Implications of Gondwana glaciations in the Baltic late Ordovician and Silurian and a carbon isotopic test of environmental cyclicity

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Key word. – Baltica, Carbon isotopes, Glaciations, Gondwana, Ordovician, Palaeoclimates, Silurian.

Abstract. – Four glaciations – the extensively studied Hirnantian episode and three in the Llandovery-earliest Wenlock – are well established on the Gondwana palaeocontinent. New data [Hamoumi, 1999] shift the beginning of the glacial epoch to the early Caradoc when Baltica was moving from middle to low latitudes of the southern Hemisphere. Despite the rather considerable distance between polar areas of Gondwana and subtropical Baltica all four glacial events are reflected via global climatic mechanisms in the East Baltic. It is generally accepted that glaciations are marked by positive excursions of $\delta^{18}O$ and $\delta^{13}C$ values caused by increase of the polar ice caps, bioproduction and decrease of oceanic water temperature, etc. Based on these relationships, the Gondwana glacial events are correlated with coeval isotopic shifts established in sections of Baltica. In addition, agreement of the oceanic processes and corresponding carbon isotopic trends predicted by Jeppsson [1990] to real measured values is analysed.

The following positive $\delta^{13}C$ excursions are recorded in the Baltic area (peak values in parentheses) : middle Caradoc (2.2 ‰), early Ashgill (2.5 ‰), Hirnantian (6 ‰), early Aeronian (3.7 ‰), early Telychian (2.7 ‰), early Wenlock (5.2 ‰). Most of these shifts correlate well with glacio-eustatic sea level lowstands and biodiversity changes, as shown by the most extensive Oandu crisis in the Caradoc, Hirnantian mass extinction and the Wenlock Ireviken Event.

Analysis of data allows the following conclusions : (1) all four Gondwana glaciations identified by tillites, microconglomeratic clays, etc. and dated biostratigraphically are recognised in the Baltic area through clear positive carbon isotope excursions at the same levels; (2) three smaller carbon isotope excursions in the Caradoc and Ashgill together with algal abundance data suggest the presence of several colder climate episodes during the late Ordovician. This may support the idea of the earlier onset of the glacial epoch on Gondwana; however, correct biostratigraphic dating of supposed glacial sediments is required; (3) the carbon isotopic testing of the oceanic model by Jeppsson reveals too many contradictions between model predictions and measured values. This means that the environmental background of isotopic events and relationships with oceanic events should be revised ; (4) for delimitation of the climatic – oceanic episodes, a more general marker identifying environmental change via a basinal approach seems useful. For this purpose lithological, geochemical or palaeontological criteria can be used.

L'influence de la glaciation du Gondwana à l'Ordovicien supérieur et au Silurien de la Baltique. Un test de la cyclicité de l'environnement à l'aide des isotopes du carbone

Mots clés. – Baltica, Glaciation, Gondwana, Isotopes du carbone, Ordovicien, Paléoclimatologie, Silurien.

Résumé. – Sur le continent Gondwana ont été mises en évidence quatre glaciations – l'épisode Hirnantien extrêmement étudié et trois autres au Llandovérien et au commencement du Wenlock. Les nouvelles données de Hamoumi [1999] déplacent le début de l'époque glaciale au Caradocien inférieur quand la mer Baltique passe des moyennes aux basses latitudes de l'hémisphère austral [Torsvik *et al.,* 1996]. En même temps le centre de la glaciation se déplace du nord de l'Afrique au sud de l'Amérique.

Malgré la distance considérable entre les régions polaires de Gondwana et les régions subtropicales de la mer Baltique, tous les événements glaciaires susnommés sont d'une certaine manière reflétés en mer Baltique de l'est. Le mécanisme de cette influence est discutable dans le détail mais, les processus climatiques et océaniques jouent un rôle essentiel. Il est généralement admis que les glaciations sont marquées par les excursions positives de valeurs de $\delta^{18}O$ et $\delta^{13}C$ provoquées par l'augmentation de la couche de glace aux régions polaires, la bioproduction, le déplacement du carbone organique dans les sédiments et le refroidissement de l'océan.

Les relations connues entre ces différents facteurs permettent de corréler les événements glaciaires de Gondwana avec les changements simultanés de la courbe des isotopes fixée en mer Baltique. Par ailleurs, le modèle du cycle des isotopes du carbone océanique de Jeppsonn [1990] est mis en perspective avec les valeurs réelles mesurées.

Les excursions positives de $\delta^{13}C$ (les valeurs maximum entre parenthèses) sont évaluées pour la Baltique : le Caradocien moyen (2,2 ‰), l'Ashgill inférieur (2,5 ‰), l'Hirnantien (6 ‰), l'Aéronien inférieur (3,7 ‰), le Telychien inférieur (2,7 ‰), le Wenlock inférieur (5,2 ‰). Les changements pour la plupart sont en corrélation avec les baisses du niveau de l'océan, ayant évidemment un caractère glacio-eustatique. La corrélation positive se trouve aussi entre la glaciation et les changements de la biodiversité largement connus comme la crise Oandu (au Caradocien), l'extinction en masse de Hirnantia et l'événement Ireviken au Wenlock.

Les données analysées permettent de conclure que : (1) les quatre glaciations du Gondwana identifiées notamment sur la base de tillites et d'argiles microconglomératiques et biostratigraphiquement datées sont dans les profils bal-

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tiques clairement marqués par l'excursion de la courbe des isotopes du carbone ; (2) trois anomalies positives mineures à l'Ashgill et au Caradoc ainsi que des données sur l'abondance spécifique des algues, indiquent la présence d'une période climatique plus froide à l'Ordovicien inférieur. Ces données sont en faveur d'un début plus précoce de la glaciation du Gondwana, mais des datations nouvelles des roches glaciogéniques considérées sont nécessaires pour le confirmer ; (3) le test du modèle océanologique de Jeppsson à l'aide des isotopes du carbone a souvent montré des contradictions entre le modèle établi et les valeurs mesurées ; (4) on ne devrait pas représenter les épisodes climatiques-océaniques seulement sur la base de la distribution d'un petit nombre d'espèces de conodontes connus mais aussi à l'aide de marqueurs mettant en évidence les changements plus généraux du milieu marin fondés sur les critères lithologiques, géochimiques ou/et paléontologiques.

INTRODUCTION

Stable carbon and oxygen isotopes are being used increasingly in solving different geological problems, especially in stratigraphy and palaeoclimatology. In stratigraphy, isotopes, mainly carbon, are mostly exploited as event markers for correlations, and this usually does not cause serious difficulties, especially when biostratigraphy is also considered. The palaeoclimatological application of isotopes is much more complicated because of uncertain reasoning and different possibilities of interpretation of changes in the isotopic composition of rocks and fossils. Following careful analysis one can assure reasonably [e.g. Samtleben *et al.*, 1996] that it is possible to identify a primary isotopic signal, which reflects original seawater composition, formed usually according to coeval environmental conditions. Accepting this premise as a pattern, it is possible to investigate reasons for changes in the isotope record connected with glacial events established on Gondwana and to discuss the dating of these events.

For correct understanding of the events and interaction of the causal processes, exact stratigraphical dating is crucial. Biostratigraphy, based especially on graptolites and different microfossils (chitinozoans, conodonts, "microvertebrates", etc.), is a leading tool in dating, but in case of rare fossils it may give more exact results in combination with isotopic data. In the context of Gondwanan glacial history two important dating problems arise : when did the glacial epoch begin, and how correctly are individual glacial events dated ? In the latter context the late Ordovician Hirnantian event seems to be most complicated because of its specific fossil content and the many gaps in sequences through the event interval. We comment below on the use of Baltic data as supporting information.

Glaciations are accompanied by different environmental, including climatic and oceanic, but also biotic and geodynamic processes etc, which are reflected in some way in the isotopic composition of minerals forming rocks and fossil shells. For example, the increase of the polar ice caps and decrease of oceanic water temperature as a rule cause an increase of $\delta^{18}O$ values while *vice versa* a decrease of these values could be referred to melting of the ice caps and climate warming.

Relative abundance of carbon isotopes ($\delta^{13}C$) often changes parallel to oxygen, but actual connections are more complicated depending on changes in ocean circulation caused by advancing glaciation or some other reason. Downwelling of cold oxygenated water in polar areas and upwelling at low latitudes results in increased bioproduction and removal of light organic carbon to the sediment, which in turn causes a cooling phase of climate.

The above reasoning has been used by Brenchley *et al.* [1994], Marshall *et al.* [1997] and several others to explain the Hirnantian carbon isotopic event. The actual shift of the values, however, exceeds the amplitude which can be explained by the above interpretations alone [Brenchley *et al.*, 1994]. Consequently also other processes should be considered, e.g. Kump *et al.* [1999] suggested the weathering hypothesis for understanding carbon cycling connected with glacial processes. This latter idea was based on the fact that during glacial times the falling sea level opens wide areas for intense weathering, which enhances riverine carbon influx into the ocean, lowers the pCO_2 in the atmosphere and leads to an anti-greenhouse climatic situation.

These explanations have weak and strong points but they both take the CO_2 content in the atmosphere as the main driver of the climate. Recently Veizer *et al.* [2000] questioned this idea, suggesting that tectonics played the primary role in long term climatic processes. Nevertheless, despite the differences in basic hypotheses on carbon cycling, all above authors agree that glaciations are reflected usually by positive $\delta^{18}O$ and $\delta^{13}C$ excursions, which often coincide with sea level lowstands. Of course, relationships between all these and biotic events are more complicated in detail and not as one-to-one in every situation. In this context these explanations should not be considered as alternatives, but as different aspects of a complex environmental process. However, using the above general model, we discuss observed patterns in sections of the Baltic area at the event levels established on Gondwana.

Jeppsson [1990] proposed an oceanic model (see below), which became rather popular for interpreting the relationships between certain climatic, oceanic, biotic and sedimentological features. Based mainly on Jeppsson's episode descriptions, Wenzel and Joachimski [1996] and Bickert *et al.* [1997] summarized the episode characteristics in their more or less modified models. We have used these models together with Jeppsson's descriptions and episode boundary definitions for identification of intervals in our sections corresponding to warmer and cooler climate episodes and for testing the pattern of their isotopic signature. Certain complications revealed during the analysis are discussed below.

GLACIAL EVENTS ON GONDWANA

During the Ordovician and early Silurian, the Gondwana landmass was situated close to the southern polar areas [Torsvik *et al.,* 1996] with good potential for advancement of glacial processes. Until now four glaciations – the extensively studied Hirnantian one and three in the Llandovery and earliest Wenlock – are well specified by the correspond-

ing glacial rocks dated biostratigraphically as follows (listed under event names used below in the paper).

Hirnantian glacial sediments are known widely in North Africa and South America; here we mention only a few occurrences [for references see Astini, 1999; Brenchley *et al*., 1994; Caputo, 1998; Destombes *et al*., 1985; Marshall *et al*., 1997; Paris *et al*., 2000, etc].

a) *Microconglomeratic clays* and associated sediments of the Upper 2nd Bani Sandstone Formation of the Anti Atlas, Morocco, contain rare specimens of *Hirnantia sagittifera* (McCoy) among the fauna. The formation is underlain by the Lower 2nd Bani Formation which also comprises representatives of the *Hirnantia* fauna, and is overlain by Silurian graptolitic argillites, at least locally dated as the *Parakidograptus acuminatus* Zone. The whole 2nd Bani Group with a pavement of glacial striations in the top of the lower part has been correlated with the Hirnantian of Britain [Destombes *et al*., 1985].

b) *Glaciomarine diamictites* (microconglomeratic clays) of the Hassi el Hadjar Formation of NE Algerian Sahara, interpreted as products of melting of the late Ordovician ice cap and followed by post-glacial shelf sediments of the M'Kratta Formation [Paris *et al*., 2000]. These rocks are best dated by chitinozoans; *Tanuchitina elongata* (BOUCHÉ) is dominant in the diamictites, with *Spinachitina oulebsiri* PARIS, BOURAHROUH and HERISSE in the M'Kratta Formation, where the former species also occurs. These data allowed Paris *et al*. [2000] to correlate the Hassi el Hadjar Formation with the lower part of the *Normalograptus persculptus* Zone and the M'Kratta Formation with the higher part, but not the top of the Zone, i.e. these beds belong to the upper Hirnantian in terms of chronostratigraphy. According to J. Nõlvak (pers. comm.), *T. elongata* closely resembles *T. bergstroemi* LAUFELD occurring in the lower Ashgill of Baltoscandia. This similarity refers to the possibility of an older age for these glacial rocks.

c) *Diamictites* of the Iapo Formation in the Parana Basin, Brazil, contain no fossils and their middle Hirnantian age is inferred from the position below the fossiliferous Vila Maria Formation. The latter is believed to be of early Llandovery age, but on the basis of some chitinozoans it may be as young as late Aeronian-early Telychian [Caputo, 1998].

d) *Diamictites* of the Don Braulio Formation of the Argentine Precordillera are much better dated by a varied *Hirnantia* fauna in siltstones just above the glacial sediments and with *Normalograptus persculptus* (SALTER) in mudstones some ten metres higher [Astini, 1999; Marshall *et al*., 1997].

Summarizing the dating of these rocks believed to reflect the Hirnantian glaciation, we see a great variety, but the best dated sections (Morocco, Argentina) suggest that the main glacial episode occurred in the early Hirnantian, as this is in agreement with carbon isotope studies in Laurentia [Dob's Linn, Scotland, Underwood *et al*., 1997] and Baltica [Kaljo *et al*., 2001].

Early Silurian glacial events have all been established in the Amazon Basin, Brazil, where interfingering of the Nhamunda and fossiliferous Pitinga formations allows dating of the glacial events as follows [Caputo, 1998].

The early Aeronian glacial event represented by diamictites was dated by immediately overlying rocks containing *Coronograptus gregarius* (LAPWORTH) and some chitinozoans, including *Conochitina* cf. *iklaensis* NESTOR [Caputo, 1998].

The latest Aeronian – early Telychian event is dated by an association of chitinozoans in shales occurring lateral to the tillites. The association contains *Cyathochitina* sp. *B* PARIS, 1981 and *Pogonochitina djalmai* SOMMER and BOECKEL which are characteristic of the early Telychian [Caputo, 1998]. Considering also Baltic data [Kaljo and Martma, 2000], we favour dating the event as early Telychian, but we cannot be sure when the glacial episode started.

The latest Telychian – earliest Sheinwoodian glacial rocks are also dated by chitinozoans. Caputo [1998] listed a rather diverse assemblage including *Desmochitina densa* EISENACK, *Margachitina margaritana* (EISENACK) and *Salopochitina monterrosae* (CRAMER), suggesting therefore that more exact dating of the event is impossible.

Over and above these more or less well dated glacial events, repeated reports of occurrences of earlier glacial sediments have come from different parts of Gondwana [for references see Hamoumi, 1999]. These data shift the beginning of the glacial epoch to the early Caradoc when Baltica was moving from middle to low latitudes of the southern Hemisphere [Torsvik *et al.,* 1996]. At the same time the centre of glaciation moved from North Africa to South America. Despite the rather great distance between the polar areas of Gondwana and subtropical Baltica, all well dated glacial events mentioned above are reflected, as shown below, in some way in the Baltic area. Some of the pre-Hirnantian carbon isotope changes might also have a glacial background.

CHANGES IN CARBON AND OXYGEN ISOTOPIC COMPOSITION IN BALTICA

General comments

Isotope studies embracing a southwestern sector of the Baltica continent, including the present East Baltic (Estonia, Latvia, Lithuania), Gotland, Scania and the Oslo region, but also the Anglo-Welsh area, i.e. part of Avalonia which joined Baltica in the late Ordovician, commenced roughly 12-15 years ago. Data now available [Brenchley *et al*., 1994; Wenzel and Joachimski, 1996; Samtleben *et al*., 1996; Kaljo *et al.,* 1997, 1998; Marshall *et al*., 1997; Azmy *et al*., 1998; Wigforss-Lange, 1999] allow us to discuss a more or less continuous curve of $\delta^{13}C$ values beginning with the middle Caradoc Kinnekulle "big" bentonite until the Silurian-Devonian boundary beds in the Ventspils core (Latvia). In the course of this time (~38 m.y.) the following five most important positive excursions (peak $\delta^{13}C$ values reaching 4 ‰ and more; corresponding values are shown in parentheses) have been established : Hirnantian (7 ‰), early Aeronian (3.7 ‰), early Sheinwoodian (5.7 ‰), middle Homerian (4.6 ‰) and middle Ludfordian (11 ‰). Several shifts show lower peak $\delta^{13}C$ values (below 3 ‰), e.g. in the middle Caradoc (2.2 ‰), early Ashgill (2.5 ‰), early Telychian (2.7 ‰) [Ainsaar *et al.,* 1999; Kaljo *et al.,* 1999;

Kaljo and Martma, 2000]. Most of these shifts correlate more or less with sea level low stands, which mainly (Homerian and Ludfordian excluded) are considered glacio-eustatic in origin. The isotope shifts occur close to levels of biodiversity changes, as shown by the most widely recognized Oandu crisis in the Caradoc [Kaljo *et al.,* 1996], Hirnantian mass extinction [Brenchley *et al.,* 1994], and the Wenlock Ireviken event [Kaljo *et al.,* 1998].

The oxygen isotope record from the whole interval is less complete. However for those parts of the section in which we are interested, the trend of $\delta^{18}O$ values is well presented by different authors [Brenchley *et al.,* 1994; Wenzel and Joachimski, 1996; Samtleben *et al.,* 1996; Marshall *et al.,* 1997; Azmy *et al.,* 1998, Heath *et al.,* 1998].

The main goal of this paper is to trace the Gondwana glacial effects in Baltic sections. Therefore, in our interpretations below, we use mainly international stratigraphical terminology. Primary sources for data with all local geological terminology are given in the corresponding references.

Ordovician

A $\delta^{13}C$ curve from the Rapla core of Estonia [Kaljo *et al.,* 1999] shows three minor positive excursions below the well known Hirnantian peak : the first two in the Upper Caradoc (at levels correlated with the *Dicranograptus clingani* and *Pleurograptus linearis* zones; corresponding $\delta^{13}C$ values 1.9 and 1.7‰) and the third in the lowermost Ashgill (2.5‰). Subsequently these excursions were confirmed also in some other core sections (e.g. Orjaku, Viljandi) in Estonia. As noted in our introductory remarks, and from Jeppsson's model, peak intervals of the isotopic curve should reflect cooler climate episodes, which in some cases may give rise to ice cap formation and then coincide with sea level lowerings. This pattern is in good accord with changes in the abundance of algal debris in limestones forming the upper Ordovician in the Rapla core. Calcareous algae became an important component of the skeletal material of limestones beginning with the late Caradoc. In three intervals of the Rapla core the proportion of algal particles is well above 50 % of the whole debris and in four intervals their content is very low [Põlma, 1972]. The peaks of the $\delta^{13}C$ values noted above coincide with minima of algal abundance which occur mostly in argillaceous limestones, while, *vice versa,* lows of carbon isotopic values correlate with algal abundance maxima, generally in micritic or less argillaceous limestones [Kaljo *et al.,* 1999]. Because algae prefer habitats with clean warm water, such coincidence is logical and supports the idea that several earlier cooler intervals occurred during the late Ordovician before the main glacial episode started in the Hirnantian.

Ainsaar *et al.* [1999] established another low (1.9-2.2‰) positive $\delta^{13}C$ shift in the mid-Caradoc of the Tartu and Ristiküla cores, which according to their correlation has coeval counterparts on Laurentia, but there are also some discrepancies, for example in the interpretation of sea level changes [Patzkowsky *et al.,* 1997]. Comparison of carbon cycles and concurrent processes on two continents was based on correlation of the Kinnekulle (Baltoscandia) and Millbrig (North America) K-bentonite beds, but recently Min *et al.* [2001] showed that absolute ages of these beds differ by nearly 7 m.y. (454.8 and 448.0 Ma, respectively). This means that earlier conclusions should be re-evaluated

and new possibilities for comparison considered. For example, taking the new scheme of radiometric ages compiled by Sadler and Cooper [based on Cooper, 1999] for Ordovician biodiversity study, one can interpret the Millbrig K-bentonite as being of early Ashgill age. The positive carbon excursion above it described by Patzkowsky *et al.* [1997] is then more likely synchronous with our early Ashgill positive shift [2.5 ‰, in local terminology early Pirgu; Kaljo *et al.,* 1999]. But these correlations are opposed strongly by biostratigraphical dating of the Millbrig K-bentonite in the upper part of the *P. undatus* conodont Zone, which is considerably older. This discrepancy should be resolved before the data can be used properly.

The Rapla core was also studied for acritarch and chitinozoan diversity changes [Kaljo *et al.,* 1996]. Both groups show a continuous diversity decline beginning with the uppermost Caradoc, even though an extinction event was recorded already in the mid-Caradoc. In northern Gondwana, as demonstrated by Paris [1999], chitinozoan diversity was more changeable during the late Ordovician, but the late Caradoc diversity peak, followed by lows in the early and late Ashgill are well seen.

In summary, rather clear similarities exist in microfossil diversity dynamics in Baltica and Gondwana during the late Ordovician. The carbon isotope curve from the Baltic area can thus be interpreted as reflecting some early advances of Gondwanan glaciers. From such a conclusion, and following the rule advocated by Heath *et al.* [1998] that smaller events leave less notable isotopic signatures, we can state that, beginning in the mid-Caradoc, the possible glaciers were obviously much less widespread by comparison with the great Hirnantian ice sheet. Little is yet known about the early Caradoc, but biostratigraphical dating of the pre-Hirnantian glacial advances would be of great interest.

Silurian

The early Silurian glacial history of Gondwana is much better dated and therefore glacial events and the corresponding Baltic carbon and oxygen isotope excursions can be correlated fairly precisely. Thus, it is likely that the $\delta^{13}C$ positive shifts listed above in the early Aeronian, early Telychian and early Sheinwoodian are related to Gondwana glacial events. Apart from simple correlation, such a conclusion could also be motivated by the nature of the processes associated with these excursions, which very much resemble those connected with the Hirnantian glaciation. All these shifts were accompanied by sea level drops and mostly by extinction in some group of organisms. In the latter regard the early Aeronian event is less pronounced, but even so it is clear that the diversity curve of graptolites enters a downward phase just at this level [Kaljo *et al.,* 1995].

Another aspect is that both main glacial isotopic events (Hirnantian and early Sheinwoodian = Ireviken) have been traced globally [Baltica, see above ; Australia, Andrew *et al.,* 1994 ; Laurentia, Saltzman, 2001], but the two Llandovery episodes are known only in the East Baltic, which somewhat diminishes their value. A $\delta^{13}C$ curve published by Azmy *et al.* [1998] includes some analyses from the Llandovery of Anticosti and demonstrates two very low positive excursions in the early and latest Aeronian, in this way supporting the reliability of the Baltic Llandovery data.

The isotopic data published by Azmy *et al*. [1998] and Samtleben *et al*. [1996] show an increase in $\delta^{18}O$ values (which means, a decrease in sea water temperature) at four levels in the early Silurian of Baltica and Laurentia, which coincide well with glacial events on Gondwana. Thus these data also support the idea that the glacial influence was evident globally in low latitude areas on different continents.

The data regarding early Silurian glaciations presented above seem rather unambiguous. However, in reality the picture is much more complicated because of differences in the bathymetric curves employed, in climatic – oceanic models, and in the insufficiency of biostratigraphic dating in particular.

Some comments on sea level curves are warranted. Several papers [Azmy *et al*., 1998; Kaljo *et al.,* 1998] use the global curve compiled by Johnson *et al*. [1991], which is a general curve and for its stratigraphical framework a set of so-called standardized graptolite zones was used. Loydell [1998] published a new curve based on a more detailed zonation. Loydell's method has attracted some criticism, but the attempt to compile a bathymetric curve based on precise graptolite distribution has merit. The main advantage of this curve is that all excursions are very well dated.

As summarized earlier, the general pattern in which positive excursions of the oxygen and carbon isotopic values correlate with sea level lows and glacial episodes and occur close to different bio-events is more or less precisely valid. In comparing this pattern with the well-dated curve by Loydell [1998], one can see clear discrepancies in the early Aeronian and early Sheinwoodian. This might reflect incorrect dating of the glacial events or defects in the pattern itself, or most probably both (see below).

CARBON ISOTOPE TEST OF MODELS OF ENVIRONMENTAL CYCLICITY

Most serious difficulties arise from models in which the relationships between environmental processes are generalized. Evolution of the environment is mainly a cyclic process. Jeppsson [1990] emphasized this in his model of oceanic cycles where more humid low latitude and cooler high latitude Primo (P) climatic episodes alternate respectively with more arid and warmer Secundo (S) episodes. This alternation would involve changes in different environmental conditions, especially in oceanic circulation and nutrient flow, but also in sedimentation and bioproduction, accompanied by changes in biodiversity and carbon isotopic fractionation. The most drastic events occurred at the transition from P to S episodes, including severe extinctions among biota (e.g. the Ireviken Event as the best-known example, Jeppsson [1998]), whereas other types of changes (S-P and S-S) are, according to the model, less remarkable. Such changes might be rapid, needing, in principle, less than oceanic mixing time (a few k.y.), but the events studied so far are a hundred or more times longer [Jeppsson, 1998 suggested 100 k.y. as a mean]. The same is valid for the carbon isotope excursions that mark these events. These can be very brief, only a few metres of sediment thickness (time interval depending on the sedimentation rate), but usually are much longer [e.g. Hirnantian 0.5 m.y., Brenchley *et al*., 1994]. The duration of the early Sheinwoodian $\delta^{13}C$ excursion was about 1 m.y. [Kaljo *et al.,* 1998], which is considerably longer than that of the Ireviken Event itself.

Arranging the episodes into groups, beginning with a Primo episode followed by an event and after that a Secundo episode, we can see in the Silurian Period (with a duration of 26 m.y.) eight typical cycles and several somewhat different successions. Consequently, more or less profound changes in oceanic conditions took place on average every 0.5 m.y. in the Pridoli, every 1 m.y. in the Ludlow and Wenlock, but every 3 m.y. in the Llandovery, while no changes occurred during the first 7 m.y. It means that later the stable early Silurian environment became rather labile, especially at the end of the Period. The tendency of changes to accelerate has been noted earlier [Kaljo *et al.,* 1998] also for carbon isotope events, but with much less frequency. In both cases the hierarchy of the events and quality of the data should also be considered, which may soften the above conclusion.

According to the oceanic model [Jeppsson, 1990; Heath *et al*., 1998; Wenzel and Joachimski, 1996], $\delta^{13}C$ values should be higher in the P episodes due to enhanced removal of organic carbon and, *vice versa*, lower in the S episodes. Thus, a transition from a P episode to an S episode should show a decrease of $\delta^{13}C$ values. By contrast, Bickert *et al*. [1997] consider high $\delta^{13}C$ values typical of arid (= S by Jeppsson) and low values typical of humid (= P by Jeppsson) episodes, motivating this view in relation to changes in oceanic circulation. As both the oceanic conditions and carbon isotope cycling are controlled by the same set of environmental parameters, some correlation of changes was anticipated, and this was also postulated in the models.

To test the point, we have studied the oceanic episodes and carbon isotope excursions together in five core sections of Estonia and Latvia (Kirikuküla, Ohesaare, Ruhnu, Ventspils and Viki; three of these are demonstrated here, figs 1-3). The boundaries of the episodes in these cores were identified using conodont data following criteria given by Aldridge *et al*. [1993] and Jeppsson [1998]. The actual data used in the figures for delimitation of the episodes are summarized in the caption to figure 1. The carbon isotope data from the Ohesaare and Ruhnu cores were obtained by analysing whole rock samples using the methods explained in detail earlier [Kaljo *et al*., 1997; 1998]. The Viki curve is a new one achieved in the same way.

The results obtained through this comparative analysis can be summarized as follows.

1. – Four different states in the stratigraphical trend of $\delta^{13}C$ values were observed :

– a stable or slightly changing interval (e.g. middle Wenlock);

– a small (< 2 ‰) positive excursion (early Telychian, latest Ludfordian);

– a large (3...6‰) positive shift (early Aeronian, early Sheinwoodian, late Homerian, Middle Ludfordian);

– a notable (> 2 ‰) negative shift (late Rhuddanian, late Aeronian, close to the Wenlock/Ludlow junction, some doubtful shifts in the Upper Silurian).

2. – Most of the oceanic events established in the Baltic cores are in some way connected with the above states of the carbon isotopic curve. The early Silurian events are all followed by positive $\delta^{13}C$ shifts : the pre-Snipklint S-P Event is followed by a small positive shift, but the Ireviken
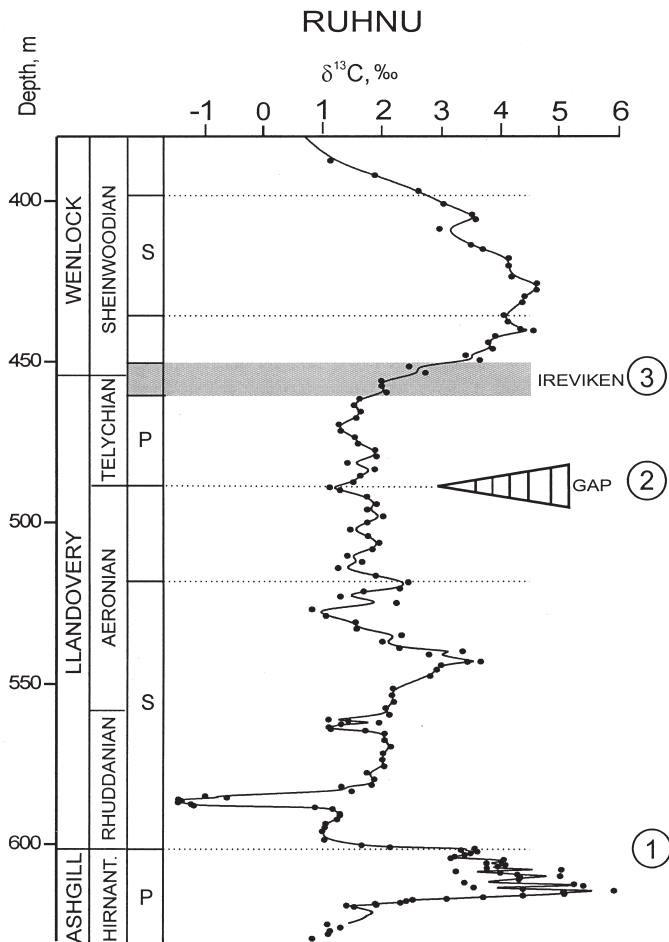
RUHNU

FIG. 1. – Carbon isotope (δ^{13}C) excursions and oceanic episodes identified in the Ruhnu core. Legend : P – Primo and S – Secundo episodes according to Jeppsson [1998]; shading shows event levels; barren parts of the column mark intervals where boundaries of the episodes cannot be identified with confidence. Numbers in circles – motivations of determination of the episode boundaries : 1. The base of the Spirodden S Episode coincides with the lower boundary of the Rhuddanian, identified by a wider biostratigraphical change. 2. The beginning of the Snipklint P Episode is defined by the FAD (=first appearance datum) of *Pterospathodus eopennatus*. In Ruhnu and Viki the FAD follows a gap, i.e. some part of the episode may be missing. 3. The Ireviken Event occurs between Datum 1 (= LAD, last appearance datum, of *Nudibelodina sensitiva)* and Datum 8 (= LAD of *Distomodus staurognathoides*) in Viki. In Ruhnu and Ohesaare Datum 1 is not found and the actual level shown is slightly higher, but below Datum 3 (= LAD of *Pt. am. amorphognathoides*) by Jeppsson [1998]. The base of the Event shown in figure 3 is most probably within the *Cyrtograptus lapworthi* zonal range [Loydell *et al.,* 1998]. 4. The Boge Event is dated by the LAD of *Kockelella walliseri*. 5. The Valleviken Event is dated by the FAD of *Pseudooneotodus* n. sp. *l* (an undescribed species by Jeppsson). 6. The lower limit of the Mulde Event is dated by the FAD of *Ozarkodina bohemica*. 7. The Klinte S Episode above the Mulde Event corresponds with the ranges of *Ctenognathodus murchisoni* and *Ozarkodina densidentata.* The following Sproge P Episode commences just above the LADs of the two named species. 8. Only the uppermost part of the Lau Event is represented. The upper limit is dated by the FAD of *Ozarkodina baccata.* 9. The Klev Event is dated by the LAD of *Ozarkodina snajdri parasnajdri.* 10. The beginning of the Mid-Pridoli Event is close to the FAD of *Ozarkodina rem. remscheidensis.* Abbreviation : Hirnant. – Hirnantian.

FIG. 1. – *La courbe des isotopes du carbone (δ^{13}C) et les épisodes océaniques fixés dans le puits de sondage de Ruhnu. Légend*e : P – *épisodes Primo et* S – *Secundo* d'après *la définition de Jeppsson [1998], l'espace ombragé marque les niveaux des événements, la partie vide de la colonne marque les intervalles, ou il n'est pas possible de fixer exactement les limites. Abbreviation* : Hirnant. – *Hirnantian.*

P-S and Mulde S-S events are followed by major positive shifts. The late Silurian Lau P-S Event coincides with a major positive excursion, but events in the Pridoli are marked
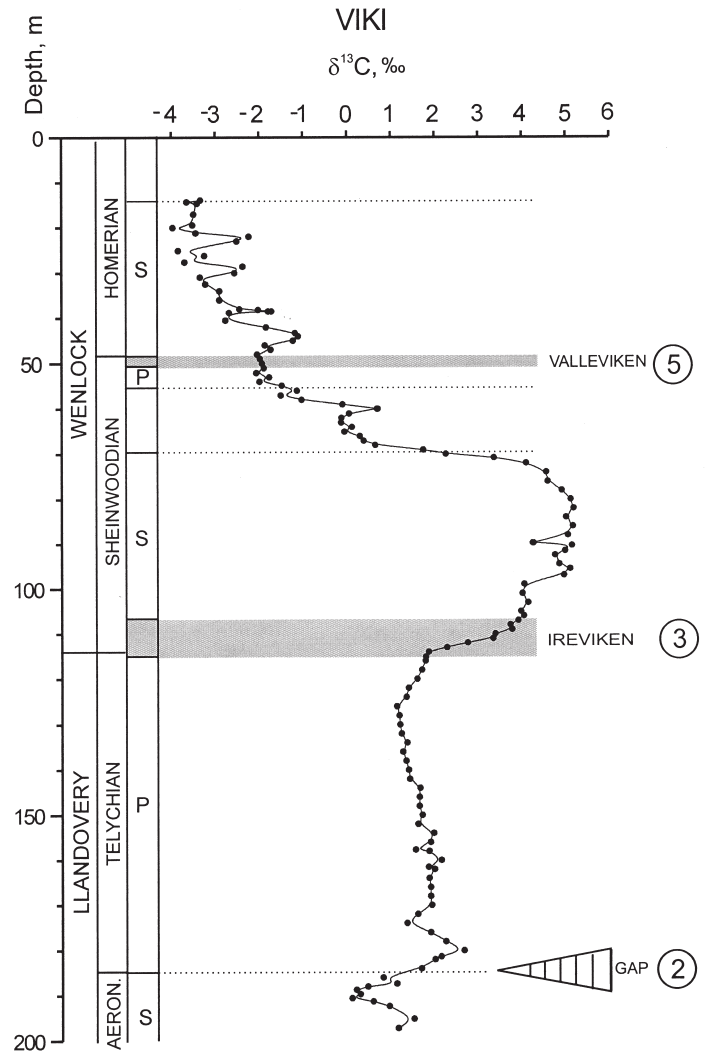
VIKI

FIG. 2. – Carbon isotope (δ^{13}C) excursions and oceanic episodes identified in the Viki core. For legend : see figure 1. Abbreviation : Aeron. – Aeronian.

FIG. 2. – *La courbe des isotopes du carbone (δ^{13}C) et les épisodes océaniques fixés dans le puits de sondage de Viki. Légende : idem. fig. 1. Abbreviation* : Aeron. – *Aeronian.*

with negative excursions. Several P-S events (Boge, Valleviken, Linde) and "normal" S-P episode replacements have no reliable carbon isotope signature.

The above results show that events of the same type (P-S or S-P) may be followed by (or coincide with) shifts of either increasing or decreasing δ^{13}C values, which means that there is no unambiguous relationship between changes of oceanic episodes and carbon isotope trend in the Silurian seas. The negative excursions require particular attention, because some of these are obviously connected with subaerial hiatuses (e.g. late Aeronian), but may also have other explanations [volcanic activity, gas hydrates etc., Kaljo and Martma, 2000]. In several cases the carbon isotopic trend is in conflict with characteristics of the model, e.g. for the Ireviken and Lau P-S events we have major positive excursions and not decreasing values as would be anticipated according to the original model.

Analysis of the results of the comparison of the carbon isotope values predicted by the model with measured values in five well sections (figs 1-3), shows that 7 of the 22 cases

belong to Primo Episodes (according to the model should show high values), 8 to Secundo Episodes (low model values) and 7 to Events (mainly P/S). Half the comparisons show disagreement, i.e. the measured values do not conform to the model predictions. Only about 1/3 of the cases give positive results, mainly those concerning the Secundo Episodes. The isotope curve through the events should show a relatively rapid increase or decrease in values depending on the type of the events, but less than 1/3 of the cases show results in agreement with the original model. A similar comparison on the basis of the Bickert *et al.* [1997] model, which mainly concerns low latitudes, gave better results for the main events (Ireviken, Lau) and some Primo Episodes (Sproge, Sanda), but yet several comparisons remain obscure.

In summary, despite the positive experience that Jeppsson's model is workable, the results of the comparison are unsatisfactory. One reason for this may be that the method of comparison did not consider all aspects of the episodes while they were determined, following the model description, based on some conodont occurrences only. Another reason might be related to the different durations of the isotopic and oceanic events and their rather varied distributional patterns (they may coincide, or partly overlap, or follow each other). Moreover, obviously not all episodes and events as well as isotopic events suggested so far can be considered to have an equal effect in their real environmental significance. Some changes of biota and lithology used to distinguish episodes may be too local, and therefore not sufficiently affecting the carbon isotope fractionation. Differences in responses of carbon isotopic signatures to certain oceanic events show that principal reasons for $\delta^{13}C$ excursions can be somewhat variable during the Silurian : bioproductivity, burial of organic carbon, type of oceanic circulation, sea level changes, etc. Also, volcanic activities, glaciations and related effects were influential on many occasions in the early Silurian. And last but not least, a marker derived from sets of different criteria including fossils, lithology, geochemistry, etc. characterizing the environment as a whole on a basinal scope would be useful for determination of boundaries of the episodes. Such a revision, including delimitation of the episodes, will surely benefit from wider use of carbon and oxygen isotopes.

CONCLUSIONS

(1) All four Gondwana glaciations identified by tillites, microconglomeratic clays, etc. and dated biostratigraphically are recognized in the Baltic area through clear positive carbon isotope excursions.

(2) Three smaller carbon isotope excursions in the Ashgill and Caradoc, together with algal abundance data suggest the presence of several cooler climatic episodes during the late Ordovician. This may support the view of an earlier beginning of the glacial epoch on Gondwana, but correct biostratigraphical dating of the supposed glacial sediments is required.

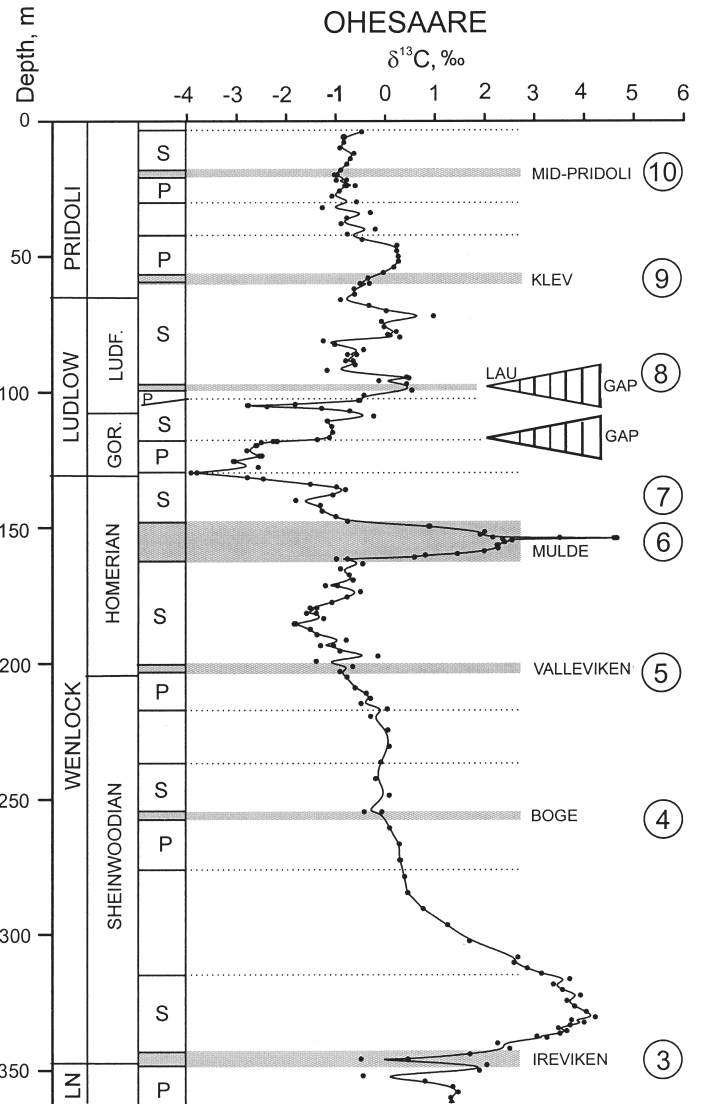(3) The carbon isotopic test of the oceanic model proposed by Jeppsson reveals too many contradictions between model predictions and measured values. This indicates that the environmental background of isotopic events, their relationships with oceanic events and boundaries of the episodes should be revised.

(4) For delimitation of the climatic – oceanic episodes a more general marker identifying the environmental change based on a basinal approach would be useful. For this purpose lithological, geochemical or palaeontological criteria can be used.

FIG. 3. – Carbon isotope ($\delta^{13}C$) excursions and oceanic episodes identified in the Ohesaare core. For legend : see figure 1. Abbreviations : Gor. – Gorstian, Ln – Llandovery, Ludf. – Ludfordian.
FIG. 3. – *Courbe des isotopes du carbone ($\delta^{13}C$) et les épisodes océaniques fixés dans le puits de sondage de Ohesaare. Légende : idem. fig. 1. Abbreviations : Gor. – Gorstian, Ln – Llandovery, Ludf. – Ludfordian.*

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