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Upper Katian (Upper Ordovician) trans-Atlantic δ^{13}C chemostratigraphy: The geochronological equivalence of the ELKHORN and PAROVEJA excursions and its implications

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Since 2010 when the North American ELKHORN and Baltoscandic PAROVEJA isotope excursions were first described and named, their mutual age relations have remained uncertain, if not controversial. This was at least partly due to the incompleteness of the ELKHORN excursion in its reference section in western Ohio. The unexpected discovery of an apparently complete ELKHORN excursion in a drill core from St. Marys in western Ohio has led to the conclusion that in terms of stratigraphic position and δ^{13}C curve correspondence, the ELKHORN and PAROVEJA excursions are so similar that they apparently represent the same isotopic curve perturbation. The ELKHORN/PAROVEJA excursion occurs in the *D. pacificus* Graptolite Zone and uppermost *A. ordovicicus* Conodont Zone in the uppermost Katian Stage (Stage Slice Ka4 of Bergström *et al.* 2009). Because the designation PAROVEJA was published two months before that of ELKHORN, it has priority as excursion designation. This excursion is particularly well represented in the carbonate successions in the Great Basin of western USA. Chemostratigraphy and biostratigraphy in that region show that the Richmondian transgression was contemporaneous with the beginning of the middle Katian WHITEWATER /MOE excursion. The onset of the Richmondian transgression has long been controversial but now available evidence suggests that it is of essentially the same age across large regions of the southern, western, and central USA.

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Comprehensive research during the last two decades in especially Baltoscandia, North America, China, and Argentina has led to the establishment of a detailed δ^{13}C chemostratigraphy through the entire Ordovician. Currently, approximately 17 positive and negative δ^{13}C excursions have been defined and named (Fig. 1). Among these, the most prominent and geographically most widely recognized are the Middle Darriwilian Isotopic Carbon Excursion (MDICE), the Guttenberg Isotopic Carbon Excursion (GICE), and the Hirnantian Isotopic Carbon Excursion (HICE). Each of these has been recorded on several continents and proved to be extremely useful tools for local and global correlations.

In the middle and upper Katian δ^{13}C curves, there are generally two other significant positive perturbations known as the WAYNESVILLE (in Baltoscandia SAUNJA) and WHITEWATER (in Baltoscandia MOE) excursions (e.g. Bergström *et al*. 2009). In the stratigraphic interval between the WHITEWATER/MOE and the HICE, there is a third excursion that was described from Ohio in the North

American Midcontinent as the ELKHORN excursion (Bergström *et al.* 2010). From a similar stratigraphic position in the Ordovician, and in the same year, Ainsaar *et al.* (2010) recognized an excursion in Latvia which they named the PAROVEJA excursion. Both these excursions were based on samples from drill cores in which biostratigraphically diagnostic fossils were not recorded in the excursion intervals. Hence, it has-remained uncertain if these excursions are the same or represent two different stratigraphic intervals. The correlation problem was also complicated by the fact that in the Elkhorn drill core the excursion is represented only by its rising limb, most of the excursion being cut by the prominent unconformity that is widely distributed around the Ordovician/Silurian boundary in much of the eastern Midcontinent.

To facilitate understanding of the Baltoscandic and North American Upper Ordovician stratigraphic terminology used in this paper, pertinent terms are summarized in Figure 2.

During the course of a multiyear project on the Llandovery biostratigraphy of Ohio and adjacent states, we happened to get access to a previously undescribed Middle Ordovician-Lower Silurian drill core, here referred to as the St. Marys drill core, which was drilled at a quarry in Auglaize County in westernmost Ohio approximately 95 km north of the Elkhorn drill site (Fig. 3). Our chemostratigraphic investigation of this drill core shows that unexpectedly, the topmost portion of the Ordovician contains what appears to be a complete representation of the ELKHORN excursion. This $\delta^{13}C$ curve perturbation is so similar to the PAROVEJA excursion in Latvia that we interpret the ELKHORN and PAROVEJA as representing the same excursion, especially as they occur in a geochronologically closely similar stratigraphic position. In the present report, we describe this excursion from a number of key localities in Baltoscandia and North America and illustrate the use of this and other Katian excursions not only for trans-Atlantic correlations but also for solving a long-standing problem of precisely dating the magnificent Upper Ordovician successions in the mountain ranges in the Great Basin of western North America.

Late Katian chemostratigraphy

Because only a very limited amount of information is available from the original descriptions of the PAROVEJA and ELKHORN excursions, we feel it is appropriate to summarize some of the basic excursion data. In Figure 4 we show the location of two Baltoscandic key sections, namely the drill sites of the Jurmala 1-R in Latvia and Röstånga-1 in southern Sweden.

In publications issued at about the same time, Bergström *et al.* (2010) introduced the designation ELKHORN for a late Katian excursion in Ohio and Ainsaar *et al.* (2010) proposed the name PAROVEJA for an excursion in a similar stratigraphic position in Latvia. There was no contact between these research groups and introducing these separate names was appropriate in view of the then tenuous trans-Atlantic correlations of the late Katian stratigraphic interval. These excursion names have been used in several publications and these designations, along with those of two older excursions, may be considered well-established. The fact that the designation PAROVEJA was published in August, 2010 and that of ELKHORN in October, 2010, means that the former term has a few weeks priority that justifies its international use. However, in an attempt to avoid terminology confusion, in the present study we use in places the terms WAYNESVILLE/SAUNJA, WHITEWATER/MOE, and PAROVEJA excursions.

The PAROVEJA excursion in the Baltoscandic region

Although shown in the late Katian $\delta^{13}C_{carb}$ curves in pioneer studies of the Upper Ordovician chemostratigraphy in the East Baltic (e.g. Ainsaar *et al.* 2004) and informally referred to as the mid-Ashgill excursion (cf. Kaljo *et al*. 2007), the designation PAROVEJA excursion was first introduced by Ainsaar *et al*. (2010) in a paper published in August that year. Although no reference section has been proposed, the excursion is apparently completely represented in the Jurmala R-1 drill core from Latvia

(Ainsaar *et al.* 2010, fig. 3) and this may be taken as a suitable reference section. In this drill core (Fig. 5), the $\delta^{13}C_{carb}$ values increase from ~1‰ to ~2‰ within a ~20 m thick interval located just below the prominent HICE, which shows $\delta^{13}C_{carb}$ values as high as near 5‰. In the carbon isotope zonation introduced by Ainsaar *et al.* (2010), the PAROVEJA excursion was referred to their Isotope Zone 14. Although employed by Bergström *et al.* (2015) in a trans-Atlantic comparison of Middle and Upper Ordovician chemostratigraphty, this isotope zone system has not yet found widespread use. As far as we are aware, little detailed information on the Jurmala R-1 drill core has been published but the excursion occurs in the middle-upper portion of the Pirgu Stage (Fig. 5) and in the upper Katian Stage Slice Ka4 of Bergström *et al*. (2009). In some East Baltic successions there is a minor stratigraphic gap at the contact between the Katian and Hirnantian stages but if this applies also to the Jurmala R-1 drill core remains uncertain.

Among the successions currently investigated in southern Sweden, the PAROVEJA excursion has been recognized in the Röstånga-1 drill core (Bergström *et al.* 2016) in which there is a modest excursion in the middle portion of the Lindegård Mudstone between the WHITEWATER/MOE and HICE perturbations (Fig. 5). Importantly, in this drill core, there are biostratigraphically important graptolites of the *Dicellograptus complanatus* Zone in the interval of the WHITEWATER/MOE excursion which indicate that the PAROVEJA excursion is younger than this geographically widespread and biostratigraphically important graptolite zone. In several publications from the East Baltic (e.g. Kaljo *et al.* 2004), the PAROVEJA is shown as corresponding to the late Katian *D. anceps* Graptolite Zone but we are not aware of any section in that region where the PAROVEJA excursion is directly associated with graptolites of that zone. In terms of chitinozoan biostratigraphy in Baltoscandia, the Paroveja excursion occurs in the upper part of the *Conochitina rugata* Zone. It should be noted that a minor excursion just below the PAROVEJA interval in the Röstånga 1 drill core, which was identified as the ELKHORN? Excursion by Bergström *et al*. (2016, fig. 3), is now interpreted as rather representing a still unnamed minor excursion between the WHITEWATER/MOE and the PAROVEJA excursions.

The North American ELKHORN excursion

Across much of the North American Midcontinent, the Ordovician/Silurian boundary is marked by a locally prominent gap in the succession but the magnitude of this shows a great deal of local variation. Whereas in Ohio the Hirnantian and part of the uppermost Katian are missing, there are Hirnantian strata in Illinois, Missouri, and Oklahoma (e.g. Bergström *et al.* 2012). Further north, in the Bruce Peninsula-Manitoulin Island region of Ontario, southern Canada (Bergström *et al.* 2011), the succession is different from that of Ohio and Hirnantian strata are present, especially on the Bruce Peninsula. The regionally irregular development of the systemic boundary interval makes it necessary to study each section in detail to clarify the local stratigraphic development.

Discovery. ---The ELKHORN excursion was first discovered in North America during investigation of a drill core within the framework of a regional Ordovician/Silurian project conducted by Kleffner and Bergström over much of the Midcontinent (e.g. Bergström *et al.* 2012). The excursion was originally noted in a drill core from near Elkhorn Creek in westernmost Ohio approximately 3 km south-east of the City of Richmond in easternmost Indiana. The drill site is located in Preble County in Ohio on the west side of a small pond ~2.5 km east of the Ohio/Indiana state border (Fig. 3) ~4 km south of Interstate-70 and 0.7 km east of Ohio Highway 320. The geological description of this drill core, which is now known as the Elkhorn core, remains unpublished but the core was logged in detail by the late Greg Schumacher and reported in Ohio Division of Geological Survey File Report no. 3023. The approximately 400 m (1200 feet) cored succession ranges from the Llandovery downward through the entire Cincinnatian Series and underlying strata to end approximately 40 feet (12 m) down into the Sandbian Black River Group.

As noted by Bergström *et al*. (2010), in the top 40 m of the Ordovician part of the Elkhorn drill core, the isotopic curve shows a rising limb of a distinctive $\delta^{13}C_{carb}$ excursion, which starts in what is classified as the upper Whitewater Formation and continues upwards to the Ordovician/Silurian boundary (Fig. 6). The shape of the excursion curve suggests that most of this perturbation was cut off by the unconformity at the Ordovician/Silurian boundary. Unfortunately, the incomplete record of the ELKHORN excursion in this drill core made comparisons with Katian excursions in Baltoscandia difficult and uncertain, especially in the absence of biostratigraphically diagnostic fossils suitable for trans-Atlantic correlations. In their study Bergström *et al.* (2010, fig. 1) regarded the ELKHORN excursion as being in the Baltic Isotope Zone 13, hence as older than the PAROVEJA excursion in Baltic Isotope Zone 14. However, the precise relations between these excursions have remained uncertain, or even controversial.

The St. Marys drill core. - A few years later, our study of another drill core from westernmost Ohio has provided much needed improved information about this excursion (Bergström & Kleffner 2018). This previously completely undescribed drill core was drilled at the Con-Ag Inc. quarry at St. Marys, Auglaize County approximately 95 km north of the Elkhorn drill site (Fig. 3). Coordinates for this locality are 40° 59′ 39′′ 16′′′ N and 84° 38′ 20′′ 18′′′ W. The lower 26 feet (8 m) of the cored succession is shaly and lithologically reminiscent of that of the Whitewater Formation but pending further study, it is here informally classified as Cincinnatian undifferentiated (Fig. 6). This interval is overlain by 17 feet (5 m) of shales and mudstones here referred to as the Elkhorn Formation. This unit is overlain by 37.5 feet (12 m) of clastic strata by the drillers referred to as "Clinton sand", which is overlain by 17 feet (6 m) of lithological variable, mostly fine-clastic, strata which we classify as upper Katian undifferentiated. On the top of this follow Llandovery dolomites. Conodonts from the 240 feet level includes species of *Aphelognathus, Rhipidognathus*, and other typical Ordovician taxa and some species found in samples higher stratigraphically may be interpreted to suggest that the local base of the Silurian may be as high as at the 240-feet core level.

In order to establish the chemostratigraphy of the Upper Ordovician and lowermost Silurian of the St. Marys drill core, rock samples for $\delta^{13}C_{carb}$ analysis were collected through this core interval. These samples were further prepared at the isotope lab at the Kansas Geology Department by removing about 2 ml of surficial material using a Dremel rotary drill mounted with a diamond wheel point. Sample material for analysis was collected by drilling below the cleaned area again using Dremel and diamond wheel point. The resulting finely powdered sample was collected into a plastic 1 ml mini-centrifuge tube and labeled. Approximately 100 mg of sample was weighed into a stainless steel boat using a Mettler Toledo Microbalance. Stainless steel boats were placed into a brass convoy and samples were vacuum-roasted at 200°C for 1 hour to remove volatiles. Samples were then analyzed and sample CO_2 generated by reaction with three drops of 105% H_3PO_4 at 7O°C for 540 seconds using a ThermoScientific Kiel IV Carbonate Device interfaced to the inlet of a ThermoFinnigan MAT 253 dual inlet mass spectrometer. Carbonate $\delta^{13}C$ and $\delta^{18}O$ isotope data are reported relative to VPDB. Precision was monitored through the daily analysis of NBS-18 and/or NBS-19 and is better than 0.10‰ for both $\delta^{13}C$ and $\delta^{18}O$.

Results. - The. $\delta^{13}C_{carb}$ values obtained from our samples from the St. Marys drill core are shown in Table 1. The ELKHORN excursion appears to start at the 344 feet level (Fig. 6) at the beginning of a rapidly rising limb similar to that in the Elkhorn drill core. The excursion peak values of 1.25‰ to 1.75‰ are reached in the interval between 320 feet and 282 feet and the total thickness of the excursion interval is ~74 feet (22.2 m). The increase in $\delta^{13}C_{carb}$ values around the 260 feet level to the 280 feet level is notable but its chemostratigraphic significance remains uncertain.

A comparison between the St. Marys and Jurmala isotopic curves shows a striking similarity in shape (Fig. 7) supporting the idea that they represent the same perturbation. However, there is no occurrence in the St. Marys drill core of the very high $\delta^{13}C$ values of the HICE in the Jurmala R-1 core. We interpret this as indicating that Hirnantian strata apparently are missing in the St. Marys drill core. Yet, it cannot be completely excluded that the increased $\delta^{13}C_{carb}$ values between 260 feet and 240 feet in this drill core represent the rising limb of the HICE and hence the presence of early Hirnantian strata. However, this idea needs additional supporting biostratigraphic evidence, perhaps from chitinozoans and other microfossils.

In Figure 8, we compare the $\delta^{13}C$ isotopic curve from the St. Marys drill core with that from the Röstånga-1 drill core. The similarity in the Katian part of the isotopic curve is obvious but the absence of possibly all but the onset of the HICE in the St. Marys drill core is a major difference.

Great Basin comparison

Some of the greatest outcrops of Katian rocks in North America occur in the mountain ranges in the Great Basin of Nevada, Utah, and adjacent states (e.g. Sweet 1979, 1984, 2000, Ross *et al.* 1979, Budge & Sheehan 1980, Carpenter *et al.* 1986, Harris & Sheehan 1996, 1997, Finney *et al.* 1997, Finney & Berry 1999, Harris *et al.* 1974, Saltzman & Young 2005, Bergström *et al*. 2010, Jones *et al.* 2016). In terms of depositional environment, the Great Basin Upper Ordovician carbonate successions dealt with herein range from shallow shelf (South Egan Range, Barn Hills) to deep-water marine basin or upper lope (Martin Ridge). The total thickness of the Upper Ordovician succession varies but at many localities it is approximately 150 m. The Katian carbonate sequence rests unconformably on the Eureka Quartzite, the upper part of which remains undated in the absence of biostratigraphically age diagnostic fossils. At some localities the Katian succession is overlain by a thin development of Hirnantian strata (e.g. Jones *et al*. 2016) but at other sections, the Katian succession is directly overlain by Silurian or Devonian deposits. In the sketch-map (Fig. 9) we illustrate the location of the three Great Basin localities discussed in the present study.

The Great Basin Katian carbonate successions are of special interest because they represent a relatively thick, well-exposed, and stratigraphically rather complete succession of relatively unmetamorphosed rock sequences that contains a seemingly well-preserved record of $\delta^{13}C$ changes. The choice of our three study sections was based on the availability of $\delta^{13}C$ data and adequate conodont biostratigraphy. In view of the fact that these sections represent different depositional environments, they also had the potential to yield valuable information about possible environmental control of the vertical and horizontal ranges of individual conodont taxa and of isotope records.

Previous age interpretations

Because age diagnostic macrofossils, such as graptolites and brachiopods, are rare or missing at most localities, the precise age of the Great Basin Katian successions in Nevada and Utah has been difficult to establish and has remained controversial. Early interpretations (e.g. Twenhofel *et al.* 1954) suggested a Richmondian age, or an Edenian-Richmondian age (e.g. Ross *et al*. 1983). Several later authors (e.g. Harris & Sheehan 1996, 1997, and Sheehan & Harris 1997) interpreted the scarce brachiopod fauna as being of Maysvillian-Richmondian age.

The relatively sparse conodonts originally obtained from the Ely Springs and Hanson Creek formations were interpreted as being of Maysvillian-Richmondian age (e.g. Harris *et al.* 1979). According to Sweet (1979), strata in Utah, Wyoming, and Colorado equivalent to the lowest portion of the Katian carbonate succession in Nevada contain conodonts suggesting an Edenian age. A more recent but still unpublished, much more extensive, conodont study based on sections in eastern Great Basin (Leatham 1987) also favored a Maysvillian-Richmondian age for the post-Eureka carbonate succession, and this age assignment has been followed by most later authors. However, Bergström (2003), in a widely overlooked paper, noted that graptolite, conodont, and brachiopod biostratigraphy indicated the absence of pre-Richmondian Ordovician strata above the Eureka Quartzite in the Great Basin. This interpretation is in conflict with the opinion expressed in a recent chemostratigraphic study of the Ely Springs Dolomite and Hanson Creek Formation in the eastern Great Basin by Jones *et al*. (2016), who favored a Maysvillian-Richmondian age. In the text below, we review the evidence indicating that the Katian carbonate succession in the Great Basin lacks pre-Richmondian strata. For our discussion, we have selected three sections with adequate $\delta^{13}C$ chemostratigraphy as well as biostratigraphy. As noted above, these include the sections at Monitor Range (Figs. 10 and 11), South Egan Range (Figs 12 and 13), both being located in Nevada, and the Barn Hills in western Utah (Fig. 14). However, we believe that our age results from these sections are applicable also to many other Great Basin Katian sections, especially those located in Nevada and Utah. Although one of us (SMB) has visited the Monitor Range and South Egan Range sections, the first one several times, our conclusions are not based on new collections but on re-interpretation of previously published data.

The Monitor Range, Nevada
The carbonate part of the Upper Ordovician of this extensive section, which is classified as the Hanson Creek Formation (Fig. 10), is more than 220 m thick and consists of deep-water carbonate and shale. Importantly, this formation contains relatively common and taxonomically diverse graptolites (Finney *et al.* 1997, 1999; Storch *et* al. 2011) as well as conodonts (Sweet 1984, 2000) that provide a useful biostratigraphic framework that is more detailed than that described from most other Katian sections in the Great Basin.

The $\delta^{13}C$ chemostratigraphy of the Martin Ridge succession has been the subject of several studies (e.g. Finney *et al*. 1997, Finney & Berry 1979; Kump *et al.* 1999; Saltzman & Young 2005) that show the presence of a modest excursion, here identified as the PAROVEJA excursion (Fig. 10), just below a very prominent positive excursion which clearly represents the HICE. The stratigraphic interval of the PAROVEJA is ~40 m thick and covers most of the *P. pacificus* Graptolite Zone. Sweet (2000) recorded 17 conodont species from the PAROVEJA interval, including the zonal index *Amorphognathus ordovicicus*. Of special interest for the correlation with other Great Basin successions is the record of *Gamachignathus ensifer, Pristognathus rohneri, Oulodus ulrichi, Pseudobelodina inclinata,* and *Pseudobelodina vulgaris*, a species association that is similar to that present in the upper Ely Springs Formation at other localities in the Great Basin (cf. Leatham 1987). The lower ~70 m of the Hanson Creek Formation at Martin Ridge contains relatively common graptolites which represent the Pacific Province *D. ornatus* Graptolite Zone. This zone is considered to be broadly equivalent to the Atlantic Province *Dicellograptus complanatus* Graptolite Zone. The fact that the WHITEWATER/MOE excursion occurs in the latter graptolite zone in Sweden (cf. Bergström *et al.* 2012) makes it very likely that the positive perturbation in the lower Hanson Creek Formation represents this excursion. The conodont fauna of the basal Hanson Creek Formation recorded by Sweet (2000) is not very diverse but the presence of the zone index *A. ordovicicus* indicates a Richmondian age. A chemostratigraphic comparison between the Monitor Range succession and that at Röstånga (Fig. 11) illustrates the obvious similarities between these successions, including the stratigraphic position of the PAROVEJA excursion below the prominent HICE and above the WHITEWATER/MOE interval.

The South Egan Range, Nevada
Whereas the Monitor Range succession was laid down in relatively deep water in a ramp setting, that at the South Egan Range represents an outer shelf environment with significantly shallower water. For detailed descriptions and discussions of this Upper Ordovician succession, see for instance, Budge & Sheehan (1980) and Carpenter *et al*. (1987). In an unpublished Ph.D. dissertation, Leatham (1987)

described the conodont fauna of this succession based on 32 samples from the slightly more than 150 m thick Ely Springs Dolomite (Fig. 12).

The conodont fauna includes approximately 35 species and is one of the most taxonomically diverse known from the Katian interval in the Great Basin. Because the zone indices of Sweet's (1984) Richmondian conodont zones are not present in such a way that his zones can be recognized, we herein tentatively subdivide the Ely Springs succession into three, each approximately 50 m thick, conodont faunal intervals referred to as Fauna A, B, and C. The Fauna A interval contains approximately 25 species among which a dozen are restricted to this interval.

Contrary to some statements in the literature (e.g. Jones *et al*. 2016), the conodont fauna of the lower part of the Ely Springs Dolomite does not include a single species diagnostic of the Maysvillian Stage in its type area in the Cincinnati region. The fauna is more similar to that of the Richmondian Stage and this is in agreement with the fact that the zone index *Amorphognathu ordovicicus*, which in the Cincinnati region appears well above the base of the Richmondian (MacKenzie & Bergström 1993; Bergström & MacKenzie 2003), is recorded from an interval 100=120 m above the base of the Ely Springs Dolomite at the South Egan section. This species has also been recorded from a similar stratigraphic interval at other Ely Springs outcrops (cf. Leathan 1987). It should be noted that the base of the *A. ordovicicus* Zone is based on the evolution of *A. superbus* to *A. ordovicicus (*e.g. Bergström 1983). Hence, the South Egan Range conodont evidence supports the idea that there are no Maysvillian strata in the basal part of the Ely Springs Dolomite at this locality.

The conodont species association of Fauna B includes about 14, mostly long-ranging, species, and that of Fauna C about 18 species among which half a dozen are restricted to this faunal interval. This fauna is clearly of latest Katian age and its interval may correspond broadly to Sweet's (1984) *Aphelognathus shatzeri* Zone, the zone index species being recorded from a single stratigaphic level.

In a recent study, Jones *et al.* (2016) described the $\delta^{13}C_{carb}$ chemostratigraphy through the Ely Spring Dolomite at South Egan Range and three other Great Basin carbonate successions and compared the results with those published from Martin Ridge and the standard section in the Cincinnati region. Herein, we first compare the South Egan Range isotope curve with that from the PAROVEJA reference succession in Latvia (Fig. 13). The position of the excursion just below the HICE suggests that it is the PAROVEJA excursion, an interpretation in agreement with that of Jones *et al.* (2016). However, in agreement with the conditions in the Monitor Range succession, we interpret the stratigraphically next lower excursion, namely that in the lower part of the Ely Springs Dolomite, as the WHITEWATER/MOE rather than WAYNESVILLE/SAUNJA excursion. In this interpretation, we avoid the stratigraphically awkward problem noted by Jones *et al*. (2016) of having the beginning of the Richmondian transgression in the Great Basin as older in the in shallow-water facies, such as that at South Egan Range, than in the deeper-water setting such as that at Monitor Range. In our interpretation, there is no significant age difference between the bases of the Hanson Creek and Ely Springs formations, both corresponding to levels in the *D. complanatus/D. ornatus* Graptolite Zone and coeval with part of the Whitewater Formation of the Richmondian Stage in the Cincinnati region.

In a discussion involving this graptolite zone it is of interest to note that Goldman & Bergström (1997) described the discovery of the zone index *D. complanatus* from the Ft. Atkinson Formation of the Maquoketa Group in Illinois, a unit commonly correlated with the Whitewater Formation of the Cincinnati region (e.g. Bergström & MacKenzie 2005, fig. 2). No $\delta^{13}C$ data have yet been published from the Ft. Atkinson Formation but Bergström *et al*. (2010, fig. 5) recorded the WAYNESVILLE/SAUNJA excursion from the underlying Elgin Formation in Iowa, which represents the lower *A. ordovicicus* Zone. It is quite likely that the WHITEWATER/MOE excursion will be found in the Ft. Atkinson Formation when its chemostratigraphy is investigated.

The Barn Hills, Utah

This locality is situated in the Confusion Range in Toole County at the approximate coordinates $33^0 59'$ to $33^0 54' 11''$ N to $113^0 23' 49''$ to $114^0 15' 23''$W. For a panorama photo of this spectacular outcrop, see Budge & Sheehan (1980, fig.3).

At this locality the Ely Springs Dolomite has a total thickness of about 160 m, but youngest Ordovician (Hirnantian) strata are missing, the Katian succession being overlain by Silurian deposits (cf. Jones *et al*. 2016, fig. 7). In ascending order, the Ely Springs Dolomite is subdivided into the Ibex, Barn Hills, Lost Canyon, and Floride Mountains members (Fig. 14).

Based on still unpublished distribution data from Leatham (1987), the vertical ranges of conodont taxa are summarized in Figure 14. The Ely Springs conodont fauna at this locality includes about 24 species, hence a slightly lower number than that at the Egan Range locality. This may be due to the fact that the Barn Hills collections include only about 1100 specimens compared with more than 7000 specimens from South Egan Range and quite a few taxa are represented by only single specimens. However, it is uncertain if the absence of some uncommon species may be due to collecting failure or some other factor. However, solution of this problem requires further studies based on larger collections. It is important to note that such characteristic conodont taxa as *Amorphognathus ordovicicus, Coelocerodontus digonius, Columbodina occidentalis, C. penna,* and *Pristognathus rohneri* have not yet been recorded from the Barn Hills section. Otherwise, there is a great deal of similarity between the Katian conodont species associations from South Egan Range and those from Barn Hills.

Of special biostratigraphic interest is the presence of the conodont zone index species *Aphelognathus divergens* in an interval around 40-55 m above the base of the Ely Springs Dolomite. As is the case at several Great Basin localities, the topmost few meters of the Katian Ely Springs Dolomite contain specimens of *Aphelognathus shatzeri* indicating the presence of the *A. shatzeri* Zone of Sweet (1984).

The Barn Hills Katian $\delta^{13}C_{carb}$ curve (Fig. 14) is rather similar to that from South Egan Range. Elevated values up to >2‰ characterize most of the interval of the Barn Hills Member of the lower Ely Springs Dolomite. Based on a comparison with the Monitor Range and South Egan Range successions, we identify this interval as representing the WHITEWATER/MOE excursion. At about 80 m above the base of the formation, the top of this excursion interval is marked by a sudden decline of the isotopic values down to almost -3‰. If this is due to a small stratigraphic gap remains uncertain. Above this level is a rather steady increase in isotopic values through the Lost Canyon Member until, near the base of the Floride Member, there is again a marked increase in isotopic values that clearly represents the PAROVEJA excursion. This excursion continues to the top of the formation, which is overlain by Silurian rocks. As noted above, there are no Hirnantian strata and no development of its prominent excursion, the HICE.

In the left part of Figure 15 we present a summary of our opinion on the correlation of our Katian study successions (Fig. 15A), which is based primarily on chemostratigraphy and conodont biostratigraphy. In the right part of this figure (Fig. 15B) we show some previous interpretations of the range of the Great Basin Katian successions. Among these, Sweet's (2000, fig. 2) graphic correlation of these successions and their correlation to the Cincinnatian Series standard have been particularly influential. Unfortunately, that study was based on partly outdated information that resulted in significant errors. For instance, the *Dicellograptus ornatus* (*D. complanatus*) Graptolite Zone was shown to range downward into strata as old as the Edenian Stage. However, based on extensive collections from the type Cincinnatian Series, Bergström & Mitchell (1986) and Goldman & Bergström (1997, fig. 9) had shown that the base of this graptolite zone is much younger and occupies a level well above the base of the Richmondian Stage. Furthermore, according to Sweet (2000, fig. 2), the top of this graptolite zone is shown to correspond to the base of the Richmondian Stage when, in fact, it occupies a much younger position within that unit. It should be stressed that only a handful of biostratigraphically significant conodont species are shared between the Cincinnati region and the Great Basin and all of these occur in the Cincinnati region only in the Richmondian Stage. It is our opinion that a combination of chemostratigraphy and conodont biostratigraphy provides a much more reliable basis for the correlation of the Great Basin Katian successions than those presented previously.

The Richmondian transgression

Although the PAROVEJA excursion has not yet been recorded in large parts of the southern and eastern USA, it is likely to be present in the upper *A. ordovicicus* Zone in the Maravillas Formation of the Marathon area, Texas (Bergström 1977; Goldman *et al*. 1995), the lower part of which contains *D. complanatus* Zone graptolites, the Montoya Group of New Mexico, Texas, and Arizona (e.g Sweet 1979), the Sylvan Shale of the Arbuckle Mountains in Oklahoma (e.g. Goldman & Bergström 1997), which also contains *D. complanatus* Zone graptolites, the Fernvale Formation of Tennessee, and in coeval deposits of the *A. ordovicicus* Zone in adjacent states. Unfortunately, the chemostratigraphy of the Katian successions of these regions is currently too little investigated for a meaningful comparison with that of the Great Basin. However, it is of interest to note that regionally, there is clear evidence of a major transgression in the interval of the *D. ornatus/D. complanatus* Zone of the lower Richmondian, that is, at approximately the same time as in the Great Basin. Based on a variety of evidence, Bergström (2003) arrived at this age conclusion, which is now supported by the isotope chemostratigraphy in the Great Basin sections dealt with herein. Interestingly, shallow-water, in some cases thick, carbonate-dominated formations are also known not only from, for instance, the Canadian portion of North America and Baltoscandia but also from, for instance, the Mediterranean region (Bergström & Massa 1992, Ferretti & Serpagli 1999, Sarmiento *et al*. 1999), and China (e.g. Chen *et al.* 1995). They are characterized by locally rich faunas that inhabited shallow-water carbonate depositional environments during favorable climatic conditions prior to the Hirnantian glaciations. Yet, if the PAROVEJA excursion directly or indirectly played any role in the extinction of these faunas in pre-Hirnantian times remains a matter of speculation.

Concluding remarks

There is no question that the development of isotope chemostratigraphy during the last two decades has had an extraordinary impact on both local and long-distance correlations in the lower Paleozoic. This certainly applies to the Katian interval in the Upper Ordovician dealt with in the present contribution that especially in carbonate facies has been difficult to precisely correlate over long distances because of pronounced faunal provincialism. The recognition of the Katian WAYNESVILLE/SAUNJA, WHITEWATER/MOE, and the HICE excursions now provides a useful chemostratigraphic framework for both local and global correlations. The conclusion expressed herein that the North American ELKHORN and the Baltoscandic PAROVEJA excursions represent the same perturbation in the $\delta^{13}C$ curves provides us with a new tool for solving, for instance, previous unclear trans-Atlantic correlation problems in the interval between the WHITEWATER/MOE and the HICE. Mainly due to the very limited chemostratigraphic research carried out up to now in the critical interval, the PAROVEJA excursion is known from only a limited number of localities in Baltoscandia and North America. However, we predict that further studies will show that it has a global distribution in strata of latest Katian age and that it becomes an international guide horizon that complements the other Katian excursions in local and long-distance correlations, also between continents. This idea received quite recent support by a paper that appeared after the present paper was submitted for publication. In an interesting study by Myrow *et al*. (2018), the Paroveja excursion was recorded from a section of the Pin Formation in Parahio Valley, Himachal Pradesh, in northern India. Unfortunately, the currently available conodont biostratigraphy of this calcareous Katian succession is insufficient for a reliable biostratigraphic dating of its several recognized $\delta^{13}C_{carb}$ excursions but the chemostratigraphic correlation to the Great Basin succession proposed by Myrow *et al.* (2018, fig. 12) appears valid, the Katian $\delta^{13}C_{carb}$ curves from the two geographically widely separated regions being strikingly similar. Following our revision of the identity of the Great Basin Katian excursions, we tentatively recognize in the Pin Formation the WAYNESVILLE/SAUNJA excursion (~0-130 m above the Pin section base), the WHITEWATER/MOE excursion (~150-180 m above section base), and the PAROVEJA excursion (just below the uppermost Ordovician sandstone). We hope that detailed work on the conodont biostratigraphy will confirm these excursion identifications in this important Gondwana succession.

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Figures

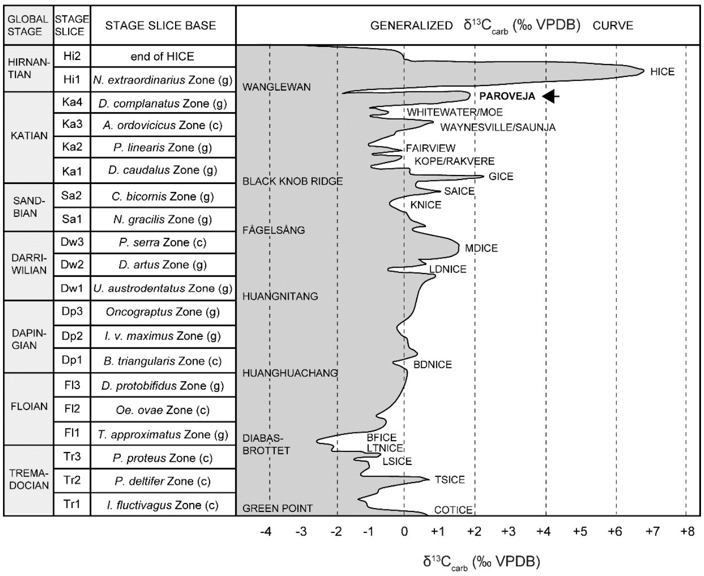

Fig. 1. Named Ordovician positive and negative $\delta^{13}C$ excursions and their relations to global stages and stage slices. Also listed is the name of the GSSP of each stage.

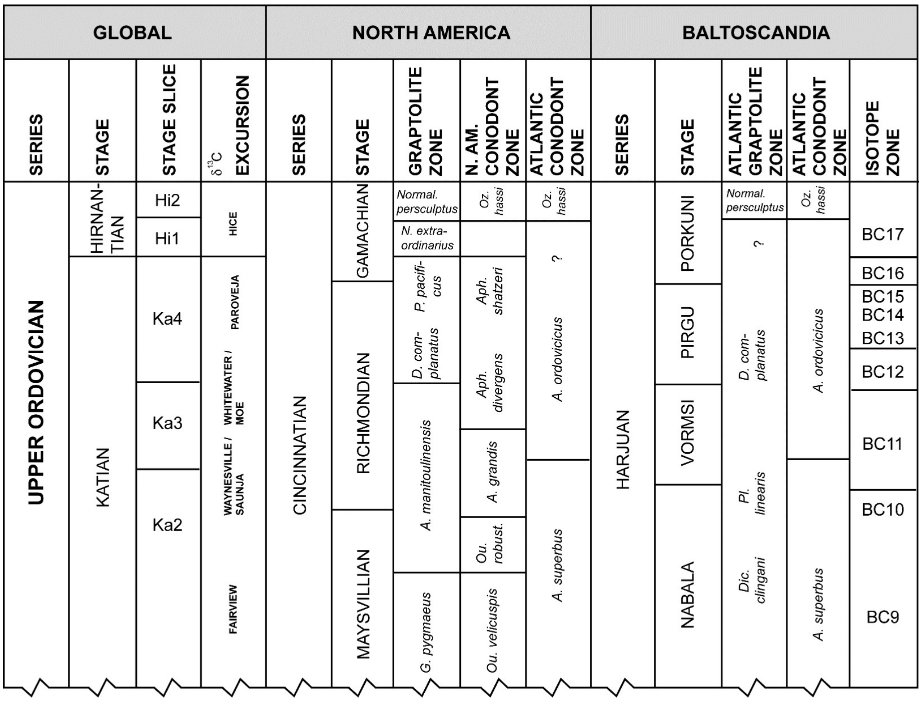

Fig. 2. Review of the relations between major Upper Ordovician stratigraphic terms, graptolite and conodont zones, Baltic isotope zones, and $\delta^{13}C$ excursions in Baltoscandia and North America. *Ou. robust.*, *Oulodus robustus.*

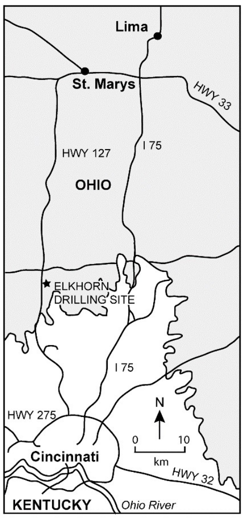

Fig. *3*. Sketch-map of southwestern Ohio showing locations of the Elkhorn and St. Marys drill sites. White area around the City of Cincinnati is the outcrop area of Upper Ordovician (Cincinnatian) rocks, grey shading marks the Silurian outcrop region.

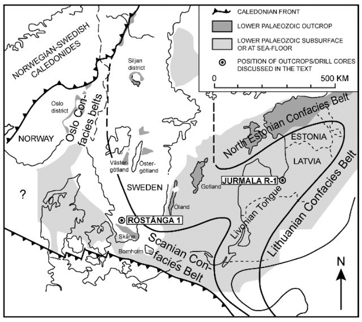

Fig. 4. Sketch-map of southern Baltoscandia showing the geographic location of the Jurmala R-1 drill site in Latvia and the Röstånga-1 drill site in southern Sweden.

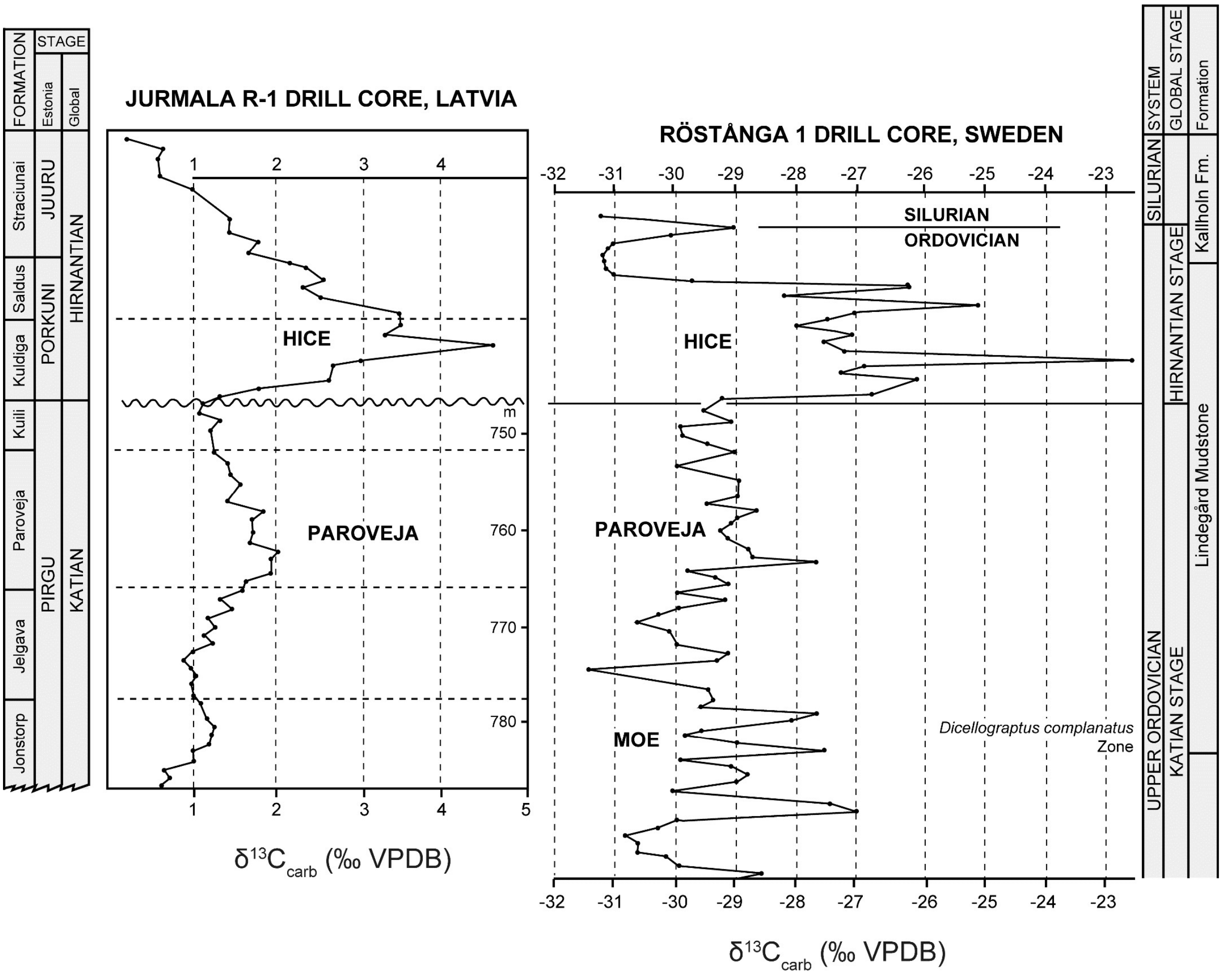

Fig. 5. Comparison between the $\delta^{13}C$ curves of the Jurmala R-1 and the Röstånga-1 drill cores. Note that the PAROVEJA excursion can be recognized in the Röstånga-1 $\delta^{13}C_{org}$ curve.

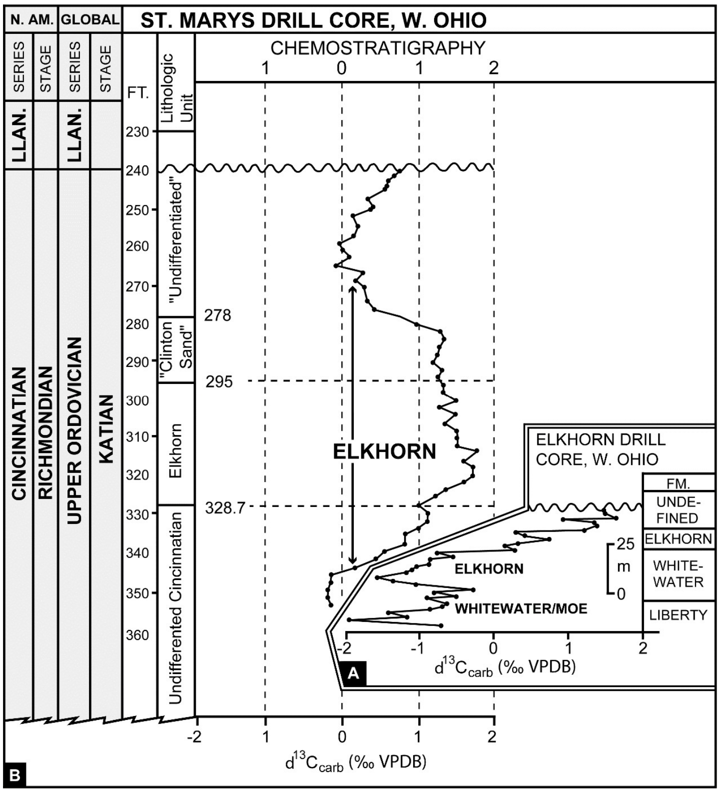

Fig. 6. Comparison between the original Elkhorn $\delta^{13}C_{carb}$ curve (inset figure) and that from the St. Marys drill core. Note the stratigraphic incompleteness of the Elkhorn drill core curve compared with that from St. Marys.

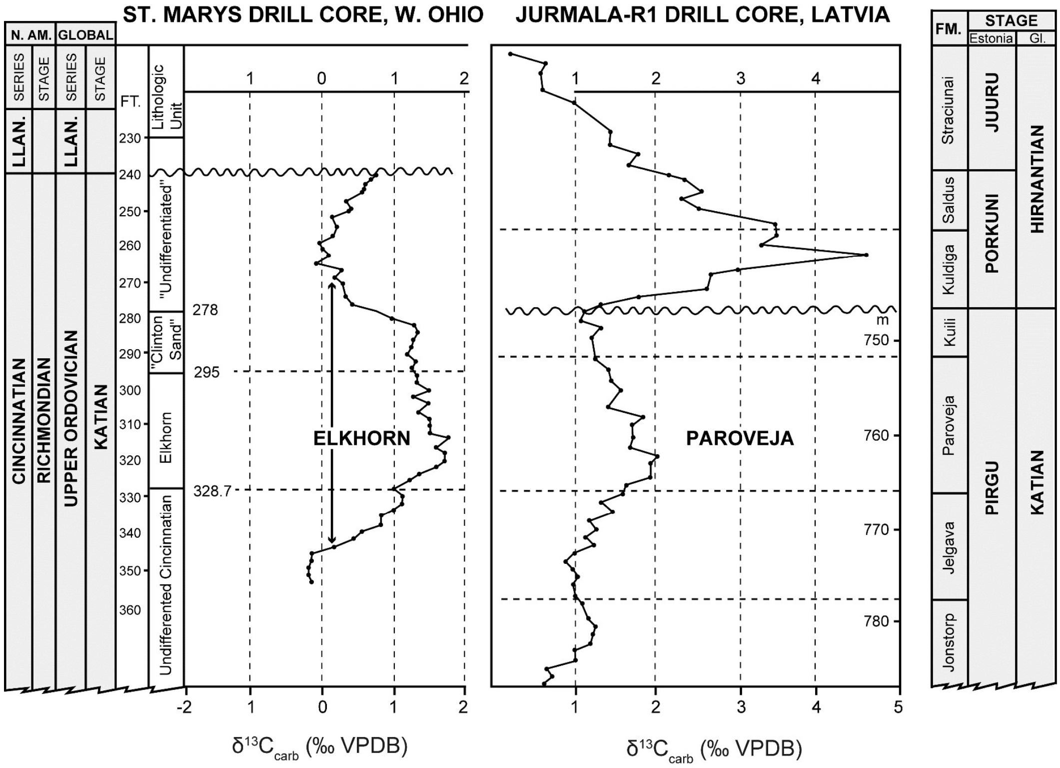

Fig. 7. Comparison between the $\delta^{13}C_{carb}$ curves from the St. Marys drill core and the Jurmala R-1 drill core. Note the very close similarity between the North Ameerican ELKHORN and the Latvian PAROVEJA excursions in the two drill cores which suggests that they represent the same excursion. Also note that in the St. Marys drill core, there is a major unconformity between the Upper Katian undifferentiated interval, which contains Late Ordovician conodonts, and overlying Llandovery strata.

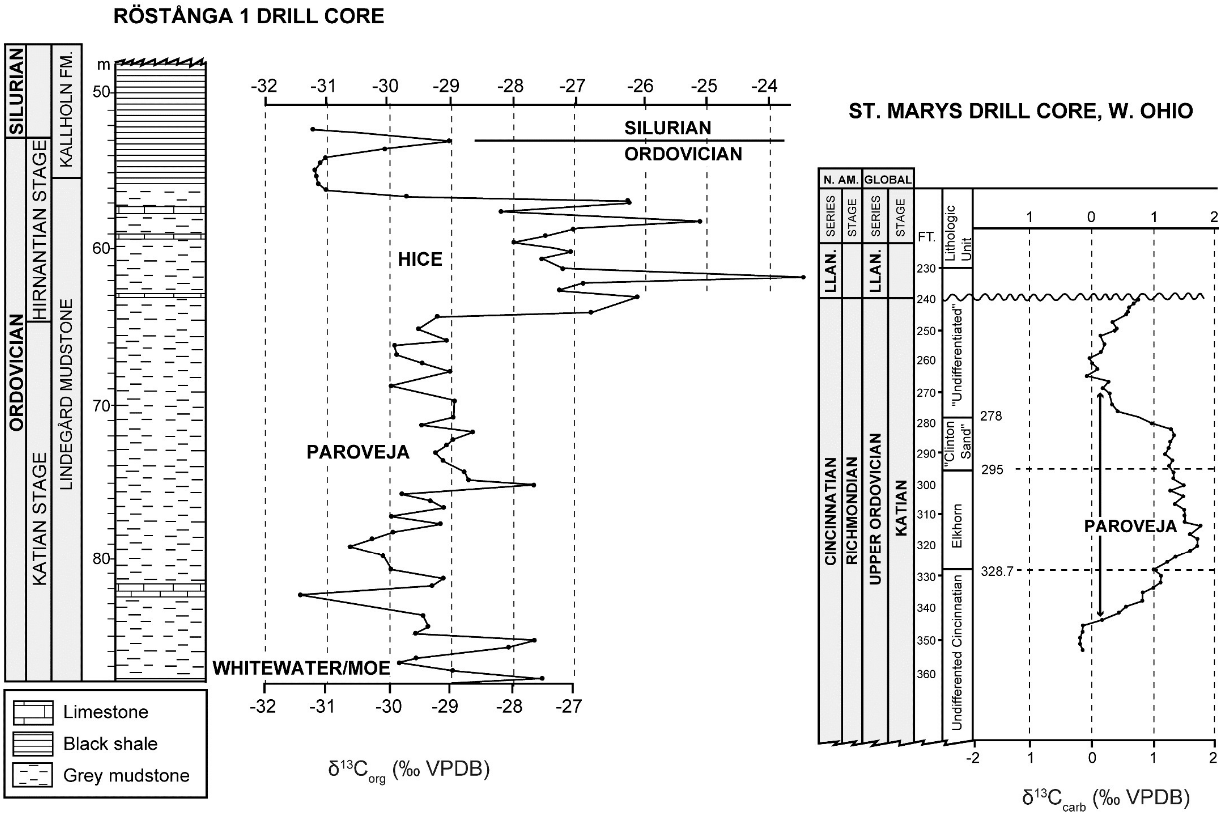

Fig. 8. Comparison between the $\delta^{13}C_{org}$ curve of the Röstånga-1 drill core and the $\delta^{13}C_{carb}$ curve from the St. Marys drill core. Note the absence of the HICE in the St. Marys succession. The Elkhorn Formation has yielded middle-upper Katian conodonts at other localities (e.g. Kohut & Sweet 1968).

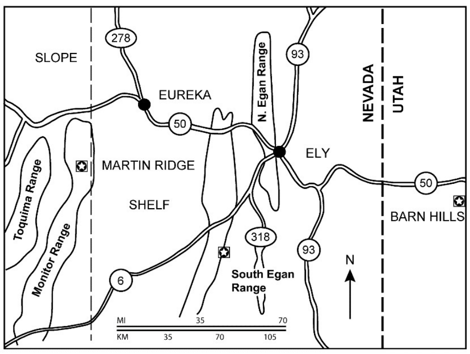

Fig. 9. Sketch-map of the Great Basin region in Nevada and adjacent states showing the location of the Monitor Range, the South Eagan Range, and the Barn Hills sections. Note that whereas the Monitor Range section represents an upper slope succession, the rocks of the two other successions were deposited in a shelf environment.

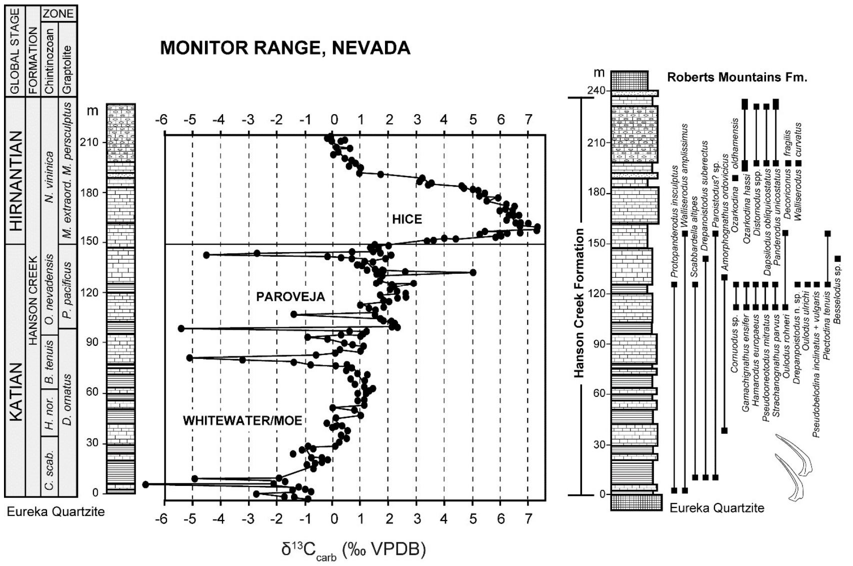

Fig. 10. Ranges of conodonts and the $\delta^{13}C_{carb}$ curve in the Hanson Creek Formation at Monitor Range, Nevada. Isotope curve after Jones *et al.* (2016) and conodont records after Sweet (2000).

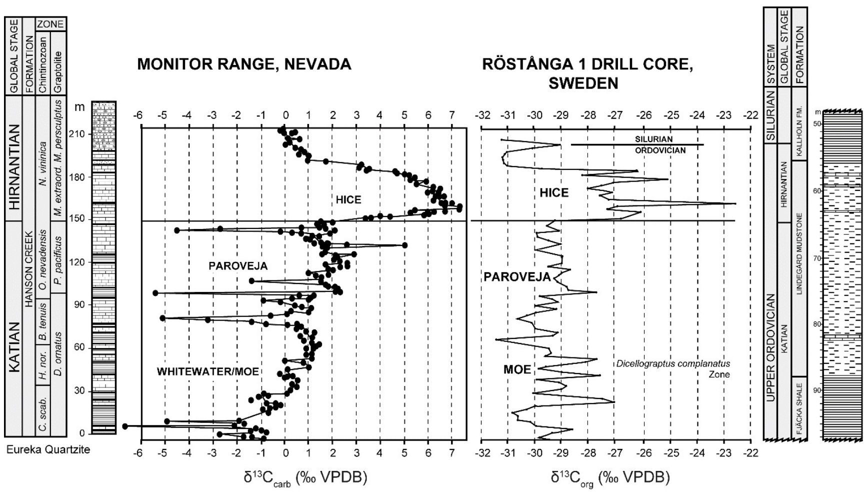

Fig. 11. Comparison between the $\delta^{13}C_{carb}$ curve from the Monitor Range and the $\delta^{13}C_{org}$ curve from the Röstånga -1 drill core.

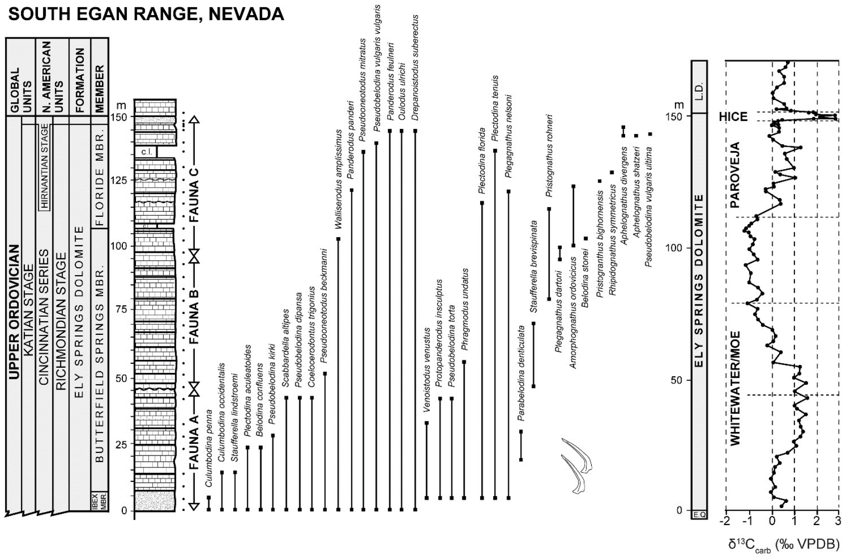

Fig. 12. Conodont species ranges (after Leatham 1987) and $\delta^{13}C_{carb}$ chemostratigraphy (after Jones *et al.* (2016)) through the Ely Springs Dolomite in the South Egan Range, Nevada. Note the well-developed WHITEWATER/MOE and PAROVEJA excursions.

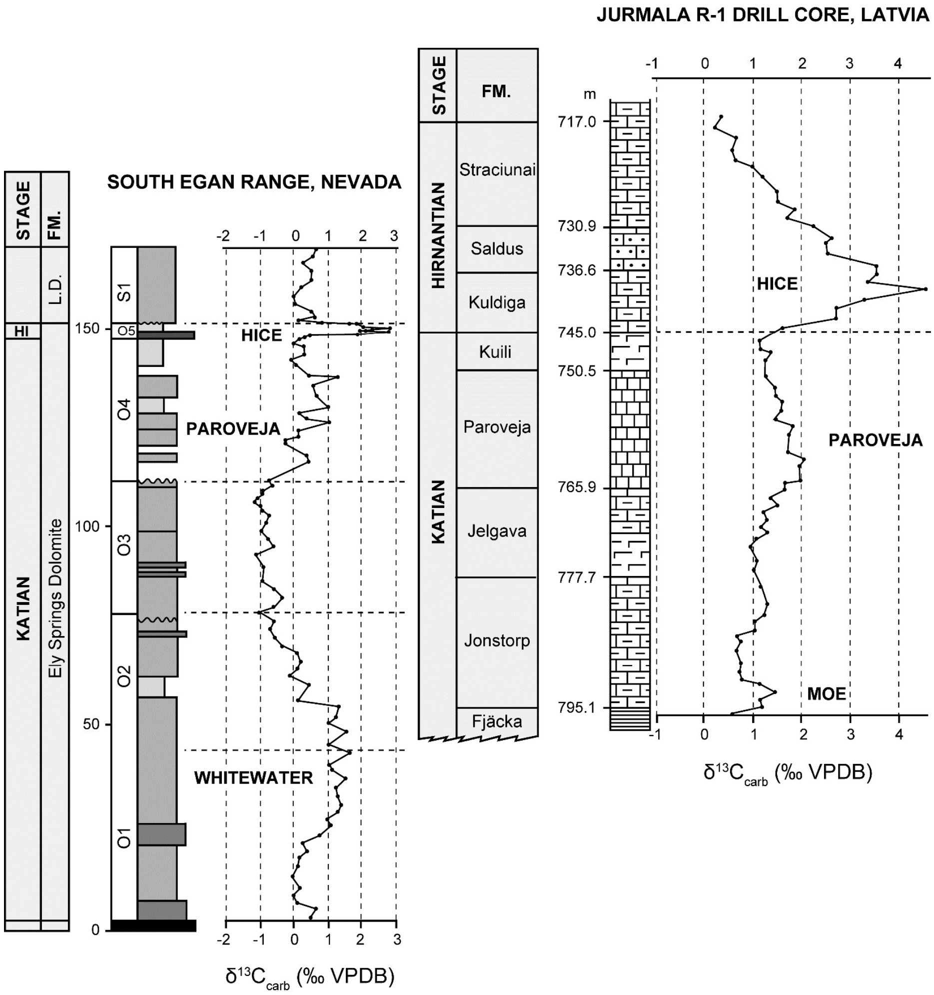

Fig. 13. Comparison between the $\delta^{13}C_{carb}$ curve from South Egan Range and that of the Jurmala R-1 drill core from Latvia. The similarity between these curves shows the possibility of close long-distance correlations between these geographically widely separate successions.

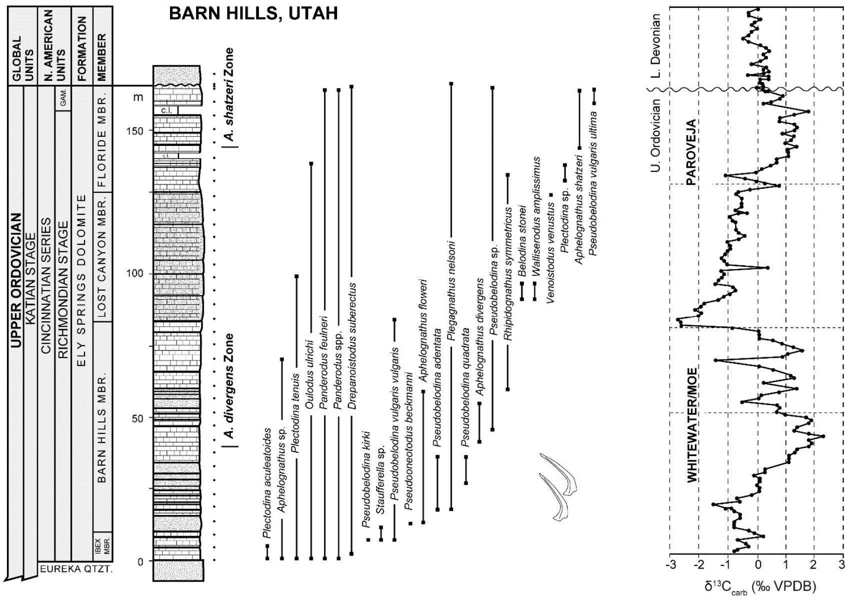

Fig. 14. Ranges of conodont taxa (based on Leatham 1987) and the $\delta^{13}C_{carb}$ curve (after Jones *et al.* 2016) through the Ely Springs Dolomite at the Barn Hills section in Utah. Note the well-developed WHITEWATER/MOE and PAROVEJA excursions.

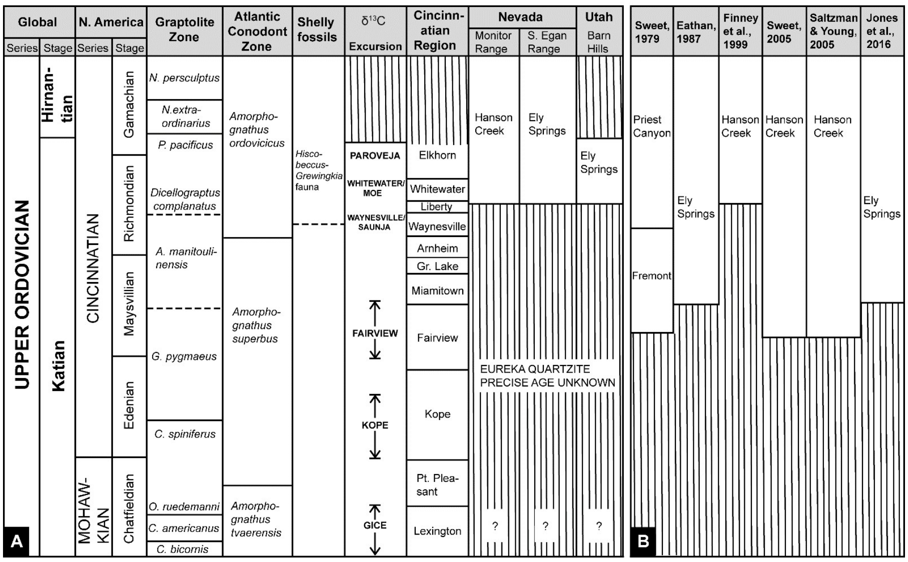

Fig. 15. Summary diagram showing our re-interpretation of the Katian biostratigraphy of the Great Basin (A). The right portion of the diagram (B) shows some previous interpretations. In our opinion, some of these are off by more than a stage.

Table 1. $\delta^{13}C_{carb}$ values from the St. Marys drill core. Sample numbers refer to foot levels in the drill core.

Sample No.	d ^{13}C VPDB	$d^{13}C/^{12}C$ Std Dev	d ^{18}O VPDB	$d^{18}O/^{16}O$ Std Dev
16MK1-240	0.80	0.01	-3.16	0.02
16MK1-242	0.76	0.02	-2.53	0.03
16MK1-242	0.80	0.01	-2.37	0.02
16MK1-244	0.54	0.01	-1.93	0.03
16MK1-246	0.57	0.01	-1.35	0.04
16MK1-248	0.32	0.02	-2.67	0.01
16MK1-250	0.45	0.01	-2.63	0.01
16MK1-252	0.18	0.01	-3.11	0.01
16MK1-254	0.26	0.00	-2.30	0.03
16MK1-256	0.15	0.03	-2.54	0.03
16MK1-258	-0.02	0.02	-2.71	0.03
16MK1-260	0.02	0.04	-3.12	0.04
16MK1-262	0.16	0.02	-2.79	0.02
16MK1-264	-0.04	0.01	-2.96	0.02
16MK1-266	0.34	0.01	-2.61	0.02
16MK1-268	0.30	0.01	-2.31	0.02
16MK1-268	0.28	0.01	-2.23	0.02
16MK1-270	0.39	0.02	-2.28	0.04
16MK1-270	0.35	0.01	-2.21	0.01
16MK1-272	0.34	0.01	-2.43	0.01
16MK1-274	0.38	0.02	-2.19	0.02
16MK1-276	0.44	0.01	-2.91	0.02
16MK1-278	0.80	0.01	-2.19	0.01
16MK1-280	1.02	0.01	-2.11	0.01
16MK1-282	1.34	0.00	-2.05	0.02
16MK1-284	1.37	0.01	-2.24	0.02
16MK1-286	1.31	0.00	-2.09	0.03
16MK1-288	1.29	0.01	-2.24	0.02
16MK1-290	1.23	0.01	-2.08	0.02
16MK1-292	1.37	0.01	-2.20	0.02
16MK1-294	1.30	0.00	-1.70	0.02
16MK1-296	1.39	0.00	-2.86	0.03
16MK1-298	1.35	0.00	-2.96	0.01
16MK1-300	1.54	0.01	-2.45	0.02
16MK1-302	1.30	0.01	-1.99	0.01
16MK1-304	1.52	0.01	-2.41	0.02
16MK1-306	1.39	0.01	-2.57	0.02
16MK1-308	1.56	0.01	-2.37	0.01
16MK1-310	1.57	0.01	-2.70	0.03

16MK1-312	1.52	0.01	-3.37	0.02
16MK1-312	1.51	0.01	-3.39	0.01
16MK1-314	1.81	0.01	-2.83	0.02
16MK1-316	1.63	0.01	-3.14	0.02
16MK1-318	1.73	0.01	-2.86	0.02
16MK1-320	1.73	0.01	-2.87	0.02
16MK1-322	1.61	0.02	-3.03	0.04
16MK1-324	1.37	0.02	-3.32	0.01
16MK1-326	1.21	0.01	-3.22	0.02
16MK1-328	1.00	0.02	-3.42	0.05
16MK1-330	1.14	0.02	-3.05	0.04
16MK1-330	1.15	0.02	-3.05	0.02
16MK1-332	1.14	0.01	-3.10	0.02
16MK1-334	1.02	0.01	-3.53	0.03
16MK1-336	0.82	0.01	-3.54	0.03
16MK1-338	0.82	0.01	-3.68	0.02
16MK1-340	0.56	0.01	-3.39	0.03
16MK1-342	0.44	0.01	-2.98	0.01
16MK1-344	0.15	0.01	-3.74	0.01
16MK1-346	-0.11	0.01	-4.62	0.02
16MK1-348	-0.12	0.02	-3.57	0.02
16MK1-350	-0.18	0.01	-4.04	0.01
16MK1-352	-0.20	0.01	-3.76	0.02
16MK1-354	-0.16	0.01	-3.30	0.01