Geological Quarterly, 2005, **49** (2): 223–234

The Wenlock-Ludlow carbon isotope trend in the Vidukle core, Lithuania, and its relations with oceanic events

Tõnu MARTMA, Antanas BRAZAUSKAS, Dimitri KALJO, Donatas KAMINSKAS and Petras MUSTEIKIS

Martma T., Brazauskas A., Kaljo D., Kaminskas D. and Musteikis P. (2005) — The Wenlock-Ludlow carbon isotope trend in the Vidukle core, Lithuania, and its relations with oceanic events. Geol. Quart., **49** (2): 223–234. Warszawa.

A Wenlock to Ludlow terrigenous-carbonate succession in the Vidukle core in Central Lithuania represents a deep shelf environment with a general upwards-shallowing trend, interrupted by brief deepening episodes. The carbon isotope trend, based on 115 whole-rock analyses, shows three main excursions: (1) a major excursion ($\delta^{13}C$ values reach 3.2‰) in the lower Wenlock, (2) low shifts (1.3‰ and 1.6‰) at two levels in the uppermost Wenlock Siesartis Formation corresponding to the *Monograptus ludensis* Biozone, (3) the most prominent excursion ($\delta^{13}C$ values reach 8.2‰) occurs in the upper Ludlow Mituva Fm. The upper Ludlow excursion is dated by the last occurrences of *Polygnathoides siluricus* below the main shift and the appearance of *Ozarkodina wimani* and *O. crispa* above the excursion. The excursion stratigraphically coincides with the Lau oceanic Event and is correlated with the mid-Ludfordian *Neocucullograptus kozlowskii-Bohemograptus bohemicus tenuis* Biozone. Changes in the carbon isotope trend are in general harmony with some aspects of the rock (CaO, terrigenous component) and fossil content of the section. The data presented are consistent with an arid climate model for the Ludfordian isotope event.

Tõnu Martma and Dimitri Kaljo, Institute of Geology, Tallinn University of Technology, 7 Estonia Blvd., 10143 Tallinn, Estonia, e-mail: martma@gi.ee, kaljo@gi.ee; Antanas Brazauskas, Donatas Kaminskas and Petras Musteikis, Department of Geology and Mineralogy, Vilnius University, 21/27 Ciurlionio Str., LT-2009 Vilnius, Lithuania, e-mails: antanas.brazauskas@gf,vu.lt, donatas.kaminskas@gf.vu.lt, petras.musteikis@gf.vu.lt (received: December 11, 2004; accepted: March 24, 2005).

Key words: Lithuania, Silurian, carbon isotopes, oceanic events, sedimentary facies.

INTRODUCTION

The role of carbon dioxide as a climate driver has become a subject of great interest in modern environmental policy, but also in palaeoclimatology (Kump, 2000; Veizer *et al*., 2000). In this context data on the long-term carbon cycling and its impact on the various aspects of global change are highly necessary. The general mechanism of carbon cycling is well established (Holser *et al*., 1995), but interpretation of actual data and different models varies greatly, including implications of primary productivity, carbon burial, biological oxidation and oceanic processes. A short-term event like the release of methane from gas hydrates or influx of volcanic CO_2 (Weissert, 2000) may change the above scenario, even if these effects are hard to measure. Another complicating question is to what degree a carbon isotope anomaly is induced or deformed by local and global factors. Application of carbon isotopes for stratigraphical correlations is causing less ambiguity, but biostratigraphic control is highly desirable.

Silurian facies and faunas, with biotic and stable isotope events linked to atmospheric, oceanic and tectonic changes (Landing and Johnson, 1998, 2003) are well-studied and can provide a good base for an integrated analysis of the entire environmental complex. A general pattern of the Silurian carbon isotope trend seems to be sufficiently well-founded, only in part of Llandovery and Pridoli the available documentation (Azmy *et al*., 1998; Kaljo *et al*., 1998; Kaljo and Martma, 2000; Saltzman, 2001) is relatively scarce.

Three positive carbon isotope excursions have been recognized in the Wenlock and Ludlow sequences of the world. The first excursion, with the $\delta^{13}C$ values reaching 4–5‰, occurs in the lowermost Wenlock and is the most well known Silurian shift (for a summary see Munnecke *et al*., 2003). The second excursion, observed in the top of the Wenlock, is double peaked and depending on sedimentary facies, is showing different $\delta^{13}C$ values. In deep shelf rocks values remain below 2‰ (Kaljo *et al*., 1997, 1998; Porębska *et al*., 2004), but in slightly shallower ones in Britain and on Gotland they reach 3–4‰ (Corfield *et al*., 1992; Azmy *et al*., 1998; Samtleben *et al*., 2000).

A record high value of 4.6‰ is known from the Ohesaare core, Estonia (Kaljo *et al*., 1997). The youngest among the three excursions is the most prominent one, even in terms of the entire Phanerozoic. It is recognized by δ^{13}C values of over 10‰ in the upper Ludlow (Ludfordian) of Baltica, Laurentia, Perunica and Australia, giving evidence of the truly global dimension of this stable isotope event. The same evaluation is also acceptable for the first two excursions.

These excursions are stratigraphically related to the following consecutive oceanic events: the early Wenlock Ireviken Event, the late Wenlock Mulde Event and the late Ludlow Lau Event, proposed by Jeppsson (1993, 1998) and by Jeppsson and Aldridge (2000) based on a variety of environmental signals and conodont biodiversity changes. Each event involves interesting problems (Kaljo *et al*., 1997, 1998, 2003; Munnecke *et al*., 2003; Porębska *et al*., 2004) deserving special study, but here we concentrate on the Lau Event, which coincides with an extraordinarily strong positive carbon isotope excursion (in Australia the δ^{13}C values reach 12‰, Andrew *et al*., 1994). Marked biodiversity changes in several groups of biota (corals, graptolites, vertebrates, conodonts, acritarchs; Kaljo *et al*., 1995) have been registered in approximately the same interval of the Ludfordian, making the event highly intriguing.

We also discuss the earlier, Wenlock excursions in order to better understand the relationships between the environmental dynamics and accompanying changes in carbon cycling, as well as its global and local aspects. We assume that the reasons for both the isotopic and biotic changes can be established through a detailed study of the relationships between these phenomena and their bio- and lithofacies background. This paper was written to contribute to this aim. T. M. was responsible for isotope studies, A. B. for conodont palaeontology, D. K. (Tallinn) for stratigraphy and facies interpretation, D. K. (Vilnius) for geochemistry and lithology, P. M. for brachiopod community evolution.

PREVIOUS STUDIES ON THE LATE LUDLOW δ^{13}C EXCURSION

Jux and Steuber (1992) first noted the Ludfordian positive stable isotope shift in the Burgsvik, Hamra and Sundre beds of Gotland (Fig. 1), with a $\delta^{13}C_{carb}$ peak of 5.7‰ (mean of 6 bulk rock samples) in the Hamra Beds and $\delta^{13}C_{org}$ peak in the Burgsvik Beds. The authors did not have samples from the underlying Eke Beds. Based on analyses of brachiopod shells, Wenzel and Joachimski (1996) showed a more complete curve of the same $\delta^{13}C_{carb}$ excursion beginning in the Lower Eke Beds (mean value 6.9‰), reaching peak values (8.1‰) in the Upper Eke Beds and continuing through the Burgsvik (6.8‰) and Hamra (3.7‰) beds. The authors of both papers highlighted a correlation between the global sea level curve and changes in the distribution of carbon isotopes: the high δ^{13}C values, generally confined to sea level low-stand episodes, were regarded as indications of enhanced primary productivity and possibly increased burial of C_{org} in Silurian seas.

In studying the Ludfordian excursion on Gotland (with a gap corresponding to the Burgsvik Beds), Samtleben *et al*. (1996) and Bickert *et al*. (1997) obtained the same range of values as above. New data from the Burgsvik Sandstone (values up to 7.7‰) by Samtleben *et al*. (2000) produced a continuous profile of the excursion. Their interpretation of the C isotope trend was based on the interpretation that climatic changes controlled the facies distribution (Primo and Secundo episodes of Jeppsson, 1990, corresponding to the Humid and Arid states of

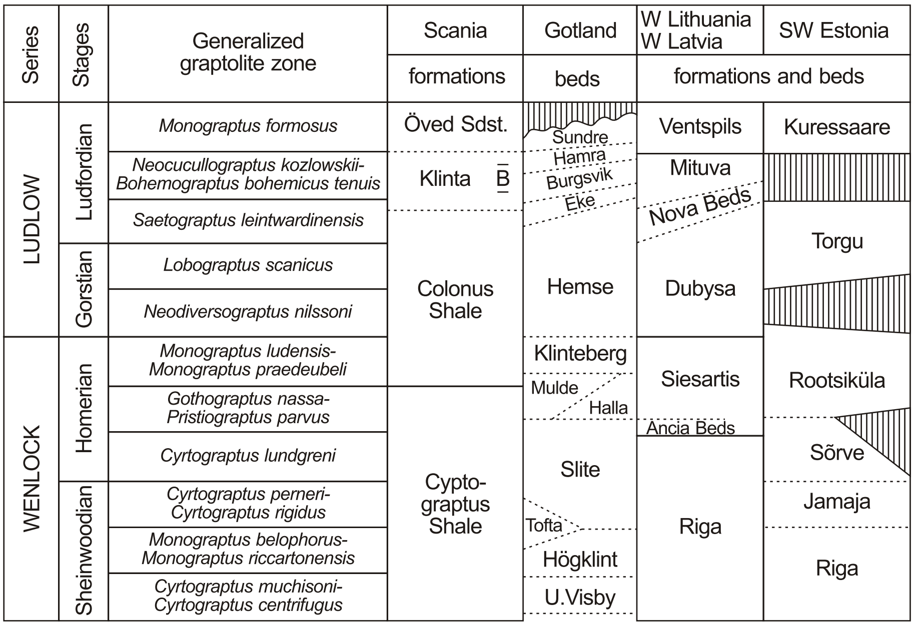

Fig. 1. Stratigraphical classification and terminology employed in the paper (sources: standard units — Kaljo *et al*., 1995; Scandinavia — Bassett *et al*., 1989; Baltic area — Paškevičius *et al*., 1994; Kaljo *et al*., 1997)

B — Bjärsjölagård Member

the latter authors) with less emphasis on sea level changes. High $\delta^{13}C$ values were linked with arid climate conditions with reef growth, evaporation, onshore-directed anti-estuarine circulation of surface ocean waters and anoxic deep ocean (Bickert *et al*., 1997).

Azmy *et al*. (1998, table DR1) also reported several $\delta^{13}C$ values from Gotland, including identifications from the Eke (4.9–5.4‰) and Hamra (4.7–7.4‰) beds, correlated respectively with the *Bohemograptus bohemicus tenuis* and *Neocucullograptus kozlowskii* graptolite biozones. The authors note correlation of the shift with a sea level lowstand, but the role of enhanced primary production on the burial of C_{org} was considered unclear.

In the East Baltic the Ludfordian $\delta^{13}C$ excursion has been established (Kaljo *et al*., 1997, 1998) in three core sections from Latvia (Fig. 1). In the Priekule core the peak values reach 5.9‰ in the Nova Beds of the Dubysa Formation (further abbreviated Fm.), in the Pavilosta core (4.2‰) in the lower part, and in the Ventspils core (5.0‰) in the top, of the Mituva Fm. In the Ohesaare core the peak level is represented by a gap. The shift was correlated with the early and mid-Ludfordian sea level lowstand and the following sea level rise, with two bioevents (serious extinctions in several groups of biota, Kaljo *et al*., 1995) and with the Lau Event of Jeppsson (1993).

Data from the Bol'shezemel'skaya Tundra section in the Timan–Pechora region (Russia) on the NE shelves of Baltica show much lower $\delta^{13}C$ values in the Ludfordian than usual at this level in the Baltic gulf area. Modzalevskaya and Wenzel (1999) note that the peak values in the Tselebej Fm. (correlated with the lower part of the middle Ludfordian *Collarothyris canaliculata* Brachiopod Zone) reach only 1.5‰, but the total rise from the bottom of the curve in the underlying Sizim Fm. (= *Didymothyris didyma* Zone) is over 4‰. Such low values might have been caused by diagenetic factors, but the original carbon isotope trend is still preserved. According to these authors the oxygen isotope content was even less (!) influenced by diagenesis and therefore the low $\delta^{13}C$ values are most likely related to specific regional oceanographic and climatic conditions differing from those in the Baltic area.

In Scania the Ludfordian carbon isotope shift reaches extremely high $\delta^{13}C$ values (11.2‰, Wigforss-Lange, 1999), in the oncoid limestones of the Bjärsjölagård Member (Klinta Fm., Öved — Ramsåsa Group). Wigforss-Lange stressed that such high $\delta^{13}C$ values cannot be explained only by enhanced primary production and/or by burial of organic carbon. These seem to be the main reasons for values up to 5‰, but values above 6‰ contain a fraction generated by the photosynthesizing activity of cyanobacteria and algae related to the abundance of oncoids in the Bjärsjölagård Member.

Very high $\delta^{13}C$ levels were documented also by Andrew *et al*. (1994) in the upper Ludlow Jack Limestone in Australia. The actual values are not given in the text, but peak values measured from figure 3 of Andrew *et al*. (1994) were 12–13‰. The shift is located in the MBC section (Broken Hill, Queensland) just above the Pentamerid (or End-*siluricus*) Event and 40 m above the only known occurrence of *Polygnathoides siluricus*. Andrew *et al*. (*op. cit*.) emphasized causal ties between biotic and isotope events.

In North America the $\delta^{13}C$ values of the Ludfordian excursion are slightly lower than 4‰ (Saltzman, 2001). In the Highway 77 section cut in the Arbuckle Mountains of Oklahoma the excursion peak (3.6‰) is located just above the *P. siluricus* conodont Biozone in the lowermost Henryhouse Fm. In the Pete Hanson Creek II section (Robert Mountains, central Nevada) the exact dating of the peak (3.8‰) in the Robert Mountains Fm. is more problematic. According to figure 3 of Saltzman (2001) the shift occurs at the top of the range of the conodont *Kockelella variabilis* and within that of *Saetograptus chimaera*. If the latter species has been identified correctly, this indicates a level below the bottom of the Ludfordian Stage, i.e. clearly an older event than the $\delta^{13}C$ shift in the Highway 77 section. Judging from the Baltoscandian experience, this seems unlikely and the dating should be checked before any conclusions are drawn. In discussing the excursion, Saltzman (2001) noted a connection with the Pentamerid or End-*siluricus* Bioevent and similarities with the early Wenlock Ireviken Event accompanied by a lowering of sea level.

Recently, Lehnert *et al*. (2003) reported the first record of the Ludfordian excursion in connection with the Lau Event from the peri-Gondwana area (Perunica). The excursion (max. $\delta^{13}C$ whole-rock values of 4.6‰) is well dated by conodonts and brachiopods in the Muslovka section near Prague: the excursion started 3 m above the last occurrence of *Polygnathoides siluricus* and ended 1 m below the first occurrence of *Ozarkodina snajdri*. The peak level occurs just above a sharp sea level fall and above several faunal extinction events recorded in the section. In terms of graptolite biozonation, the beginning of the excursion was placed into the upper part of the *Neocucullograptus kozlowskii* Biozone, but the sharp shift with the highest values continues into the next *Monograptus latilobus* Biozone (fig. 2 in Lehnert *et al*., 2003). This date is slightly younger than that discussed below.

MATERIAL AND METHODS

The isotope analyses on the Vidukle core were performed at the Palaeoclimatological Laboratory of the Institute of Geology at the Tallinn University of Technology. A total of 115 samples were analysed from a 324 m long section and the isotope data obtained are shown in Table 1. The mean sampling interval was 2.8 m, though around 1 m close to event levels. Whole-rock samples were crushed, the material was powdered and treated with 100% phosphoric acid at 100°C for 15 min and analysed with a *Finnigan MAT Delta-E* mass spectrometer. The results are given in the usual δ-notation, as per mil deviation from the VPDB standard. Reproducibility of replicate analyses was generally better than 0.1‰.

The main advantage of the whole-rock method is that sampling could be performed at regular intervals not depending on the occurrence of bioclasts. Previous studies (Kaljo *et al*., 1997; Heath *et al*., 1998; Brenchley *et al*., 2003) show little diagenetic alteration of Baltic early Palaeozoic rocks, indicating that good results of carbon isotope analysis of bulk rock samples may be expected from the Vidukle core. According to the conodont colour alteration index (CAI 1-1.5), the Wenlock and Ludlow rocks in the core were heated to less than 100°C, suggesting that temperature has had only a limited influence on diagenesis.

Table 1

Carbon and oxygen isotope data from the Vidukle core

Depth [m]	Stratigraphy	δ^{13}C [‰]	δ^{18}O [‰]
1	2	3	4
1080.0	Minija Fm., Pridoli	0.06	–5.74
1086.5	Minija Fm., Pridoli	0.10	–5.93
1092.7	Minija Fm., Pridoli	–0.02	–4.76
1098.4	Ventspils Fm.	1.04	–6.72
1102.0	Ventspils Fm.	1.42	–5.66
1106.4	Ventspils Fm.	1.56	–4.90
1110.7	Ventspils Fm.	–0.37	–5.89
1115.0	Ventspils Fm.	–0.85	–6.24
1115.5	Mituva Fm.	0.04	–5.83
1116.2	Mituva Fm.	1.24	–4.88
1120.0	Mituva Fm.	2.21	–2.93
1125.0	Mituva Fm.	3.38	–5.57
1130.5	Mituva Fm.	4.43	–5.92
1133.0	Mituva Fm.	4.43	–6.11
1137.2	Mituva Fm.	6.41	–4.77
1138.5	Mituva Fm.	5.31	–5.05
1140.5	Mituva Fm.	7.11	–5.21
1142.5	Mituva Fm.	7.37	–5.27
1145.2	Mituva Fm.	6.36	–4.85
1146.5	Mituva Fm.	7.60	–4.66
1147.5	Mituva Fm.	8.17	–4.68
1148.9	Mituva Fm.	4.63	–4.88
1150.0	Mituva Fm.	4.56	–4.66
1152.5	Mituva Fm.	4.42	–4.35
1155.5	Mituva Fm.	3.40	–4.52
1157.5	Mituva Fm.	2.92	–4.46
1159.0	Mituva Fm.	1.87	–4.63
1164.0	Mituva Fm.	0.80	–5.00
1166.6	Mituva Fm.	0.77	–4.87
1169.8	Dubysa Fm.	–0.53	–4.66
1174.8	Dubysa Fm.	–1.39	–4.46
1178.5	Dubysa Fm.	–1.54	–4.55
1181.6	Dubysa Fm.	–0.88	–4.81
1184.5	Dubysa Fm.	0.40	–5.29
1187.0	Dubysa Fm.	0.32	–5.29
1192.5	Dubysa Fm.	0.71	–5.09
1197.2	Dubysa Fm.	0.74	–5.38
1200.1	Dubysa Fm.	0.21	–5.58
1202.5	Dubysa Fm.	0.01	–6.10
1207.1	Dubysa Fm.	0.17	–4.97
1211.7	Dubysa Fm.	0.48	–4.95
1216.3	Dubysa Fm.	0.11	–5.12
1221.7	Dubysa Fm.	–0.03	–4.80
1227.8	Dubysa Fm.	–0.32	–4.70
1232.8	Dubysa Fm.	0.01	–5.61
1235.4	Dubysa Fm.	–0.19	–4.63
1238.0	Dubysa Fm.	0.01	–4.79
1240.2	Dubysa Fm.	–0.55	–4.16
1243.3	Dubysa Fm.	–1.20	–3.67
1248.0	Dubysa Fm.	–0.26	–4.87
1252.9	Dubysa Fm.	–0.21	–5.26
1255.0	Dubysa Fm.	–0.70	–4.22
1258.2	Dubysa Fm.	0.49	–4.21
1259.8	Dubysa Fm.	–1.14	–4.92
1260.0	Dubysa Fm.	–1.79	–4.78
1261.0	Dubysa Fm.	–0.17	–5.13
1262.8	Dubysa Fm.	–0.12	–4.71
1267.9	Dubysa Fm.	–0.32	–5.56
1272.9	Dubysa Fm.	–0.12	–4.93
1278.3	Dubysa Fm.	–0.05	–5.32
1280.5	Dubysa Fm.	0.38	–5.37
1281.4	Dubysa Fm.	1.42	–4.91
1281.6	Dubysa Fm.	1.47	–5.23
1283.0	Siesartis Fm.	0.57	–5.16
1284.4	Siesartis Fm.	1.56	–4.94
1286.1	Siesartis Fm.	1.31	–4.65
1287.3	Siesartis Fm.	0.76	–3.27
1289.8	Siesartis Fm.	0.53	–3.38
1291.0	Siesartis Fm.	0.77	–3.92
1292.2	Siesartis Fm.	0.14	–4.08
1293.6	Siesartis Fm.	0.75	–3.86
1295.0	Siesartis Fm.	1.16	–4.08
1296.5	Siesartis Fm.	1.25	–4.16
1297.9	Siesartis Fm.	1.01	–5.56
1298.8	Siesartis Fm.	1.23	–5.30
1299.5	Siesartis Fm.	1.31	–4.34
1301.9	Siesartis Fm.	0.75	–3.46
1304.1	Siesartis Fm.	0.61	–3.54
1305.0	Siesartis Fm.	0.69	–3.91
1306.8	Siesartis Fm.	0.15	–3.44
1307.6	Siesartis Fm.	0.16	–3.39
1307.9	Siesartis Fm.	–0.17	–3.29
1309.0	Riga Fm.	0.48	–4.29
1310.0	Riga Fm.	–0.09	–3.11
1311.2	Riga Fm.	–0.01	–3.69
1311.8	Riga Fm.	–0.02	–3.69
1313.3	Riga Fm.	0.10	–5.60
1315.3	Riga Fm.	–0.03	–4.19
1317.3	Riga Fm.	–0.40	–5.30
1319.3	Riga Fm.	–0.25	–5.63
1321.3	Riga Fm.	–0.34	–5.29
1323.3	Riga Fm.	–0.60	–5.60
1325.3	Riga Fm.	–0.36	–5.33
1327.3	Riga Fm.	–0.50	–5.81
1329.3	Riga Fm.	–0.23	–5.74
1332.6	Riga Fm.	0.52	–4.27
1335.3	Riga Fm.	–1.05	–4.91
1339.3	Riga Fm.	–1.14	–5.97
1343.3	Riga Fm.	–0.54	–5.22
1347.5	Riga Fm.	–0.62	–5.08
1351.5	Riga Fm.	–0.76	–5.23
1355.5	Riga Fm.	–0.77	–4.76
1359.3	Riga Fm.	–0.72	–5.80
1363.3	Riga Fm.	–0.32	–5.20
1367.3	Riga Fm.	–0.20	–5.42
1371.3	Riga Fm.	–0.20	–5.19
1375.3	Riga Fm.	1.59	–4.72
1379.3	Riga Fm.	2.13	–4.72
1383.3	Riga Fm.	2.67	–4.55
1387.5	Riga Fm.	3.16	–5.04
1391.5	Riga Fm.	2.62	–5.15
1395.5	Riga Fm.	2.05	–5.63
1399.5	Riga Fm.	0.80	–5.78
1401.5	Riga Fm.	0.67	–5.77
1403.5	Rasyte Fm., Lland.	0.94	–5.66

The reliability of isotope signals in the Ordovician and Silurian rocks of Estonia and elsewhere in Baltoscandia has been discussed in several papers (Samtleben *et al*., 1996; Brenchley *et al*., 2003). The main conclusion is that isotope values measured from the early Palaeozoic rock samples reflect the primary isotopic composition of sea water. Another question is how reliable whole-rock isotope data are, of the Baltic rocks in particular. Comparison of the Baltic Ordovician and Silurian whole-rock data with brachiopod shell isotope data shows slight differences in $\delta^{13}C$ values, but a great similarity of curves produced by both approaches (Samtleben *et al*., 1996; Marshall *et al*., 1997; Heath *et al*., 1998; Brenchley *et al*., 2003). The oxygen isotope ratios are more sensitive to diagenesis (Marshall, 1992) and therefore data from whole-rock analysis may not be trustworthy. Another difficulty arises from the fact that Baltic carbonate rocks are mostly highly variable mixtures of calcite and dolomite, which have clearly different oxygen isotope fractionation factors. Considering these aspects, we do not discuss the oxygen analytical data presented in Table 1.

Data on the content of CaO and MgO in the Ludlow rocks of the Vidukle core, presented in Table 2, were supplied by the chemical laboratory of the Geological Survey of Lithuania according to a VSEGEI standard method of *s.c.* "wet chemical analysis". Terrigenous component, calcite and dolomite were calculated from the data using the formulas and methodology described by Kaljo *et al*. (1997, p. 213).

GEOLOGICAL SETTING

EAST BALTIC STRATIGRAPHY AND CORRELATION WITH OTHER AREAS

The Baltic Silurian stratigraphy, and that of Lithuania in particular, is summarized in several papers (Bassett *et al*., 1989; Paškevičius *et al*., 1994; Nestor, 1997; Paškevičius, 1997). For that reason, we restrict this introduction to a brief account of the most important background information. The stratigraphical framework for our study is given in Figure 1, where the corresponding local terminology and units (regional stages and formations) are correlated with the Wenlock and Ludlow part of the standard classification of the Silurian System. Most of the discussion below concerns East Baltic sequences, but Scandinavian and Polish materials are also involved. Therefore the correlation chart comprises partly also the latter areas, while other data are linked to ours through standard stratigraphical terminology. The correlation of the units in Figure 1 is based mainly on the publications mentioned above and additionally on Jeppsson *et al*. (1994), Kaljo *et al*. (1997) and Viira (1999). Only a few refinements were made in this study. The reasons for these changes are dealt with in detail in the discussion section below.

The East Baltic stratigraphical nomenclature makes use of three categories of units: bio-, litho- and chronostratigraphical units, but in the regional part of Figure 1 only lithostratigraphical formations and a few "beds" are shown. To save space, the regional stages were left out and the necessary graptolite and conodont data are included in the description of the Vidukle section. The lithostratigraphic formations, members and beds, which make up the East Baltic regional stages in different parts of the basin, are often diachronous and therefore their boundaries need not coincide with those of the chronostratigraphical units. Several cases of the diachrony playing an essential role in our topic are shown in Figure 1.

Table 2

Geochemical data from the Ludlow rocks of the Vidukle core

Depth [m]	CaO [%]	MgO [%]	CaO/ MgO	Calcite [%]	Dolomite [%]	Terrigenous component [%]
1097.0	53.3	1.0	53	92.9	4.3	2.9
1098.1	54.8	0.8	69	95.9	3.6	0.5
1102.6	50.0	2.4	21	83.7	10.3	6.0
1108.5	49.4	2.0	25	83.6	8.3	8.1
1112.9	21.0	6.9	3	23.4	25.9	50.7
1116.3	46.1	4.1	11	72.6	17.9	9.5
1119.5	20.8	13.3	2	6.2	56.9	36.9
1120.9	52.0	1.2	43	90.1	5.0	4.9
1125.1	54.1	0.5	108	95.5	2.0	2.5
1133.4	53.8	0.9	59	93.9	3.9	2.1
1138.4	28.0	7.7	4	32.9	31.4	35.7
1142.9	50.8	1.9	26	86.3	8.2	5.5
1146.8	51.0	1.8	28	86.9	7.7	5.3
1149.7	24.2	10.8	2	18.5	45.6	35.9
1151.7	47.8	2.7	18	79.2	11.5	9.4
1155.4	45.1	3.6	13	72.5	14.8	12.7
1157.4	28.0	6.9	4	35.1	27.3	37.6
1165.7	44.7	1.1	40	78.2	3.1	18.7
1166.7	47.9	1.3	36	83.1	4.7	12.2
1171.4	16.9	8.3	2	12.8	31.8	55.4
1174.9	39.8	4.0	10	62.6	15.7	21.8
1186.2	8.9	6.0	1	5.5	19.3	75.2
1191.6	49.4	1.7	29	84.5	6.9	8.6
1195.1	17.8	5.3	3	22.2	17.6	60.2
1199.5	42.0	2.0	21	71.4	6.6	21.9
1203.0	4.6	4.8	1	1.3	12.6	86.1
1208.2	7.9	4.9	2	6.8	13.6	79.7
1215.7	12.6	6.0	2	11.6	19.9	68.4
1218.0	48.5	1.8	27	82.6	7.2	10.2
1224.2	14.8	6.2	2	14.9	21.4	63.7
1235.5	39.4	3.3	12	63.4	12.6	23.9
1241.0	16.4	7.2	2	14.9	26.4	58.7
1245.2	12.3	8.7	1	4.0	33.1	62.9
1251.4	5.9	5.1	1	2.7	14.5	82.8
1251.8	35.3	2.3	15	59.2	7.0	33.8
1257.4	42.9	2.9	15	70.5	11.5	18.1
1257.8	9.5	5.5	2	7.8	17.0	75.2
1269.1	8.4	5.2	2	6.6	15.3	78.1
1274.3	8.7	4.2	2	9.9	10.3	79.8
1275.3	38.1	2.2	17	64.1	7.1	28.8

GENERAL FACIES ZONATION IN THE BALTIC AREA WITH SOME DETAILS FOR LITHUANIA

The Vidukle core is located in the southern area of the Baltic Gulf (Fig. 2), lying as a part of the Baltoscandian palaeobasin on the western pericratonic margins of the Baltica palaeocontinent.

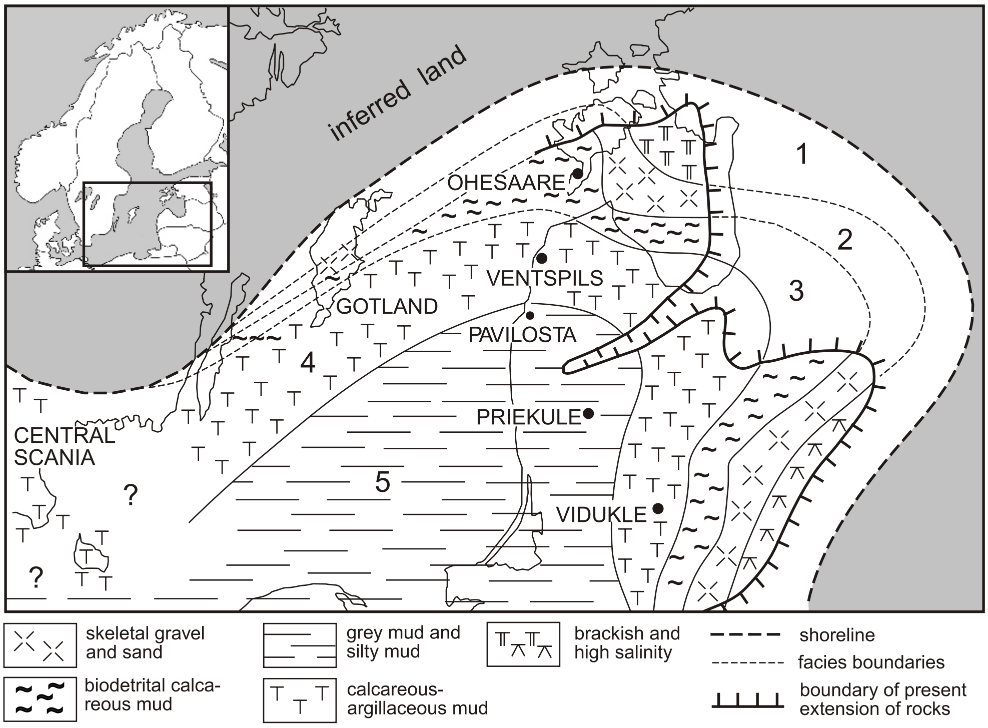

Fig. 2. Location of the study area and core sections, and general facies zonation of the Baltic Gulf during early Ludlow *nilssoni* time (modified from Bassett *et al*., 1989)

Facies belts: 1 — tidal flat/lagoon, 2 — shoal, 3 — open shelf, 4 — transition from open to deeper shelf, 5 — shelf depression

By the beginning of the Wenlock epoch the continent, drifting from middle latitudes of the Southern Hemisphere, reached the equatorial belt (Cocks and Torsvik, 2002). This means that the local climate became tropically warm, and towards the Devonian some signs of increasing aridity and evaporation have been observed (e.g. gypsum inclusions in lower Ludlow rocks distributed in Central and East Lithuania, Paškevičius, 1997; see facies belt 1 in Fig. 2 here). The general facies pattern for an early Ludlow time-slice (Fig. 2, composed according to the facies model by Nestor and Einasto, 1997) more or less applies also to the Wenlock and especially to later times through the Ludlow. Here, some differences should be mentioned (seen in Fig. 3), demonstrating basin development in terms of the evolution and distribution of brachiopod communities.

The earliest Wenlock was a time (after a short shallowing event) when sea level was in general high and was characterized by a wide distribution of graptolite-bearing and other deep shelf deposits, partly even in the central epicratonic areas of Baltica. But this highstand interval was changing in time and displayed some regional variability. For example, a mid-shelf limestone-marl alteration with reef mounds of the Upper Visby Beds on Gotland shows an upwards increase of a carbonate content, but in the East Baltic the maximum distribution of graptolitic rocks was confined to the early *riccartonensis* time (Bassett *et al*., 1989). Slow, but steady regression of the Palaeobaltic Sea, even if interrupted by brief transgressive episodes, began in late *riccartonensis* time, marked by magnificent reef/bioherm structures of the Högklint (Gotland) and Ninase (= upper Riga in Fig. 1; Saaremaa Island, Estonia) formations. By the end of the Ludlow the regression had caused considerable restriction of the basin and movement of the shallow shelf and ramp facies belts, together with brachiopod communities (Fig. 3), to the south-west (Bassett *et al*., 1989; Nestor and Einasto, 1997; Paškevičius, 1997).

Facies changes are apparent in the relationships between communities, benthic assemblages and facies belts (Musteikis and Paškevičius, 1999). The shallowest-water brachiopod community listed in Figure 3 is that of *Sphaerirhynchia wilsoni*, belonging to both BA 2 and 3 occurring usually in the shallowest part of the open shelf facies belt (3 in Fig. 2). All communities listed in BA 3 and the *Dayia-Isorthis* community from BA 3–4 occur in the deeper part of the open shelf belt. The remaining communities belonging to BA 3–4, 4 and 4–5 are distributed in the transition facies belt (4 in Fig. 2) along the deepening gradient towards the shelf depression (5 in Fig. 2) occupied by a pelagic community with or without rare benthic fossils of a more or less level sea floor.

The general trend of sea level is barely expressed through the Wenlock in the Vidukle area in the deep facies belt. Even the Homerian sea level falls well documented on Gotland and Saaremaa (Nestor, 1997; Calner and Jeppsson, 2003) cannot be traced there. In the Ludlow the sedimentary environment around the drilling site is progressively more changeable (Figs. 3 and 4) and shallower with a more variable bottom topography.

The Vidukle core (Fig. 4) comprises a series of terrigenous-carbonate rocks, showing upsection continuous shallowing of the sea with a few deepening episodes in the Ludlow. The Riga Fm. is represented by rather deep-water dark grey to black argillites and clayey marlstones with abundant graptolites. In the middle part rare *Jonesea grayi*, and in the upper part several occurrences of *Plagiorhyncha depressa*, have been reported. Higher lies the Siesartis Fm. consisting of graptolitic argillaceous marlstones with thin limestone interbeds. At the very top, rare *P. depressa* have been found. The Ludlow begins with the Dubysa Fm. subdivided into two parts (Fig. 4). The Šešupe Beds are more argillaceous, containing marls with interbeds of nodular limestones rich in graptolites and shelly fauna (mainly the *Jonesea grayi* community) and are more calcareous, especially at the top; the Nova Beds consist of alternating nodular limestones and marly intercalations. Pelagic and shelly faunas alternate, the latter prevailing. From the bottom upwards the following succession of brachiopod communities is observed: *Lissatrypa obovata* (BA 4) at 1215 m, *Dayia* (BA 4) at 1204–1212 m, *Dayia-Isorthis* (BA 3–4) several times

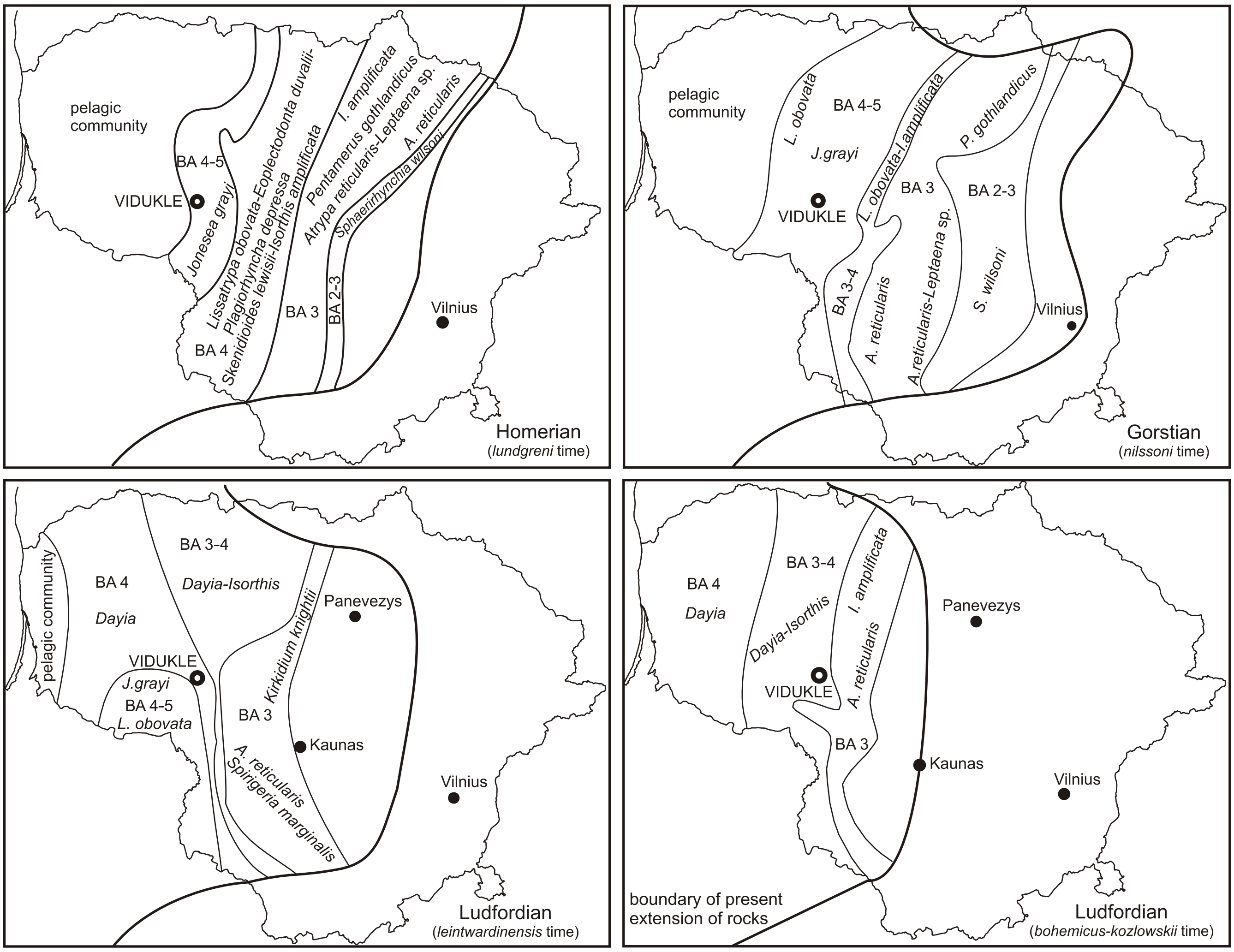

Fig. 3. Distribution of benthic assemblages (BA) in Lithuania through the late Wenlock to the late Ludlow

In the belts marked by BA indices brachiopod taxa representing certain communities are shown; the easternmost belts without community names are represented by dolomites, where no brachiopods have been identified; the figure is based on a series of community distribution maps compiled by P. Musteikis

between 1281 and 1287 m and *Protochonetes piltenesis* from the Atrypoidea community (BA 2) at the very top.

The upper Ludlow Ludfordian Stage comprises two formations. The lower, Mituva Fm. is represented by nodular and laminated limestones with marl intercalations; in the upper part, skeletal limestones with oncolite intercalations prevail. A succession of brachiopod communities, clearly expressing the shallowing tendency of the basin, is recognized: *Alaskospira ludloviensis* (BA 1–2) at the lower boundary, *Dayia-Isorthis* (BA 3–4) at 1158–1162 m, alternating *Isorthis ovalis*, *Atrypa reticularis*, *Protochonetes piltenensis* and *Microsphaeridiorhynchus nucula* (BA 2–3) between 1140 and 1157 m. Higher, especially at 1120–1135 m, members of the Atrypoidea community (BA 2) dominate. The *Herrmannina* community occurs at the upper boundary, together with Atrypoidea continuing also into the overlying Ventspils Fm. The Ventspils Fm. consists mainly of clayey laminated limestones with silty marls. Its upper part marks a short-lived drowning event (occurrence of BA 3 brachiopods *Isorthis ovalis* and *Atrypa reticularis*). The lower Pridoli Minija Fm. (above 1093 m) is represented by nodular limestones with thick marl interbeds. The upper Ventspils Fm. and the Minija Fm. mark the beginning of a specific infilling stage of sedimentation of the Palaeobaltic basin, highlighted by a marked increase in the influx of terrigenous material into the sea (Nestor and Einasto, 1997).

CARBON ISOTOPE TREND AND DATING OF THE EXCURSIONS

The carbon isotope trend shows the following main excursions:

1. A major carbon isotope excursion (δ^{13}C values reach 3.2‰ at 1387.5 m) occurs in the lower Wenlock; higher, the values remain below or close to 0‰.

2. In the uppermost Wenlock Siesartis Fm. slightly greater values were recorded at two levels: 1.3‰ at 1299.5 m and 1.6‰ at 1284.4 m. Graptolites found (Paškevičius *et al.*, 1994) in this bed date these weak shifts to the *Monograptus ludensis* Biozone.

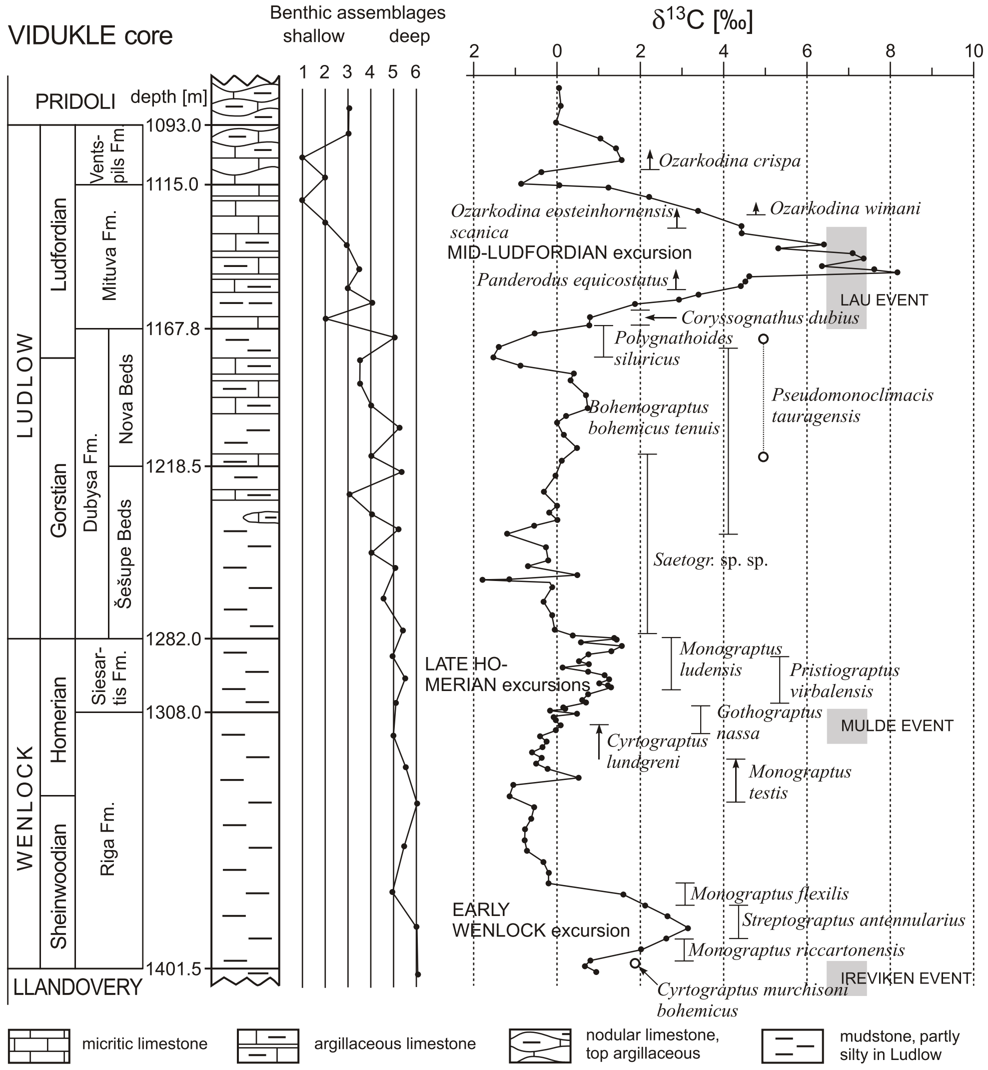

Fig. 4. The Vidukle core section: stratigraphy, lithology, sea level changes interpreted as benthic assemblages (BA) succession and the δ^{13}C trend dated by graptolite (Paškevičius *et al.*, 1994) and conodont biostratigraphy

Location of oceanic events after Jeppsson (1998); arrows — the first or last occurrences, intervals — the full ranges, open circles — single occurrences of taxa

3. The lower Ludlow Dubysa Formation shows also low values (0 to 0.7‰) with a negative shift reaching –1.5‰ at the top. The shift is dated by the last occurrence of *Bohemograptus bohemicus tenuis* and by the appearance of *Polygnathoides siluricus* (Fig. 4).

4. In the upper Ludlow Mituva Fm. the carbon isotope trend changes completely, values of the positive δ^{13}C excursion reach 8.2‰ (at 1147 m) and commencing from 1178 m, the entire shift reaches 9.7‰. The excursion occupies the entire formation (Fig. 4). A negative shift (–0.9‰ at 1115 m), similar to that at the start of the excursion, occurs at the boundary with the overlying Ventspils Fm. The beginning of the excursion is dated by the last occurrences of *Polygnathoides siluricus* (depth 1167 m) just below the main shift and together with the first appearances of *Coryssognathus dubius*. The latter forms a narrow but distinct biozone at the very beginning of the positive shift. The highest peak of the excursion coincides exactly with the *Panderodus equicostatus* Biozone (1152.5–1133.0 m), which is also known from the upper part of the Lau Event on Gotland (Jeppsson, 1998). The first appearances of *Ozarkodina eosteinhornensis scanica* and *O. ambiqua* at 1130.5 m and *O. wimani* at 1126.7 m date the upper falling limb of the excursion. The true *O. crispa* appears above the upper negative shift at 1107.5 m in the lowermost Ventspils Fm. The conodont occurrences allow us to date the excursion as of middle Ludfordian age.

5. In the uppermost Ludlow the carbon isotope values returned to about 1‰.

DISCUSSION

STRATIGRAPHIC DATING OF THE MAIN SHIFTS

The early Wenlock excursion is well dated by graptolite occurrences (Kaljo *et al.*, 1997), and so the correlation of the peak level with the *Monograptus riccartonensis* Biozone is commonly accepted (Azmy *et al*., 1998; Saltzman, 2001). The excursion, however, is broad and in some sections (Kaljo *et al*., 2003; Munnecke *et al*., 2003) its slowly rising limb begins in the topmost Llandovery; in the Vidukle core (Fig. 4) it continues above the *riccartonensis* Biozone (*sensu stricto*). The falling limb reaches the *M. flexilis* Biozone. The data from the Vidukle core show clearly that the Ireviken oceanic Event as defined by Jeppsson (1998) occurs below the peak of the early Wenlock δ^{13}C excursion.

The same relationships are obvious also in the case of the Mulde Event (Jeppsson, 1998; Calner and Jeppsson, 2003) and the mid-Homerian δ^{13}C excursion. New data from the Vidukle core allow us to correct an earlier dating of that excursion suggested by Kaljo *et al*. (1997). The graptolites (Fig. 4) reported by Paškevičius *et al*. (1994) prove the occurrence of the double shift in the Vidukle core to lie within the *Monograptus ludensis* Biozone. This dating is in accord with the data by Saltzman (2001) from North America. The situation in the Vidukle core seems very clear and the dating is well-constrained, but we are not fully convinced that all these weak shifts observed in the Ohesaare, Priekule and Vidukle cores are situated at the same level of the *ludensis* Biozone. A recent paper by Porębska *et al*. (2004) reported about two very weak shifts in the *dubius* and *praedeubeli* zones and this suggests such a possibility also exists in the East Baltic area.

The relationships between the mid-Ludfordian δ^{13}C excursion and the Lau Event seem not to be constant. Above, we showed their nearly full coincidence (Fig. 4), but there exists some discrepancy in the dating of the excursion. Graptolites are very rare in the Ludfordian of the Baltic–Scandinavian Region, except for in Poland, which belongs to the East European Platform (Urbanek and Teller, 1997). On the basis of a few graptolite occurrences and/or on conodont distributions most authors have correlated this excursion and event with the *Neocucullograptus kozlowskii-Bohemograptus bohemicus tenuis* (Fig. 1) graptolite Biozone or a part of it (Kaljo *et al*., 1997, 1998; Azmy *et al*., 1998; Jeppsson and Aldridge, 2000). Several other authors have placed the excursion at the more or less same level — into the post-Leintwardinian Ludfordian or upper Ludlow (Wenzel and Joachimski, 1996; Bickert *et al*., 1997; Wigforss-Lange, 1999). Only Lehnert *et al*. (2003) suggested a slightly higher position, with the peak values in the lower part of the *Monograptus latilobus* Biozone. In the Mušlovka section an erosional surface occurs just below the main δ^{13}C shift in top of a dark micritic limestone bed. The bed and the surface were interpreted as an indication of a marked sea level fall and the *latilobus/kozlowskii* zonal boundary was placed at that level. The erosional event makes the actual starting point of the excursion questionable, but more importantly the lower boundary of the *latilobus* Biozone is by no means proven because of the lack of graptolite occurrences. We think that also in Mušlovka the mid-Ludfordian shift marks the *kozlowskii* Biozone.

The distribution of conodonts also allows a different correlation and therefore the dating problem deserves further attention. Paškevičius (1997) correlated the Mituva Fm. and the local *Monograptus balticus* Biozone with the *kozlowskii-bohemicus tenuis* Zone (Fig. 1). This is a possibility, but the position expressed by Urbanek and Teller (1997) based on Polish core sections with a rich graptolite assemblage seems more firmly grounded. Their data show that *Pseudomonoclimacis latilobus* and *Monograptus (Slovinograptus) balticus* occur together above the *Neocucullograptus kozlowskii* Biozone, and the boundary between these zones marks an important change in graptolite faunas.

An additional aspect linked to this dating problem is the correlation of the Eke, Burgsvik and Hamra beds of Gotland with the Mituva Fm. of Lithuania and with some part of the Klinta Fm. of Scania and, on the whole, with the *kozlowskii-bohemicus tenuis* Zone. Based on the location of the carbon isotope excursion, this correlation seems secure, while only the Sundre Beds and perhaps the upper part of the Hamra Beds could be placed into the higher *latilobus/balticus* Zone.

RELATIONSHIPS OF THE δ^{13}C EXCURSIONS WITH SEDIMENTARY CHANGES

Changes in the sedimentary environment in West Lithuania are in general terms reflected in Figure 4 by the lithological log of the Vidukle core and succession of the benthic assemblages in the section and in the area (Fig. 3). Some additional characteristics could be added in part of the Ludlow rocks based on geochemical data presented in Table 2 and in form of trend lines for calcite, dolomite and terrigenous component plotted against the δ^{13}C excursion in Figure 5.

The Wenlock part of the sequence represented by predominantly highly argillaceous rocks (mudstones, marlstones) with pelagic fossil assemblages (graptolites, a few benthic brachiopods in more carbonaceous intercalations), exhibits a rather stable environmental situation. The Vidukle core represents deposition on the deep shelf where striking facies changes (e.g. appearance of skeletal limestones with organic buildups) observed in the shallower shelf areas (Gotland and Saaremaa islands) did not play any essential role. Still the facies pattern of the basin or a

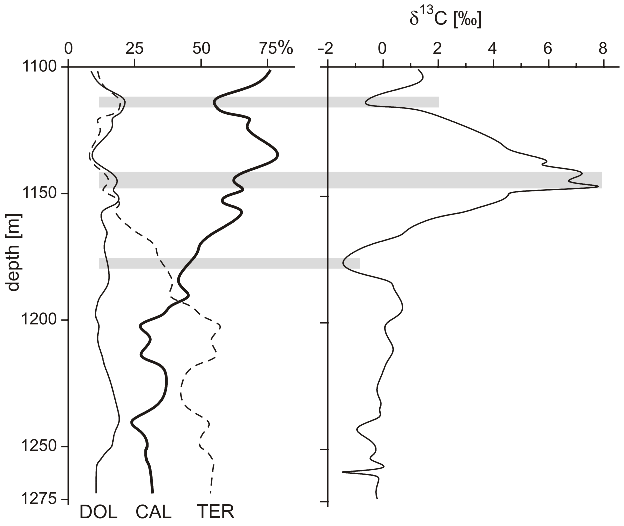

Fig. 5. Changes in the contents of dolomite (DOL), calcite (CAL), terrigenous component (TER) correlated with the δ^{13}C trend in the Ludlow rocks of the Vidukle core

Contents of dolomite and calcite is given as 5-point moving average based on Table 2 large part of it should be kept in mind, when discussing the environmental background of the carbon isotope excursions.

The early Wenlock (more precisely early Sheinwoodian) and the late Wenlock (= late Homerian) $\delta^{13}C$ excursions have been regarded (Bickert *et al*., 1997; Munnecke *et al*., 2003) as the A-periods with evaporation and low rate of continental weathering at low latitudes in conditions of arid climate. On shallow shelves reefs and carbonate platforms were expanding, while on the mid-shelf grey shales and limestones and deeper black shales occurred. During the A-periods the oceanic circulation followed an anti-estuarine (i.e. shore-wards directed at a surface) pattern and clear waters showed high $\delta^{13}C$ values, which were decreasing with water depth. Interpreting the Vidukle data set in the context of an A-period as described above according to the model by Bickert *et al*. (1997) we can note several difficulties, wide distribution of argillaceous and limited occurrences of carbonaceous rocks in particular. The latter proxies, especially in a basin-wide background, are more indicative for a H-period of humid climate, but should have low $\delta^{13}C$ values. However, considering also Gotland and Saaremaa data and high $\delta^{13}C$ values in the Vidukle core we believe that these two carbon isotope excursions can be fitted into the A-period pattern.

In the Ludlow rocks of the Vidukle section the content of the CaO, MgO, calcite, dolomite and terrigenous component was analysed. The data show the following distribution pattern:

1. The terrigenous component (TER) dominates over the carbonates in the mudstones and marlstones (several calcite-rich interbeds excluded, Table 2) of the Dubysa Fm., but in limestones of the Mituva Fm. its content remains below 20% and above 1150 m even below 10%. Exceptions are dolomitic interbeds where TER content reaches 36–38%. The CaO and calcite contents are variable (especially in the Dubysa Fm.), but increase up to the top of the Mituva Fm. (correspondingly over 50 and 90%), with a few less calcareous levels (calcite 18–33%). The MgO content is low and varies below 10%; in the Mituva Fm. it is below 5% (dolomitic interbeds excluded). Figure 5 demonstrates that in the latter interval the dolomite is mainly tied to the terrigenous component.

2. The $\delta^{13}C$ positive shift coincides with the beds (dolomitic interbeds excluded) where the CaO content is consistently over 40% and calcite content 72–96%; both negative shifts before and after the mid-Ludfordian excursion occur in rocks with a relatively high clay content.

3. In detail some correlations between the CaO content and the CaO/MgO ratio on the one hand, and the $\delta^{13}C$ values on the other, show a fairly regular pattern. For example, in the clay-rich Šešupe Beds (Fig. 4 and Table 2), where the CaO content is as a rule below 10% and the CaO/MgO ratio is 1–2, the $\delta^{13}C$ values remain below 0‰ (–0.1 to –0.7‰). In a few limestone interbeds where the CaO/MgO ratio is about 15 the $\delta^{13}C$ values increase up to 0.5–1‰. In the Nova Beds the mean CaO content is twice as high as in the beds below and the $\delta^{13}C$ values also increase above 0‰ up to 1‰.

4. Intervals with high $\delta^{13}C$ values in the Mituva Fm. show the following pattern of correlation between Ca and C geochemistry: the mean CaO values, corresponding to the $\delta^{13}C$ values 2–4, 4–6 and over 6‰, are 44.7 (49 when excluding one argillaceous interlayer), 41.9 (50.8) and 43.2 (51)%. This sequence of numbers shows only a very general correlation, as mentioned in the item 2 and as it might be expected.

In summary, it should be pointed out that the above discussed relationships as well as a pattern demonstrated in Figure 5 show a step-by-step decrease of influx of the terrigenous material into the basin and increase of calcium carbonate sedimentation. The change of dominating process occurred slightly before the commencement of the mid-Ludfordian carbon isotope excursion. This change could be interpreted as a replacement of humid type of sedimentary environment with a more arid one. As an additional proxy we refer to the occurrence of oncolites in the upper part of the Mituva Fm. in the Vidukle core. Oncolites are common in this part of the section also on Gotland (Eke and Hamra beds, Samtleben *et al*., 1996) and in Scania (Bjärsjölagård Member, Wigforss-Lange, 1999).

On the other hand, these data and Figure 5 reveal that correlation between different proxies is only very general, not strictly one to one, which means that the data discussed here allow to pinpoint only some factors of the carbon cycling while several others remain obscure. The latter may include, for example, the primary production and role of organic carbon burial, which seem to be important because of the extinction of biota close to carbon isotope events (Ireviken, Lau events, Jeppsson, 1998). However, it is quite clear that the disappearance of ten or more taxa at a datum plane did not affect seriously bioproduction in general (based more on the planktic microbial production) and, therefore, it is difficult to identify their influence. But the biotic changes indicate that something is happening in the environment and we do think that this is the climate in general and its specific implications, which affect the biota in very different ways. In this context the Vidukle data and comparisons with other ones show that the main driver of the carbon isotope trend is global factors, local ones play only a modifying role.

Considering the high values reached and the very steep rising limb of the excursion, the environmental change that caused the mid-Ludfordian isotopic event must have been rather rapid. The excursion commenced from –1.5‰ at 1178.5 m and the peak (8.2‰) was reached at 1147.5 m; this yields 9.7‰ for the total shift. In terms of the IUGS 2004 time-scale for Ludlow the thickness of the rock sequence 31 m may correspond to 700 000 years. Based on these figures we calculated that the rise of the $\delta^{13}C$ values through 31 m was 0.3‰ per metre or 1‰ per 70 000 years. The topmost part of the peak was much steeper (1.44‰ per metre) and the last 4‰ were added only during 55 000 years. The falling limb of the excursion is of the same length that means the entire excursion corresponds to around 1.4 Ma. This time span is a considerable interval even in geological terms for environmental changes, the same should be stressed also about the initial part of the shift and only the highest peak was formed rather rapidly, although it would be hard to classify the event as a catastrophic one.

CONCLUSIONS

Based on data from the Vidukle core, the following conclusions can be made:

1. The Wenlock carbon isotope excursions agree well with earlier data from Baltica and elsewhere, and the $\delta^{13}C$ values clearly reflect the depth of the sedimentary basin. In both cases the oceanic events directly precede the carbon isotope events. The Ireviken Event precedes the major early Wenlock $\delta^{13}C$ excursion and the Mulde Event the late Homerian less prominent but double shift.

2. The peak values of the mid-Ludfordian $\delta^{13}C$ excursion occur within the limits of the Lau Event as defined by conodonts, but the rising and falling limbs are at least in part located before and after the Event. This indicates that the global processes causing the carbon isotope excursion and the Lau oceanic Event were active to a large extent during the same time span.

3. The mid-Ludfordian positive excursion began and ended with negative shifts, which seem to reflect the inherent pattern of the Late Silurian carbon isotope trend. These negative shifts correlate to some extent with sedimentological changes suggesting oceanic and climatic processes characteristic of more humid episodes; the positive excursion itself may be referred to an arid episode and the entire interval studied is a part of a longer aridisation period.

Acknowledgements. The authors thank A. Munnecke and J. Zalasiewicz for useful constructive comments, T. Kiipli is thanked for assistance at geochemical calculations. G. Baranov, A. Noor and H. Kukk for technical and linguistic help. The study was partly supported by the Estonian Science Foundation (grants no. 5042 and 6127). The paper is a contribution to the IGCP Project 503.

REFERENCES

ANDREW A. S., HAMILTON P. J., MAWSON R., TALENT J. A. and WHITFORD D. J. (1994) — Isotopic correlation tools in the mid-Paleozoic and their relation to extinction events. Australian Petrol. Explor. Ass. J., **34**: 268–277.

AZMY K., VEIZER J., BASSETT M. G. and COPPER P. (1998) — Oxygen and carbon isotopic composition of Silurian brachiopods: implications for coeval seawater and glaciations. Geol. Soc., Am. Bull., **110**: 1499–1512.

BASSETT M. G., KALJO D. and TELLER L. (1989) — The Baltic region. In: A Global Standard for the Silurian System (eds. C. H. Holland and M. G. Bassett). Nat. Mus. Wales. Geol. Ser., **9**: 158–170.

BICKERT T., PÄTZOLD J., SAMTLEBEN C. and MUNNECKE A. (1997) — Paleoenvironmental changes in the Silurian indicated by stable isotopes in brachiopod shells from Gotland, Sweden. Geochim. Cosmochim. Acta, **61** (13): 2717–2730.

BRENCHLEY P. J., CARDEN G. A., HINTS L., KALJO D., MARSHALL J. D., MARTMA T., MEIDLA T. and NÕLVAK J. (2003) — High resolution isotope stratigraphy of Late Ordovician sequences: constraints on the timing of bio-events and environmental changes associated with mass extinction and glaciation. Geol. Soc., Am. Bull., **115**: 89–104.

CALNER M. and JEPPSSON L. (2003) — Carbonate platform evolution and conodont stratigraphy during the middle Silurian Mulde Event, Gotland, Sweden. Geol. Mag., **140**: 173–203.

COCKS L. R. M. and TORSVIK T. H. (2002) — Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. J. Geol. Soc. London, **159**: 631–644.

CORFIELD R. M., SIVETER D. J., CARTLIDGE J. E., McKERROW W. S. (1992) — Carbon isotope excursion near the Wenlock-Ludlow (Silurian) boundary in the Anglo-Welsh area. Geology, **20**: 371–374.

HEATH R. J., BRENCHLEY P. J. and MARSHALL J. D. (1998) — Early Silurian carbon and oxygen stable-isotope stratigraphy of Estonia: Implications for climatic change. In: Silurian Cycles — Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic and Tectonic Changes (eds. E. Landing and M. E. Johnson). N. Y. St. Mus. Bull., **491**: 313–327.

HOLSER W. T., MAGARITZ M. and RIPPERDAN R. L. (1995) — Global isotopic events. In: Global Events and Event Stratigraphy in the Phanerozoic (ed. O. H. Walliser): 63–88. Springer-Verlag. Berlin-Heidelberg-New York.

JEPPSSON L. (1990) — An oceanic model for lithological and faunal changes tested on the Silurian record. J. Geol. Soc. London, **147**: 663–674.

JEPPSSON L. (1993) — Silurian events, the theory, and the conodonts. Proc. Estonian Acad. Sc. Geol., **42**: 23–27

JEPPSSON L. (1998) — Silurian oceanic events: summary of general characteristics. In: Silurian Cycles — Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic and Tectonic Changes (eds. E. Landing and M. E. Johnson). N. Y. St. Mus. Bull., **491**: 239–257.

JEPPSSON L. and ALDRIDGE R. J. (2000) — Ludlow (late Silurian) oceanic episodes and events. J. Geol. Soc. London, **157**: 1137–1148.

JEPPSSON L., VIIRA V. and MÄNNIK P. (1994) — Silurian conodont-based correlations between Gotland (Sweden) and Saaremaa (Estonia). Geol. Mag., **131**: 201–218.

JUX U. and STEUBER T. (1992) — C_{carb} und C_{org} — Isotopenverhältnisse in der silurischen Schichtenfolge Gotlands als Hinweise auf Meeresspiegelschwankungen und Krustenbewegungen. N. Jb. Geol. Paläont., Mh., **7**: 385–413.

KALJO D., BOUCOT A. J., CORFIELD R. M., LE HERISSE A., KOREN T. N., KRIZ J., MÄNNIK P., MÄRSS T., NESTOR V., SHAVER R. H., SIVETER D. J. and VIIRA V. (1995) — Silurian Bio-Events. In: Global Events and Event Stratigraphy in the Phanerozoic (ed. O. H. Walliser): 173–224. Springer-Verlag.

KALJO D., KIIPLI T. and MARTMA T. (1997) — Carbon isotope event markers through the Wenlock-Pridoli sequence in Ohesaare (Estonia) and Priekule (Latvia). Palaeogeogr., Palaeoclimatol., Palaeoecol., **132**: 211–224.

KALJO D., KIIPLI T. and MARTMA T. (1998) — Correlation of carbon isotope events and environmental cyclicity in the East Baltic Silurian. In: Silurian Cycles — Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic and Tectonic Changes (eds. E. Landing and M. E. Johnson). N. Y. St. Mus. Bull., **491**: 297–312.

KALJO D. and MARTMA T. (2000) — Carbon isotopic composition of Llandovery rocks (East Baltic Silurian) with environmental interpretation. Proc. Estonian Acad. Sc. Geol., **49**: 267–283.

KALJO D., MARTMA T., MÄNNIK P. and VIIRA V. (2003) — Implications of Gondwana glaciations in the Baltic late Ordovician and Silurian and a carbon isotopic test of environmental cyclicity. Bull. Soc. Geol. France, **174** (1): 59–66.

KUMP L. R. (2000) — What drives climate? Nature, **408**: 651–652.

LANDING E. and JOHNSON M. E. eds. (1998) — Silurian cycles — linkages of dynamic stratigraphy with atmospheric, oceanic and tectonic changes. N. Y. St. Mus. Bull., **491**.

LANDING E. and JOHNSON M. E. eds. (2003) — Silurian lands and seas. Paleogeography outside of Laurentia. N. Y. St. Mus. Bull., **493**.

LEHNERT O., FRYDA J., BUGGISCH W. and MANDA Š. (2003) — A first report of the Ludlow Lau Event from the Prague Basin (Barrandian, Czech Republic). In: Proc. 7th IGC-FMSSS (eds. G. Ortega and G. F. Acenolazas). INSUGEO, Ser. Correlat. Geol., **18**: 139–144.

MARSHALL J. D. (1992) — Climatic and oceanographic isotopic signals from the carbonate rock record and their preservation. Geol. Mag., **129**: 143–160.

MARSHALL J. D., BRENCHLEY P. J., MASON P., WOLFF A., ASTINI R. A., HINTS L. and MEIDLA T. (1997) — Global isotopic events associated with mass extinction and glaciation in the Late Ordovician. Palaeogeogr., Palaeoclimat., Palaeoecol., **132**: 195–210.

MODZALEVSKAYA T. L. and WENZEL B. (1999) — Biostratigraphy and geochemistry of Upper Silurian brachiopods from the Timan-Pechora region (Russia). Acta Geol. Pol., **49** (2): 145–157.

MUNNECKE A., SAMTLEBEN C., BICKERT T. (2003) — The Ireviken Event in the lower Silurian of Gotland, Sweden — relation to similar Palaeozoic and Proterozoic events. Palaeogeogr., Palaeoclimat., Palaeoecol., **195**: 99–124.

MUSTEIKIS P. and PAŠKEVIČIUS J. (1999) — Brachiopod communities of the Lithuanian Silurian. In: Paleocommunities: a Case Study from the Silurian and Lower Devonian (eds. A. J. Boucot and J. D. Lawson). World Reg. Geol. Ser., **11**: 305–326. Cambridge Univ. Press. Cambridge.

NESTOR H. (1997) — Silurian. In: Geology and Mineral Resources of Estonia (eds. A. Raukas and A. Teedumäe): 89–106. Estonian Acad. Publ. Tallinn.

NESTOR H. and EINASTO R. (1997) — Ordovician and Silurian carbonate sedimentation basin. In: Geology and Mineral Resources of Estonia (eds. A. Raukas and A. Teedumäe): 192–204. Estonian Acad. Publ. Tallinn.

PAŠKEVIČIUS J. (1997) — The geology of the Baltic republics. Vilnius Univ. Geol. Surv. Lithuania. Vilnius.

PAŠKEVIČIUS J., LAPINSKAS P., BRAZAUSKAS A., MUSTEIKIS P. and JACYNA J. (1994) — Stratigraphic revision of the regional stages of the Upper Silurian part in the Baltic Basin. Geologija, **17**: 64–87.

PORĘBSKA E., KOZŁOWSKA-DAWIDZIUK A. and MASIAK M. (2004) — The lundgreni event in the Silurian of the East European Platform, Poland. Palaeogeogr., Palaeoclimat., Palaeoecol., **213** (3–4): 271–294.

SALTZMAN M. R. (2001) — Silurian $\delta^{13}C$ stratigraphy: a view from North America. Geology, **29**: 671–674.

SAMTLEBEN C., MUNNECKE A. and BICKERT T. (2000) — Development of facies and C/O-isotopes in transects through the Ludlow of Gotland: evidence for global and local influences on a shallow-marine environment. Facies, **43**: 1–38.

SAMTLEBEN C., MUNNECKE A., BICKERT T. and PÄTZOLD J. (1996) — The Silurian of Gotland (Sweden): facies interpretation based on stable isotopes in brachiopod shells. Geol. Rundsch., **85**: 278–292.

URBANEK A. and TELLER L. (1997) — Graptolites and stratigraphy of the Wenlock and Ludlow Series in the East European Platform. Palaeont. Pol., **56**: 23–57.

VEIZER J., GODDERIS Y. and FRANCOIS L. M. (2000) — Evidence for decoupling of atmospheric CO_2 and global climate during the Phanerozoic eon. Nature, **408**: 698–701.

VIIRA V. (1999) — Late Silurian conodont biostratigraphy in the northern East Baltic. Bollettino Soc. Paleont. Italiana, **37**: 299–310.

WEISSERT H. (2000) — Deciphering methane's fingerprint. Nature, **406**: 356–357.

WENZEL B. and JOACHIMSKI M. M. (1996) — Carbon and oxygen isotopic composition of Silurian brachiopods (Gotland/Sweden): palaeoceanographic implications. Palaeogeogr., Palaeoclimat., Palaeoecol., **122**: 143–166.

WIGFORSS-LANGE J. (1999) — Carbon isotope ^{13}C enrichment in Upper Silurian (Whitcliffian) marine calcareous rocks in Scania, Sweden. GFF, **121**: 273–279.