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Biostratigraphy and geochemistry of Upper Silurian brachiopods from the Timan-Pechora region (Russia)

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ABSTRACT:

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This paper presents biostratigraphical and geochemical (trace element, stable isotopes) data relating to the Upper Silurian brachiopods from Bol'shezemel'skaya Tundra, Timan-Pechora region. The Upper Silurian sections exposed in this region are characterized by monotonous carbonate-dominated deposits. The brachiopod biostratigraphy is based on the evolution of athyrids. Trace element contents (Sr, Mn, Na, Fe) and shell microstructures of nonluminescent (NL) brachiopods compare well with those of modern brachiopods. Isotopic data derived from Upper Silurian NL brachiopod samples show a significant negative $\delta\ ^{13}C$ excursion during the Early Ludfordian (*Didymothyris didyma* Zone). Above this horizon, increasing $\delta\ ^{13}C$ values can be observed both for brachiopods from the northeastern edge of the East European Platform (samples from the Baltic area) and carbonate whole rock samples from Austria and Australia. The Middle Ludfordian isotope variation is probably a worldwide chemostratigraphical marker level, although the magnitudes of positive isotope excursions show large interregional differences, which may be related to regional oceanographical differences.

Key words: Biostratigraphy, brachiopods, isotopes, Silurian, Timan-Pechora region.

INTRODUCTION

Three units may be distinguished within the Timan-Pechora region of European Russia: Bol'shezemel'skaya Tundra, Izhem and Kos'yu-Kozhim. The first two units are within the area of the East European Platform, the third one is a part of the Polar Urals (Text-fig. 1). The river Kozhim and Bol'shezemel'skaya Tundra sections are the key-sections for the Silurian of the Timan-Pechora region (TSYGANKO & CHERMNYKH 1983, ANTOSHKINA & *al.* 1989). The Upper Silurian parts of these sections represent the stratotype sections of the regional stages (Gerd'yu,

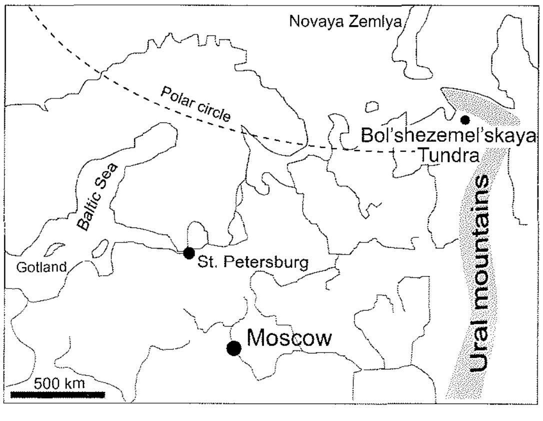

Fig. 1. Geographical position of the Bol'shezemel'skaya Tundra area

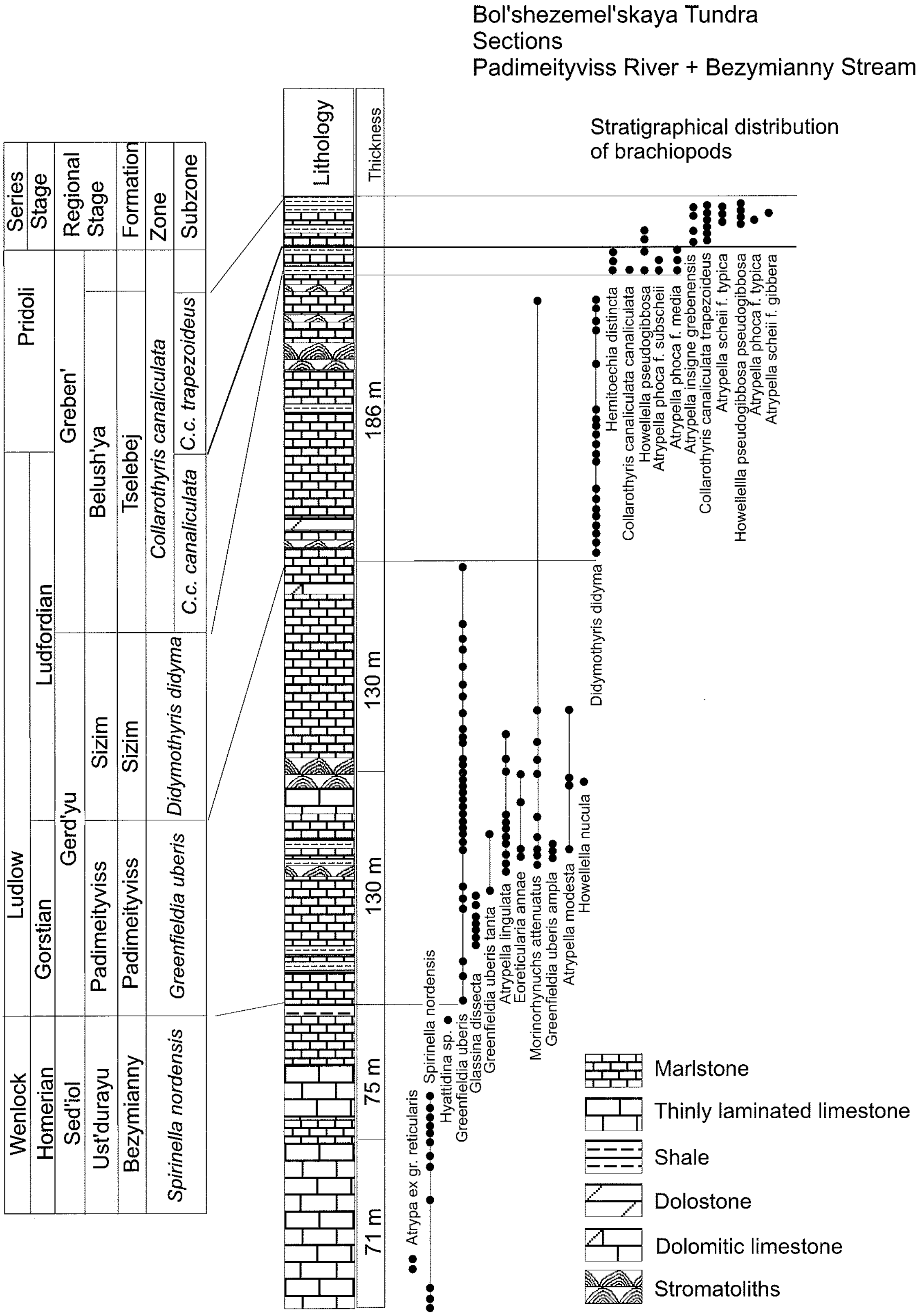

Fig. 2. Stratigraphical subdivision, lithology and brachiopod faunas of the Padymeityviss River and Bezymianny Stream sections of Bol'shezemel'skaya Tundra

Padimeityviss, and Sizim; see Text-fig. 2) as distinguished in northeastern European Russia, the Urals and, in part, in the Arctic Islands. The stratigraphical subdivision of the sampled section of the Bol'shezemel'skaya Tundra was composed of the Padimeityviss river section and the Bezymianny stream section (Text-fig. 2). This section represents a monotonous shallow-marine continuous succession of carbonates (KOREN & *al.* 1995) spanning the Wenlock and Pridoli. The relatively uniform subtidal carbonates of the Wenlock and Ludlow contain a number of biostrome and stromatolitic horizons. Such a monotonous succession is ideally suited for biostratigraphical analysis based on brachiopod lineages. The biozones recognized are defined by the first appearances of the index taxa. The boundaries of formations are characterized by evolutionary changes of athyrids, which were the dominant faunal elements in the Urals-Novaya Zemlya area during the Late Silurian (MODZALEVSKAYA 1997a). Their appearances, extinctions, radiations and further bursts are the main distinctive events, and coincide with zonal boundaries.

BRACHIOPOD BIOSTRATIGRAPHY

The following brachiopod zones were defined for the Upper Silurian (in ascending order): "*Greenfieldia*" *uberis*, *Didymothyris didyma*, *Collarothyris canaliculata* (with three subzones: *C. canaliculata canaliculata*, *C. canaliculata trapezoideus*, and *C. canaliculata lata*) (*see* Text-fig. 2). This zonal scheme can be correlated with the standard subdivision of the Silurian (*see* MODZALEVSKAYA 1997b). There are no clear faunal and facies changes at the Wenlock/Ludlow boundary in the sections of the Timan-Pechora region and the Urals-Novaya Zemlya area.

The Upper Silurian brachiopod assemblages are characterized by large numbers of specimens, however, their taxonomic diversity is rather low.

The *Greenfieldia uberis* Zone can be distinguished in almost all sections in the northern part of the Urals-Novaya Zemlya area. The brachiopod assemblages in this zone are characterized by low taxonomic diversity, and are composed of smooth atrypids, athyrids, and spiriferids, and ribbed rhynchonellids. Atrypids and athyrids are particularly diagnostic. Representatives of *Greenfieldia* usually occur as complete shells and form coquina beds. *G. uberis* is unknown in the western part of the East European Platform. *Glassina dissecta* appears in the brachiopod association together with atrypids and is relatively common.

The base of the succeeding *Didymothyris didyma* Zone is marked by the first appearance of the index taxon. It is a very well known species, described originally from the Hemse Bed of Gotland, Sweden. It is regarded as one of the most characteristic forms of the Ludfordian fauna and was found in many localities in both eastern and western parts of the East European Platform. It is a very good index taxon, enabling correlation throughout Baltica. Besides the index taxon, the *didyma* Zone is characterized by the occurrence of smooth atrypids genus *Morinorhunchus*, which typical of North American sections.

The *C. canaliculata canaliculata* Subzone corresponds to the lower part of the Greben' Regional Stage (= upper Ludlow), and besides in the studied section was also recognized on the western slope of the Polar Urals and in the Vaigah Island.

In the Greben' Stage (upper Ludlow + Pridoli) the brachiopod assemblages are characterized by the highest taxonomic diversity within the studied interval. The evolution mainly affected the internal structures, whereas the external morphology remained unchanged, being similar to that of the Ludfordian forms. Morphological trends are most clearly seen in the evolutionary succession of from *Didymothyris* to *Collarothyris*. This succession can be recognized in all sections of the Urals-Novaya Zemlya area. Brachiopod assemblages of the Greben' Stage are characterized by the first appearance of the genera *Hemitoechia*, *Collarothyris*, and *Proreticularia*.

At the base of the *C. canaliculata trapezoideus* Subzone the number of smooth atrypids significantly increased. They are typical elements of the Urals-Novaya Zemlya area, as well as of Arctic Russia and the Canadian Arctic Archipelago. *A. scheii* and *A. phoca* are known from Somerset, Bichey, Prince of Wales, Ellesmere and Devon islands. Due to the occurrence of transitional forms the specific distinction of these two species was questioned and they were consequently synonymised by JONES (1977). The analysis of the topotype material (SMITH & JOHNSON 1977) showed, however, that they differ enough to be regarded as separate species and, moreover, have different stratigraphical ranges, *A. scheii* being older than *A. phoca*. The atrypids are accompanied by numerous other spire-bearing athyrids and spiriferids (*C. canaliculata*, *H.*

pseudogibbosa). A gradual impoverishment of the brachiopod fauna is observed toward the end of the Greben' stage, where only two species (*A. scheii* and *C. canaliculata*) were found.

The evolutionary succession of *Didymothyris* and *Collarothyris* was also recognized in the Baltic and Podolian successions despite the rather incomplete stratigraphical record in those areas. This transition coincides with the *Andreolepis hedei* Event. Thus, the extinction of *D. didyma* and the following flood appearance of other brachiopod species, progressively developing in Pridoli time, could have taken place during the Middle Ludfordian (MODZALEVSKAYA & MÄRSS 1991, MODZALEVSKAYA 1997a, b).

BRACHIOPOD GEOCHEMISTRY

Analytical methods

To detect potential diagenetic alterations of the Upper Silurian brachiopods from the Bol'shezemel'skaya Tundra, shell microstructures, cathodoluminescence characteristics and trace element composition of representative subsamples were investigated. Studies of Silurian and Devonian brachiopod shells demonstrated that diagenetically altered microstructures cannot always be detected reliably by light microscopy of thin-sectioned brachiopod shells (POPP & *al.* 1986, WENZEL 1997). The preservation of the microstructure of the Russian brachiopods was therefore investigated using a scanning electron microscope (SEM; type Cam Scan Mk.II) SEM photomicrographs were taken from both broken shell fragments and polished and slightly etched shell surfaces. This technique facilitates a direct comparison of microstructures and luminescence intensities in distinct portions of the shells. Cathodoluminescence characteristics of sectioned and polished shell surfaces were investigated with a cold cathodoluminescence microscope stage (type Technosyn 8200)

Since most brachiopod shells from the Bol'shezemel'skaya Tundra are relatively small (shell thickness < 2 mm), only some larger shells could be investigated for their trace elemental composition. Sr, Na, Mn, and Fe contents were determined using an inductively coupled plasma atom emission spectrometer (ICP-AES; type spectroflame). Samples of approximately 10 mg powdered shell calcite were dissolved in 5 ml of 5% HCL and diluted to 10 ml sample residue (I.R. less than 1.5%), solutions were not filtered. Element concentrations are usually well above the experimental detection limits (Sr: 0.5 ppm; Na: 10 ppm; Mn: 0.8 ppm; Fe: 50 ppm). Accuracy and reproducibility were determined relative to the standard BCS-CRM 393 and for all elements are better than ±10%. Carbonate powders for stable isotope analysis (approximately 0.5 mg) were drilled with a 0.5 mm dental drill and reacted with 100% H_3PO_4 at 75^0C in an online carbonate preparation device (Kiel-Carbo) connected to a Finnigan Mat 252 mass spectrometer. All values are reported in permil relative to V-PDB. Analytical precision (1δ) is ± 0.05‰ for $\delta^{13}C$ and ± 0.08‰ for $\delta^{18}O$, based on duplicate sample analysis and multiple analysis of NBS 19.

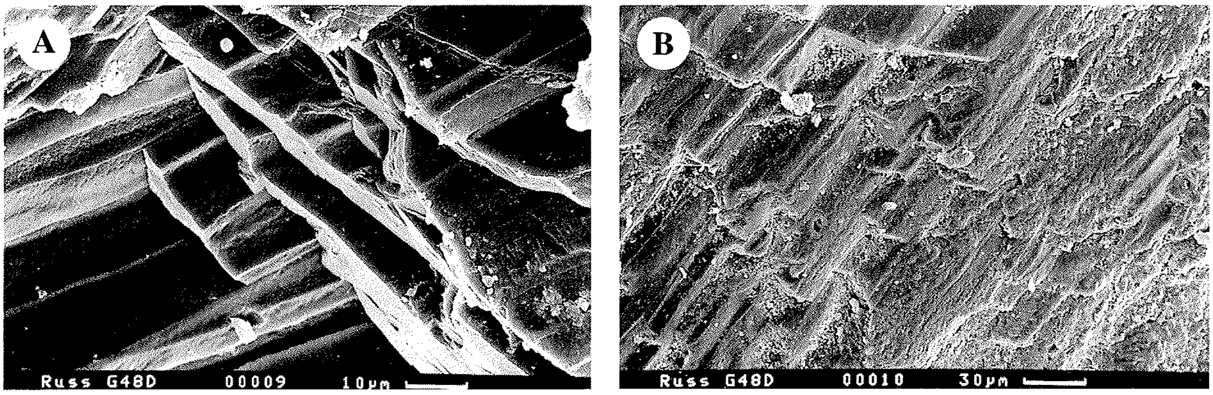

Fig. 3. SEM photomicrographs of the secondary layer of an atrypid shell (*Atrypella phoca forma media*; sample G48 – Upper Ludfordian) from Bol'shezemel'skaya Tundra (Padimeityviss section); A – well preserved calcite fibres of a central NL shell area; B – transition from partly cemented and corroded shell portion (left hand side) to completely recrystallized calcite fibres at the margin of a brachiopod shell (right hand side; same specimen as in A)

Microstructural and geochemical preservation of brachiopod shells

It is assumed that geochemical and microstructural composition of most brachiopod genera have not changed significantly since Cambrian time (LOWENSTAM 1961, WILLIAMS 1968, RICHTER 1972, EMIG 1990). Therefore microstructures and trace element contents serve as indicators to evaluate the preservation of fossil shells prior to stable isotope analysis (GROSSMAN 1994, VEIZER & *al.* 1997).

Upper Silurian atrypids and athyrids from Bol'shezemel'skaya Tundra sections reveal shell microstructures similar to those of modern rhynchonellid and terebratulid shells (*cf.* WILLIAMS 1968). Most of the brachiopod shells examined are characterized by fibrous secondary shell layers composed of stacked rows of calcite fibres (Text-fig. 3). Different degrees of shell alteration are commonly developed within individual specimens. The central shell layers of nonluminescent brachiopod shells usually reveal perfectly preserved calcite fibres, whereas the outer shell areas and shell surfaces close to diagenetic calcite cements are frequently characterized by corroded and partly recrystallized calcite fibres (Text-fig. 3). The distribution suggests that diagenetic alteration due to fluid/calcite exchange preferentially affected the outer surfaces of brachiopod shells (ADLIS & *al.* 1988).

Because the central layers of nonluminescent (NL) shells are often characterized by better preserved microstructures than those of luminescent (L) shells (*see also* GROSSMAN & *al.* 1991), trace element determination and isotopic analysis were focused on the central areas of NL shell material. Generally, brachiopods from the Bol'shezemel'skaya Tundra are characterized by a relatively high percentage of NL shells (78% out 128 investigated specimens).

Table 1 shows the trace elemental composition of NL and L brachiopods, and of different calcite components from the Bol'shezemel'skaya Tundra sections together with the trace element contents of modern brachiopods. It appears that most Silurian NL brachiopod shells are characterized by Mn, Fe, Sr, and Na concentrations similar to those of their modern counterparts. No significant difference is observed for the Mn contents of NL and L brachiopod shells, although Mn is an important activator of orange cathodoluminescence in calcite (MACHEL & *al.* 1991). SAVARD & *al.* (1995) showed that nonluminescence as well as dull and bright luminescence can be observed for natural and synthetic calcites with Mn concentrations below 225 ppm. It was concluded that for this range of Mn concentrations other factors govern cathodoluminescence characteristics. Some Silurian NL brachiopod shells are characterized by significantly enriched Fe contents (> 1000 ppm). Fe is known to be one of the most important quenchers of luminescence in calcite (MACHEL & *al.* 1991), but the values of Silurian NL shells mostly below the experimentally determined threshold for Fe-quenching of Mn-induced luminescence (~ 1400 ppm; SAVARD & *al.* 1995).

The Sr and Na contents of most Silurian NL and L brachiopod shells are comparable to values of modern brachiopods although the data reveal a larger scatter. The brachiopod genera *Atrypella* and *Spirinella* always reveal significantly lower Sr and Na contents than *Greenfieldia*, *Didymothyris* and *Collarothyris* (Text-fig. 4). Similar differences in Sr and Na contents also characterize these same brachiopod genera in another Upper Silurian section of the Urals ("Kozhim River"; WENZEL 1997). The differences in Sr and Na contents do not correlate with the Mn and Fe concentrations (Text-fig. 5) or with the different microstructural preservation of these brachiopod genera. It is therefore concluded that these differences are not due to different susceptibilities to diagenetic alteration, but rather reflect primary, biologically induced variation. Vital fractionation effects on Sr and Na values were repeatedly observed both for modern and fos-

	Mn (ppm)	Fe (ppm)	Sr (ppm)	Na (ppm)
modern brachiopods	10 - 56 (-460*)	20 - 700	740 - 2150	500 - 3800
Bol'shez. Tundra				
NL (br. (28)	8 - 75 (150**)	70 - 1250	560 - 1830	190 - 1500
L br. (4)	12 - 38	(1610**)	790 - 1360	620 - 1530
carb. matrix (12)	51 - 900	80 - 140	180 - 760	120 - 220
blocky spar cem. (7)	66 - 370	260 - 5400 950 - 2900	200 - 350	130 - 970

Table 1. Trace element concentrations (ppm) of NL and L brachiopods, carbonate matrix and calcite spar cements of the Bol'shezemel'skaya section compared to values for modern brachiopods (POPP & *al.* 1986); element concentrations of matrix samples refer to the acid soluble fraction; * *after* MORRISON & BRAND (1986); ** enriched Mn and Fe values were observed only for one NL brachiopod shell

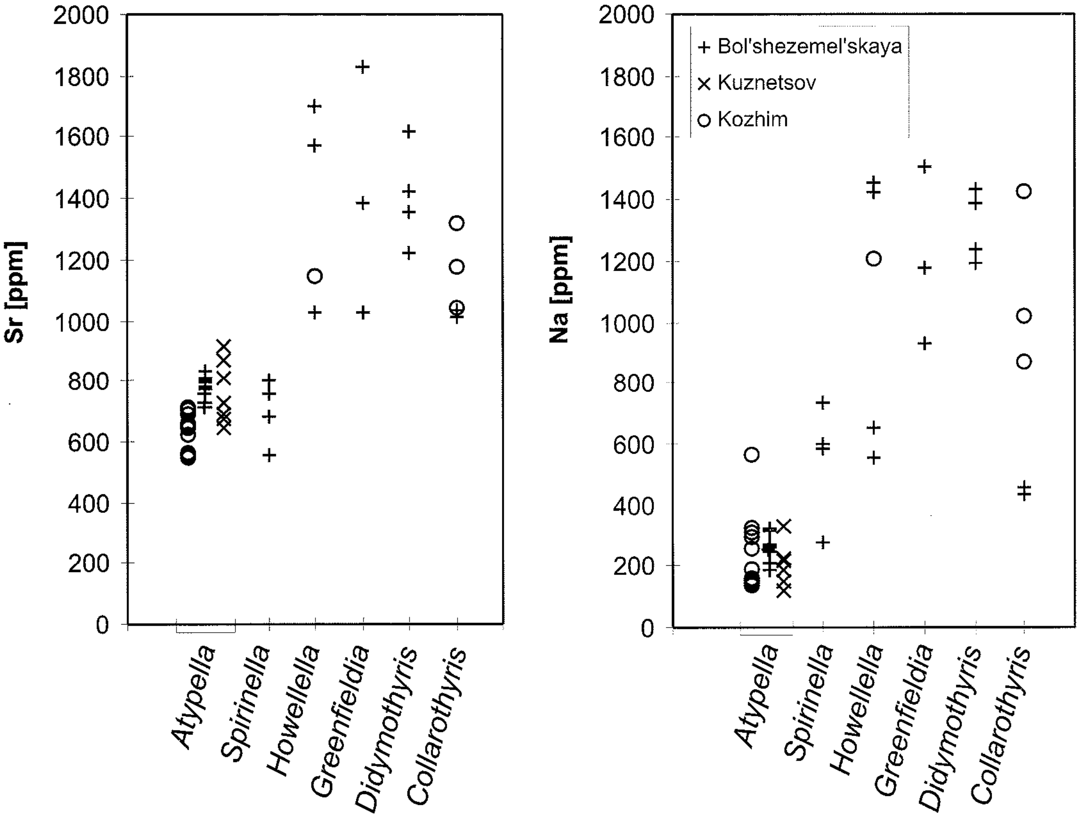

Fig. 4. Sr and Na values for different genera of Upper Silurian NL brachiopods (n = 50); included are samples from coeval Silurian sections exposed at Bol'shezemel'skaya Tundra, Novaya Zemlya (Kuznetsov river) and the Russian Polar Urals (Kozhim river; data *after* WENZEL 1997); in all sections *Atrypella* and *Spirinella* are characterized by significantly lower Sr and Na values than other brachiopod genera

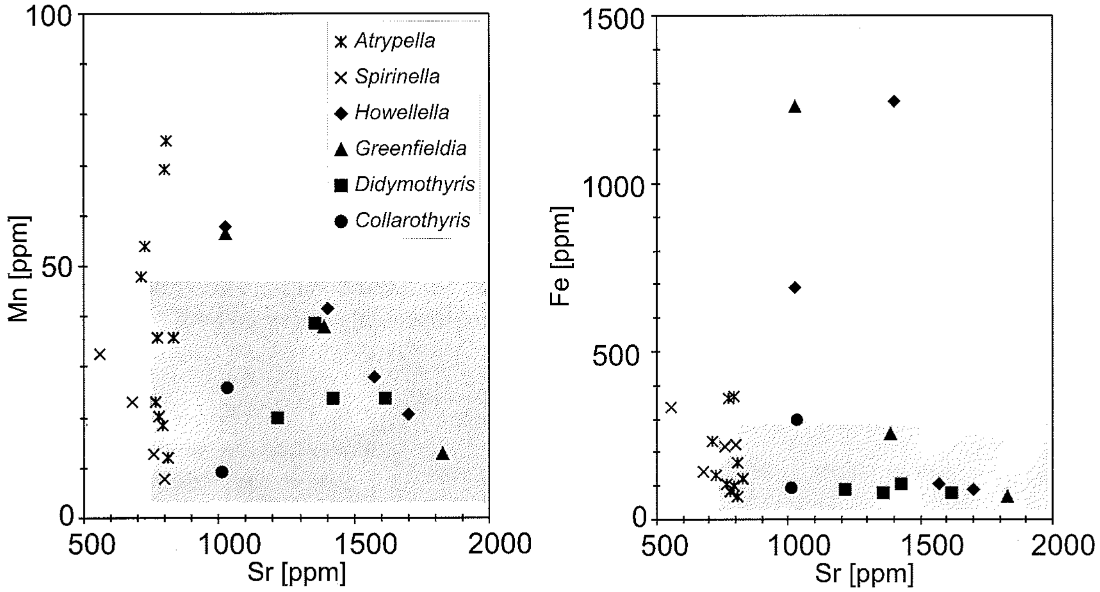

Fig. 5. Sr plotted against Mn and Fe contents of different brachiopod genera from Bol'shezemel'skaya Tundra; gray stippled field marks element concentrations of modern brachiopods (*after* POPP & *al.* 1986 and MORRISON & BRAND 1986)

sil brachiopods (Morrison & Brand 1986, Popp & *al.* 1986, Bates & Brand 1991). Since it is assumed that diagenetic recrystallization of shell calcite leads to a homogenization of trace element contents, such species effects point towards good preservation of primary geochemical signatures in fossil brachiopod shells (Grossman 1994).

Stable isotope data

The stable isotope composition of Silurian NL brachiopods, micritic matrix samples and blocky calcite cements from the Bol'shezemel'skaya Tundra is shown in Text-fig. 6. A significant correlation of $\delta^{18}O$ and $\delta^{13}C$ values is observed both for NL brachiopod shells ($r = 0.74$; $n = 71$) and matrix samples ($r = 0.54$; $n = 21$). Together with significantly lower carbon and oxygen isotopic values than those of modern tropical brachiopods (Carpenter & Lohmann 1995) and of other Silurian samples (Text-fig. 6), this may point toward diagenetic alterations of the Silurian samples that could not be detected by means of microstructural and trace elemental analysis (Land 1995). However, extrapolation of the isotopic data from the Bol'shezemel'skaya Tundra does not result in values comparable to those of modern tropical brachiopods (Text-fig. 6). It is therefore unlikely that the correlation of the Silurian isotope data is simply due to mixing of brachiopod shell calcite characterized by a "modern" isotopic composition and diagenetic calcite ("mineral end-member mixing; Given & Lohmann 1985). Similar correlation of carbon and oxygen isotopic values were also observed for microstructurally and geochemically well preserved Ordovician brachiopods from the Baltic area and Silurian brachiopods from Gotland (Text-fig. 6) and were interpreted as a result of primary palaeoenvironmental variation (Brenchley & *al.* 1994, Samtleben & *al.* 1996, Wenzel & Joachimski 1996).

Diagenetic alteration of brachiopod shells often leads to a significant scatter of isotopic data (*cf.* Rush & Chafetz 1990, Wenzel 1997). For the brachiopods from the Bol'shezemel'skaya Tundra, a considerable scatter of carbon isotopic values is characteristic both for the whole sample set (average: -0.9‰ ± 1.4‰) and for individual beds (Text-fig. 7). Oxygen isotopic values are more homogenous (average: -5.2‰ ± 0.5‰). Thus, both very low carbon isotopic values and the large scatter of $\delta^{13}C$ values of the NL brachiopods indicate some degree of diagenetic alteration. This could be due to partial re-equilibration of brachiopod shell calcite with hydrocarbons. Bitumen and kerogen are characterized by very low $\delta^{13}C$ values (e.g. –24 to –39‰ for oil derived from Ordovician source rocks; Hatch & *al.* 1987), such that even partial exchange of calcite with hydrocarbons may result in significantly lowered $\delta^{13}C_{calcite}$ values. Significant amounts of bitumen can be found within the microsparitic carbonate matrix and calcite spar cements from the *Didymothyris didyma* horizon. The matrix samples and brachiopods from this horizon are characterized by the lowest $\delta^{13}C$ values of all samples from the Bol'shezemel'skaya Tundra (Text-fig. 7) and therefore may be, at least partly, influenced by increased diagenetic alteration. Trace elemental composition of brachiopods form this horizon could not be determined due to the small size of *Didymothyris didyma*.

It is difficult to determine whether or not oxygen isotope values were also affected by secondary alteration. NL brachiopod shells from individual stratigraphical horizons show tightly clustered $\delta^{18}O$ values (Text-fig. 7). This and the similarity to other Silurian data (Text-fig. 6; *see also* Wadleigh

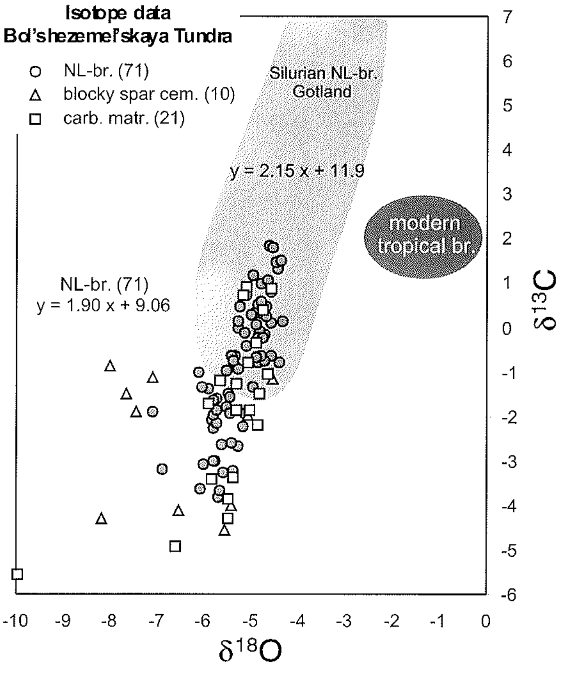

Fig. 6. Stable isotopic composition of various calcitic components from Bol'shezemel'skaya Tundra; values of Silurian brachiopods from Gotland *after* Wenzel & Joachimski (1996) and of modern tropical brachiopod shells after Carpenter & Lohmann (1996)

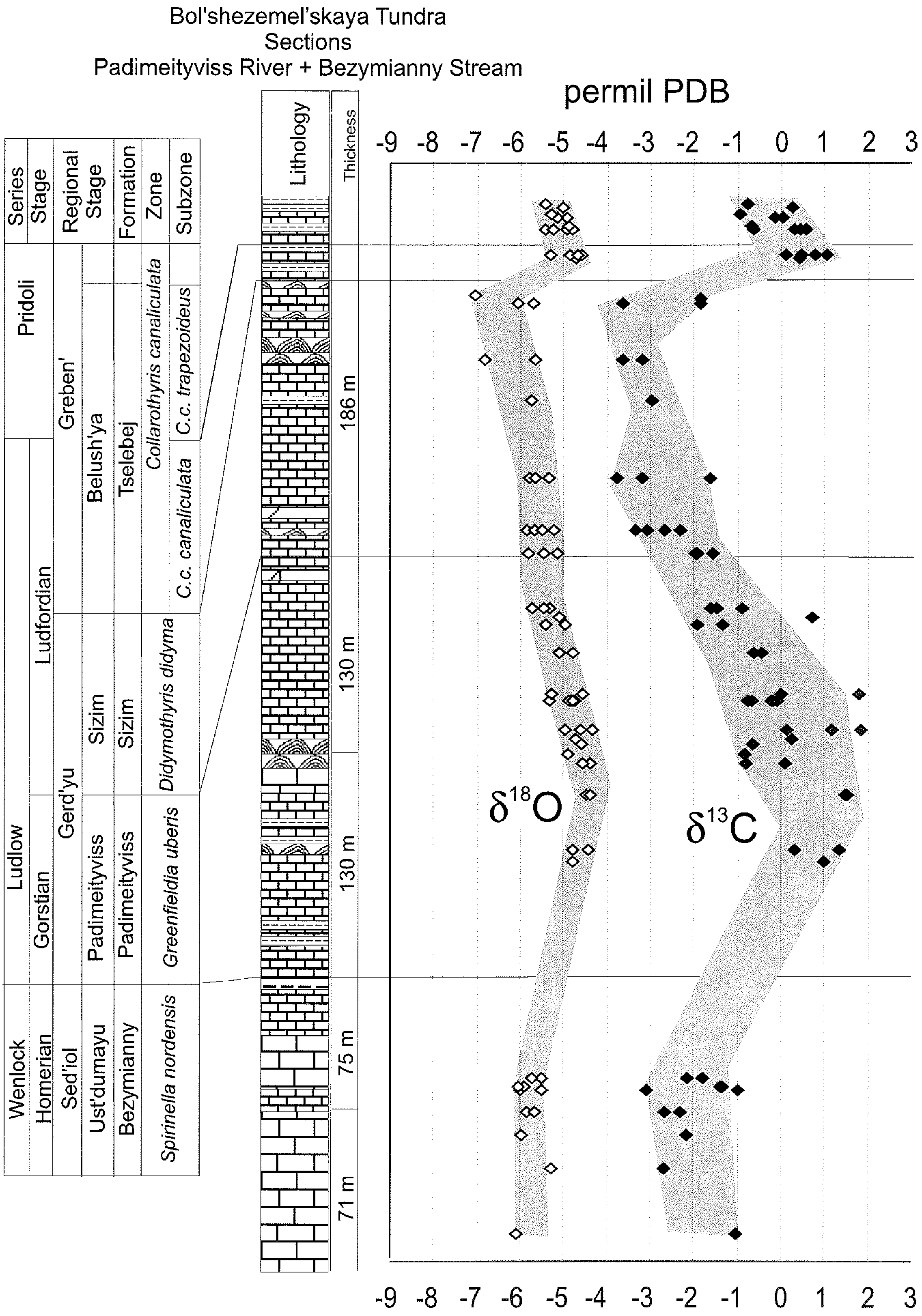

Fig. 7. Isotopic composition of NL brachiopods from Bol'shezemel'skaya Tundra, plotted as a function of their stratigraphical position (legend as in Text-fig. 2)

& Veizer 1992) does not indicate significantly altered $\delta^{18}O$ values of the samples from the Bol'shezemel'skaya Tundra sections.

Stratigraphical significance of stable isotopic data

The above discussed distribution of isotopic data suggests at least some degree of diagenetic alteration of the carbon isotopic signatures, although the microstructures, trace element contents and cathodoluminescence characteristics do not indicate significant alteration of the Silurian brachiopods. A further test for the preservation of primary isotopic signatures is comparison with the coeval data from other areas. In Text-fig. 8 the highest (supposedly best preserved) isotopic values of NL brachiopods from the Bol'shezemel'skaya Tundra are plotted together with data derived from brachiopod shells and carbonate whole rock samples from Gotland and the Cellon section of the Carnic Alps (Austria). Correlation of the Bol'shezemel'skaya Tundra sections and the succession exposed on Gotland is based on the distribution of index brachiopods and vertebrate remains (Märss 1992, Modzalevskaya 1985, Modzalevskaya & Märss 1991; *see also* Text-fig. 8 of this paper). The Silurian conodont zonation serves to correlate the Gotland section and the Cellon section of the Carnic Alps (Jeppsson 1983, Jeppsson & *al.* 1994, Schönlaub & *al.* 1994). The resulting isotope curves for the Upper Silurian show a negative $\delta^{13}C$ excursion during the lower Ludfordian (*Didymothyris didyma* Zone). Increasing carbon isotopic values can be observed for both brachiopod shells and carbonate whole rock samples from the

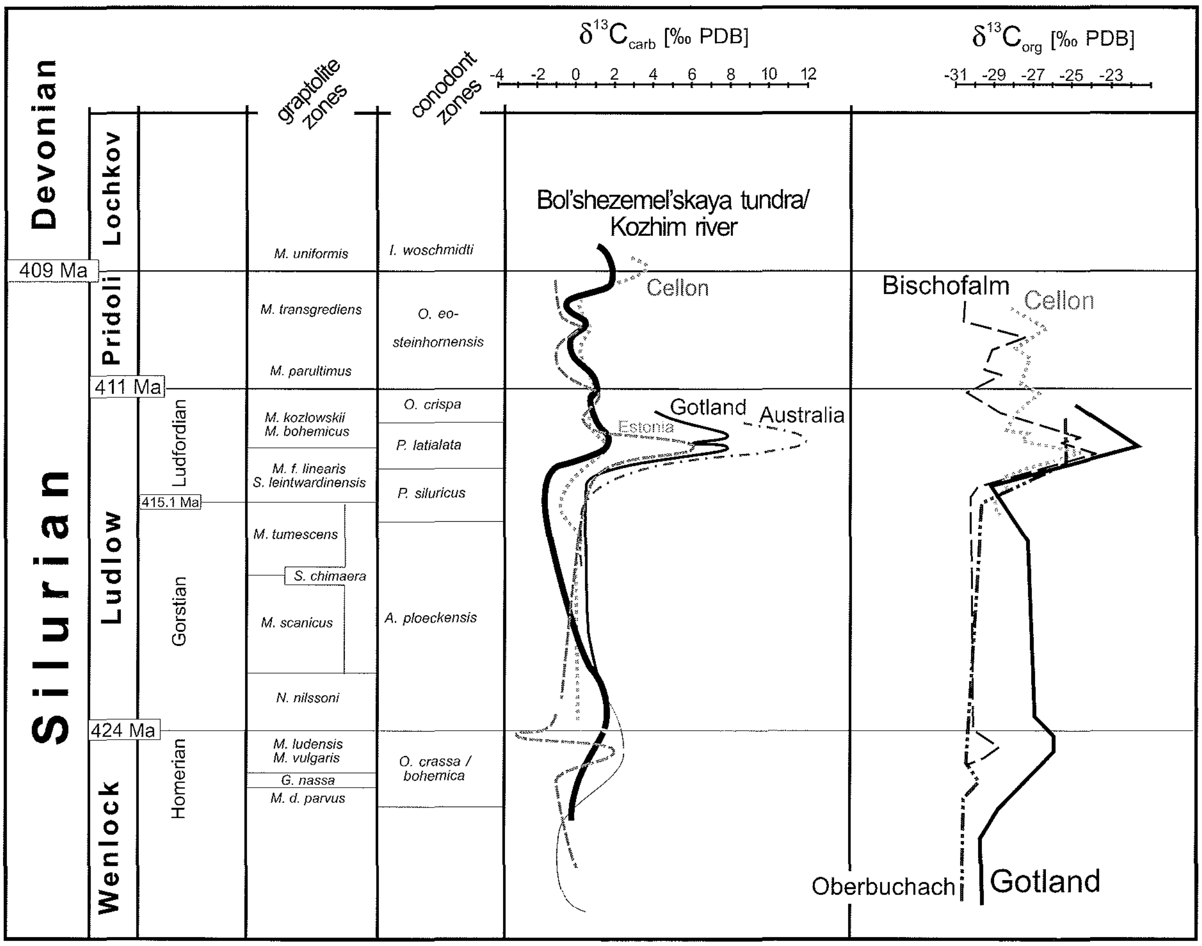

Fig. 8. Composite carbon isotope stratigraphy (carbonates and sedimentary bulk organic carbon) for the Upper Silurian; $\delta^{13}C_{carb}$ data for Kozhim river and Cellon section *after* Wenzel (1997), for Gotland after Wenzel & Joachimski (1996), for Estonia *after* Kaljo & *al.* (1997) and for Australia *after* Andrew & *al.* (1994); $\delta^{13}C_{\text{organic carbon}}$ – Bischofalm, Cellon, Oberbuchach: Wenzel 1997; Gotland – Jux & Steuber 1994, Wenzel 1997

northeastern edge of the East European Plate (Timan-Pechora region, this study), samples from the Baltic area (Gotland: SAMTLEBEN & *al.* 1996, WENZEL & JOACHIMSKI 1996; Estonia: KALJO & *al.* 1997), and carbonate whole rock samples from Austria (Carnic Alps: WENZEL 1997) and Australia (ANDREW & *al.* 1994). A coeval positive shift of sedimentary organic carbon isotope values was observed for the Gotland sections (JUX & STEUBER 1992, WENZEL 1997) and deeper water shales exposed in the Carnic Alps (WENZEL 1997; Text-fig. 8 of this study). Isotopic signatures of Lower Ludlow (Gorstian) brachiopods from the Timan-Pechora region and Gotland are relatively similar, whereas isotopic values of brachiopods from the upper Ludfordian of Gotland, Estonia, and Australia ($\delta^{13}C$ > +5‰) are much higher than those for samples of the Timan-Pechora region ($\delta^{13}C$: +1.5‰ – see Text-fig. 8). Given the above discussed indications for diagenetic alteration of $\delta^{13}C$ values in the Russian brachiopod shells, this could in part be due to differential preservation. But the general coincidence of relative variations in the carbon isotopic values for a number of globally distributed areas suggests that at least the original trend is still preserved.

Regional differences can be also observed in the oxygen isotopic values of NL brachiopod shells from Gotland and the Bol'shezemel'skaya Tundra sections. Lower Ludlow (Gorstian) samples from both areas exhibits relatively similar $\delta^{18}O$ values, whereas much higher $\delta^{18}O$ contents characterize Upper Ludlow (Ludfordian) brachiopods from Gotland Text-fig. 9). Since microstructures, trace element contents and the scatter of $\delta^{18}O$ values in the Russian NL brachiopod shells do not indicate significant diagenetic alteration, this difference is most likely a primary feature. A similar spread of oxygen isotopic values was reported for Silurian brachiopod shells from other areas (WADLEIGH & VEIZER 1992) and it may be related to regional oceanographical differences of the shelf seas bordering the northeastern and southwestern edges of Baltica.

SUMMARY

Relatively complete sections of Upper Silurian shallow water shelf sediments are exposed in the Bol'shezemel'skaya Tundra. Uniform subtidal carbonate facies favored the development of continuous brachiopod lineages (mainly atrypids and athyrids) that can be used for stratigraphical subdivision and interregional correlation of the sections.

Trace element contents (Sr, Mn, Na, Fe) and shell microstructures of nonluminescent (NL-) brachiopods from the Bol'shezemel'skaya Tundra and Kozhim River compare well with data for modern brachiopods. It is therefore assumed that the shells were not strongly affected by diagenetic alteration. This is confirmed by the fact that significant differences of Sr and Na values of atrypids and spiriferids, as compared

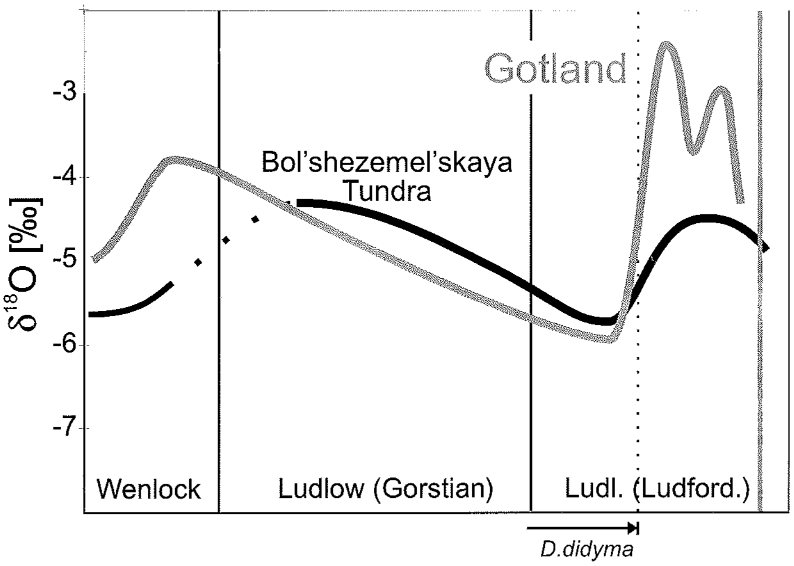

Fig. 9. Oxygen isotopic composition of Upper Silurian NL brachiopods from Bol'shezemel'skaya Tundra (*this study*) and Gotland (*after* WENZEL & JOACHIMSKI 1996); correlation of both samples sets is based on the distribution of *Didymothyris didyma* (*after* MODZALEVSKAYA & MÄRSS 1991)

to athyrids (*Greenfieldia*, *Didymothyris*, *Collarothyris*), can be observed. Scattered carbon isotopic values and much lower $\delta^{13}C$ values of the Russian brachiopods when compared to those of coeval Silurian brachiopods and modern samples indicate some degree of diagenetic alteration of this parameter. Small variations of $\delta^{18}O$ values for individual brachiopod populations (standard deviation < 0.5 ‰) and the similarity to Silurian brachiopod-based $\delta^{18}O$ data from other areas do not indicate significantly altered oxygen isotopic values. The resulting isotope curves for the Upper Silurian show a significant excursion at the level of *Didymothyris didyma* (Lower Ludfordian). Above this zone, increasing $\delta^{13}C$ values can be observed for brachiopods from the northeastern edge of the East European Platform (Timan-Pechora region) as well as for brachiopods and carbonate whole rock samples from the Baltic area (Gotland, Estonia), Austria (Carnic Alps) and Australia. The Middle Ludfordian isotope variation is thus probably a worldwide chemostratigraphical marker level, although the magnitude of the positive isotope excursion shows large interregional differences. Isotopic signatures of Lower Ludlow (Gorstian) brachiopods from the Timan-Pechora region are similar to those of Baltic brachiopods (Gotland), whereas much higher values are observed for upper Ludfordian samples from Gotland (Eke/Burgsvik beds: $\delta^{13}C$ +6 to 8‰; $\delta^{18}O$ –3 to –2.5‰ VPDB) when compared to samples from the Timan-Pechora region ($\delta^{13}C$: +1.5‰, $\delta^{18}O$: -5‰). This may be related to regional oceanographical and/or climatic differences between held seas bordering the northeastern and southwestern edges of Baltica.

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