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Dating of sedimentary rock intervals using visual comparison of carbon isotope records: a comment on the recent paper by Bergström *et al.* concerning the age of the Winneshiek Shale

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The recently published *Lethaia* paper by Bergström *et al.* (https://doi.org/10.1111/let.12269) on the age of the Ordovician Winneshiek Shale (Iowa, USA), and the impact that formed the Decorah crater which hosts this rock unit, is an interesting scientific contribution, although there are a number of problems with the interpretations and data presentation that merit comment. Due mainly to a lack of adequate critical assessment of δ^{13}C data and biostratigraphical control, we contend that the conclusions of Bergström *et al.* are poorly founded and should not be cursorily accepted and propagated in future scientific literature. □ *δ^{13}C, chemostratigraphy, correlation, Decorah impact crater, Ordovician, Whiterockian.*

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Published palaeontological data indicate that the Winneshiek Shale, a peculiar Konservat-Lagerstätte interval formed within the ca. 5.5-km-wide Decorah impact crater in Iowa, USA, is at least in part Darriwilian (Whiterockian) in age; but detailed biostratigraphical and temporal control is yet missing and only the uppermost part of the rock unit has been extensively sampled (Witzke *et al.* 2011; Liu *et al.* 2017). By inference, through lateral stratigraphical contexts and comparisons to conodont faunas elsewhere, Liu *et al.* (2017) tentatively assigned the rock unit to the middle–upper Darriwilian (cf. Witzke *et al.* 2011). Bergström *et al.* (2018) utilized organic-carbon isotope ($\delta^{13}C_{org}$) chemostratigraphy in an effort to deduce the age of the Winneshiek Shale more precisely by correlating to previously published carbonate-carbon isotope ($\delta^{13}C_{carb}$) records.

Chemostratigraphical interpretations and problems

In short, the Winneshiek Shale records an apparent small rise in $\delta^{13}C_{org}$ values and drastically decreased scatter in the data up-section (Bergström *et al.* 2018, fig. 4); the lower 5 m of the rock unit yield an average δ^{13}C of approximately −31 ± 1.5‰ (adjacent values may differ by >4‰), whereas the average of the interval above is approximately −29.5 ± 0.5‰ (a numerical data set is lacking). From a smoothed running average line of their data (see below), Bergström *et al.* (2018) interpret the $\delta^{13}C_{org}$ trends as representing an interval covering much of the Dw1 and Dw2 stage slices of the Darriwilian (Middle Ordovician; see Bergström *et al.* 2009). No alternative scenarios are considered or discussed. The slightly elevated $\delta^{13}C_{org}$ values in the upper part of the Winneshiek Shale are taken to represent the MDICE (a small-amplitude positive carbon excursion possibly of global significance; e.g., Ainsaar *et al.* 2010; Schmitz *et al.* 2010; Edwards & Saltzman 2016; Lindskog *et al.* in press). In the basal Winneshiek Shale, Bergström *et al.* (2018, p. 507) identify a positive 'so far unnamed small excursion' allegedly corresponding to the *Lenodus variabilis*–*Yangtzeplacognathus crassus* conodont Zone boundary interval. This is overlain by a temporary dip in (average) δ^{13}C values identified by the aforementioned authors as an equivalent to the LDNICE of Lehnert *et al.* (2014). Regardless of broader-scale interpretations, the LDNICE is problematic as a stratigraphical tool, as it is difficult/impossible to apply outside of the Siljan area, Sweden, where it was originally identified in a severely condensed limestone interval spanning the boundary between the Volkhov and Kunda Baltoscandian stages (*Megistaspis limbata*–*Asaphus expansus* trilobite Zone boundary; cf. Hessland 1949; Jaanusson & Mutvei 1951; Ainsaar *et al.* 2010; Wu *et al.* 2018). The LDNICE embraces a succession of biozones, at least including the upper *Baltoniodus norrlandicus*, the *L. variabilis*, *Y. crassus* and basal *Eoplacognathus pseudoplanus* conodont zones (Löfgren 1995, 2003, 2004), and thus cannot be pinpointed to a specific stratigraphical level (in fact, few significant excursions can). It is noteworthy that the nadir of the LDNICE spans the interval identified by Bergström *et al.* (2018) as being characterized by a positive excursion.

Already at the very outset, the approach used by Bergström *et al.* (2018) is problematic, as the stratigraphical patterns of carbon isotopes (both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$) can clearly vary laterally both at the regional and global scales (Panchuk *et al.* 2006; Fanton & Holmden 2007; Ainsaar *et al.* 2010; Edwards & Saltzman 2016; Henderson *et al.* 2018; Lindskog *et al.* in press). The potential for confident age interpretations based on the data from the Winneshiek Shale (Bergström *et al.* 2018, fig. 4) is further made problematic as $\delta^{13}C_{org}$ does not necessarily follow $\delta^{13}C_{carb}$ patterns (see, e.g. Young *et al.* 2008, fig. 8; Edwards & Saltzman 2016, fig. 10; Edwards *et al.* 2017, fig. 1; Henderson *et al.* 2018, figs 10, 11), wherefrom the reference data cited by the authors stem. In the case of areas outside of normal marine conditions, there is especially

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great risk involved when utilizing bulk $\delta^{13}C_{org}$ analyses for chronostratigraphical correlation. The Konservat-Lagerstätte characteristics of the Winneshiek Shale attest to unusual conditions during formation and diagenesis of the strata, and the local palaeoenvironment has been interpreted as restricted and possibly brackish-water (Liu *et al.* 2009; Witzke *et al.* 2011; Bergström *et al.* 2018). Due to poor contact and exchange with open oceanic water masses, the stratigraphical patterns of $\delta^{13}C_{org}$ within such an area cannot *a priori* be expected to reflect global patterns.

Notwithstanding the obvious pitfalls of uncritical interpretation of $\delta^{13}C$ data (especially in non-normal marine environments), there are a number of factors that contribute to bulk $\delta^{13}C_{org}$ values, including: (1) temperature dependent fractionation between dissolved inorganic carbon (DIC) and CO_2 in seawater; (2) photosynthetic fractionation (ε_p) associated with carbon fixation by primary producers (which differs between species); (3) organic-matter source variation; (4) secondary biological fractionation (heterotrophy, remineralization); and (5) diagenesis (e.g. thermal alteration; Hayes *et al.* 1999; Kienast *et al.* 2001; Royer *et al.* 2001). Despite these numerous complicating factors, bulk $\delta^{13}C_{org}$ data still have the potential to record a global signal that could be interpreted as strictly a change in $\delta^{13}C_{DIC}$ (i.e. $\delta^{13}C_{carb}$). However, one has to either employ compound-specific $\delta^{13}C$ techniques to ensure a marine phytoplankton organic carbon signal or systematically rule out the other factors that can influence $\delta^{13}C_{org}$ (Joachimski *et al.* 2002; Young *et al.* 2008). In mid-continent Laurentia, the organic-walled microfossil *Gloeocapsomorpha prisca* has been widely documented in strata with high total organic carbon content and it has even been found to be a dominant local source of organic matter (rather than other marine algal signatures; Hatch *et al.* 1987; Jacobson *et al.* 1988, 1995). For example, studies of biomarkers in Upper Ordovician strata in Iowa demonstrate that *G. prisca* compounds can show wider enrichments in $\delta^{13}C$ than other marine algae and that organic matter sources clearly shifted during the GICE (Pancost *et al.* 1998, 1999).

Despite being aware of the unusual characteristics of the Winneshiek Shale, Bergström *et al.* (2018) interpret their $\delta^{13}C_{org}$ data as representing a global chemostratigraphical signal. There is no discussion on the nature of their geochemical data nor do the authors acknowledge any possible complicating factors, and there is no attempt at relating the data to the local palaeoenvironmental (or, sedimentological) conditions and development. Neither the absolute range of $\delta^{13}C_{org}$ values (~−34‰ to −28.5‰) recorded within the Winneshiek Shale nor the trends towards positive values are uniquely lower–middle Darriwilian—in fact, these ranges and trends in $\delta^{13}C_{org}$ data have been documented in essentially every global stage within the Ordovician System (Edwards & Saltzman 2016, fig. 10). In many areas, the interval corresponding to the Whiterockian is characterized by a general rise in $\delta^{13}C$ values with recurring minor drops (Bergström *et al.* 2009; Ainsaar *et al.* 2010; Schmitz *et al.* 2010; Lehnert *et al.* 2014; Edwards & Saltzman 2016). As such, (assuming that they indeed represent a global signal) the $\delta^{13}C_{org}$ data trends seen in the Winneshiek Shale actually fit well with much of this interval, and within the very broad confines of the scant biostratigraphical data (see Witzke *et al.* 2011; Liu *et al.* 2017), there are a great many scenarios for chemostratigraphical dating not considered by Bergström *et al.* (2018). The $\delta^{13}C_{carb}$ data from the Hällekis quarry, Sweden (Schmitz *et al.* 2010), which Bergström *et al.* (2018, fig. 4) use as a reference section, offer one illustrative example of the many possible chemostratigraphical 'age models' for the Winneshiek Shale (Fig. 1). Given the lack of biostratigraphical, palaeoenvironmental and diagenetic information, it remains unclear how Bergström *et al.* (2018) arrived at their confident interpretations concerning the stratigraphical and temporal constraints of this rock unit.

Problematic data presentation and discussions

The overall interpretations by Bergström *et al.* (2018) are further compounded by problematic data presentation and (in places, lack of) discussions, and a peculiar selectivity concerning relevant reference literature.

To begin with, other than stating that the local fauna lacks biostratigraphically diagnostic fossils and that the age of this unit is 'probably middle to late Darriwilian', Bergström *et al.* (2018) do not elucidate the basic biostratigraphical context of the Winneshiek Shale. Given the very general pattern exhibited by their $\delta^{13}C$ data (see above), adequate biostratigraphical (and/or other chronostratigraphical) control is essential. Ultimately, the interpretations of Bergström *et al.* (2018) hinge upon visual comparison of chemostratigraphical trends. When looking in closer detail, the three-point running average line seen in the $\delta^{13}C_{org}$ data from the Winneshiek Shale (Bergström *et al.* 2018, fig. 4) is perplexing as it spans all data points and appears to include details at a higher resolution than the data allow (see, for example, in the 16–17 m interval). Moreover, the data from the Hällekis quarry are not reproduced by Bergström *et al.* (2018, fig. 4) as originally presented by Schmitz *et al.* (2010, fig. 4; see Fig. 1). As neither of the aforementioned papers provides numeric data sets, we could not check which version of the Hällekis quarry data is accurate. Regardless of the details of the chemostratigraphical data, the absence in the Winneshiek Shale of the geographically widespread *Histiodella–Paraprioniodus–Pteracontiodus–Fahraeusodus* conodont fauna that characterizes the early Darriwilian (see Liu *et al.* 2017) is problematic for the interpretations of Bergström *et al.* (2018).

A minor although ultimately important detail, as Bergström *et al.* (2018) repeatedly refer to it, is the numeric age of the Decorah impact event and the Winneshiek Shale, and in extension the putatively enhanced influx of extra-terrestrial matter during the Middle Ordovician. The age cited by Bergström *et al.* (2018) for the interval in question, but given without any indication of error limits (and without correct reference for the updated age calculation), is 465.46 Ma – an age that in its context(s) within the paper appears quite precise, but is in fact ultimately deceptive as it is associated with a ~±3.5 Ma uncertainty (i.e. a time span corresponding to most of the Darriwilian Stage; e.g., Gradstein *et al.* 2012; Schmitz 2012). Recent work in high-precision zircon U-Pb geochronology indicates that an age of ~465 Ma belongs in the middlemost–upper Dw2 stage slice (e.g. Sell *et al.* 2011) and that the Dw1–Dw2 boundary lies close to 467.5 Ma (Lindskog *et al.* 2017). Integration of the U-Pb framework and cosmic-ray exposure ages of fossil meteorites indicates that the breakup of the L-chondrite parent body occurred at 468 ± 0.3 Ma (cf. Bergström *et al.* 2018, p. 508).

With reference to a publication by Schmitz *et al.* (2008), in which it was argued that there is a causal link between an enhanced meteorite influx and the so-called Great Ordovician Biodiversification Event (GOBE; e.g., Webby *et al.* 2004; Servais & Harper 2018) during the Middle Ordovician (cf. Rasmussen *et al.* 2007; Lindskog *et al.* 2017), Bergström *et al.* (2018) discuss how the Decorah impact event may have contributed to biodiversity trends. Bergström *et al.* (2018, p. 508) conclude that they 'see little evidence of conspicuous organism evolution' and that 'the Winneshiek fauna does not add numerically very substantially to the early Darriwilian global biodiversity', although readers are offered little insight into what this means. Only for conodonts are species numbers mentioned and the overall fauna is merely discussed in terms of relative abundance within fossil collections (i.e. taxonomic composition). Allusions are made to richer 'coeval carbonate' faunas, but details and references are entirely missing. Curiously, however, in their Conclusions section Bergström *et al.* (2018, p. 510) more specifically (and with a reference included) discuss comparisons to what are called 'some of the other' Sandbian–Katian formations with richer fossil faunas. It is unclear how this information has any bearing on assessing biodiversity during the Darriwilian and how it relates to the Winneshiek Shale. The lack of temporal constraints on the rock unit makes it difficult to determine what diversity and evolutionary development can even be expected, especially when taking into account that most hitherto collected fossils stem from a limited stratigraphical interval (Liu *et al.* 2017). In contrast to what is implied by Bergström *et al.* (2018, p. 508), Thorslund (1940) and Frisk &

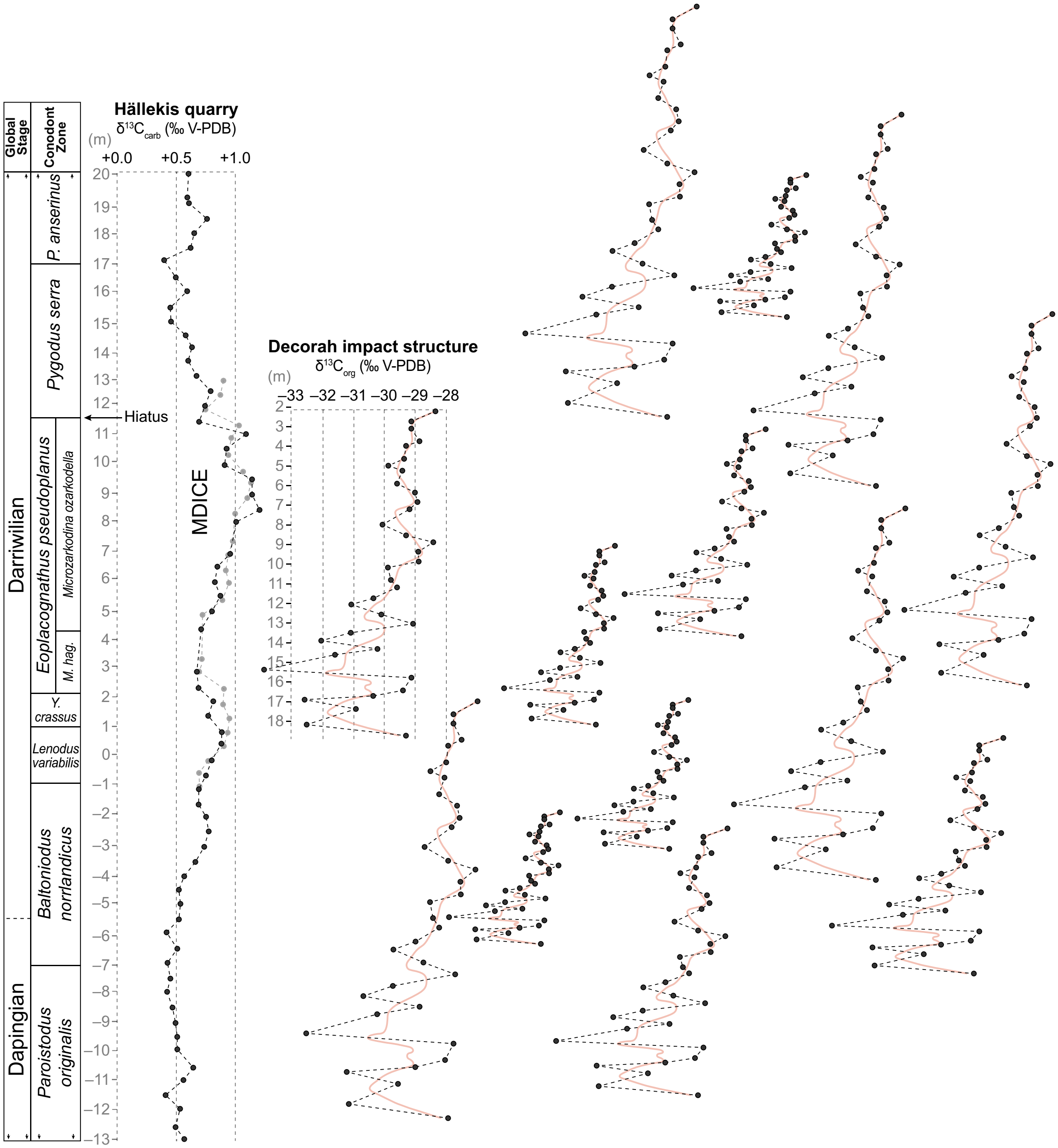

Fig. 1. $\delta^{13}C_{carb}$ chemostratigraphy at the Hällekis quarry, modified from Schmitz *et al.* (2010; Dapingian added according to Bergström *et al.* 2009), with grey points indicating the data as reproduced by Bergström *et al.* (2018, fig. 4). To the right, a selection of potential fits of the Winneshiek Shale $\delta^{13}C_{org}$ data (Bergström *et al.* 2018) against the Hällekis data are indicated, in order to illustrate the many arbitrary scenarios possible when assessing the age of the Winneshiek Shale succession based merely on visual comparison of $\delta^{13}C$ records (note: we do not propose any of these scenarios to be correct). The leftmost version represents the approximate scenario preferred by Bergström *et al.* (2018). Note the extreme difference in the amplitude of $\delta^{13}C$ variability between the Winneshiek and Hällekis data sets, and that these simple 'age models' do not take into account potential problems of correlating $\delta^{13}C_{org}$ with $\delta^{13}C_{carb}$ locally, regionally and globally (see main text). [Colour figure can be viewed at wileyonlinelibrary.com]

Harper (2013) actually documented rich and taxonomically diverse faunas in Ordovician crater environments in Sweden. Concerning the overall theme of biodiversity, it stands to be noted that what by Schmitz *et al.* (2008, p. 49; cf. pp. 51, 52) was called a 'precise coincidence' between an enhanced influx of extra-terrestrial matter and the onset of the GOBE proper has somehow evolved into a 'broad geochronological link' (Bergström *et al.* 2018, p. 505; cf. p. 508). We cannot help but to read some influence from more recent—yet unreferenced—literature into this transformation of concepts.

Although any detailed discussion on the cratering record of the Ordovician is beyond the aims of this commentary text, we note that Bergström *et al.* (2018) largely base their final section (Other Ordovician meteorite craters) on information found in the Earth Impact Database (http://www.passc.net/EarthImpactDatabase). This website serves as a useful overview of astroblemes on Earth, but discussions concerning the cratering record should rely on scientific publications. Issues related to uncritical use of information found in the database were recently brought up by Meier & Holm-Alwmark (2017). Looking into the scientific literature, it is apparent that some of the craters suggested by Bergström *et al.* (2018, pp. 508–509) to be related to the breakup of the L-chondrite parent body are only very roughly and/or ambiguously dated (e.g., Clearwater East and Couture in Canada, Hummeln in Sweden; Bottomley *et al.* 1990; Lindström *et al.* 1999; Biren *et al.* 2016) and some are arguably (directly) unrelated to this event. For example, the Slate Islands crater (Canada) appears quite young (436 ± 3 Ma; Dressler *et al.* 1999) and geochemical data implicate a non-ordinary-chondritic impactor for the Brent crater (Canada; e.g., Goderis *et al.* 2010). Bergström *et al.* (2018) fail to acknowledge the literature that allows them to infer a binary-impact scenario for the Lockne and Målingen craters (Sweden; Alwmark *et al.* 2014; Ormö *et al.* 2014).

Regardless of interpretations and views, scientific discussions are best served by an holistic perspective involving alternative explanations and adequate referencing of relevant literature.

Conclusions

In light of the many $\delta^{13}C$ chemostratigraphical ‘age models’ possible within the currently known biostratigraphical constraints of the Winneshiek Shale, the interpretations and subsequent conclusions of Bergström *et al.* (2018) are poorly founded and thus questionable. The reliability is further lowered by a fundamentally uncritical approach, inadequate data presentation and discussion, and unwarranted selectivity among reference literature. Ultimately, utilizing $\delta^{13}C$ as a tool for correlation across platforms, basins, and palaeocontinents can and should be done; however, this type of chemostratigraphical correlation should always be performed within adequate overall stratigraphical context and should not be based merely on general similarities of stratigraphical patterns. Claiming ‘precise’ correlations of non-unique chemostratigraphical data without robust biostratigraphical or other chronostratigraphical frameworks may set an alarming precedent, especially so when suggesting extended implications of interpretations (in this case related to the impact record of Earth). Although it might eventually turn out that the chemostratigraphical interpretations and correlations of Bergström *et al.* (2018) are indeed correct, until more biostratigraphical or other independent chronostratigraphical data (e.g., strontium isotope stratigraphy, K-bentonites, ejecta deposits) are documented, the ages of the Decorah impact event and the Winneshiek Shale must be considered no further refined than previously published literature suggests. Consequently, any possible relationship between the Decorah impact event and an enhanced influx of L-chondritic matter during the Middle Ordovician remains conjectural.

Post-review addendum

While this manuscript was out for review, two scientific papers that provide more in-depth perspectives on the Decorah crater were published (see Briggs *et al.* 2018; French *et al.* 2018). In summary, stratigraphical constraints show that the Decorah impact event occurred sometime between the middle Tremadocian and the middle/late Darriwilian stages of the Ordovician (~480–460 Ma in the timescale of Gradstein *et al.* 2012). Substantial erosion of the crater and its surroundings indicates that a long period of time (possibly ~10–20 Myr according to French *et al.* 2018) passed before overlying sediment covered the area. Hence, in light of the collective stratigraphical data, it seems unlikely that ($\delta^{13}C$ chemostratigraphy of) the Winneshiek Shale provides an accurate date for the Decorah impact event – rather, this formation only provides a minimum age for the crater structure and its complex history of sedimentary infilling.

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References

Ainsaar, L., Kaljo, D., Martma, T., Meidla, T., Männik, P., Nõlvak, J. & Tinn, O. 2010: Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: a correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology 294*, 189–201.

Alwmark, C., Alwmark-Holm, S., Ormö, J. & Sturkell, E. 2014: Shocked quartz grains from the Målingen structure, Sweden – evidence for a twin crater of the Lockne impact structure. *Meteoritics and Planetary Science 49*, 1076–1082.

Bergström, S.M., Chen, X., Gutiérrez-Marco, J.C. & Dronov, A. 2009: The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and to $\delta^{13}C$ chemostratigraphy. *Lethaia 42*, 97–107.

Bergström, S.M., Schmitz, B., Liu, H.P., Terfelt, F. & McKay, R.M. 2018: High-resolution $\delta^{13}C_{org}$ chemostratigraphy links the Decorah impact structure and Winneshiek Konservat-Lagerstätte to the Darriwilian (Middle Ordovician) global peak influx of meteorites. *Lethaia 51*, 504–512.

Biren, M.B., van Soest, M.C., Wartho, J.-A., Hodges, K.V. & Spray, J.G. 2016: Diachroneity of the Clearwater West and Clearwater East impact structures indicated by the (U–Th)/He dating method. *Earth and Planetary Science Letters 453*, 56–66.

Bottomley, R.J., York, D. & Grieve, R.A.F. 1990: *40Argon-39Argon Dating of Impact Craters*, *Proceedings of the 20th Lunar and Planetary Science Conference,* 421–431.

Briggs, D.E.G., Liu, H.P., McKay, R.M. & Witzke, B.J. 2018: The Winneshiek biota: exceptionally well-preserved fossils in a Middle Ordovician impact crater. *Journal of the Geological Society 175*, 865–874.

Dressler, B.O., Sharpton, V.L. & Copeland, P. 1999: Slate Islands, Lake Superior, Canada: Aamid-size, complex impact structure. *Geological Society of America Special Paper 339*, 109–124.

Edwards, C.T. & Saltzman, M.R. 2016: Paired carbon isotopic analysis of Ordovician bulk carbonate ($\delta^{13}C_{carb}$) and organic matter ($\delta^{13}C_{org}$) spanning the Great Ordovician Biodiversification Event. *Palaeogeography, Palaeoclimatology, Palaeoecology 458*, 102–117.

Edwards, C.T., Saltzman, M.R., Royer, D.L. & Fike, D.A. 2017: Oxygenation as a driver of the Great Ordovician Biodiversification Event. *Nature Geoscience 10*, 925–929.

Fanton, K.C. & Holmden, C. 2007: Sea-level forcing of carbon isotope excursions in epeiric seas: implications for chemostratigraphy. *Canadian Journal of Earth Sciences 44*, 807–818.

French, B.M., McKay, R.M., Liu, H.P., Briggs, D.E.G. & Witzke, B.J. 2018: The Decorah structure, northeastern Iowa: geology and evidence for formation by meteorite impact. *GSA Bulletin 130*, 2062–2086.

Frisk, Å. & Harper, D.A.T. 2013: Late Ordovician brachiopod distribution and ecospace partitioning in the Tvären crater system, Sweden. *Palaeogeography, Palaeoclimatology, Palaeoecology 369*, 114–124.

Goderis, S., Vleminckx, B., Paquay, F.S., Chakrabarti, R., Renson, V., Debaille, V., Sluyts, W., Canhaecke, F., Spray, J., Jacobsen, S.B. & Claeys, P. 2010: Geochemistry of the Brent impact structure, Ontario, Canada. *Geochimica et Cosmochimica Acta 74*, A340.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (eds) 2012: *The Geologic Time Scale 2012*, 1176 pp. Elsevier, Boston.

Hatch, J.R., Jacobson, S.R., Witzke, B.J., Risatti, J.B., Anders, D.E., Watney, W.L., Newell, K.D. & Vuletich, A.K. 1987: Possible late Middle Ordovician carbon isotope excursion: evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and East-Central United States. *American Association of Petroleum Geologists Bulletin 71*, 1342–1354.

Hayes, J.M., Strauss, H. & Kaufman, A.J. 1999: The abundance of ^{13}C in marine organic matter and isotopic fractionation in the global biogeochemical cycle of carbon during the past 800 Ma. *Chemical Geology 161*, 103–125.

Henderson, M.A., Serra, F., Feltes, N.A., Albanesi, G.L. & Kah, L.C. 2018: Paired isotope records of carbonate and organic matter from the Middle Ordovician of Argentina: intrabasinal variation and effects of the marine chemocline. *Palaeogeography, Palaeoclimatology, Palaeoecology 458*, 107–130.

Hessland, I. 1949: Investigations of the Lower Ordovician of the Siljan district, Sweden I. Lower Ordovician ostracods of the Siljan district, Sweden. *Bulletin of the Geological Institutions of the University of Uppsala 33*, 97–408.

Jaanusson, V. & Mutvei, H. 1951: Ein Profil durch den Vaginatum-Kalkstein im Siljan-Gebiet, Dalarna. *Geologiska Föreningens i Stockholm Förhandlingar 73*, 630–636.

Jacobson, S.R., Hatch, J.R., Teerman, S.C. & Askin, R.A. 1988: Middle Ordovician organic matter assemblages and their effect on Ordovician-derived oils. *American Association of Petroleum Geologists Bulletin 72*, 1090–1100.

Jacobson, S.R., Finney, S.C., Hatch, J.R. & Ludvigson, G.A. 1995: *Gloeocapsomorpha prisca*-driven organic carbon isotope excursion, late Middle Ordovician (Rocklandian), North America mid-continent: New data from Nevada and Iowa. In Cooper, J., Droser, M.L. & Finney, S.F. (eds): *Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System*, 305–308. Society for Sedimentary Geology (SEPM), Fullerton.

Joachimski, M.M., Pancost, R.D., Freeman, K.H., Ostertag-Henning, C. & Buggisch, W. 2002: Carbon isotope geochemistry of the Frasnian-Famennian transition. *Palaeogeography, Palaeoclimatology, Palaeoecology 181*, 91–109.

Kienast, M., Calvert, S.E., Pelejero, C. & Grimalt, J.O. 2001: A critical review of marine sedimentary $\delta^{13}C_{org}$-pCO_2 estimates: new palaeorecords from the South China Sea and a revisit of other low-latitude $\delta^{13}C_{org}$-pCO_2 records. *Global Biogeochemical Cycles 15*, 113–127.

Lehnert, O., Meinhold, G., Wu, R., Calner, M. & Joachimski, M.M. 2014: $\delta^{13}C$ chemostratigraphy in the upper Tremadocian through lower Katian (Ordovician) carbonate succession of the Siljan district, central Sweden. *Estonian Journal of Earth Sciences 63*, 277–286.

Lindskog, A., Costa, M.M., Rasmussen, C.M.Ø., Connelly, J.N. & Eriksson, M.E. 2017: Refined Ordovician timescale reveals no link between asteroid breakup and biodiversification. *Nature Communications 8*, 14066. https://doi.org/(10.1038/ncomms14066).

Lindskog, A., Eriksson, M.E., Bergström, S.M. & Young, S.A. in press: Lower–Middle Ordovician carbon and oxygen isotope chemostratigraphy at Hällekis, Sweden: implications for regional to global correlations and palaeoenvironmental development. *Lethaia*. https://doi.org/10.1111/let.12307.

Lindström, M., Flodén, T., Grahn, Y., Hagenfeldt, S., Ormö, J., Sturkell, E.F.F. & Törnberg, R. 1999: The lower Palaeozoic of the probable impact crater of Hummeln, Sweden. *GFF 121*, 243–252.

Liu, H.P., McKay, R.M., Witzke, B.J. & Briggs, D.E.G. 2009: The Winneshiek Lagerstätte, Iowa USA and its depositional environments. *Geological Journal of China Universities 15*, 285–295.

Liu, H.P., Bergström, S.M., Witzke, B.J., Briggs, D.E.G., McKay, R.M. & Ferretti, A. 2017: Exceptionally preserved conodont apparatuses with giant elements from the Middle Ordovician Winneshiek Konservat-Lagerstätte, Iowa, USA. *Journal of Paleontology 91*, 493–511.

Löfgren, A. 1995: The middle Lanna/Volkhov Stage (middle Arenig) of Sweden and its conodont fauna. *Geological Magazine 132*, 693–711.

Löfgren, A. 2003: Conodont faunas with *Lenodus variabilis* in the upper Arenigian to lower Llanvirnian of Sweden. *Palaeontologica Polonica 48*, 417–436.

Löfgren, A. 2004: The conodont fauna in the Middle Ordovician *Eoplacognathus pseudoplanus* Zone of Baltoscandia. *Geological Magazine 141*, 505–524.

Meier, M.M.M. & Holm-Alwmark, S. 2017: A tale of clusters: no resolvable periodicity in the terrestrial impact cratering record. *Monthly Notices of the Royal Astronomical Society 467*, 2545–2551.

Ormö, J., Sturkell, E., Nõlvak, J., Melero-Asensio, I., Frisk, Å. & Wikström, T. 2014: The geology of the Målingen structure: a probable doublet to the Lockne marine-target impact crater, central Sweden. *Meteoritics and Planetary Science 49*, 313–327.

Panchuk, K.M., Holmden, C.M. & Leslie, S.A. 2006: Local controls on carbon cycling in the Ordovician midcontinent region of North America, with implications for carbon isotope secular curves. *Journal of Sedimentary Research 76*, 200–211.

Pancost, R.D., Freeman, K.H., Patzkowsky, M.E., Wavrek, D. & Collister, J.W. 1998: Molecular indicators of redox and marine photoautotroph composition in the late Middle Ordovician of Iowa, USA. *Organic Geochemistry 29*, 1649–1662.

Pancost, R.D., Freeman, K.H. & Patzkowsky, M.E. 1999: Organic-matter source variation and the expression of a late Middle Ordovician carbon isotope excursion. *Geology 27*, 1015–1018.

Rasmussen, C.M.Ø., Hansen, J. & Harper, D.A.T. 2007: Baltica: a mid Ordovician diversity hotspot. *Historical Biology 19*, 255–261.

Royer, D.L., Berner, R.A. & Beerling, D.J. 2001: Phanerozoic CO_2 change: evaluating geochemical and paleobiological approaches. *Earth-Science Reviews 54*, 349–392.

Schmitz, M.D. 2012: Radiometric ages used in GTS2012. In Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (eds): *The Geologic Time Scale 2012, 1045–1082*. Elsevier, Boston.

Schmitz, B., Harper, D.A.T., Peucker-Ehrenbrink, B., Stouge, S., Alwmark, C., Cronholm, A., Bergström, S.M., Tassinari, M. & Xiaofeng, W. 2008: Asteroid breakup linked to the Great Ordovician Biodiversification Event. *Nature Geoscience 1*, 49–53.

Schmitz, B., Bergström, S.M. & Xiaofeng, W. 2010: The middle Darriwilian (Ordovician) $\delta^{13}C$ excursion (MDICE) discovered in the Yangtze Platform succession in China: implications of its first recorded occurrences outside Baltoscandia. *Journal of the Geological Society 167*, 249–259.

Sell, B.K., Leslie, S.A. & Maletz, J. 2011: New U-Pb zircon data for the GSSP for the base of the Katian in Atoka, Oklahoma, USA and the Darriwilian in Newfoundland, Canada. *Cuadernos del Museo Geominero 14*, 537–546.

Servais, T. & Harper, D.A.T. 2018: The Great Ordovician biodiversification event: definition, concept and duration. *Lethaia 51*, 151–164.

Thorslund, P. 1940: On the Chasmops Series of Jemtland and Södermanland (Tvären). *Sveriges Geologiska Undersökning C 436*, 1–191.

Webby, B.D., Paris, F., Droser, M.L. & Percival, I.G. (eds) 2004: *The Great Ordovician Biodiversification Event*, 484. Columbia University Press, New York.

Witzke, B.J., McKay, R.M., Liu, H. & Briggs, D.E.G. 2011: The Middle Ordovician Winneshiek Shale of northeast Iowa – correlation and paleogeographical implications. *Geological Society of America Abstracts with Programs 43*, 315.

Wu, R.-C., Calner, M., Lehnert, O., Lindskog, A. & Joachimski, M. 2018: Conodont biostratigraphy and carbon isotope stratigraphy of the Middle Ordovician (Darriwilian) Komstad Limestone, southern Sweden. *GFF 140*, 44–54.

Young, S.A., Saltzman, M.R., Bergström, S.M., Leslie, S.A. & Xu, C. 2008: Paired $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ records of Upper Ordovician (Sandbian–Katian) carbonates in North America and China: implications for paleoceanographical change. *Palaeogeography Palaeoclimatology Palaeoecology 270*, 166–178.