enhanced in the Sommerodde-1 core record by a change in organic

matter composition in the deep marine environment that did not affect shallower marine environments so significantly.

Supplementary material: A table of organic carbon isotope data from the Jabalón River section, Corral de Calatrava, central Spain is available at

A major surprise of integrating $\delta^{13}C_{org}$ data with the graptolite biostratigraphy (Loydell *et al.* 2017) of the Sommerodde-1 core, Bornholm, Denmark was the discovery of a pronounced positive excursion (amplitude approximately 4‰) in the *Oktavites spiralis* graptolite Biozone of the Telychian, with higher $\delta^{13}C_{org}$ values (peaking at -25.4‰) than either the very well-known Hirnantian (HICE; peaking at -27.7‰) or early Sheinwoodian (ESCIE; peaking at -27.1‰) excursions (Hammarlund *et al.* 2019). This was clearly not the Valgu excursion (Munnecke and Männik 2009) which is stratigraphically older, nor the more recently identified Manitowoc excursion (McLaughlin *et al.* 2019), which is stratigraphically younger (see discussion below), but a previously very largely unrecognised and unnamed perturbation in the carbon isotope record. Hammarlund *et al.* (2019) named it the Sommerodde excursion (SOCIE). Other high magnitude Late Ordovician and Silurian positive $\delta^{13}C$ excursions are associated with major global environmental (and biotic) changes – thus the discovery of a new major excursion suggested that the Telychian might host another, previously unrecognised, interval of significant environmental changes, potentially with similarly previously unrecognised impacts on biotic diversity.

The aims of this paper are (1) to review further potential records of the SOCIE, mostly published after 2019, showing that the Sommerodde excursion varies in magnitude dramatically, ranging from a high magnitude excursion (in sections representing deeper water environments), comparable to that seen in the Sommerodde-1 core, to a low magnitude excursion or unrecognisable in sections representing the shallowest environments; (2) to present new $\delta^{13}C_{org}$ data from a section in central Spain, in which the Sommerodde excursion is a very minor event; and then (3) to discuss why the SOCIE shows such a wide variation in magnitude and is so pronounced in the Sommerodde-1 core $\delta^{13}C_{org}$ record, concluding that a change in organic matter composition in deeper water areas is the most likely reason. This is the first Silurian positive $\delta^{13}C$ excursion to show a pattern of increasing magnitude with increasing depositional water depth. Our study demonstrates that the Silurian $\delta^{13}C$ record and the causes of Silurian $\delta^{13}C$ perturbations are more varied than previously recognised.

Published records of the Sommerodde excursion (SOCIE)

The Baltic localities discussed herein, including Sommerodde (Bornholm), are shown in Fig. 1. In the Sommerodde-1 core the SOCIE was recorded in several samples extending over approximately 10 m of core (between depths of *c.* 80 m to 70 m; Fig. 2). Graptolites (Loydell *et al.* 2017) demonstrate that much of the excursion (77.02–70.59 m) lies within the middle part of the *Oktavites spiralis* graptolite Biozone (Fig. 3). It commenced in strata lacking graptolites, but which are underlain by beds yielding lower *spiralis* Biozone graptolites (Fig. 3). The excursion therefore must commence within either the lower or middle *spiralis* Biozone and end within the middle *spiralis* Biozone.

Hammarlund *et al.* (2019) summarized previous carbon isotope studies through this interval and were able to recognise the SOCIE in two $\delta^{13}C_{carb}$ curves from the Baltic states. In the Ventspils D-3 core, Latvia (Fig. 1) the positive $\delta^{13}C_{carb}$ excursion reaches its peak in strata bracketed by lower and middle *spiralis* Biozone graptolite assemblages (Loydell and Nestor 2006; Hammarlund *et al.* 2019, fig. 7). The SOCIE is the highest magnitude excursion in the Llandovery of this core, the peak value also exceeding that of the well-known mid Homerian excursion, but of significantly lower magnitude than either the ESCIE or mid Ludfordian excursions (Kaljo *et al.* 1998). In other sections, however, the SOCIE was either of limited magnitude (e.g., Ruhnu (500) core, Estonia; Hammarlund *et al.* 2019, fig. 7) or unrecognisable (Viki core, Estonia; Kaljo *et al.* 2003; see below for discussion of Richardson *et al.*'s (2019) $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ data from Viki). It was also unrecognisable in the Knapp Creek core, Iowa, USA (McAdams *et al.* 2017).

It is possible that the SOCIE is represented in the $\delta^{13}C_{org}$ record from the Zwierzyniec-1 core, Poland (see Fig. 1 for location). The rather limited carbon isotope and graptolite biostratigraphical data (from Sullivan *et al.* 2018) are summarized in Fig. 4. *Stimulograptus vesiculosus* (2952.95 m) is a middle–upper *Oktavites spiralis* Biozone species, whilst *Streptograptus wimani* (2951.4 m) first appears at the base of the succeeding *Cyrtograptus lapworthi* graptolite Biozone. The presence of *Monoclimacis vomerina sensu lato*, identified by Zalasiewicz and Williams (in Sullivan *et al.* 2018, appendix A) from 2956.50–2956.75 m, indicates an age of no older than *Monoclimacis crenulata* graptolite Biozone. The basal Sheinwoodian biozonal index *Cyrtograptus murchisoni* was present in the 2949–2950 m sample. The most positive late Telychian $\delta^{13}C_{org}$ value is thus in a stratigraphical position consistent with that of the SOCIE.

Biostratigraphical data are similarly rather limited from the Altajme core, Gotland (see Fig. 1 for location). The $\delta^{13}C_{carb}$ record from here includes a small magnitude (*c.* 0.5‰), double-peaked positive excursion in strata at depths between 320 m and 317 m (Hartke *et al.* 2021, fig. 3); *Oktavites spiralis* is recorded from a depth of 322.14 m and strata up to 316 m are assigned to the *spiralis* Biozone. The biostratigraphical data are thus consistent with this excursion representing the SOCIE. The magnitude of this excursion is far less than that of the ESCIE (*c.* 3‰, referred to by Hartke *et al.* as the Ireviken excursion), but is comparable to that in the Ruhnu (500) core, Estonia (Hammarlund *et al.* 2019, fig. 7), which lies in the same facies belt (Fig. 1).

Richardson *et al.* (2019) provided both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ data from the Viki core, Estonia (previously analysed for $\delta^{13}C_{carb}$ by Kaljo *et al.* (2003)). The same Viki core data were plotted also by Yan *et al.* (2022). Based on correlation of graptolite and conodont biozones (e.g. Männik 2007), the SOCIE should be looked for in the *Pterospathodus amorphognathoides lennarti* and lower *P. a. lithuanicus* conodont biozones. Richardson *et al.*'s (2019) supplementary data table enables integration of their geochemical data with the conodont biozonation for the Viki core of Männik (2007). There are rather limited data through the key interval (four $\delta^{13}C_{carb}$ analyses and three $\delta^{13}C_{org}$ analyses between 160 m and 150 m depth). The $\delta^{13}C_{carb}$ value falls from 2.15‰ in the upper *Pterospathodus amorphognathoides angulatus* conodont Biozone (155.65 m) to 1.43‰ in the *Pt. a. lennarti* Biozone (153.6 m), rising to 1.73‰ and 1.78‰ in the lower *Pt. a. lithuanicus* Biozone (151.68 m and 151.17 m respectively). There is no $\delta^{13}C_{org}$ analysis for the uppermost *Pt. a. angulatus* Biozone sample (155.65 m). The sample below (160.25 m) has a $\delta^{13}C_{org}$ value of -26.78‰, the *Pt. a. lennarti* Biozone (153.6 m) sample is a little more positive (-26.46‰), rising further into the lower *Pt. a. lithuanicus* Biozone (-26.09‰ at 151.68), before falling back to -26.71‰ at 151.17 m. The limited data therefore support the presence of a minor positive $\delta^{13}C_{org}$ excursion at a level correlative with the SOCIE in the Sommerodde core, with no obvious positive excursion revealed by the $\delta^{13}C_{carb}$ data.

Young *et al.* (2020) presented $\delta^{13}C_{org}$ data from the Aizpute-41 core, Latvia (Fig. 1; see Loydell *et al.* 2003 for biostratigraphy of this core and Cramer *et al.* 2010 for $\delta^{13}C_{carb}$ data). An approximately 1‰ positive shift is present at a depth of 944.7 m in the core (table 2 in their supplementary data, but not shown on Young *et al.*'s fig. 4), rising from -27.40‰ at 945.7 m to -26.35‰ at 944.7 m and declining again to -27.27‰ at 942.7 m. Loydell *et al.* (2003) assigned strata from 944.62–941.88 m to the middle *spiralis* graptolite Biozone, so this positive shift is at the correct biostratigraphical level for the SOCIE (Fig. 5). This -26.35‰ value is the most positive in the entire dataset, which includes the *sedgwickii* excursion (referred to by Young *et al.* (2020) as the late Aeronian excursion), Valgu excursion (discussed briefly below) and the ESCIE (with -26.56‰ recorded from the *Monograptus riccartonensis* graptolite Biozone at 910.3 m). So, the Aizpute-41 data match those from the Sommerodde-1 core, with the SOCIE having the most positive recorded $\delta^{13}C_{org}$ value. Like Sommerodde, Aizpute is one of the deepest water localities (Fig. 1) from which published Telychian carbon isotope data are available.

Young *et al.* (2020) showed the Valgu excursion extending over a much greater stratigraphical interval than other authors, to a level (at 945.7 m depth in the Aizpute-41 core) high within the lower *spiralis* Biozone (and within the middle of the *Pterospathodus celloni* conodont Superzone). Munnecke and Männik (2009) showed the Valgu excursion to be confined to the *Pterospathodus eopennatus* conodont Superzone (see also Hammarlund *et al.* 2019, fig. 6), the top of which correlates with a level in the lower to middle *crenulata* graptolite Biozone (Loydell *et al.* 2003, fig. 17; Männik 2007, fig. 5). Young *et al.*'s (2020) Telychian $\delta^{13}C_{org}$ data are plotted in Fig. 5, with the graptolite biostratigraphy corrected (from Loydell *et al.* 2003); the 944.7 m value, representing the SOCIE, is now included. Overall, the Telychian in the Aizpute-41 core exhibits significantly more positive $\delta^{13}C_{org}$ values than the upper Rhuddanian, lower and middle Aeronian and lowermost Sheinwoodian (Young *et al.* 2020, fig. 4) and, despite there being fluctuations in $\delta^{13}C_{org}$ values, it is difficult to identify individual excursions, in part perhaps because of the condensation of much of the lower–middle Telychian, with the combined *turriculatus*, *crispus*, *sartorius* and *griestoniensis* graptolite biozones represented by only 6 m of strata, less than the individual thicknesses of either the *crenulata* (c. 7 m) or *spiralis* (c. 10 m) graptolite biozones.

Cichon-Pupienis *et al.* (2021) recorded a significant positive $\delta^{13}C_{org}$ excursion, tentatively identified as the SOCIE, in the upper part of the Jūrmala Formation of the Vežaičiai-2 (V-2) core, western Lithuania (Fig. 1). This is of similar magnitude to the ESCIE, but of lesser magnitude than two excursions lower in the Telychian, tentatively identified by Cichon-Pupienis *et al.* (2021) as the Valgu and Kallholn excursions. The graptolite biostratigraphy of the V-2 core is yet to be established, with the biozones shown based on correlation with the succession in the Viduklė-61 core, 90 km to the ESE in south-central Lithuania (Fig. 1). A very interesting feature of the putative SOCIE in the V-2 core is that it is developed within the thickest development of greenish grey mudstones within the Telychian (Fig. 6). This parallels its development within a thick interval of predominantly paler strata within the Sommerodde-1 core (Fig. 2).

Strauss *et al.* (2020) integrated $\delta^{13}C_{carb}$ and graptolite biostratigraphical data from the Mount Hare Formation, Road River Group of northern Yukon, Canada. A positive excursion (of *c.* 1.5‰) is seen within the *spiralis* Biozone (Fig. 7), commencing just over half way through the strata assigned to the biozone (which is not divided biostratigraphically into lower, middle and upper, and is overlain by 8.4 m of strata lacking diagnostic graptolites). Assuming that this is the SOCIE, its relative magnitude is similar to that in the Ventspils D-3 core, Latvia, i.e. exceeding that of the mid Homerian excursion and less than the ESCIE and Ludfordian excursions. The assumed SOCIE in the Road River Group is also of lesser magnitude than the Valgu excursion, which was not seen in the Ventspils core as no analyses were carried out through the relevant stratigraphical interval. In terms of environment, the analysed Road River Group samples were from towards the southern end of the Richardson Trough (Strauss *et al.* 2020), which is described as an intraplatformal deep-water basin formed by rifting along the Great American Carbonate Bank on the margin of Laurentia.

Yan *et al.* (2022, p. 9) refer to a positive $\delta^{13}C_{org}$ excursion in the lower *Pterospathodus amorphognathoides amorphognathoides* Superzone of the Baizitian section, Sichuan, China, 'that is equivalent to the SOCIE of Denmark.' Their figure 7 shows a significant positive excursion (4‰) at this level (but labelled Manitowoc OCIE), but this is younger than the age of the SOCIE on Bornholm; the base of the *Pterospathodus a. amorphognathoides* Superzone correlates with that of the *Cyrtograptus lapworthi* graptolite Biozone (Loydell *et al.* 2010), which succeeds the *Oktavites spiralis* Biozone, in the middle of which the SOCIE terminates. In addition, and very significantly, Yan *et al.*'s (2022) figure 5 shows an unconformity in the Telychian of the Baizitian section resulting in an absence of the conodont biozones (uppermost *Pterospathodus amorphognathoides angulatus* to *P. a. lithuanicus*) that are correlative with the *Oktavites spiralis* graptolite Biozone and thus the SOCIE could not be represented in this section. The Baizitian data thus support what is suggested below - that there are two separate $\delta^{13}C$ excursions in the *O. spiralis* and *C. lapworthi* biozones.

Is the SOCIE a junior synonym of the Manitowoc excursion?

Yan *et al.* (2022, p. 7) suggested that the Manitowoc excursion and SOCIE are synonymous. We discuss the evidence for this below and conclude that they are separate excursions.

McLaughlin *et al.* (2019) identified a new positive $\delta^{13}C_{carb}$ excursion in the Telychian of the Michigan Basin which they named the Manitowoc excursion. In those sections in Wisconsin where the excursion was identified, it occurs immediately above 'the top of a cluster of hardgrounds', a level which was used as a correlation datum. In the Sheboygan SH-

541 core, Wisconsin (the core used for correlation with Baltica by McLaughlin *et al.* (2019) and for correlation with sections elsewhere in Laurentia, in Baltica and in South China by Yan *et al.* (2022)), this correlation datum lies just above a depth of 250 m. In their summary correlation diagram, McLaughlin *et al.* (2019, fig. 8) showed the Manitowoc excursion to be within the upper part of Silurian Stage Slice Te3, equating to the uppermost *Pterospathodus eopennatus* conodont Biozone through to the top of the *Pt. amorphognathoides lithuanicus* conodont Biozone (Cramer *et al.* 2011, fig. 3). These conodont biozones correlate with the *Monoclimacis crenulata* and *Oktavites spiralis* graptolite biozones and on this basis the Manitowoc CIE and SOCIE would appear at first sight to be potentially synonymous. Note, however, that no conodont biostratigraphical data were presented from the Sheboygan SH-541 core.

McLaughlin *et al.* (2019) noted a 'striking similarity' of the $\delta^{13}C_{carb}$ curve in the Sheboygan SH-541 core to that of 'the biostratigraphically well-constrained Estonian Viki core' of Kaljo *et al.* (2003) and correlated the Sheboygan and Viki $\delta^{13}C_{carb}$ curves (McLaughlin *et al.* 2019, fig. 2). The key correlation datum in Wisconsin, above which the Manitowoc Excursion lies, is correlated with a level in the lower part of the *Pt. amorphognathoides amorphognathoides* conodont Biozone. This, however, is within Cramer *et al.*'s (2011) Stage Slice Te4, *not* Te3. On this basis the Manitowoc Excursion, as originally defined, is rather younger than McLaughlin *et al.* (2019, fig. 8) indicated and would lie within the *Cyrtograptus lapworthi* graptolite Biozone, within which there was a well-documented eustatic fall in sea-level (Loydell 1998, 2007). McLaughlin *et al.* (2019) noted, as had Loydell (2007), that 'the ascending limbs of the positive $\delta^{13}C_{carb}$ excursions correspond with facies changes consistent with progressive sea-level fall'. If McLaughlin *et al.*'s (2019, fig. 2) correlation is correct, then the Manitowoc Excursion is likely to be associated with the mid-*lapworthi* Zone sea-level fall.

Yan *et al.* (2022) generated a rather different concept of the Manitowoc Excursion from that originally presented by McLaughlin *et al.* (2019). They expanded the excursion to include strata below the correlation datum cluster of hardgrounds in the Sheboygan SH-541 core and also divided the excursion into three parts. The conspicuous positive excursions shown in the Sheboygan SH-541 core within Interval 1 and the lower part of Interval 2 in Yan *et al.* (2022, fig. 8) both lie below these hardgrounds and thus also below the level of the Manitowoc Excursion as originally defined. The excursion within Yan *et al.*'s (2022) Interval 1 is *c.* 50 m below the correlation datum and shown to lie within the upper part of the

Pterospathodus eopennatus conodont Superzone. That within the lower part of Interval 2 is shown as in the lower part of the *Pterospathodus amorphognathoides angulatus* conodont Biozone. McLaughlin *et al.* (2013) is cited as the reference for the stratigraphy of Sheboygan core, but no conodont data for the core are presented in this work to support the conodont biozonation presented. Indeed McLaughlin *et al.* (2013, p. 15) had stated that there is 'poor biostratigraphic control'.

The Manitowoc CIE is also identified by Yan *et al.* (2022, fig. 8) in the Viki core, Estonia, using both the $\delta^{13}C_{carb}$ curve of Richardson *et al.* (2019), which differs little from that of Kaljo *et al.* (2003) used for correlation by McLaughlin *et al.* (2019), and Richardson *et al.*'s (2019) $\delta^{13}C_{org}$ curve. The most pronounced $\delta^{13}C_{carb}$ excursion (of *c.* 0.7‰) is within Interval 1, which lies in the upper half of the *Pterospathodus amorphognathoides angulatus* conodont Biozone (equivalent to the upper *Monoclimacis crenulata* and lowermost *Oktavites spiralis* graptolite biozones; Männik 2007). There are minor excursions within Intervals 2 (of *c.* 0.4‰) and 3 (a single analysis at 135.48 m of 1.49‰, with 15 stratigraphically lower and higher samples, between 141.27 m and 122.07 m, showing little variation, between 1.07‰ and 1.28‰), with only that in Interval 3 corresponding to the stratigraphical level of the Manitowoc excursion according to the correlation of McLaughlin *et al.* (2019).

Based on the available evidence, it seems best to continue to referring to the positive $\delta^{13}C$ excursion in the *spiralis* graptolite Biozone (terminating in its middle) as the SOCIE and to use the term Manitowoc excursion for a later Telychian excursion, in the Lower *Pt. a. amorphognathoides* conodont Biozone (as shown by the integrated chemostratigraphical and biostratigraphical data of Yan *et al.* 2022 from Baizitian, China), which is likely to correlate with a sea-level fall in the middle *Cyrtograptus lapworthi* graptolite Biozone.

The Jabalón River section, Corral de Calatrava, Spain: new $\delta^{13}C_{org}$ data

A richly fossiliferous Telychian–Sheinwoodian, largely black shale succession is very well-exposed in the Jabalón River section, Corral de Calatrava, central Spain (Fig. 8). The graptolite and conodont biostratigraphy of the section were studied by Štorch *et al.* (1998) and Loydell *et al.* (2009). As lithological samples from all horizons had been retained, this seemed an ideal opportunity to determine how well developed the SOCIE is in a graptolitically well-dated section in a different facies and palaeogeographical setting from Sommerodde (Bornholm).

This part of central Spain was part of the Central Iberian Zone (Fig. 8) of peri-Gondwanan Europe during the Silurian, at a much higher (southern) latitude setting than Bornholm and the Baltic states (part of Baltica), on the other side of the Rheic Ocean (Torsvik and Cocks 2013; Fig. 9). Robardet and Gutiérrez-Marco's (2002) tentative palaeogeographical reconstruction of the North Gondwanan regions during the Silurian Period (see also Loydell *et al.* 2015, fig. 3) shows the study area to be towards the outer part of what is described as 'inner shelf'.

The middle Telychian (upper *Monoclimacis crenulata* graptolite Biozone) to lower Sheinwoodian (lower Wenlock, *Monograptus riccartonensis* graptolite Biozone) part of the section was studied in detail by Loydell *et al.* (2009), when it was hoped that the section would be a potential candidate replacement GSSP for the base of the Wenlock Series. Like so many apparently complete sections, however, the Jabalón River section contains unconformities (Fig. 8): two significant ones were recognised, detectable biostratigraphically and marked in one case by a thin shell bed and in the other by an abrupt facies change to an impure limestone overlain by brachiopod-rich shale. So, what at first sight looked to be a stratigraphically continuous Telychian section is in fact missing the uppermost Telychian (upper *Cyrtograptus lapworthi* graptolite Biozone and the entirety of the *C. insectus* and *C. centrifugus* graptolite biozones; Fig. 8). The presence of *Oktavites spiralis* in the highest Telychian sample below the lower unconformity (overlain by Wenlock strata) is biostratigraphically very significant. In more complete graptolitic sections in the Czech Republic and Wales *O. spiralis* makes its last appearance in the lower half of the *lapworthi* graptolite Biozone (Loydell and Cave 1996; Štorch 2023). Thus, any biotic or environmental changes occurring during the latest Telychian (late *lapworthi* to *centrifugus* zones) can have left no record in the Jabalón River section in the fossil or isotope record. An absence of strata from this stratigraphical level has been widely reported (see e.g., Loydell *et al.* 2003, 2010 for examples from Baltica). The second unconformity in the Jabalón River section affects part of the lower Sheinwoodian (encompassing at least the entirety of the *Monograptus firmus* graptolite Biozone; Fig. 8).

Unconformities such as these can explain the sudden disappearances and appearances of taxa within a section and also will significantly influence the shape of isotope curves, either by removing excursions partially or entirely from the record (e.g., the absence of the HICE in the Road River Group of the Peel River section; Strauss *et al.* 2020) or by generating dramatically steepened limbs, such as seen in the Jabalón River section $\delta^{13}C_{org}$ data for the rising limb of the ESCIE (Fig. 10).

Methods

The samples from the Jabalón River section were collected by the authors in June, 1999. To retrieve the concentrations and isotopic composition of organic carbon in the samples, the powdered (<63 µm) samples were acid treated with 1 M HCl then washed and dried. The samples were analysed at Iso-Analytical in the UK with an EA-IRMS in April, 2020, calibrated with a set of IAEA standards. Standards of known isotopic composition and with similar concentration as the samples were analysed in parallel. The isotopic composition of carbon is reported relative to the Vienna Pee Dee Belemnite (V-PDB). Uncertainty in the standardization gives an error for $\delta^{13}C$ of 0.1‰.

Results

The range of $\delta^{13}C_{org}$ values in the Jabalón River section samples is quite limited (Fig. 10), ranging from a low of -28.7‰ (recorded in the *murchisoni* graptolite Biozone) to a high of -27.5‰ (in the *riccartonensis* graptolite Biozone). It makes sense to consider the Telychian and Sheinwoodian isotope records individually as they are separated by a significant unconformity.

The Telychian $\delta^{13}C_{org}$ record in the Jabalón River section

The overall trend through the upper *crenulata* graptolite Biozone through to the unconformity in the lower *lapworthi* graptolite Biozone is towards more negative values (Fig. 10). The penultimate *crenulata* Biozone sample records the most positive value of -27.7‰. In the Sommerodde-1 data (Hammarlund *et al.* 2019), values fluctuate above the Valgu excursion between strata yielding *crenulata* and lower *spiralis* Biozone graptolites so it is not surprising to see something similar in the Jabalón River section $\delta^{13}C_{org}$ data.

The negative trend is interrupted by a few slightly more positive values (labelled SOCIE on Fig. 10) within the lower to middle *spiralis* Biozone, but if the SOCIE was not being looked for these would be unlikely to be commented upon. Interestingly, four thin micaceous siltstones are present within this interval; Fig. 10). These are the only slightly coarser clastic horizons within the entire studied middle Telychian–lower Sheinwoodian part of the section, suggesting that some significant environmental change was occurring at this time, but, strangely, it was not one that has affected $\delta^{13}C_{org}$ record to any great extent. Biostratigraphically, these siltstones and the very minor positive excursion are at a comparable level to the SOCIE in the Sommerodde-1 core. In both sections *Streptograptus nodifer* has its FAD within the SOCIE and *Oktavites excentricus* has its FAD just above it (Fig. 11). The FADs of both are consistently recorded elsewhere from the middle of the *spiralis* Biozone (e.g., Bjerreskov 1975; Loydell *et al.* 2003, 2010, 2017; Loydell and Nestor 2006; Štorch and Piras 2009).

The Sheinwoodian $\delta^{13}C_{org}$ record

The lower and middle *murchisoni* graptolite Biozone record the lowest $\delta^{13}C_{org}$ values within the studied part of the section, with a positive shift of 0.4‰ occurring in the upper part of the biozone (Fig. 10). This is a typical level for the commencement of the ESCIE (Cramer *et al.* 2010; Loydell and Large 2019). The next sample, from the *riccartonensis* graptolite Biozone, is above an unconformity (the *firmus* graptolite Biozone is missing; Fig. 10). The $\delta^{13}C_{org}$ value of -27.5~~1~~‰ is the most positive in the section. In all sections studied worldwide the *riccartonensis* graptolite Biozone is within the protracted peak of $\delta^{13}C$ values within the ESCIE (Cramer *et al.* 2010), so again the Jabalón River section is showing what is typically seen.

Why is the magnitude of the SOCIE so variable?

The results (above) from the Jabalón River section in Spain revealed only a very small positive excursion at the same biostratigraphical level from which the SOCIE is recorded as a major positive excursion in the Sommerodde-1 core, Bornholm. The fact that the ESCIE in the Jabalón River section is at the same stratigraphical level (commencing upper *murchisoni* graptolite Biozone, peak value in *riccartonensis* graptolite Biozone) from which it is well-known world-wide (see Loydell and Large 2019 for a recent study and discussion) strongly suggests that the $\delta^{13}C_{org}$ values from the Jabalón River section are a reliable record of environmental changes here. So, the question is: why is the SOCIE so weakly developed in the Jabalón River section? Or perhaps the question should be: why is the Sommerodde excursion (SOCIE) so well developed in the Sommerodde-1 core data, extending over several samples through 10 m of strata with a magnitude exceeding that of the HICE and ESCIE? Possible answers to these questions are discussed below, together with the unusual features of the SOCIE.

Changes in excursion magnitude with depositional water depth

The SOCIE exhibits a very unusual feature. The consistent pattern seen in other Silurian positive carbon isotope excursions is that their magnitude decreases into deeper water strata. This was highlighted by Loydell (2007) for $\delta^{13}C_{carb}$, with evidence presented for excursions from East Baltic and Arctic Canadian sections. Loydell (2007, p. 534) concluded: 'Given this consistent pattern of offshore decline in the magnitude of isotope excursions it is to be expected that the $\delta^{13}C$ record of deeper water sections will record clearly only the most significant events.'

The SOCIE, however, has its greatest magnitude in the deepest water setting studied thus far (the Sommerodde-1 core, $\delta^{13}C_{org}$). It is readily identifiable, but of lesser magnitude, in the $\delta^{13}C_{org}$ and $\delta^{13}C_{carb}$ records in what are interpreted to be slightly less deep water settings (Aizpute, Ventspils and Vežaičiai, Fig. 1; and probably the Peel River, Yukon), and becomes a minor event in the $\delta^{13}C_{org}$ and $\delta^{13}C_{carb}$ records (Ruhnu, Altajme, Fig. 1; Jabalón River section, Fig. 10) or unrecognisable (e.g. in the $\delta^{13}C_{carb}$ record of Viki, Fig. 1) with increased shallowing/proximity to palaeoshorelines.

Palaeobathymetry gradients in $\delta^{13}C$ values

Recent papers have demonstrated palaeobathymetry gradients in both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ in Lower Palaeozoic sections. In South China, Li *et al.* (2018, fig. DR2) recorded decreasing $\delta^{13}C$ values (both carbonate and organic) with increasing depositional water depth in the upper Cambrian, and a similar pattern is revealed in Yang *et al.*'s (2020, fig. 9) data from the Upper Ordovician: in the Linxiang Formation shallow water $\delta^{13}C_{org}$ values are ~ -27 to -26‰, deeper water values are ~ -29‰; in the Wufeng, Daduhe and Tiezufeike formations shallow water $\delta^{13}C_{org}$ values are ~ -29 to -28‰, deeper water values are ~ -31 to -30‰. Unfortunately, for the Baltic basin $\delta^{13}C_{org}$ data through the *spiralis* Biozone (and thus the SOCIE interval) are available only for the deeper water sections, preventing such a comparison. For the ESCIE (Sheinwoodian), however, it appears that there is no major variation in the lowest $\delta^{13}C_{org}$ values in the Baltic Region prior to the excursion, with ~ -29‰ consistently recorded from the shallower water Gotland sections (e.g. Vandenbroucke *et al.* 2013; Hartke *et al.* 2021), the deeper water Vežaičiai (Cichon-Pupienis *et al.* 2021) and Ventspils (Young *et al.* 2020) sections, and the deepest water Sommerodde section (Hammarlund *et al.* 2019).

The association of positive carbon isotope excursions with graptolite extinctions

As a general rule, the larger Hirnantian and Silurian positive carbon isotope excursions are associated with facies changes indicating shallowing and the onset of the major excursions is coincident with graptolite extinctions (Loydell 2007). It is noted above that the strata hosting the SOCIE in the Jabalón River section are the only ones in the middle Telychian to lower Sheinwoodian part of the section to include clastic rocks of coarser grade than shale: the micaceous siltstones present are consistent with shallowing and shoreline progradation at this time.

The *spiralis* Biozone is not, however, associated with any obvious graptolite extinction event. The limited biotic impact of the environmental changes associated with the SOCIE may be a reflection of the very high sea-levels at this time (Loydell 1998). It has also been noted (Loydell and Abouelresh 2021) that not all Silurian positive isotope excursions coincide with graptolite extinctions. Whilst the *sedgwickii*, ESCIE, mid Homerian and mid Ludfordian excursions all saw graptolite extinctions and species turnover (Loydell 2007), the smaller positive excursions (e.g., mid Rhuddanian and early Aeronian), by contrast, occurred at times of graptolite species diversification. This suggests that the graptolites' preferred habitat was not affected by the environmental changes occurring at these times. It is assumed that the same is true for the SOCIE, with this strongly suggesting that the SOCIE is not reflecting a major change in global climate, and that its amplitude has been somehow enhanced in the Sommerodde-1 $\delta^{13}C_{org}$ record.

Low carbon content in the Sommerodde core and the impact of TOC on $\delta^{13}C_{org}$ values

It could be argued (J. Frýda, pers. comm.) that the carbon content of Telychian samples from the Sommerodde-1 core is too low (0.48–0.87 wt% TOC) to enable reliable $\delta^{13}C_{org}$ analyses. This though cannot explain why there is a positive $\delta^{13}C_{carb}$ excursion at the same biostratigraphical level in the Ventspils D-3 core, Latvia (Kaljo *et al.* 1998; Hammarlund *et al.* 2019) and a positive δ^{13}C$_{org}$ excursion at the same stratigraphical level in other Baltic sections. It is significant also that the well-known and widely recorded excursion straddling the Aeronian/Telychian boundary, the Rumba low (which appears in the Silurian carbon isotope compilations of Cramer *et al.* (2011) and Sullivan *et al.* (2018)), is very well developed in the Sommerodde-1 core data (Hammarlund *et al.* 2019, fig. 5), in samples with an even lower carbon content (0.31–0.51 wt% TOC) than within the SOCIE and that the Valgu excursion can be identified in the Sommerodde-1 core data at the same biostratigraphical level as in the Peel River, Yukon, Canada (Strauss *et al.* 2020). There is again a low carbon content (0.33–0.70 wt% TOC) in the Sommerodde-1 core Valgu excursion samples. So, it seems reasonable to see the SOCIE as a genuine reflection of environmental change at this time.

Interestingly, Cichon-Pupienis *et al.* (2021) have recently noted that the magnitude of carbon isotope excursions in the Silurian of Lithuania seems to be inversely proportional to the TOC content of the samples analysed. The carbon content of the Jabalón River *spiralis* graptolite Biozone samples varies between 5.15% and 7.86%, very much higher than the 0.48–0.87% in the Sommerodde core SOCIE samples, in agreement with Cichon-Pupienis *et al.*'s observation. Cichon-Pupienis *et al.* (2021) stated that this inverse relationship seems to be related to the quantity and composition of organic matter and its preservation.

Diagenetic effects

Cichon-Pupienis *et al.* (2021) suggested that δ^{13}C$_{org}$ excursions could be the result of the early diagenetic partial oxidation of organic matter resulting in isotopically more ^{13}C-enriched organic matter. The supporting reference cited (Hatch and Leventhal 1997) states that the oxidation took place during subaerial exposure of overlying carbonates. Subaerial exposure of the Sommerodde-1 sediments, deposited during a time of high global sea-levels (Loydell 1998) and in a deep-water environment (Fig. 1; Bjerreskov and Jørgensen (1983) estimated a water depth of 1000 ± 300 m for Bornholm during the early Homerian), seems very unlikely. Hammarlund *et al.* (2019) also commented on the mixing of isotopic fingerprints associated with early diagenesis, noting that this occurs only in shallow water environments (Holmden *et al.* 1998; Fanton and Holmden 2007; Ahm *et al.* 2018; Higgins *et al.* 2018), so that an excursion in a deeper water setting (such as the SOCIE in the

Sommerodde-1 core) should serve as a reliable record of a global perturbation of the carbon cycle.

The question arises of course as to whether oxidation of organic matter on and within oxygenated sediment in a deep marine environment could also similarly affect $\delta^{13}C_{org}$ values and generate or enhance a positive $\delta^{13}C_{org}$ excursion. Evidence from studies on more recent sediments (e.g. McArthur *et al.* 1992; Freudenthal *et al.* 2001; Lehmann *et al.* 2002) strongly suggests that this is unlikely, however.

In many areas, the Telychian as a whole has long been recognised as preserving sediments more characteristic of oxygenated environments, with more pale-coloured and more bioturbated strata and marine red beds (Ziegler and McKerrow 1975) and fewer graptolitic shales, than the preceding Rhuddanian and Aeronian (Llandovery) or succeeding Sheinwoodian (Wenlock). The stratigraphical distribution of early Silurian marine anoxia was summarized diagrammatically by Page *et al.* (2007, fig. 2), with a conspicuously largely oxygenated Telychian, and recently Hounslow *et al.* (2021) have referred to a ‘Telychian oxygenation event’. In the Sommerodde-1 core there is an interval of strata encompassing the SOCIE that is noticeably paler grey on the optic televiewer (OPTV) image of the borehole wall (Fig. 2; Loydell *et al.* 2017, fig. 20) and this can be seen in photos of the core itself (e.g., Loydell *et al.* 2017, fig. 5, a photo of the 75.45–71.80 m interval). The change in colour is gradual and is associated with a decreased proportion of darker, graptolitic horizons, although these are still present. So, the possibility that oxidation of organic matter during an interval of very high bottom water oxygen levels has generated isotopically more ^{13}C-enriched organic matter and thus a more pronounced excursion might seem worth consideration (but see comments at end of previous paragraph). The questions then arise as to what caused the more widespread occurrence of oxygenated environments in the Telychian in general and why particularly in the middle *spiralis* graptolite Biozone in the Sommerodde-1 core.

Perhaps there was an influx of cooler, more oxygenated water into the Silurian Baltic basin at this time. No glacial deposits have been recorded from the Telychian of Gondwana (but precise dating of Silurian glacial deposits has only rarely been achieved; e.g. Caputo and dos Santos 2020). Both the sea-level curve of Loydell (1998; Fig. 8) and the oxygen isotope data from the Viki core, Estonia (Fig. 1) presented by Lehnert *et al.* (2010, fig. 3) indicate that there were numerous glacial advances and retreats during the *spiralis* Zone (or correlative *lennarti* and *lithuanicus* conodont zones). Or perhaps there was a temporary change in bottom water circulation resulting from relatively nearby tectonic activity? Hurst *et* *al.* (1983) referred to substantial platform carbonate collapse over a large area, following continental collision involving northern Baltica, at the northern Iapetus Ocean margin; in Greenland, platform carbonates are replaced in the Telychian succession by basinal turbidites. Dating of the continental collision is enabled by the extraordinary thickness (500 m) of *spiralis* graptolite Biozone strata in Greenland (Bjerreskov 1986), reflecting erosion of uplifted source areas. Thus, this collision coincides at least in part with the SOCIE. Inevitably there is speculation here, but something exceptional and presumably short-lived is required to explain what appears to be an anomalous Sommerodde-1 core isotope record in the unusually pale strata of the *spiralis* Biozone and in particular the presence of the high magnitude SOCIE.

The impact of changes in the composition of deposited organic matter on $\delta^{13}C_{org}$

There is a similar, Late Ordovician example of an unusually high magnitude (nearly 8‰) positive $\delta^{13}C_{org}$ excursion. Pancost *et al.* (1999) suggested that the anomalously high $\delta^{13}C_{org}$ values recorded by the Guttenberg excursion (GICE) in the Katian of Iowa could reflect a change in organic matter composition: the colonial mat-forming organic-walled microfossil *Gloeocapsomorpha prisca* (sometimes referred to as an alga, more frequently as probably cyanobacterial; Foster *et al.* 1989, 1990) became abundant in the excursion interval. Carbon isotope analyses of individual biomarkers of *G. prisca* by Pancost *et al.* (1999) indicated that these were enriched in ^{13}C by 7‰ relative to compounds derived from other algal sources. *Gloeocapsomorpha prisca* characterizes very shallow marine and intertidal environments in the Ordovician, so is very unlikely to have been involved in generating the enhanced Sommerodde-1 $\delta^{13}C_{org}$ values. But, this Ordovician example demonstrates the potential for a profound change in the nature and relative abundance of organic-walled organisms to enhance dramatically the magnitude of an isotope excursion. Unfortunately, many of these organic-walled organisms would have partially decayed (so as to be unidentifiable) as they descended through the water column to reach the seafloor as amorphous organic matter (AOM). Vandenbroucke *et al.* (2013, p. 95) emphasized the importance of (and need for) unidentifiable contributors within AOM to explain the bulk $\delta^{13}C_{org}$ values in the Telychian–Sheinwoodian of Gotland, Sweden.

Vandenbroucke *et al.* (2013) discussed various previous studies on the differing $\delta^{13}C$ values of organic-walled fossils, and analysed the $\delta^{13}C$ of chitinozoans (traditionally viewed as metazoan egg cases, but recently re-interpreted as protists; Liang *et al.* 2020, but see Vodička *et al.* 2022) and scolecodonts (polychaete worm jaws), but both of these organic-walled microfossils had more negative $\delta^{13}C$ values than bulk values. Lecuyer and Paris (1997) recorded the following $\delta^{13}C$ values from picked organic remains from a residue from the late Ludlow Kopanina Formation of the Czech Republic: graptolites -29.5‰; scolecodonts -28.0‰; leiospheres -27.0‰. It is easy to see how the $\delta^{13}C_{org}$ of a bulk organic sample dominated by graptolites could differ significantly from one dominated by leiospheres. Similarly, a change in the contribution to AOM by organisms with very different $\delta^{13}C$ values would inevitably influence bulk rock $\delta^{13}C_{org}$.

A change in the relative proportions of the organic matter preserved on the sea floor resulting from an organism enriched in ^{13}C flourishing in waters overlying the deep water environment at Sommerodde at the time of the SOCIE represents a potential explanation both for the excursion itself and, assuming that the organism was restricted to this deep marine environment or the waters above it, also the atypical increasing magnitude of the SOCIE with increasing water depth.

Conclusions

The Sommerodde excursion (SOCIE) extends through 10 m of pale, organic-poor, deep marine strata in the *Oktavites spiralis* graptolite Biozone of the Sommerodde-1 core, Bornholm. It has the highest magnitude of any Upper Ordovician–lower Silurian positive isotope excursion in this core. Elsewhere, however, with the exception of the Aizpute-41 core, Latvia (also a deeper water palaeoenvironment), the magnitude of the excursion is much less pronounced, becoming a minor event (or even unrecognisable) in shallower water settings, thus revealing a trend unique within the Silurian of increasing excursion magnitude with water depth.

Vandenbroucke *et al.* (2013) emphasized the challenges of interpreting changes in $\delta^{13}C_{org}$, stating: ‘the interpretation of $\delta^{13}C_{org}$ can be complex because of the various factors that influence the values, including varying sources of organic matter (e.g., bacteria, phytoplankton, zooplankton), varying production rates of the organic material, growth rates and geometry of phytoplankton cells, and the potential presence of carbon concentrating mechanisms, properties of the ambient sea water (temperature, pCO_2, light, nutrients), preservation and diagenesis, the inorganic C pool, and the analytical (e.g., acid digestion) method.' This host of factors must be borne in mind.

With due consideration of the factors listed in the previous paragraph, many of which are impossible to know or quantify in the geological record, we suggest that the unusually high magnitude of the SOCIE in the Sommerodde-1 core is most probably the result of a change in the relative contributions of different sources of the organic carbon preserved and analysed, with an organism with higher ^{13}C flourishing at this time only in the seas above deeper water environments.

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Fig. 1. Location of boreholes referred to in the text on a map of the East Baltic region, with Silurian facies shown (but not shorelines or the extension northwards of shallow marine facies into Sweden). Map has been modified from that in Sullivan *et al.* (2018).

Fig. 2. The $\delta^{13}C_{org}$ record through the Telychian and Sheinwoodian of the Sommerodde-1 core, with named excursions indicated. Graptolite biozonation (from Loydell *et al.* 2017), optic televiewer (OPTV) log and geophysical log stratigraphical units (from Schovsbo *et al.* 2015) and $\delta^{13}C_{org}$ curve (from Hammarlund *et al.* 2019) for the Telychian–Sheinwoodian of the Sommerodde-1 core, Bornholm. Abbreviations: *c – crenulata*; *g – griestoniensis*; *cr – crispus*; ESCIE – early Sheinwoodian carbon isotope excursion; SHEIN. – Sheinwoodian; SOCIE – Sommerodde carbon isotope excursion.

Fig. 3. The SOCIE in the Sommerodde-1 core, Bornholm. The occurrences of stratigraphically significant graptolite species are shown.

Fig. 4. $\delta^{13}C_{org}$ curve and occurrences of biostratigraphically significant graptolites in the Zwierzyniec-1 core, Poland. Data from Sullivan *et al.* (2018).

Fig. 5. $\delta^{13}C_{org}$ data for the Aizpute-41 core, Latvia, from Young *et al.* (2020). The graptolite biozonation applied by Young *et al.* (2020, fig. 4) is shown, together with the original graptolite biozonation of Loydell *et al.* (2003). Strata lacking biostratigraphically diagnostic graptolites are shown with a question mark. Note that the *Streptograptus sartorius* Biozone (*s*) is represented by a single sample at 960.25 m, whilst the *Spirograptus turriculatus* Biozone (*t*) is represented by two closely spaced samples between 964.58 m and 968.62 m (which overlie unfossiliferous strata down to the lower *sedgwickii* Biozone at 969.05 m); both biozones are therefore represented by a line rather than a box. The single $\delta^{13}C_{org}$ analysis representing the SOCIE is at the same biostratigraphical level as the SOCIE in the Sommerodde-1 core.

Fig. 6. $\delta^{13}C_{org}$ curve for the Telychian–Sheinwoodian of the Vežaičiai-2 core, western Lithuania. Note that the graptolite biostratigraphy shown is based on correlation with the

Viduklė-61 core, 90 km to the ESE, hence the tentative identification of the excursions in the Telychian. Figure modified from Cichon-Pupienis *et al.* (2021).

Fig. 7. $\delta^{13}C_{org}$ curve for the Mount Hare Formation, Road River Group of northern Yukon (from Strauss *et al.* 2020). The Valgu excursion recognised by Strauss *et al.* is shown, together with the SOCIE and possible Manitowoc excursion (identified as the "Ireviken excursion" = ESCIE by Strauss *et al.*, but occurring at too low a biostratigraphical level, in the Llandovery rather than the Wenlock, to be this excursion). *s/l.* = *Cyrtograptus sakmaricus*/*Cyrtograptus laqueus* graptolite Biozone.

Fig. 8. Location of the Jabalón River section, Corral de Calatrava, central Spain including (inset) a map of the Iberian peninsula showing the Iberian Massif (pale grey) and Central Iberian Zone (grey). The distribution of lithologies and unconformities within the middle Telychian–Sheinwoodian of the section and their relationship to the early Silurian sea level curve of Loydell (1998) is shown, as is a field photo of the section (strata young to the left). Maps, section and sea-level curve from Loydell *et al.* (2009).

Fig. 9. Location of sections referred to in text on the Telychian palaeogeographical map of Torsvik and Cocks (2013). J: Jabalón River section, Spain; Y: Peel River, Yukon, Canada; Z: Zwierzyniec, Poland. Unlabelled red squares cover localities in the Baltic States shown in Fig. 1. Yellow star: Sommerodde, Bornholm.

Fig. 10. $\delta^{13}C_{org}$ curve for the middle Telychian–lower Sheinwoodian of the Jabalón River section, Spain. *ricc.* = *riccartonensis.* Biozonation and lithological log from Loydell *et al.* (2009).

Fig. 11. Comparison of the SOCIE in the Sommerodde-1 core Bornholm (left) with the Jabalón River section, Spain (right). Occurrences of selected, biostratigraphically significant graptolite species are shown (from Loydell *et al.* 2009, 2017). Note in particular

Streptograptus nodifer and *Oktavites excentricus*, which have a similar relationship to the SOCIE in both sections.

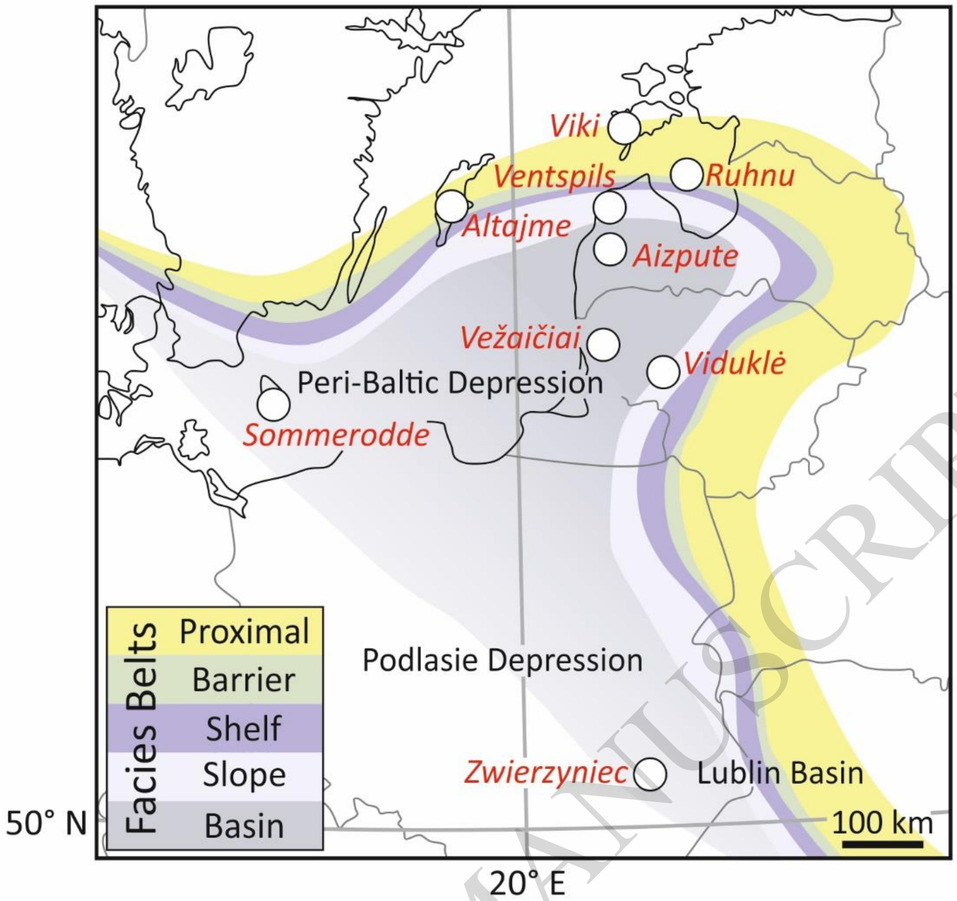
Viki
Ventspils
Ruhnu
Altajme
Aizpute
Vežaičiai
Viduklė
Peri-Baltic Depression
Sommerodde
Facies Belts
Proximal
Barrier
Shelf
Slope
Basin
Podlasie Depression
Zwierzyniec
Lublin Basin
50° N
100 km
20° E

Figure 1

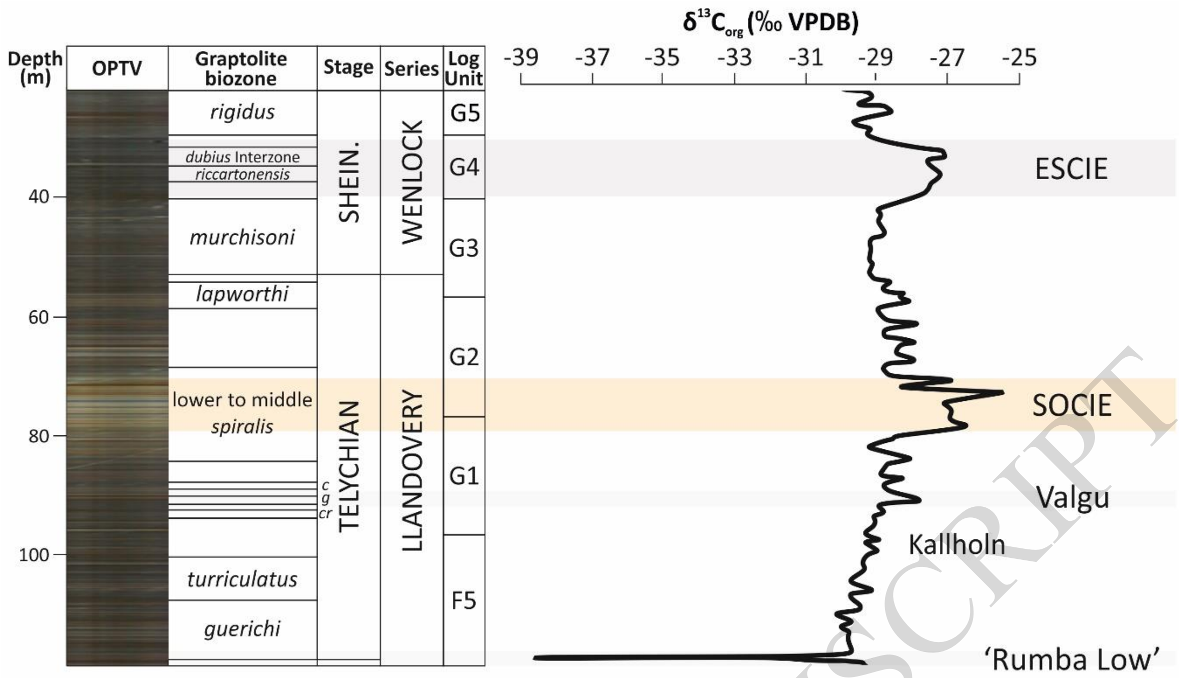
δ13Corg (‰ VPDB)
-39
-37
-35
-33
-31
-29
-27
-25
Depth (m)
OPTV
Graptolite biozone
Stage
Series
Log Unit
40
60
80
100
rigidus
dubius Interzone
riccartonensis
murchisoni
lapworthi
lower to middle spiralis
c
g
cr
turriculatus
guerichi
SHEIN.
TELYCHIAN
WENLOCK
LLANDOVERY
G5
G4
G3
G2
G1
F5
ESCIE
SOCIE
Valgu
Kallholn
'Rumba Low'

Figure 2

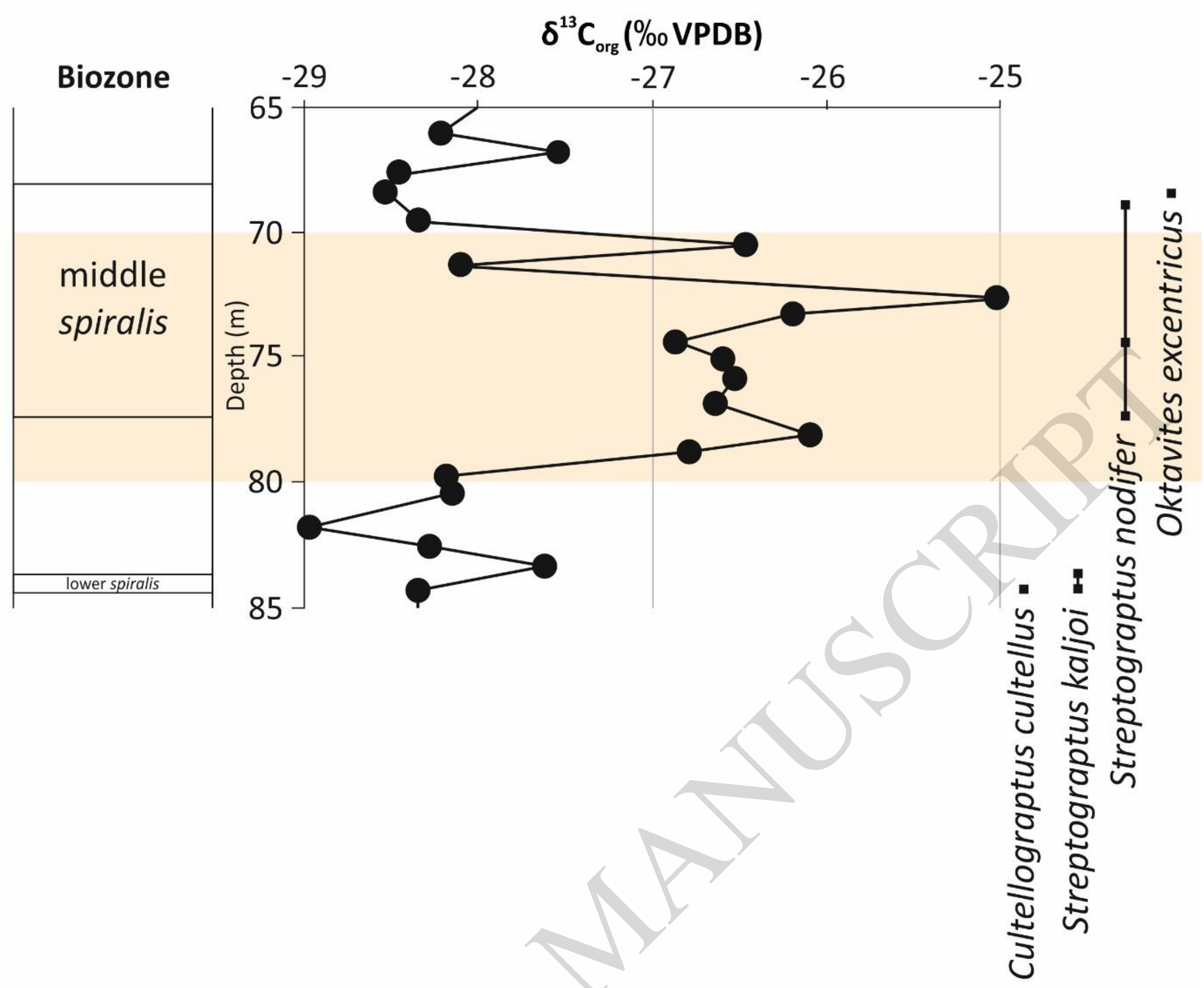
$\delta^{13}C_{org}$ (‰ VPDB)
Biozone
-29
-28
-27
-26
-25
65
70
75
80
85
Depth (m)
middle *spiralis*
lower *spiralis*
Cultellograptus cultellus
Streptograptus kaljoi
Streptograptus nodifer
Oktavites excentricus

Figure 3

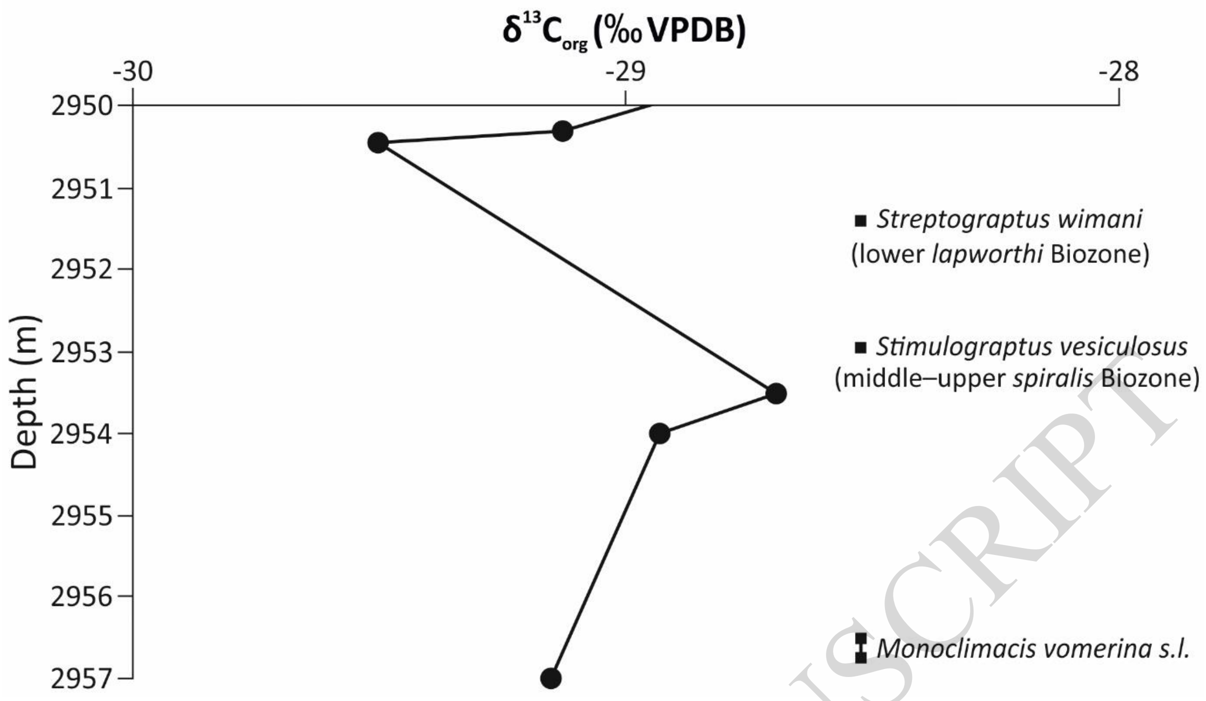
δ13Corg (‰ VPDB)
-30
-29
-28
Depth (m)
2950
2951
2952
2953
2954
2955
2956
2957
■ Streptograptus wimani
(lower lapworthi Biozone)
■ Stimulograptus vesiculosus
(middle–upper spiralis Biozone)
Monoclimacis vomerina s.l.

Figure 4

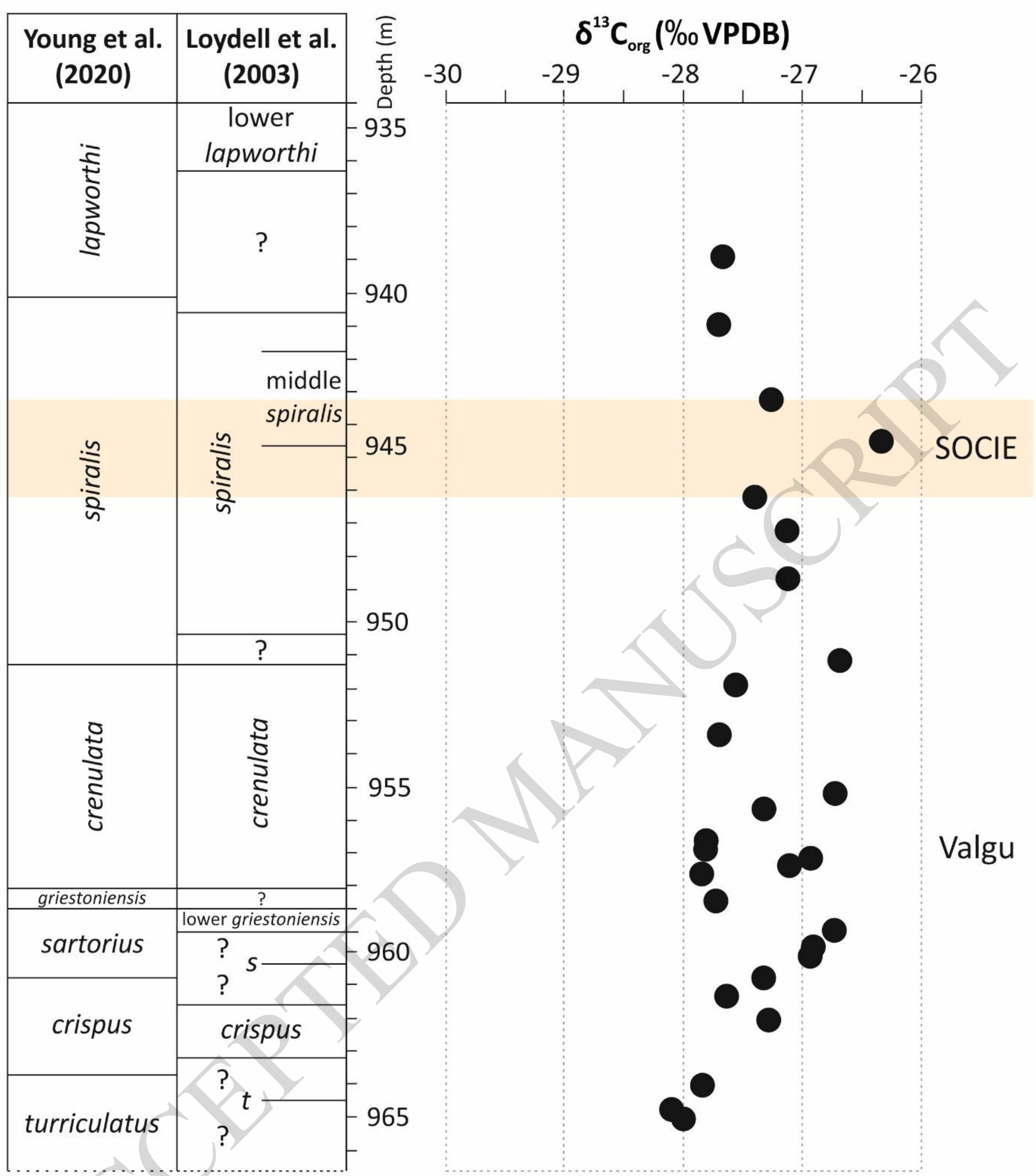
Young et al. (2020)
Loydell et al. (2003)
Depth (m)
$\delta^{13}C_{org}$ (‰ VPDB)
-30
-29
-28
-27
-26
lapworthi
spiralis
crenulata
griestoniensis
sartorius
crispus
turriculatus
lower lapworthi
?
middle spiralis
spiralis
?
crenulata
?
lower griestoniensis
?
s
?
crispus
?
t
?
935
940
945
950
955
960
965
SOCIE
Valgu

Figure 5

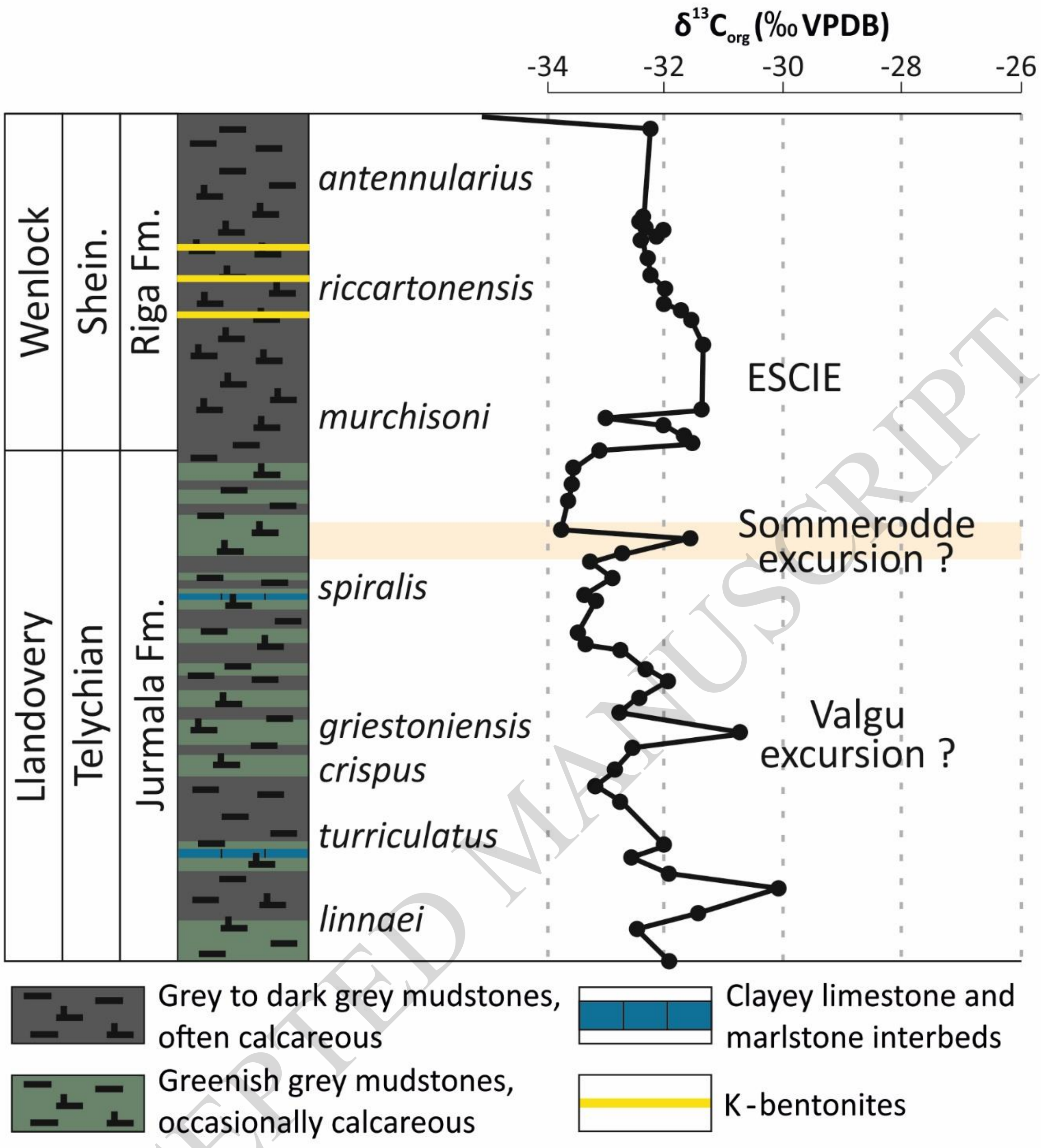
$\delta^{13}C_{org}$ (‰ VPDB)
-34
-32
-30
-28
-26
Wenlock
Shein.
Riga Fm.
Llandovery
Telychian
Jurmala Fm.
antennularius
riccartonensis
murchisoni
spiralis
griestoniensis
crispus
turriculatus
linnaei
ESCIE
Sommerodde excursion ?
Valgu excursion ?
Grey to dark grey mudstones, often calcareous
Greenish grey mudstones, occasionally calcareous
Clayey limestone and marlstone interbeds
K-bentonites

Figure 6

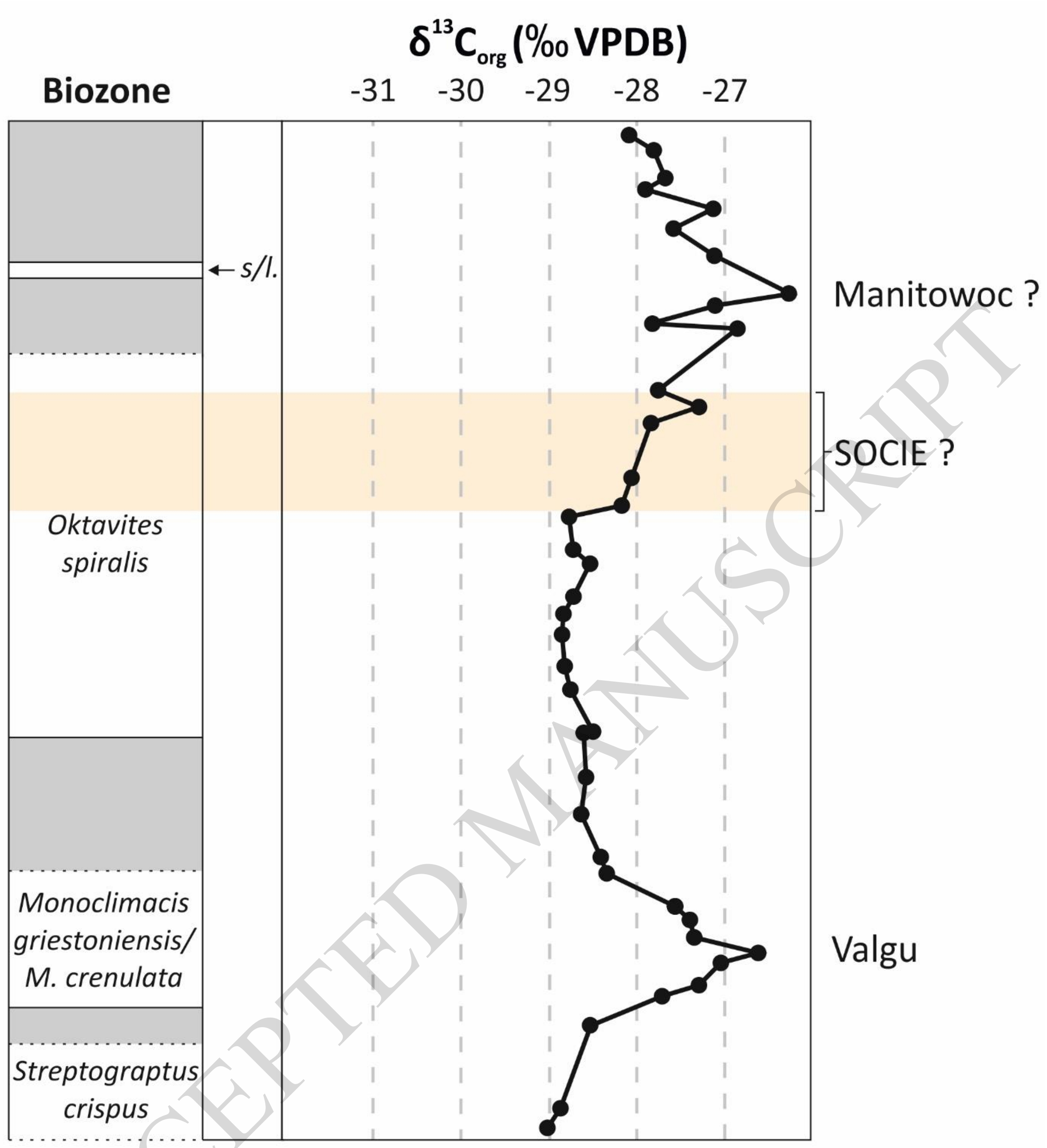
$\delta^{13}C_{org}$ (‰ VPDB)
Biozone
-31
-30
-29
-28
-27
s/l.
Manitowoc ?
SOCIE ?
Oktavites spiralis
Valgu
Monoclimacis griestoniensis/ M. crenulata
Streptograptus crispus

Figure 7

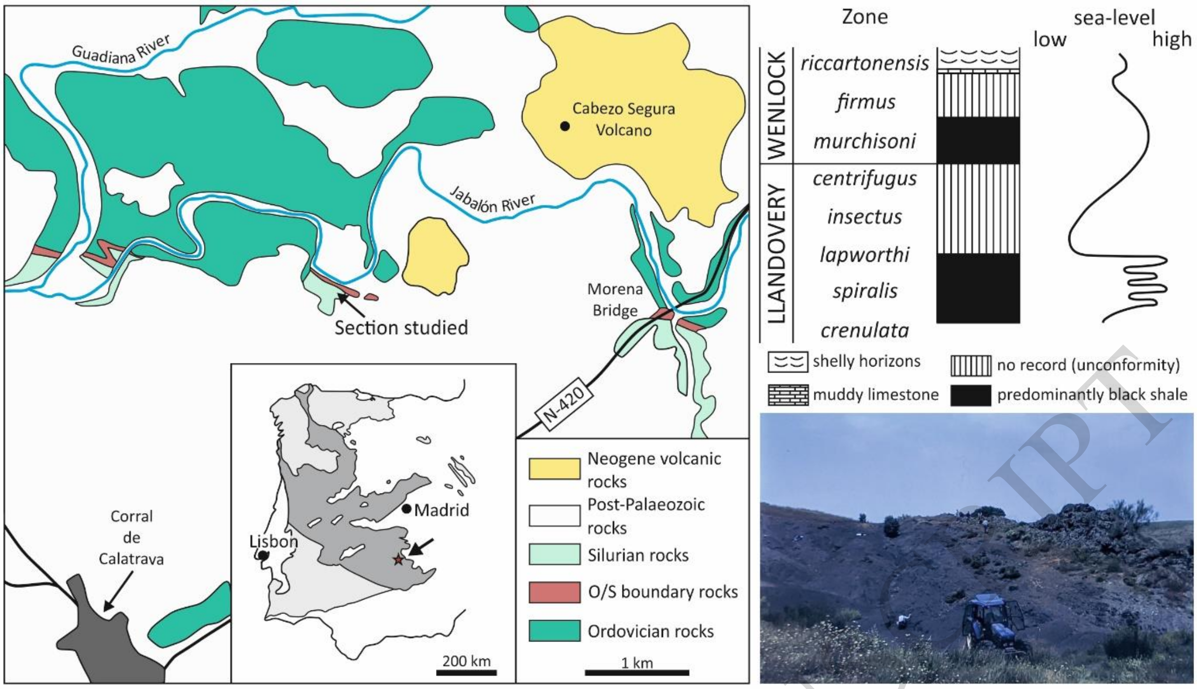
Guadiana River
Jabalón River
Cabezo Segura Volcano
Section studied
Morena Bridge
N-420
Corral de Calatrava
Madrid
Lisbon
200 km
Neogene volcanic rocks
Post-Palaeozoic rocks
Silurian rocks
O/S boundary rocks
Ordovician rocks
1 km
Zone
sea-level
low
high
WENLOCK
LLANDOVERY
riccartonensis
firmus
murchisoni
centrifugus
insectus
lapworthi
spiralis
crenulata
shelly horizons
muddy limestone
no record (unconformity)
predominantly black shale

Figure 8

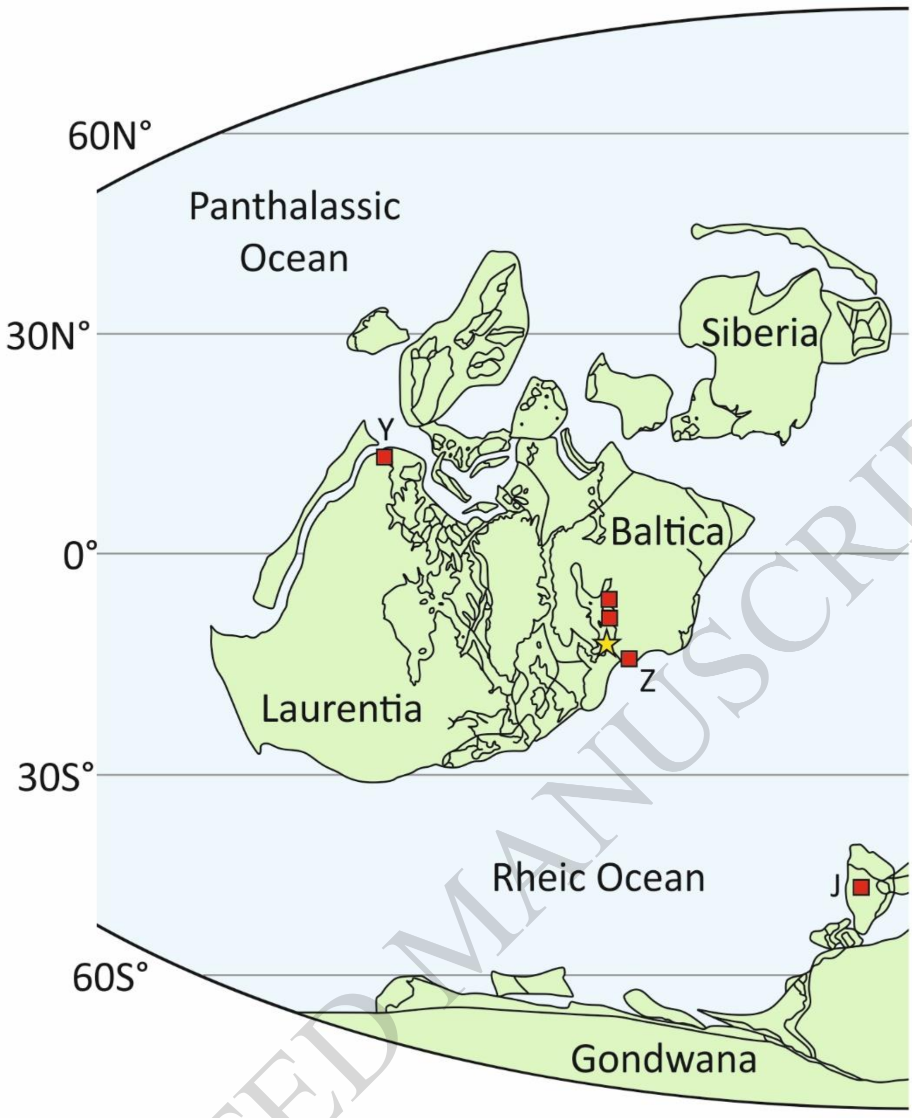
60N°
30N°
0°
30S°
60S°
Panthalassic Ocean
Siberia
Y
Baltica
Z
Laurentia
Rheic Ocean
J
Gondwana

Figure 9

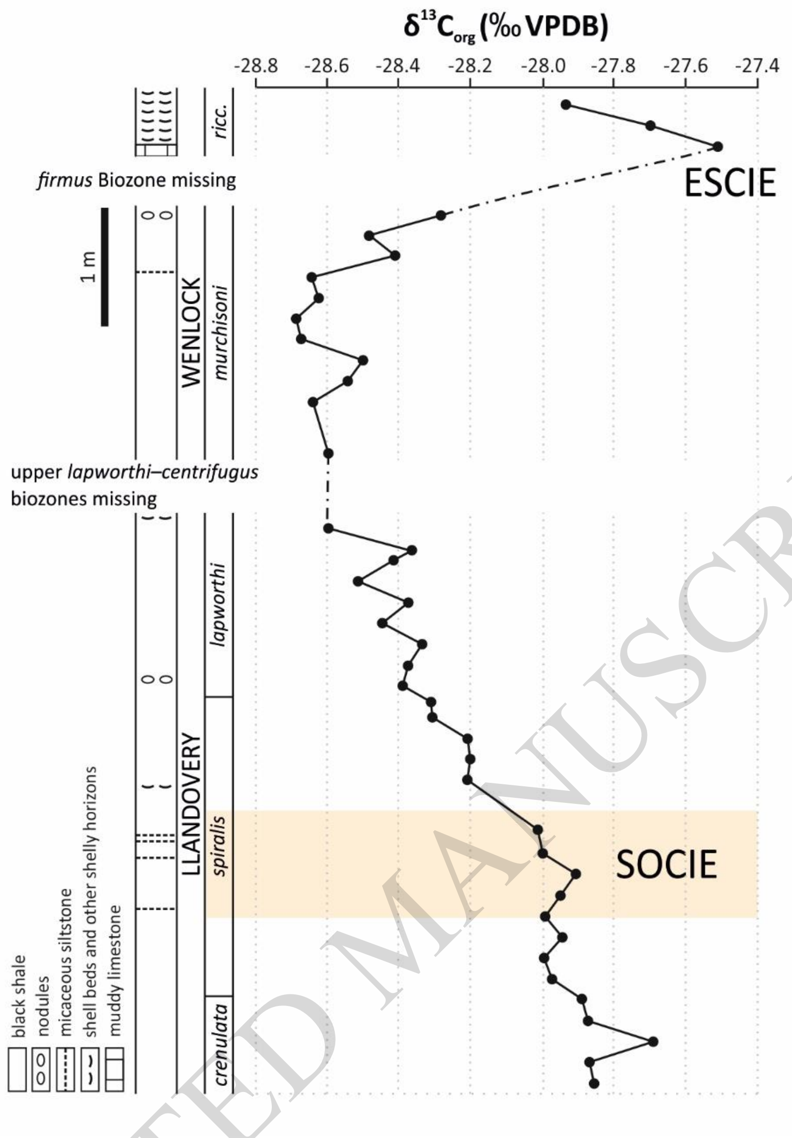
$\delta^{13}C_{org}$ (‰ VPDB)
-28.8
-28.6
-28.4
-28.2
-28.0
-27.8
-27.6
-27.4
ricc.
firmus Biozone missing
ESCIE
1 m
WENLOCK
murchisoni
upper *lapworthi–centrifugus* biozones missing
lapworthi
LLANDOVERY
spiralis
SOCIE
crenulata
black shale
nodules
micaceous siltstone
shell beds and other shelly horizons
muddy limestone

Figure 10

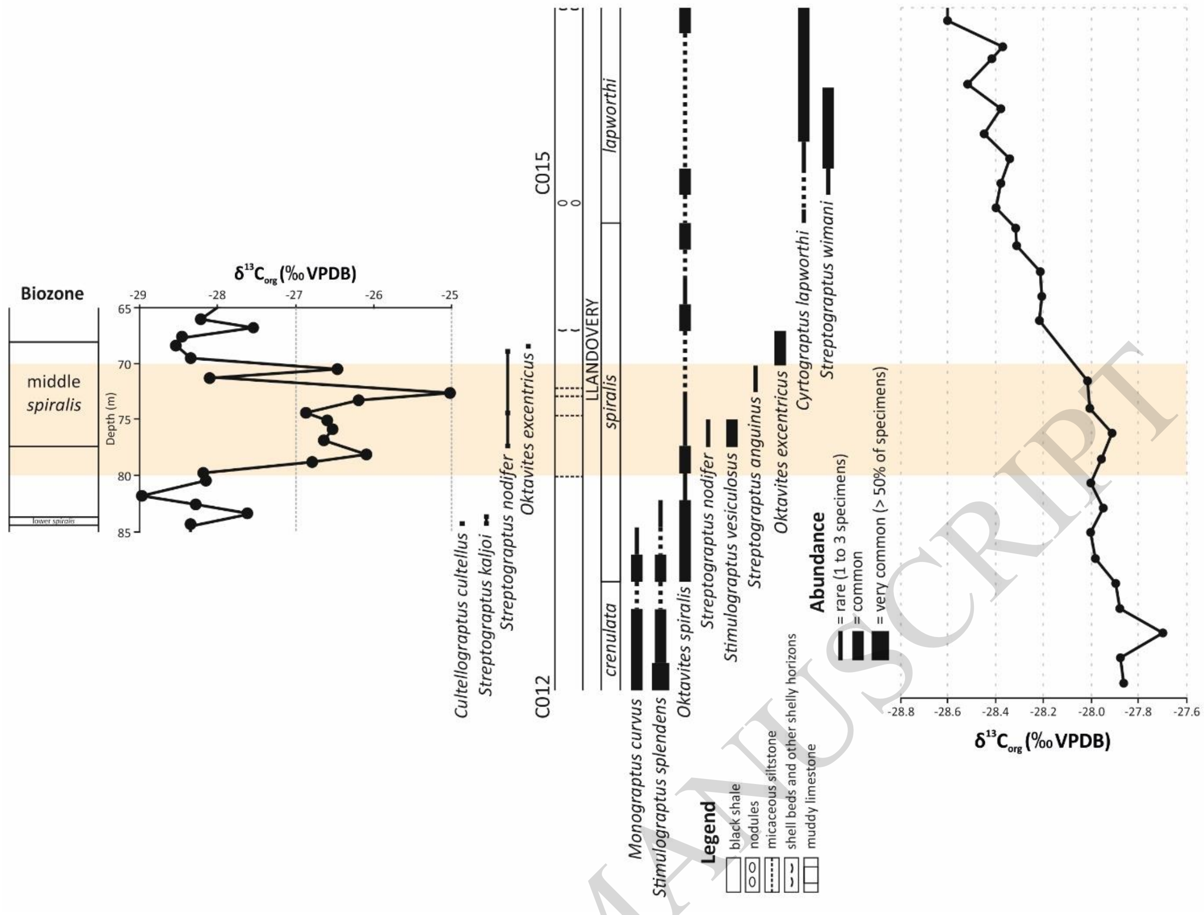
Biozone
middle
spiralis
lower spiralis
Depth (m)
65
70
75
80
85
$\delta^{13}C_{org}$ (‰ VPDB)
-29
-28
-27
-26
-25
Cultellograptus cultellus
Streptograptus kaljoi
Streptograptus nodifer
Oktavites excentricus
C012
C015
LLANDOVERY
crenulata
spiralis
lapworthi
Monograptus curvus
Stimulograptus splendens
Oktavites spiralis
Streptograptus nodifer
Stimulograptus vesiculosus
Streptograptus anguinus
Oktavites excentricus
Cyrtograptus lapworthi
Streptograptus wimani
Legend
black shale
nodules
micaceous siltstone
shell beds and other shelly horizons
muddy limestone
Abundance
= rare (1 to 3 specimens)
= common
= very common (> 50% of specimens)
-28.8
-28.6
-28.4
-28.2
-28.0
-27.8
-27.6
$\delta^{13}C_{org}$ (‰ VPDB)

Figure 11