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Trans-Atlantic application of the Baltic Middle and Upper Ordovician carbon isotope zonation

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Abstract. Application of the recently introduced Baltic δ^{13}C isotope zonation to a composite North American Darriwilian through Hirnantian succession shows that in most intervals there is good trans-Atlantic agreement not only between the isotope zones but also with the available biostratigraphic data. This indicates that this isotope zonation is a useful tool for improving previously uncertain long-distance correlations.

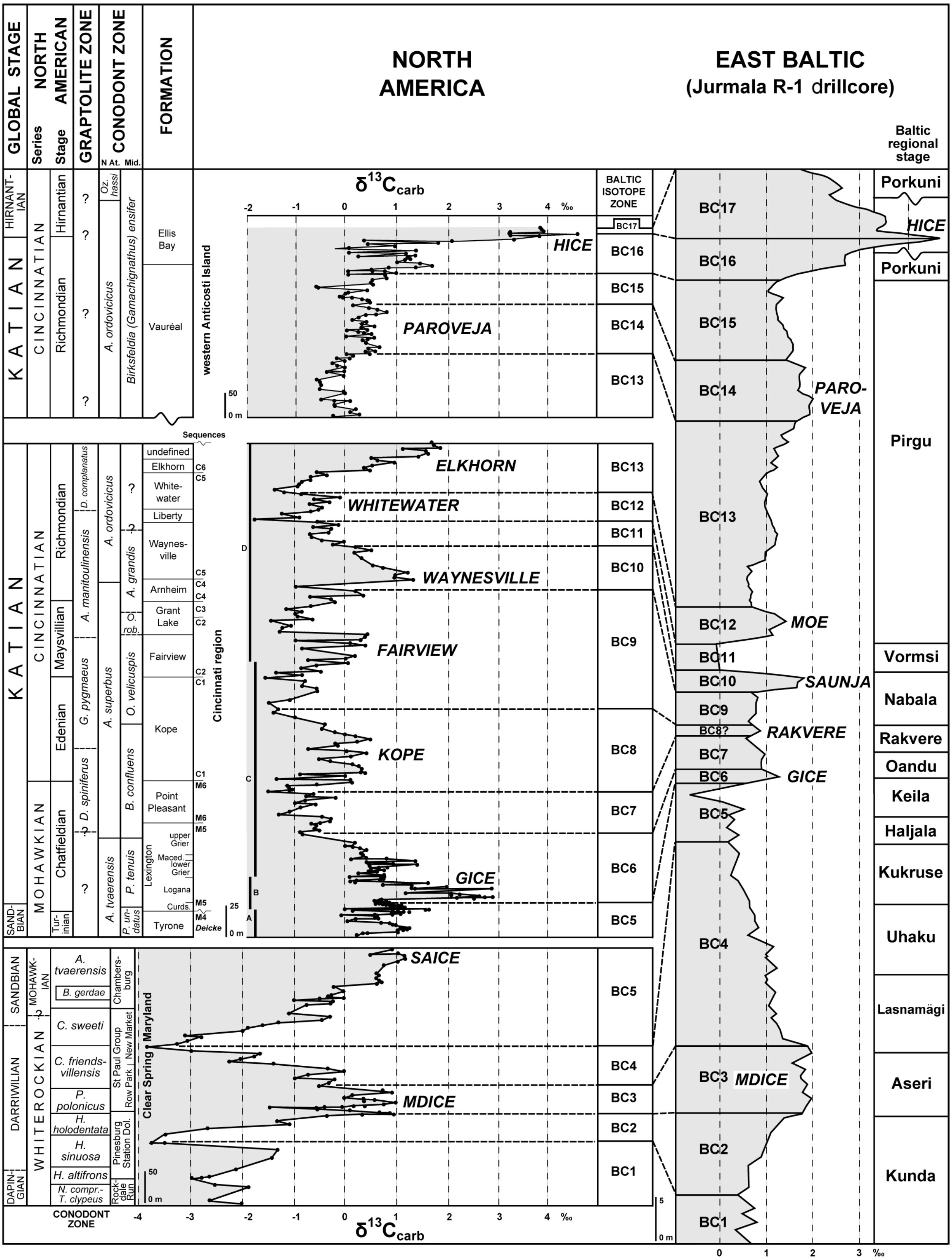
Key words: isotope chemostratigraphy, Baltoscandia, North America, Ordovician, biostratigraphy.

INTRODUCTION

Recent extensive geochemical investigations in several parts of the world have firmly established the usefulness of δ^{13}C chemostratigraphy for both local and long-distance correlations of Ordovician sedimentary rock successions. Of key importance for such work is the presence of the positive δ^{13}C isotope excursions that have been recognized in the Middle and Upper Ordovician, ten of which have been formally named (Fig. 1). The most extensive work on these excursions has so far been carried out in the East Baltic region (e.g. Kaljo et al. 2004; Ainsaar et al. 2010) and North America (e.g. Ludvigson et al. 2004; Young et al. 2005; Bergström et al. 2006, 2007, 2010a, 2010b, 2014; Barta et al. 2007), whereas far less information is currently available from other regions, such as China and South America. Many, if not most, of these studies have been centred on specific areas with only limited attempts to use the excursions for global correlations. Exceptions to this include the Hirnantian Isotopic Carbon Excursion (HICE) that has been recognized as a global stratigraphic tool in several investigations (e.g. Bergström et al. 2014). Also the Guttenberg (GICE) and the Mid-Darriwilian (MDICE) isotopic carbon excursions have proved to be useful for global correlations (e.g. Bergström et al. 2010b; Schmitz et al. 2010; Albanesi et al. 2013). Trans-Atlantic correlation of the Katian through Hirnantian excursions recognized in North America and Baltoscandia was first proposed by Bergström et al. (2007) and later expanded by Bergström et al. (2010b) and Ainsaar et al. (2010).

In an important summary paper, Ainsaar et al. (2010) subdivided the post-Tremadoc succession in Baltoscandia into 17 isotope zones named BC1 to BC17. These numbered zones (Fig. 1) were based on the excursion intervals as well as the intervals separating the excursions. Because most of the Tremadoc in Baltoscandia consists of clastic sediments that are unsuitable for $\delta^{13}C_{carb}$ studies, the Baltoscandic chemostratigraphy

Fig. 1. Preliminary application of the Baltic Dapingian through Hirnantian isotope zones to a composite North American succession. The lower American box illustrates the chemostratigraphy in the Interstate Highway 70 road cut near Clear Spring, Maryland, based on Leslie et al. (2011). The middle American box illustrates the chemostratigraphy in the Cincinnati region as described by Bergström et al. (2007, 2010b). The upper box shows the δ^{13}C curve through the upper Vauréal and Ellis Bay formations of Anticosti Island, Québec as reported by Young et al. (2010). Note that *Birksfeldia* was recently interpreted to be a senior synonym of *Gamachignathus* (Bergström & Ferretti 2014). The right column (with Baltic stages along its right margin) shows the excursions and the isotope zones recognized in the reference section in the Jurmala R-1 drillcore in Latvia (after Ainsaar et al. 2010, fig. 3). Although the American succession is more than 1100 m thick and the Baltic one only about 150 m, the $\delta^{13}C_{carb}$ chemostratigraphy is in good agreement between the two successions, which makes it possible to apply the Baltic isotope zonation to the North American succession.


GLOBAL STAGE
NORTH AMERICAN Series Stage
GRAPTOLITE ZONE
CONODONT ZONE
FORMATION
NORTH AMERICA
EAST BALTIC
(Jurmala R-1 drillcore)
Baltic regional stage
BALTIC ISOTOPE ZONE
western Anticosti Island
Cincinnati region
Clear Spring Maryland
HICE
PAROVEJA
ELKHORN
WHITEWATER
WAYNESVILLE
FAIRVIEW
KOPE
GICE
SAICE
MDICE
MOE
SAUNJA
RAKVERE
PARO-VEJA
Porkuni
Pirgu
Vormsi
Nabala
Rakvere
Oandu
Keila
Haljala
Kukruse
Uhaku
Lasnamägi
Aseri
Kunda
KATIAN
HIRNANTIAN
SANDBIAN
DARRIWILIAN
DAPINGIAN
CINCINNATIAN
MOHAWKIAN
WHITEROCKIAN
Himantian
Richmondian
Maysvillian
Edenian
Chatfieldian
Turinian
Ellis Bay
Vauréal
Elkhorn
Whitewater
Liberty
Waynesville
Arnheim
Grant Lake
Fairview
Kope
Point Pleasant
Lexington
Tyrone
Chambersburg
St Paul Group
Pinesburg Station Dol.
Rockdale Run
Sequences
CONODONT ZONE
BC1 BC2 BC3 BC4 BC5 BC6 BC7 BC8 BC9 BC10 BC11 BC12 BC13 BC14 BC15 BC16 BC17

in that interval remains essentially unknown. This is a problem for trans-Atlantic correlations because the $\delta^{13}C$ chemostratigraphy has been investigated in several thick American carbonate successions (e.g. Ripperdan & Miller 1995; Buggisch et al. 2003; Azmy & Lavoie 2009). The lack of Baltoscandic data from the lowermost Ordovician forces us to restrict our study to the interval from the uppermost Dapingian to the end of the Hirnantian.

The purpose of the present investigation is to examine if the Baltoscandic isotope zone succession can be applied to North America. If that is the case, it has the potential to substantially improve the trans-Atlantic correlation between these successions that because of the well-known biogeographic faunal differention in the Ordovician has been the subject of many different, and often speculative, interpretations. The fact that there is no reasonably stratigraphically complete succession in one place in North America that can provide a stratigraphically continuous $\delta^{13}C_{carb}$ curve makes it necessary for a trans-Atlantic comparison to employ a composite curve covering the uppermost Dapingian through the Hirnantian interval. For this composite curve we use curves from sections in the eastern Appalachians of Virginia (Leslie et al. 2011), the Cincinnati region in the eastern Midcontinent (Bergström et al. 2010b) and western Anticosti Island (Young et al. 2010). We believe that this composite curve is the most complete one currently obtainable from this stratigraphic interval in North America. The gap between the first two successions in the composite corresponds to part of the *Amorphognathus tvaerensis* conodont Zone, and that between the second and third successions corresponds to only part of Stage Slice Ka4 of Bergström et al. (2009) and part of the *Amorphognathus ordovicicus* conodont Zone.

It cannot be too strongly stressed that as good biostratigraphic control as possible is essential for a reliable correlation of isotope zones. Page limitations for the present preliminary study prevent us to present a full discussion of the available biostratigraphic data. For more such discussion, see Bergström et al. (2010b, 2014). For reviews of aspects of the detailed biostratigraphy established for the Baltoscandia successions, see Ebbestad & Högström (2007) and Männik & Viira (2012).

DISCUSSION OF ISOTOPE ZONE TRANS-ATLANTIC CORRELATIONS

The application of the Baltic isotope zones to the North American study successions is illustrated in Fig. 1 and briefly discussed below starting with the base of the study interval. To save space, we omit frequent reference to this figure in the text below.

Because of pronounced faunal provincialism, the North American biostratigraphic position of the Baltic isotope zones BC1 and BC2 is difficult to establish precisely. However, the fact that the conodont *Histiodella holodentata* is recorded from the Baltoscandic upper Kunda and lower Aseri regional stages, and the conodont *Cahabagnathus friendsvillensis* is a characteristic element in the pandemic *Pygodus serra* conodont Zone in the eastern Appalachians indicates that the MDICE excursion, which corresponds to the BC3 Isotope Zone, is present in the same interval on both sides of the Atlantic. For discussions of this zone, see Schmitz et al. (2010), Leslie et al. (2011) and Albanesi et al. (2013).

The marked step-wise decrease in $\delta^{13}C_{carb}$ values in the BC4 Isotope Zone culminates in the upper part of the Baltic Kukruse Stage (Ainsaar et al. 2010, fig. 3) at the top of the BC4 Isotope Zone where it is informally known as the 'Kukruse Low'. This value decline, which extends from the lower *Pygodus serra* Zone to the lower *Amorphognathus tvaerensis* conodont Zone, can also be recognized in our Appalachian curve.

The small isotope excursion present in the BC5 Isotope Zone in the lower part of the Baltoscandic Haljala Regional Stage occupies a position round the *Baltoniodus gerdae* conodont Subzone in both Baltoscandia and North America. In North America it has been named the Sandbian Isotopic Carbon Excursion (SAICE) (Leslie et al. 2011). This excursion, which is more prominent in North America than in Baltoscandia, is present just below the GICE (BC6 Isotope Zone) in the uppermost Copenhagen Formation in central Nevada (Bergström et al. 2010a).

The BC6 Isotope Zone corresponds to the globally recognized GICE excursion, which occupies a position in the uppermost *Amorphognathus tvaerensis* conodont Zone in North America as well as in Baltoscandia. For detailed information about this excursion, see Bergström et al. (2010a). The trans-Atlantic correlation of this excursion is consistent with the fact that in the Mjøsa region of Norway, it is associated with a conodont fauna strikingly similar to that present around the GICE interval in Kentucky (Bergström et al. 2011).

Both in Baltoscandia and North America, the BC7 Isotope Zone covers an isotopically non-descript interval between the GICE and the KOPE (Rakvere) excursions in the lower *Amorphognathus superbus* conodont Zone. The latter excursion represents the BC8 Isotope Zone, the trans-Atlantic correlation of which is supported by a variety of biostratigraphic evidence (cf. Bergström et al. 2010b), including the presence in both North America and Estonia of the graptolite *Diplacanthograptus spiniferus* which has a short range in both regions. Whereas the BC8 Isotope Zone is more than 80 m thick in the Cincinnati region, its thickness in the East Baltic (Latvian)

Jurmala R-1 drillcore reference section is only about 4 m, suggesting much slower deposition in the East Baltic and/or a gap in the succession. The North American FAIRVIEW excursion, here correlated with an interval in the BC9 Isotope Zone, is poorly, if at all, developed in Baltoscandia. A possible explanation is that this excursion has an irregular occurrence also in North America and has not been recognized in the important Oklahoma and Iowa successions (Bergström et al. 2010b). In North America, this isotope excursion is present just below the boundary interval between the *Geniculograptus pygmaeus* and *Amplexograptus manitoulinensis* graptolite zones, an interval a little below the boundary interval between the north European *Dicranograptus clingani* and *Pleurograptus linearis* graptolite zones.

The fact that the base of the next younger isotope zone (BC10) is at closely the same level as the base of the global *Amorphognathus ordovicicus* conodont Zone indicates that the Estonian Saunja excursion is coeval with the North American WAYNESVILLE excursion and both represent the BC10 Isotope Zone. Both in Baltoscandia and North America, the interval (BC11 Isotope Zone) between the BC10 and BC12 isotope zones is relatively thin and shows no markedly elevated $\delta^{13}C$ values. The BC12 Isotope Zone includes the East Baltic Moe and the North American WHITEWATER isotope excursions, both of which occur in the *Dicellograptus complanatus* graptolite Zone and hence are coeval (Bergström et al. 2010b) and allow reliable trans-Atlantic correlation.

The Ordovician succession in the Cincinnati region ends with a major unconformity and there is no fossil evidence of the presence of any Hirnantian and lower Rhuddanian strata in this region. In the uppermost Richmondian Regional Stage (upper Katian Global Stage), just below the unconformity at the top of the Richmondian Stage, Bergström et al. (2010b) first recognized a rising limb of a minor positive excursion, which they named the ELKHORN excursion. Although the precise biostratigraphic dating of this isotope excursion needs further study, we tentatively correlate the ELKHORN excursion with an unnamed interval of elevated $\delta^{13}C$ values in the lower half of the BC13 Isotope Zone in the East Baltic. Alternatively, the ELKHORN excursion could represent the rising limb of the Estonian Paroveja excursion but precise biostratigraphic evidence for the age of the ELKHORN excursion is still not available.

In the famous Ordovician succession on western Anticosti Island in Québec, the lowermost exposed strata are referred to the Vauréal and Ellis Bay formations, the total thickness of this mostly unexposed interval being more than 1 km. A modest isotope excursion, which starts about 125 m above the base of the exposed interval of the Vauréal Formation, is herein correlated with the East Baltic PAROVEJA excursion that represents the BC14 Isotope Zone.

As is the case in the East Baltic, the isotope values decline above this interval of somewhat elevated values but increase sharply and suddenly slightly higher stratigraphically to reach the maximum Ordovician $\delta^{13}C_{carb}$ values characteristic of the HICE, the peak of which is taken to be the base of the BC17 Isotope Zone. The Anticosti Island representation of this excursion has been discussed repeatedly in the literature, most recently by Bergström et al. (2014). The BC17 Isotope Zone is quite thin on western Anticosti Island and, as is the case in many East Baltic successions, it is truncated by an unconformity that cuts out parts of the upper Hirnantian (Schmitz & Bergström 2007; Bergström et al. 2014). On eastern Anticosti Island, the HICE excursion (BC17 Isotope Zone) continues well into the Becsie Formation (Jones et al. 2011), that is, into strata commonly regarded as of Rhuddanian (early Llandovery) age. Interestingly, as recently shown by Ainsaar et al. (2014), this is similar to the conditions in some sections in Estonia, where the declining limb of the HICE extends into strata previously classified as Lower Silurian.

CONCLUDING REMARKS

Because this is the first attempt to apply the Baltic Ordovician isotope zones to the North American succession, it is necessarily preliminary in some respects. This is the case in, for instance, the upper Katian where currently available biostratigraphic evidence is not entirely conclusive. Also, it may well be that the boundaries of some of these isotope zones need refinement. Nevertheless, we hope the present research demonstrates the great potential of the Baltic isotope zonation, in combination with biostratigraphy, to achieve detailed correlations also between continents.

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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.

Ainsaar, L., Meidla, T., Bauert, H. & Truumees, J. 2014. New carbon isotopic data from East Baltic suggest shifting the Ordovician/Silurian boundary into the Juuru Regional Stage. In *Fourth Annual Meeting of IGCP 591, The Early to Middle Paleozoic Revolution, Estonia, June 10–19, 2014; Abstracts & Field Guide* (Bauert, H., Hints, O., Meidla, T. & Männik, P., eds), p. 9. Tartu.

Albanesi, G. L., Bergström, S. M., Schmitz, B., Serra, F., Fektes, N. A., Voldman, G. G. & Ortega, G. 2013. Darriwilian (Middle Ordovician) $\delta^{13}C_{carb}$ chemostratigraphy in the Precordillera of Argentina: documentation of the middle Darriwilian Isotope Carbon excursion (MDICE) and its use for intercontinental correlation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **389**, 48–63.

Azmy, K. & Lavoie, D. 2009. High-resolution isotope stratigraphy of the Lower Ordovician St. George Group of western Newfoundland, Canada: implications for global correlation. *Canadian Journal of Earth Sciences*, **46**, 403–423.

Barta, N. C., Bergström, S. M., Saltzman, M. R. & Schmitz, B. 2007. First record of the Ordovician Guttenberg $\delta^{13}C$ excursion (GICE) in New York State and Ontario: local and regional chronostratigraphic implications. *Northeastern Geology and Environmental Sciences*, **29**, 276–298.

Bergström, S. M. & Ferretti, A. 2014. Conodonts in the Upper Ordovician Keisley Limestone of northern England: taxonomy, biostratigraphical significance and biogeographical relationships. *Papers in Palaeontology*, doi 19.1002/spp2.1003.

Bergström, S. M., Saltzman, M. R. & Schmitz, B. 2006. First record of the Hirnantian (Upper Ordovician) $\delta^{13}C$ excursion in the North American Midcontinent and its regional implications. *Geological Magazine*, **143**, 657–678.

Bergström, S. M., Young, S., Schmitz, B. & Saltzman, M. R. 2007. Upper Ordovician (Katian) $\delta^{13}C$ chemostratigraphy: a trans-Atlantic comparison. *Acta Palaeontologica Sinica*, **46**(suppl.), 37–39.

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., Saltzman, M. R. & Huff, W. D. 2010a. The Upper Ordovician Guttenberg $\delta^{13}C$ excursion (GICE) in North America and Baltoscandia: occurrence, chemostratigraphic significance, and paleoenvironmental relationships. *Geological Society of America Special Paper*, **466**, 37–67.

Bergström, S. M., Young, S. A. & Schmitz, B. 2010b. Katian (Upper Ordovician) $\delta^{13}C$ chemostratigraphy and sequence stratigraphy in the United States and Baltoscandia: a regional comparison. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **296***,* 217–234.

Bergström, S. M., Schmitz, B., Young, S. & Bruton, D. L. 2011. Lower Katian (Upper Ordovician) $\delta^{13}C$ chemostratigraphy, global correlation and sea-level changes in Baltoscandia. *GFF*, **133**, 1–17.

Bergström, S. M., Eriksson, M. E., Young, S. A., Ahlberg, P. & Schmitz, H. 2014. Hirnantian (latest Ordovician) $\delta^{13}C$ chemostratigraphy in southern Sweden and globally: a refined integration with the graptolite and conodont zone successions. *GFF*, **136**, 355–386.

Buggisch, W., Keller, M. & Lehnert, O. 2003. Carbon isotope record of the Late Cambrian to Early Ordovician carbonates of the Argentine Precordillera. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **195**, 357–378.

Ebbestad, J. O. R. & Högström, A. E. S. 2007. Ordovician of the Siljan District, Sweden. *Sveriges Geologiska Undersökning Rapporter och Meddelanden*, **128**, 7–26.

Jones, D. S., Fike, D. A., Finnegan, S., Fisher, W. W., Schrag, D. & McKay, D. 2011. Terminal Ordovician carbon isotope stratigraphy and glacioeustatic sea-level change across Anticosti Island (Québec, Canada). *Geological Society of America Bulletin*, **123**, 1645–1664.

Kaljo, D., Hints, L., Martma, T., Nõlvak, J. & Oraspõld, A. 2004. Late Ordovician carbon isotope trend in Estonia, its significance in stratigraphy and environmental analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **210**, 165–185.

Leslie, S. A., Saltzman, M. R., Bergström, S. M., Repetski, J. E., Howard, A. & Seward, A. M. 2011. Conodont biostratigraphy and stable isotope stratigraphy across the Ordovician Knox/Beekmantown unconformity in the central Appalachians. In *Ordovician of the World* (Gutiérrez-Marco, J.-C., Rabano, I. & Garcia-Bellido, D., eds), *Publicaciones del Museo Geominero de España*, **14**, 301–308.

Ludvigson, G. A., Witzke, S. R., Schneider, C. L., Smith, E. A., Emerson, N. R., Carpenter, S. J. & Gonzales, L. A. 2004. Late Ordovician (Turinian–Chatfieldian) carbon isotope excursions and their stratigraphic and paleoceanic significance. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **210**, 187–214.

Männik, P. & Viira, V. 2012. Ordovician conodont diversity in the northern Baltic. *Estonian Journal of Earth Sciences*, **61**, 1–14.

Ripperdan, R. I. & Miller, J. 1995. Carbon isotope ratios from the Cambrian–Ordovician boundary section at Lawson Cove, Ibex area, Utah. In *Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System* (Cooper, J. D., Droser, M. L. & Finney, S. F., eds). The Pacific Section of the Society for Sedimentary Geology, Fullerton, Book 77, 129–132.

Schmitz, B. & Bergström, S. M. 2007. Chemostratigraphy in the Swedish Upper Ordovician: regional significance of the Hirnantian $\delta^{13}C$ excursion (HICE) in the Boda Limestone of the Siljan region. *GFF*, **129**, 133–140.

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

Young, S. A., Saltzman, M. R. & Bergström, S. M. 2005. Upper Ordovician (Mohawkian) carbon isotope ($\delta^{13}C$) stratigraphy in eastern and central North America: regional expression of a perturbation in the global carbon cycle. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **222**, 53–76.

Young, S. A., Saltzman, M. R., Ausich, W. I., Desrochers, A. & Kaljo, D. 2010. Did changes in atmospheric CO_2 coincide with latest Ordovician glacial-interglacial cycles? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **296**, 376–388.