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Stable oxygen and carbon isotopes in modern benthic foraminifera from the Laptev Sea shelf: implications for reconstructing proglacial and profluvial environments in the Arctic

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Abstract

Measurements of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopes in three benthic foraminiferal species from surface sediments of the eastern Laptev Sea are compared to water $\delta^{18}\text{O}$ values and $\delta^{13}\text{C}$ values of dissolved inorganic carbon (DIC). Samples investigated originate from two environmentally contrasting core locations, which are influenced by riverine freshwater runoff to a varying degree. At the river-distal site, located within relatively stable marine conditions on the outer shelf, *Elphidiella groenlandica*, *Haynesina orbiculare* and *Elphidium excavatum* forma *clavata* show a positive specific offset of 1.4‰, 1.5‰ and 1‰, respectively, in their $\delta^{18}\text{O}$ values relative to the expected value for inorganic calcite precipitated under equilibrium conditions. At the site close to the Lena River confluence, with enhanced seasonal hydrographic contrasts, calculated $\delta^{18}\text{O}$ offsets in *E. groenlandica* and in *H. orbiculare* remain about the same whereas *E. e. clavata* displays a distinctly negative offset of -1.8 ‰. The $\delta^{18}\text{O}$ variation in *E. e. clavata* is interpreted as a vital effect, a finding which limits the potential of this species for reconstructing freshwater-influenced shelf paleoenvironments on the basis of oxygen isotopes. This interpretation gains support when comparing foraminiferal $\delta^{13}\text{C}$ with the $\delta^{13}\text{C}_{\text{DIC}}$ of the water. While some of the difference in the carbonate $\delta^{13}\text{C}$ seems to be controlled by a riverine-related admixture of DIC, clearly defined $\delta^{13}\text{C}$ ranges in each of the three foraminifera at the river-proximal site shows that also the carbon isotopic signature in *E. e. clavata* is particularly affected by environmental factors.

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Keywords: benthic foraminifera; stable isotopes; Siberian shelves; Arctic paleoenvironment

1. Introduction

It is now widely accepted that the Arctic plays an important part in the climate system through changes

in surface ocean properties and atmospheric circulation (Aagaard and Carmack, 1989; Dickson, 1999; Mysak, 2001). Detailed environmental studies in the north polar region may therefore give important clues for the interpretation of modern and past global climate change (Bauch et al., 2000). A major factor of the Arctic system is the seasonal and interannual variability of sea-ice coverage, which

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Table 1

List of stable isotope and salinity data obtained from the Laptev Sea during TRANSDRIFT II expedition in 1994

Station	Sampling depth (m)	Coordinates		Bottom depth (m)	Salinity	$\delta^{18}\text{O}$ (‰VSMOW)	$\delta^{13}\text{C}_{\text{DIC}}$ (‰PDB)
		Lat. N	Long. E				
PM9470	2	72.5	130.5	15	4.696	−15.22	−3.10
PM9470	9	72.5	130.5	15	12.91	−12.27	−1.86
PM9468	2	73	130.5	22	5.104	−14.61	−4.03
PM9468	17	73	130.5	22	—	−5.05	−1.67
PM9466	2	73.5	130.5	26	11.77	−13.59	−1.95
PM9466	17	73.5	130.5	26	29.48	−4.08	−1.32
PM9474	2	72	134	17	8.307	−15.05	−2.42
PM9474	11	72	134	17	16.33	−10.77	—
PM9476	2	72.5	134	23	9.489	−14.91	−1.9
PM9476	18	72.5	134	23	27.91	−9.42	−1.35
PM9478	2	73	134	18	9.253	−14.37	−1.99
PM9478	13	73	134	18	20.16	−8.54	−2.03
PM9480	2	73.5	134	16	11.67	−13.49	−1.62
PM9480	13	73.5	134	16	27.09	−9.93	−0.9
PM9441	2	74	126	14	15.38	−11.87	−1.58
PM9441	8	74	126	14	15.95	−11.31	−1.53
PM9438	2	74	127.5	28	14.42	—	−1.57
PM9438	23	74	127.5	28	28.8	−5.03	−1.76
PM9435	2	74	129	15	12.95	−12.24	−1.88
PM9435	7	74	129	15	15.19	−11.11	−1.56
PM9433	2	74	130.5	25	14.63	−9.63	−1.59
PM9433	20	74	130.5	25	30.95	−3.91	−1.44
PM9431	2	74	131.5	22.5	14.86	−12.42	−1.49
PM9431	17	74	131.5	22.5	29.56	−5.09	−1.51
PM9429	2	74	132.5	11	13.93	−11.49	−1.42
PM9429	6	74	132.5	11	18.35	−10.34	−1.35
PM9428	2	74	133.5	12.7	17.53	−11.81	−1.31
PM9428	8	74	133.5	12.7	22.27	−9.33	−1.07
PM9426	2	74	134.5	13	15.51	−11.68	−1.37
PM9426	9	74	134.5	13	20.82	−8.35	−1.16
PM9425	2	74	135	19	15.16	—	−1.22
PM9425	14	74	135	19	22.77	−8.39	−0.32
PM9443	2	74.5	126.5	38	19.93	−8.86	−0.89
PM9443	33	74.5	126.5	38	31.7	−3.70	−1.21
PM9445	2	74.5	127.5	35	17.96	−8.87	−1.16
PM9445	35	74.5	127.5	35	31.29	−5.50	−0.57
PM9447	2	74.5	128.5	37	18.07	−8.80	−1.01
PM9447	32	74.5	128.5	37	31.55	−3.59	−1.25
PM9449	2	74.5	129.5	38	18.12	−10.52	−1.3
PM9449	33	74.5	129.5	38	32	−2.79	−1.21
PM9451	2	74.5	130.5	25	21.24	−9.40	−0.55
PM9451	25	74.5	130.5	25	30.6	−4.53	−1.05
PM9455	2	74.5	132.5	14	18.08	−8.68	−0.93
PM9455	10	74.5	132.5	14	21.55	−8.59	−0.71
PM9457	2	74.5	133.5	11	20.62	−8.29	−0.56
PM9457	5	74.5	133.5	11	20.63	−9.29	−0.59
PM9459	2	74.5	134.5	18	21.58	−8.81	−0.44
PM9459	13	74.5	134.5	18	24.76	−7.11	−0.33
PM9461	2	74.5	136	27	22.08	−9.11	—
PM9461	22	74.5	136	27	31.12	−4.34	−0.87
PM9403	2	75.5	116	24.3	30.49	−2.55	0.94

Table 1 (continued)

Station	Sampling depth (m)	Coordinates		Bottom depth (m)	Salinity	$\delta^{18}\text{O}$ (‰VSMOW)	$\delta^{13}\text{C}_{\text{DIC}}$ (‰PDB)
		Lat. N	Long. E				
PM9403	10	75.5	116	24.3	30.49	−2.69	0.89
PM9403	20	75.5	116	24.3	30.66	−2.86	0.73
PM9409	2	75.52	122.1	52.5	31.43	−1.78	1.19
PM9409	46	75.52	122.1	52.5	33.69	−1.69	0.35
PM9411	2	75.5	124	44.8	28.15	−4.73	0.11
PM9411	40	75.5	124	44.8	33.26	−2.08	−0.30
PM9415	2	75.5	128	47	27.53	−4.38	0.57
PM9415	42	75.5	128	47	33.14	−1.39	0.12
PM9419	2	75.5	132	15	25.24	−6.98	−0.10
PM9419	10	75.5	132	15	25.28	−6.91	−0.17
PM9421	2	75.5	134	34	25.74	−5.83	0.10
PM9421	29	75.5	134	34	31.8	−2.97	−0.30
PM9424	2	75.95	136.7	19	25.29	−5.89	0.15
PM9424	13	75.95	136.7	19	25.57	−6.59	0.12

is directly related to both surface salinity and temperature. Changes in salinity and temperature are most apparent in the circum-Arctic shelf seas, which usually become ice-free during the short summer season. The impact on salinity is particularly strong on the shallow Siberian shelves where huge amounts of riverine water are being discharged each summer. This riverine freshwater affects the shelf water not only by lowering its salinity but it also causes a change in the $\delta^{18}\text{O}$ composition. Because of the linkage between $\delta^{18}\text{O}$ and salinity, investigating the $\delta^{18}\text{O}$ in fossil calcite offers a chance to derive information of salinity changes on geological time scales (e.g., Duplessy et al., 1991) if other controlling factors, such as past global ice volume as well as variations in temperature and freshwater influence for the given location, are reasonably well constrained.

Stable isotope studies on Arctic shelves are often based on certain benthic foraminifers such as the widely spread foraminiferal group of Elphidiids. These species are typical inhabitants of many shallow water, formerly proglacial shelf environments (Erlenkeuser, 1985; Poole, 1994; Bodén et al., 1997). For the interpretation of isotope data from such highly variable environments like the shallow Arctic Siberian seas, it seems imperative to determine in detail the effect of these environmental factors on isotope fractionation of the species under investigations. This is particularly important when evaluating sediment records from the Siberian

shelves that cover the last glacial to Holocene time interval because of changes in northern Eurasian ice sheet configuration and sea level during this time. Concurrent with the postglacial sea level rise, the northern Eurasian shelves were subjected to extensive coastline migrations from the outer to the inner shelf (Bauch et al., 1999), and locations with nowadays relatively stable marine conditions were at certain times, during the earlier Holocene, exposed to enhanced freshwater input from deglacial and riverine sources (Hald et al., 1999; Polyak et al., 2000; Bauch et al., 2001; Lubinski et al., 2001).

In order to better evaluate the tool of benthic foraminiferal isotopes for interpreting the paleohydrography of the shallow marine shelf seas in the Arctic (e.g., Duplessy et al., 2001; Polyak et al., 2002a,b), we investigate in this study the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the benthic foraminifera *Elphidiella groenlandica*, *Haynesina orbiculare* and *Elphidium excavatum* forma *clavata* from surface sediments of the Laptev Sea. These data are compared to $\delta^{18}\text{O}$ values of the bottom water and pore water of the sediments. In addition, we also have analyzed $\delta^{13}\text{C}$ values of dissolved inorganic carbon (DIC) in the bottom water to make some further assumptions on foraminiferal ecology. The two sites selected represent a river-proximal as well as a river-distal hydrographical and depositional regime. By choosing these two contrasting environments, we expect to obtain an understanding of the sensitivity of isotope fraction-

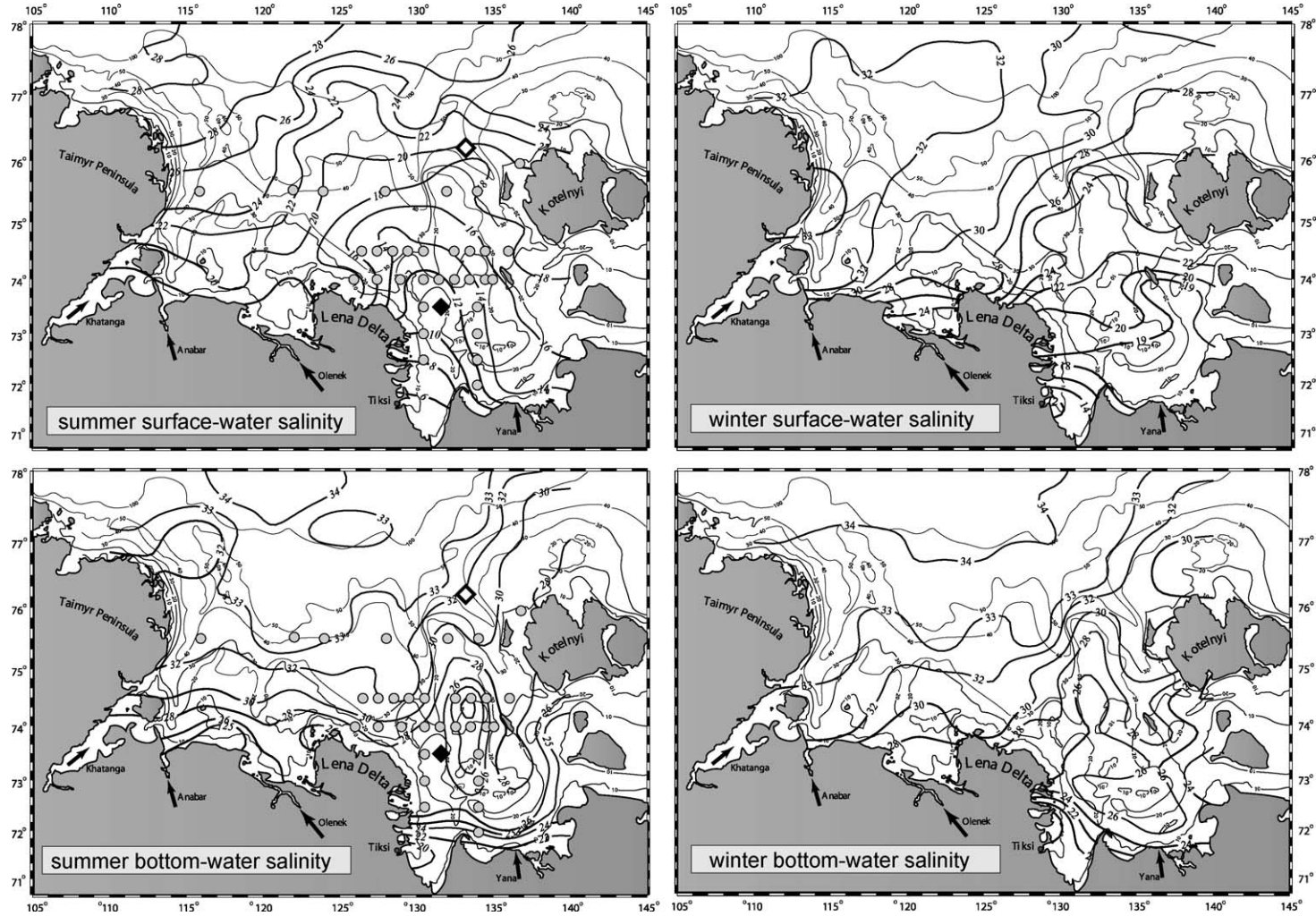


Fig. 1. Bathymetrical map (isobaths in meters) of the Laptev Sea showing the two studied locations (\diamond =PS51/135; and \blacklozenge =PS51/80) and average winter and summer salinity isolines (salinity maps redrawn from Stepanova et al., 2003); grey dots mark water stations visited during TRANSDRIFT II (see Table 1).

Table 2

Isotope data of benthic foraminifera from surface sediments of core PS51/80 at 73°28' N and 135°39' E (21 m water depth) and core PS51/135 at 76°10' N and 133°15' E (51 m water depth)

	$\delta^{13}\text{C}$ (‰) versus PDB	$\delta^{18}\text{O}$ (‰) versus PDB	Shells #
<i>Site PS51/80</i>			
<i>E. groenlandica</i>	–6.98	–0.35	1
	–8.07	0.09	1
	–9.72	–0.91	4
	–9.06	–0.98	1
	–8.78	–0.83	1
	–8.73	–0.81	1
	–15.36	–0.57	1
	–9.69	–0.49	1
	–10.74	–1.09	1
	–9.56	–0.93	1
	–10.19	–0.68	1
	–7.8	0.13	1
	–10.54	–0.75	1
	–6.68	–0.72	1
	–12.58	–0.86	1
	–8.6	–0.69	2
Average	–9.57	–0.65	
Sigma	2.13	0.35	
<i>H. orbiculare</i>	–6.51	–0.47	17
	–6.11	–0.44	16
	–6.62	–0.5	16
	–7.41	–0.48	16
Average	–6.66	–0.47	
Sigma	0.54	0.03	
<i>E. e. clavata</i>	–15.25	–3.86	25
	–15.97	–3.87	24
	–10.22	–4.61	24
	–13.08	–3.28	24
	–15.87	–3.87	18
Average	–14.08	–3.9	
Sigma	2.45	0.47	
<i>Site PS51/135</i>			
<i>E. groenlandica</i>	–1.44	2.74	1
	–1.69	2.6	1
	–1.7	2.85	1
	–1.72	2.76	1
	–1.55	2.55	1
	–1.5	2.85	1
	–1.34	2.93	1
	–1.55	2.77	1
	–1.47	2.64	1
	–1.17	2.69	1
	–1.42	2.78	1
	–1.72	2.64	1
	–1.48	2.89	1
	–1.49	2.64	1
	–1.4	2.75	1

Table 2 (continued)

	$\delta^{13}\text{C}$ (‰) versus PDB	$\delta^{18}\text{O}$ (‰) versus PDB	Shells #
<i>Site PS51/135</i>			
<i>E. groenlandica</i>	–1.46	2.62	1
	–1.44	2.84	1
Average	–1.5	2.74	
Sigma	0.15	0.11	
<i>H. orbiculare</i>	–1.67	2.77	16
	–1.13	3.03	16
	–1.34	2.89	16
	–1.82	2.71	16
Average	–1.49	2.85	
Sigma	0.31	0.14	
<i>E. e. clavata</i>	–2.26	2.34	18
	–2.21	2.33	20
	–2.23	2.28	20
	–2.35	2.27	20
	–2.27	2.31	20
	–2.11	2.36	20
	–2.10	2.39	35
	–2.25	2.36	28 ^a
Average	–2.22	2.33	
Sigma	0.08	0.04	

^a Dead specimens.

ation of foraminiferal species under various environmental conditions.

2. Material and methods

Profiles of water column samples for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}_{\text{DIC}}$ were collected during expedition TRANS-DRIFT II (Kassens and Dmitrenko, 1995) and are listed in Table 1. Bottom sediments and bottom water samples were obtained during expedition TRANS-DRIFT V in 1998 (Fig. 1). The actual bottom water and pore water of the underlying sediment were recovered with a multicorer (MUC). Using the water from the MUC seems advantageous because conventionally combined CTD–water sampling devices typically collect “bottom water” several meters above sea floor, and therefore may not reflect correctly the salinity of the actual bottom water. Water samples from the water column (100 ml) were treated with 0.2 ml of saturated HgCl_2 to stop biological activity. In addition to these samples, pore water was pressed from 1-cm-thick MUC sediment slices directly onboard under a nitrogen environment (1 bar atmospheric

pressure) and at 4 °C room temperature. The pore water samples were then stored at –30 °C.

All foraminifera studied are from the undisturbed upper 1 cm of sediment, which was taken from the surface of large trigger box corers. To later identify live foraminiferal specimens, sediment samples were treated with Rose Bengal. Due to the large test size of *Elphidiella groenlandica*, one to four specimens were used for isotope analysis. Because test sizes of *Haynesina orbiculare* and *Elphidium excavatum* forma *clavata* are smaller, multiple specimen samples were used for isotope analyses, respectively (Table 2). Isotope measurements of foraminiferal tests were conducted with the automated Kiel carbonate device (Finnigan-MAT Kiel Device Type I) for carbonate to CO₂ conversion coupled to a Finnigan-MAT 251 mass spectrometer and calibrated to the PDB scale by means of the NBS 20 carbonate isotope standard. The results are presented in the usual δ -notation. The analytical precision is ± 0.08 ‰ and ± 0.05 ‰ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$.

The water samples were analyzed for $\delta^{18}\text{O}$ applying the water–CO₂ isotope equilibration technique and a Finnigan-MAT Delta E mass spectrometer for isotope measurement. Results are calibrated to VSMOW via VSMOW, GISP and SLAP water isotope standards and are given in the δ -notation, the measurement precision being ± 0.05 ‰. Measurements of the $\delta^{13}\text{C}$ of the dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$) were carried out using the automated Kiel DICI-II device for CO₂ extraction and a Finnigan-MAT Delta E mass spectrometer (Erlenkeuser, 1995). Isotope results refer to the PDB scale (based on the NBS20 isotope standard)

and are given in the δ -notation; the measurement precision of the $\delta^{13}\text{C}_{\text{DIC}}$ is ± 0.04 ‰. The $\delta^{13}\text{C}_{\text{DIC}}$ analyses conducted on the MUC waters (TRANS-DRIFT V, 1998) are compared to water column $\delta^{13}\text{C}_{\text{DIC}}$ obtained from the Laptev Sea during TRANS-DRIFT II expedition in 1994 (Erlenkeuser, 1995).

The oxygen isotope “equilibrium calcite value”, δ_c , was calculated from water $\delta^{18}\text{O}$ (δ_w) and temperature (T), according to the paleotemperature equation of O’Neil et al. (1969) as cited by Shackleton (1974): $T = 16.9 - 4.38(\delta_c - \delta_w) + 0.1(\delta_c - \delta_w)^2$.

This equation was chosen because it covers a temperature range down to 0 °C. Conversion from $\delta^{18}\text{O}_w$ (VSMOW) to δ_w (PDB) is: $\delta_w = 0.9998 \times \delta^{18}\text{O}$ (VSMOW) – 0.2 ‰ (see Bemis et al., 1998). Applying the more recent paleotemperature equation of Kim and O’Neil (1997), with conversion of $\delta_w = 0.99973 \times \delta^{18}\text{O}$ (VSMOW) – 0.27 ‰, would lead to δ_c values which are about 0.6 ‰ lower (see Table 3), thereby also changing the estimated foraminiferal offsets by this value. Although, each equation yields different δ_c results on an absolute scale, using either of them would not affect the scope of our study, in general.

3. Hydrography

The Laptev Sea hydrography is dominated by an interaction between Arctic water masses advected from the north and riverine freshwater discharged from the south, especially from the Lena River. The Lena River is the second largest among all Arctic rivers with an

Table 3

Bottom water properties from long-term hydrographical observations (EWG, 1998; Dmitrenko and Kirillov, unpublished data) and from point measurements (August 1998)

Site		Salinity	T (°C)	$\delta^{18}\text{O}$ eq. calcite (‰ PDB) ^a		$\delta^{18}\text{O}$ eq. calcite (‰ PDB) ^b	
		\pm Sigma	\pm Sigma	Min.	Max.	Min.	Max.
PS51/80	Point value	26.4	– 0.92	– 2.15		– 2.70	
	Av. summer	27.9 \pm 0.5	– 1.02 \pm 0.06	– 1.87	– 0.98	– 2.43	– 1.47
	Av. winter	26.2 \pm 1.3	– 1.25 \pm 0.05	– 3.47	– 1.00	– 3.97	– 1.45
PS51/135	Point value	33.1	– 1.60	1.31		0.74	
	Av. summer	32.4 \pm 0.2	– 1.27 \pm 0.09	0.61	0.94	0.09	0.52
	Av. winter	32.6 \pm 0.3	– 1.49 \pm 0.06	0.60	1.18	0.16	0.08

Minimum and maximum $\delta^{18}\text{O}$ equilibrium calcite values were calculated using the average winter and summer values together with the concurrent 2-sigma standard deviation.

^a Using equation of O’Neil et al. (1969).

^b Using equation of Kim and O’Neil (1997).

annual discharge volume of 532 km³ (Global Runoff Data Center, 1998). The runoff is subject to strong seasonal variations (Fig. 1) with some notable interannual variability. The Lena River shows a 40-fold runoff increase from very low winter values to the peak flows in June and July, whereas interannual discharge rates vary by 5–20%. The surface water generally starts freezing in October (Eicken et al., 1997). After the river breaks up in early summer, a large brackish surface plume is formed that extends northward onto the shelf (Dmitrenko et al., 1999). Also with this water plume, increased amounts of suspended organic and inorganic matter is transferred onto the shelf (Gordeev et al., 1996; Mueller-Lupp et al., 2000).

The hydrographical data set used in our study was derived from many years of oceanographic monitoring (1960–1990) in the Laptev Sea (Environmental Working Group (EWG), 1998). The Russian monitoring data, as summarized in the EWG Atlas, were often obtained along defined oceanographic sections (see Kassens and Karpiy, 1994; Kassens and Dmitrenko, 1995) and are complemented in our study with sets of data obtained during many other Russian–German expeditions to the eastern Laptev Sea in the 1990s. The hydrography of the river-proximal site PS51/80 is affected by seasonal variations due to the

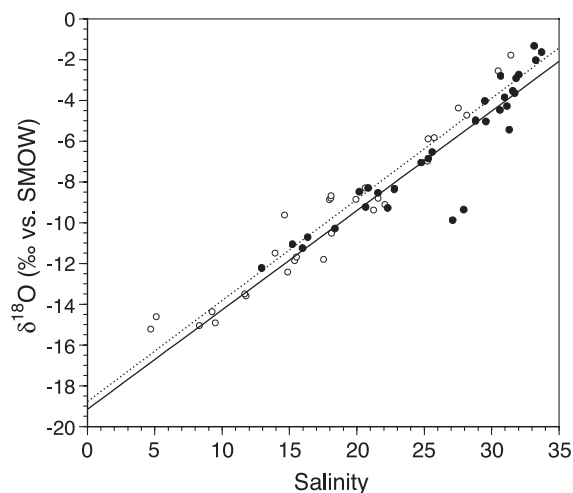


Fig. 2. $\delta^{18}\text{O}$ versus salinity of water samples from the Laptev Sea sampled during expedition TRANSDRIFT II in September 1994 (Kassens and Dmitrenko, 1995). The stippled line is a linear correlation of near-surface samples (○); the solid line shows the linear correlation of bottom waters (●).

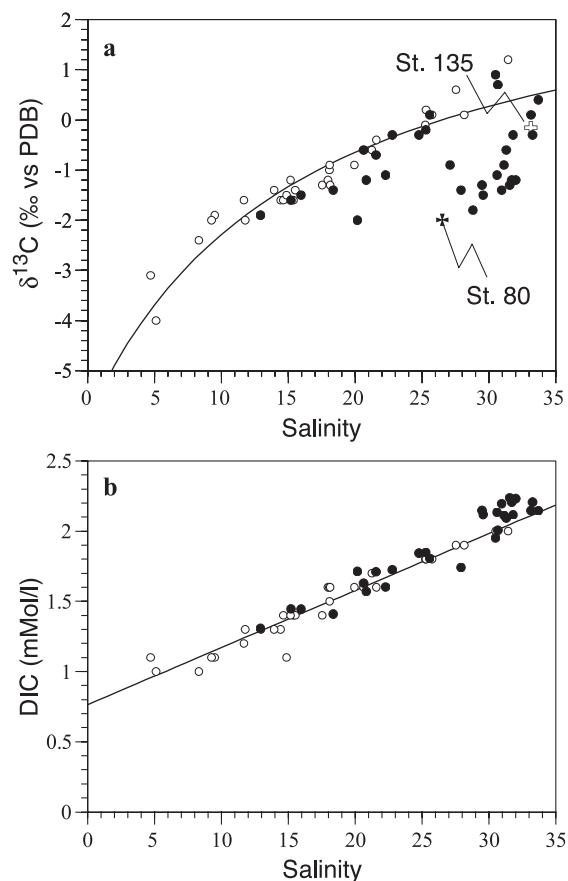


Fig. 3. DIC, salinity and $\delta^{13}\text{C}_{\text{DIC}}$ of water samples from the Laptev Sea sampled during expedition TRANSDRIFT II. Symbols of ○ depict surface samples and ● depict bottom samples. (a) $\delta^{13}\text{C}_{\text{DIC}}$ versus salinity; (b) DIC concentration versus salinity. Also indicated are the bottom water $\delta^{13}\text{C}_{\text{DIC}}$ values measured for the two sites (see also Table 4).

direct influence of riverine freshwater from the Lena River where the long-term hydrographical data show on average slightly higher bottom water salinity in summer than in winter (Table 3). The temperature variation with average values between -1.0 and -1.3 °C is negligible. At core position PS51/135, located in the northern Yana Valley far away from the river mouths, hydrographical data reveal no significant seasonal salinity variation, and bottom water temperatures also remain relatively constant with average values between -1.3 and -1.5 °C. All in all, the long-term observational data agree reasonably well with the oceanographic point values obtained

Table 4
Pore water $\delta^{18}\text{O}$ and temperature measurements together with calculated equilibrium calcite values

Site	Sediment depth (cm)	$\delta^{18}\text{O}$ (‰ VSMOW)	T ($^{\circ}\text{C}$)	$\delta^{13}\text{C}_{\text{DIC}}$ (‰)	$\delta^{18}\text{O}$ eq. calcite (‰ PDB) ^a	$\delta^{18}\text{O}$ eq. Calcite (‰ PDB) ^b
PS51/080	BW	−6.33 ^c	−0.92	−1.92	−2.15	−2.70
	0.5	−5.95	−0.92		−1.77	−2.32
	2.5	−5.97	−0.92		−1.78	−2.34
	5.5	−5.25	−0.92		−1.07	−1.62
PS51/135	BW	−3.06 ^c	−1.6	−0.11	1.31	0.74
	0.5	−2.31	−1.6		2.07	1.50
	2.5	−1.91	−1.6		2.47	1.90
	5.5	−2.09	−1.6		2.28	1.71

For comparison, calculated $\delta^{18}\text{O}$ values of bottom water (i.e., surface sediment) are also shown.

^a Using equation of O'Neil et al. (1969).

^b Using equation of Kim and O'Neil (1997).

^c $\delta^{18}\text{O}$ value derived from salinity measurement and $\delta^{18}\text{O}$ / salinity correlation of bottom waters (BW).

during TRANSDRIFT V expedition in August of 1998.

4. Water stable isotopes

Due to isotope fractionation effects and successive precipitation from the atmospheric moisture moving from west to east across the Eurasian continent (e.g., Dansgaard, 1964), Siberian river water is highly depleted in ^{18}O . Salinity and $\delta^{18}\text{O}$ values from stations near the Lena River mouth to the northern Laptev Sea reveal an overall linear correlation (Fig. 2). This correlation documents the mixing between freshwater discharged by the rivers and seawater. For zero salinity, a $\delta^{18}\text{O}$ value of -18.86 ‰ is obtained by extrapolation. Such a value for the freshwater end member is very similar to $\delta^{18}\text{O}$ values of -18.9 ‰ and -20.6 ‰ measured directly on water from the Lena River mouth (Létolle et al., 1993; Bauch et al., 1995). Thus, the relationship between $\delta^{18}\text{O}$ and salinity for all surface water samples can be described with the following equation:

$$\delta^{18}\text{O} [\text{‰}] = S \cdot 0.48 - 18.61 [\text{‰}] (r^2 = 0.915),$$

where S is salinity (see dashed line in Fig. 2).

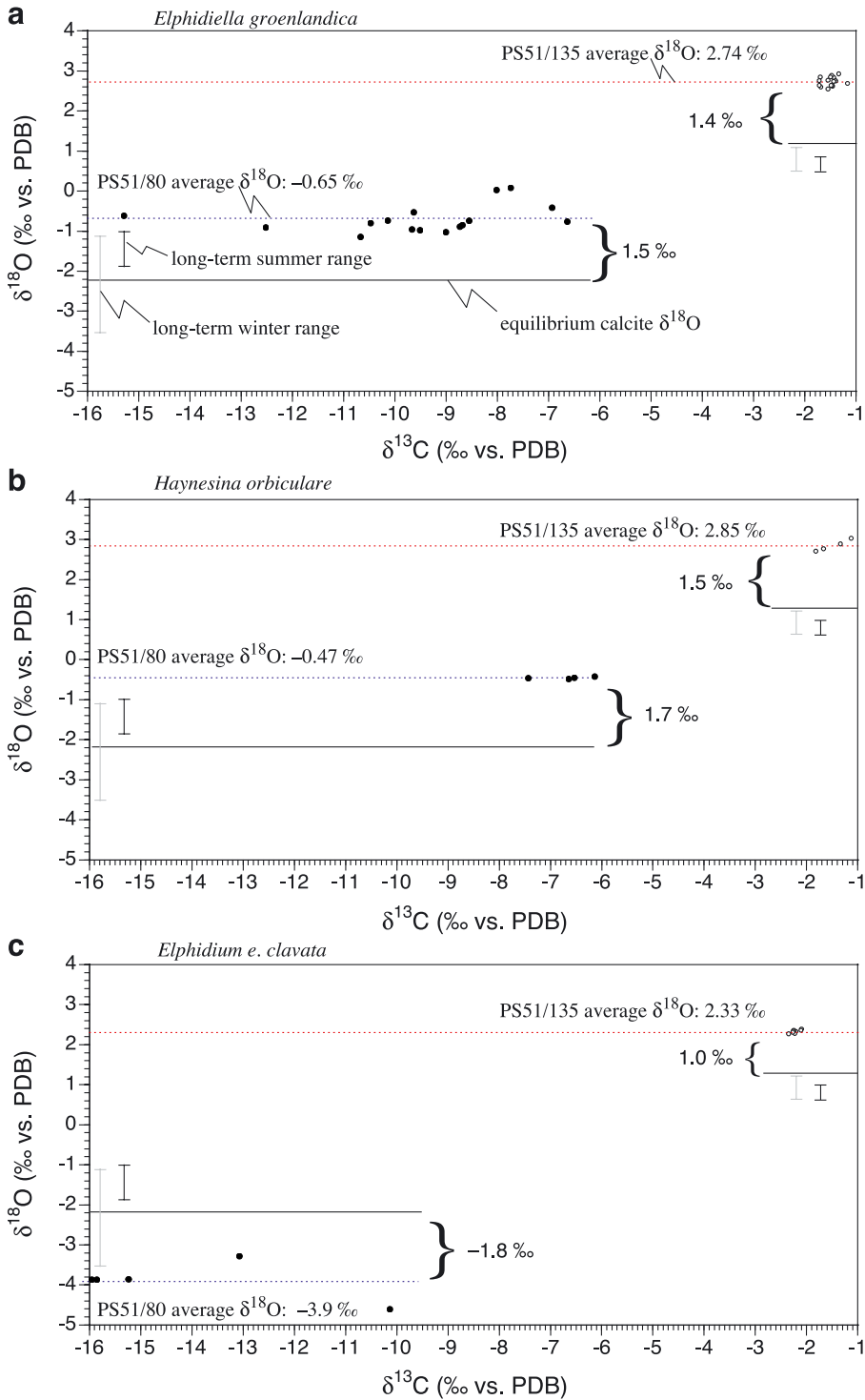
The slope of the $\delta^{18}\text{O}$ and salinity correlation for bottom water is slightly steeper (see solid line in Fig. 2), probably due to the influence of brines added to the bottom water by sea–ice formation in winter. Consequently, the apparent freshwater end member is thereby slightly lower. Bottom water values can be described with the equation:

$$\delta^{18}\text{O} [\text{‰}] = S \cdot 0.49 [\text{‰}] - 19.20 [\text{‰}] (r^2 = 0.857)$$

The $\delta^{13}\text{C}_{\text{DIC}}$ in the Laptev Sea is also strongly influenced by river water with low DIC concentration and a highly depleted $\delta^{13}\text{C}$ signal (Fig. 3). Due to changes in DIC concentration of the waters, the theoretical correlation between salinity and $\delta^{13}\text{C}_{\text{DIC}}$ is nonlinear (Erlenkeuser et al., 2003). Applying such a correlation between surface salinity and $\delta^{13}\text{C}_{\text{DIC}}$ would reveal a riverine $\delta^{13}\text{C}_{\text{DIC}}$ end member of about -6.5 ‰. Strong departure from the theoretical curve of average salinities, as observed for site PS51/80 (Fig. 3, Table 4), can be explained by remineralization of highly depleted organic matter, material which was either produced by local plankton blooms or discharged by the Lena River itself (Erlenkeuser, 1995).

Using the CTD databases (EWG, 1998; Dmitrenko et al., 1999; Dmitrenko et al., 2001; Dmitrenko and Kirillov, unpublished data), the bottom water condi-

Fig. 4. Property plot of shell $\delta^{18}\text{O}$ versus $\delta^{13}\text{C}$ values for surface samples from site PS51/80 and site PS51/135. Results are shown for all three benthic species: (a) *Elphidiella groenlandica*, (b) *Haynesina orbiculare* and (c) *Elphidium excavatum* forma *clavata*. The solid lines represent the equilibrium calcite value calculated for inorganic calcite precipitated in equilibrium with bottom water. Also given are the average values in $\delta^{18}\text{O}$ of the foraminifera and their offsets in $\delta^{18}\text{O}$ relative to equilibrium calcite values. The vertical bars indicate for each site the potential range of $\delta^{18}\text{O}$ equilibrium calcite value for summer and winter, respectively, as calculated from average long-term hydrographical observations (see Table 2).



tions together with seasonal and interannual variability were determined for the core sites, and corresponding equilibrium calcite values were derived by applying the $\delta^{18}\text{O}$ /salinity correlation for bottom water and by the paleotemperature equation (Table 3). On the basis of the 2-sigma deviations of average summer and winter conditions, for PS51/135, where only small seasonal changes occur, a range of equilibrium calcite values between 0.6‰ to 1.2‰ $\delta^{18}\text{O}$ is estimated. For site PS51/80, the overall larger seasonal variability leads to equilibrium calcite values that range between -1.9 ‰ and -1.0 ‰, and -3.5 ‰ and -1.0 ‰ for summer and winter, respectively.

5. Foraminiferal stable isotopes

At the two selected core positions, multiple samples of *Elphidiella groenlandica*, *Haynesina orbiculare* and *Elphidium excavatum* forma *clavata* were analyzed for their stable isotope composition and presented in comparison to equilibrium calcite values derived from bottom water properties (Fig. 4). These three species were chosen because they are frequently found in the Laptev Sea and on other Arctic shelves (Todd and Low, 1966; Tamanova, 1971; Lukina, 1990; Khusid, 1996; Bude, 1997). Moreover, they all have a clear affinity to

low-salinity, shallow water habitats (Korsun, 1999; Korsun and Hald, 2000; Polyak et al., 2002a,b) which makes them useful for understanding Arctic environmental change in a geological context.

In accordance with the overall south-to-north changes in salinity and riverine influence, all species show relatively high values in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ at site PS51/135 and low values at site PS51/80 (Fig. 4). Offsets in $\delta^{18}\text{O}$ between equilibrium calcite and *Elphidiella groenlandica* and *Haynesina orbiculare* are for both core positions positive and rather constant, within uncertainties. *Elphidium excavatum* forma *clavata* shows contrasting offsets in $\delta^{18}\text{O}$ relative to equilibrium calcite at the two core positions. Although this species also exhibits a positive offset from equilibrium calcite at site PS/135, similar to the other two species, the deviation is strictly negative at site PS15/80, quite opposite to *E. groenlandica* and *H. orbiculare* (Fig. 4c).

The range of $\delta^{13}\text{C}$ in each species is small at site PS51/135 (Figs. 4 and 5). The $\delta^{13}\text{C}$ values of *Elphidiella groenlandica* and *Haynesina orbiculare* are both about -1.5 ‰, while average values in *Elphidium excavatum* forma *clavata* are slightly lighter by about 0.75‰ (Table 2). This picture differs quite substantially at site PS51/80 where a large scatter is noted for *E. groenlandica* (av. -9.57 ‰)

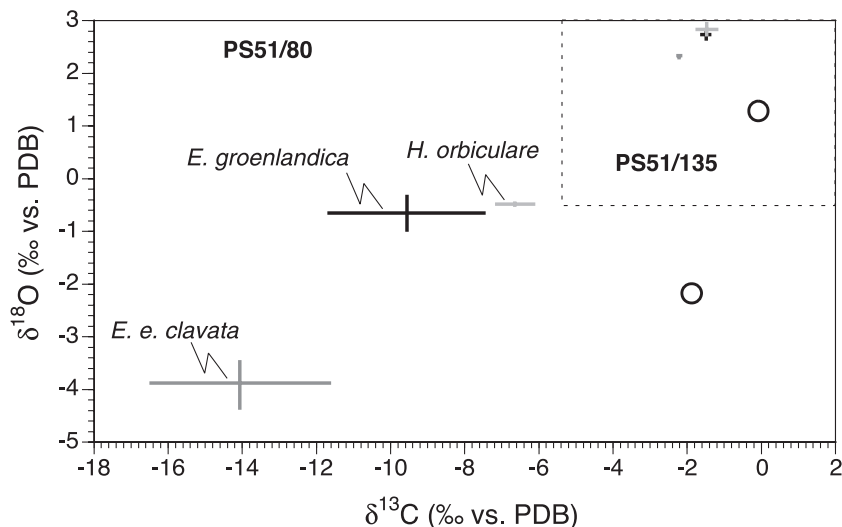


Fig. 5. Property plot of average $\delta^{18}\text{O}$ and average $\delta^{13}\text{C}$ values for *Elphidiella groenlandica* (black bar), *Haynesina orbiculare* (light grey line) and *Elphidium excavatum* forma *clavata* (dark grey bar) from surface samples of site PS51/80 and site PS51/135 (top right inset). The length of bars indicate the standard deviation. Symbols of ○ show equilibrium calcite $\delta^{18}\text{O}$ (expected) and $\delta^{13}\text{C}_{\text{DIC}}$ values in the bottom water at each site.

and *E. e. clavata* (av. -14.08‰). The large $\delta^{13}\text{C}$ range in *E. groenlandica* may partly be due to the performed single-test measurements. By far, the smallest range in all three species is noted for *H. orbiculare* whose average $\delta^{13}\text{C}$ value is -6.66‰ and, coincidentally, very close to the $\delta^{13}\text{C}_{\text{DIC}}$ extrapolated for Lena River water (Figs. 3 and 5).

6. Ecological and environmental implications

The life cycle of benthic foraminifera may span over a year; however, their main period of growth and calcification is often assumed to occur primarily during the vegetation season (e.g., Graf et al., 1995; Wollenburg and Mackensen, 1998). Although the river ice break in early June is due to highest solar radiation, the Laptev Sea becomes ice-free only during the period of August–September. Therefore, it may be concluded that the stable isotope composition of benthic foraminiferal calcite in the Laptev Sea is mainly reflecting the open water season during middle to late summer and/or the early autumn–winter period when suspended matter is more likely to settle on the sea floor due to extensive ice coverage (Wegner et al., 2003). On the other hand, each species likely has its very own habitat

and ecological preference, e.g., living an epifaunal or infaunal mode, relying on a certain food source and a specific time period of enhanced biological activity to form its calcite test. To our knowledge, there are no reports relating to the mode of life of *Elphidiella groenlandica*. *Elphidium excavatum* forma *clavata* may be living either within the sediment or on the seafloor, and *Haynesina orbiculare* is usually referred to as infaunal species (Murray, 1991). Moreover, it is generally assumed that infaunal species tend to have negative $\delta^{13}\text{C}$ values due to the oxidation of organic matter which causes a depletion in ^{13}C of the sediment pore water (e.g., Woodruff et al., 1980; Murray, 1991). From the comparison with the pore water $\delta^{18}\text{O}$ values alone, it may be concluded that all three species were calcifying at greater sediment depth at site PS51/135, but only *E. groenlandica* and *H. orbiculare* at site PS51/80 (Fig. 6). However, such an assumption is hard to reconcile considering that all analyzed specimens came from the approximately uppermost 1 cm of the sediment. If at all, it is more conceivable that the foraminiferal isotopes are affected by a seasonal overprint which is most strongly expressed at site PS51/80.

The oceanographic data used by us to derive the equilibrium calcite values and species-dependent offsets for site PS51/135 are single-point measurements

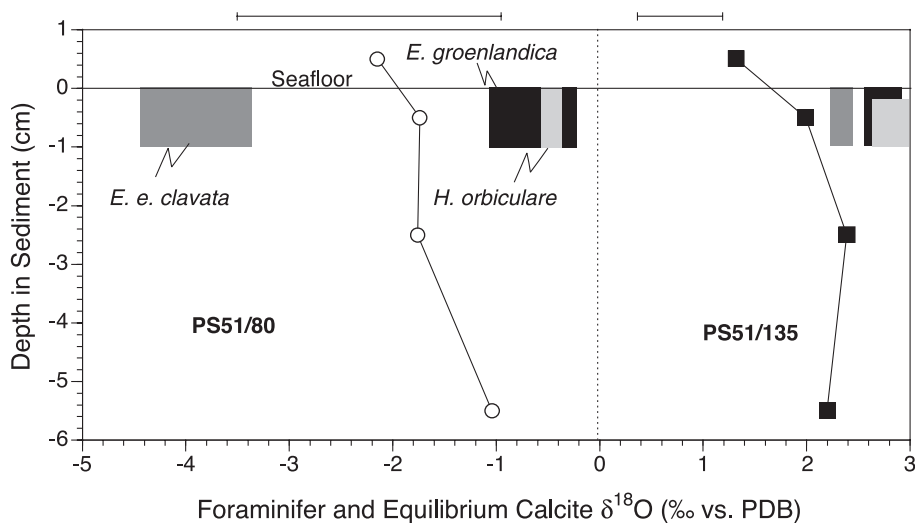


Fig. 6. Depth profiles of equilibrium calcite $\delta^{18}\text{O}$ values of pore water and bottom water for site PS51/80 (○) and site PS51/135 (■). Average $\delta^{18}\text{O}$ values of *Elphidiella groenlandica* (black bar), *Haynesina orbiculare* (light grey bar) and *Elphidium excavatum* forma *clavata* (dark grey bar) are also shown. The length of the bars represents the standard deviations. The lines on top of the graph indicate the potential range in $\delta^{18}\text{O}$ equilibrium calcite value calculated from average long-term hydrographical observations (see Table 3).

obtained during August 1998 (TRANSDRIFT V). This may lead to the conclusion that the oceanographic data are biased reflecting this particular midsummer season only and not an interannual average. Comparing our point measurements with the long-term observations from the database (Table 3, Fig. 4) as well as with the $\delta^{18}\text{O}$ values of the sediment pore water (Table 4, Fig. 6) reveals a slight deviation between the range of equilibrium calcite values, as derived from average summer and winter salinities and temperatures, and the point values taken directly from the MUC bottom water. Considering that CTD bottom water is usually sampled several meters above sea floor, the small offset of about 0.1 ‰ between equilibrium calcite and the point measurement made on the MUC bottom water seems negligible. Because the conditions at site PS51/135 are rather stable over the seasons, the offsets of 1.4 ‰, 1.5 ‰ and 1 ‰ between the $\delta^{18}\text{O}$ of equilibrium calcite and $\delta^{18}\text{O}$ values of *Elphidiella groenlandica*, *Haynesina orbiculare* and *Elphidium excavatum* forma *clavata* could be regarded as species-dependent, at least for this nearly full-marine shelf environment. The estimated uncertainties of these offset values are between 0.1 ‰ to 0.3 ‰, based on standard deviation of the multiple analyses and uncertainties in the equilibrium calcite values (Tables 2 and 3). The observed positive offsets for all three species analyzed by us at site PS51/135 is in contrast to studies which mainly revealed a negative offset for *E. e. clavata* (Polyak et al., 2003), *Elphidium excavatum* (Poole, 1994) and *Elphidium* spp. (Erlenkeuser and von Grafenstein, 1999). Because they used the same species, the recent investigation by Polyak et al. (2003) in the Kara Sea area, where seasonal environmental conditions are quite comparable to the Laptev Sea, appears conflicting. These authors found an average $\delta^{18}\text{O}$ offset of about -0.6 ‰ for *E. e. clavata*, while a single measurement on a sample with *H. orbiculare* yielded a value close to equilibrium calcite.

At site PS51/80, the $\delta^{18}\text{O}$ disequilibrium offsets in *Elphidiella groenlandica* and *Haynesina orbiculare* are constant within uncertainties relative to PS51/135, while *Elphidium excavatum* forma *clavata* responds quite differently to the highly variable river-proximal environment by showing an offset of -1.8 ‰; this value deviates by 2.8 ‰ relative to the offset observed at PS51/135 under relatively stable marine conditions. There are two possible explanations for the large $\delta^{18}\text{O}$

deviation in *E. e. clavata* between the two core positions: (1) *E. e. clavata* reflects equilibrium calcite values but of a different seasonal period than those sampled; (2) *E. e. clavata* exhibits a different isotopic fractionation in response to strong seasonal changes in environmental conditions; that is, it shows a vital effect. Although seasonal variations at core position PS51/80 are relatively large compared to PS51/135 (see Fig. 4, Table 3), they are very small to allow for a constant 1 ‰ offset in *E. e. clavata*. From the fact that the other two species keep their positive offset from the equilibrium calcite at site PS51/80, it is evident that the isotope fractionation of the species *E. e. clavata* is the one that changes under different environmental conditions. *Elphidium e. clavata* is well known to live in various highly stressed environments (Lutze, 1965; Korsun and Hald, 2000), and maybe its particular survival strategies are also imprinted in its oxygen isotopic composition (Hunt and Corliss, 1993). This assumption is supported when comparing our study with the data set from the Kara and Pechora seas, where the disequilibrium offset in $\delta^{18}\text{O}$ of *E. e. clavata* can also be both negative and positive (Polyak et al., 2003).

In contrast to oxygen isotope compositions, the reasons for differences in foraminiferal $\delta^{13}\text{C}$ are commonly less well understood as these are the combined result of both physical and biological processes. It has been noted, however, that endobenthic-living species are more prone to incorporate carbon which derives from remineralized, relatively ^{13}C -depleted organic matter, whereas epifaunal species usually reflect positive $\delta^{13}\text{C}$ (e.g., Zahn et al., 1986; McCorkle et al., 1997). Moreover, because of downward increase of remineralization CO_2 concentrations in the pore water, it is reported that dwellers living deeper in the sediment have lower $\delta^{13}\text{C}$ values than species with a shallower sediment depth habitat (Rathburn et al., 1996; McCorkle et al., 1997). Despite lack of available pore water $\delta^{13}\text{C}_{\text{DIC}}$ data in our study, it is interesting to observe different offsets between foraminiferal $\delta^{13}\text{C}$ and $\delta^{13}\text{C}_{\text{DIC}}$ in the bottom water of the two stations (Fig. 5). While at station PS51/135 this offset is with about 1.6 ‰ to 2 ‰ relatively similar for all three species investigated, at station PS51/80 each species shows its rather own distinct range. At site PS51/80, in proximity to the riverine source, $\delta^{13}\text{C}_{\text{DIC}}$ values of bottom water show a significant gradient within a

small salinity range of 26 to 33 (Fig. 3), presumably due to remineralization of highly depleted organic matter either derived from local plankton production or from suspended organic matter discharged by the Lena River itself (Erlenkeuser, 1995; Mueller-Lupp et al., 2000).

The strong variation in $\delta^{13}\text{C}_{\text{DIC}}$ evidently seems to play a significant role in the observed foraminiferal $\delta^{13}\text{C}$ offsets. Although epibenthic foraminifers are often expected to reflect the $\delta^{13}\text{C}_{\text{DIC}}$ of the ambient water (Zahn et al., 1986; Mackensen et al., 1993; McCorkle and Keigwin, 1994; Polyak et al., 2003), the shell $\delta^{13}\text{C}$ composition of endobenthic species is also influenced by several other environmental factors (McCorkle et al., 1997). Such an influence is clearly recognizable in the large offsets between the $\delta^{13}\text{C}_{\text{DIC}}$ and the foraminiferal $\delta^{13}\text{C}$ of the various species at site PS51/80 (Fig. 5). From the ecological point of view, different species-dependent microhabitat behaviour, such as food source, sediment depth habitat and seasonal preference (Linke, 1992; Corliss and van Weering, 1993; Korsun and Hald, 2000), could be likely responsible for a different $\delta^{13}\text{C}$ composition. Taking the negative calcite $\delta^{13}\text{C}$ data at face value, all three species must have an infaunal habitat, with *Haynesina orbiculare* and *Elphidiella groenlandica* living at shallower depth than *Elphidium excavatum* forma *clavata*; this is somewhat opposite to the pore water $\delta^{18}\text{O}$ results, which, at site PS51/135, could also be interpreted with a slightly deeper habitat for *H. orbiculare* and *E. groenlandica* than for *E. e. clavata* (Fig. 6).

Although no pore water $\delta^{13}\text{C}_{\text{DIC}}$ data are available for comparison, the clear separation of each species on the basis of their calcite $\delta^{13}\text{C}$ at site PS51/80 as well as their large offset from $\delta^{13}\text{C}_{\text{DIC}}$ of the near-bottom water makes a dominant influence of some ecological and/or environmental factors very likely. It is interesting to note that such low $\delta^{13}\text{C}$ values, as we have found for *Elphidium excavatum* forma *clavata* at site PS51/80, have not been observed in Kara Sea down-core sediments for which a near-fluvial environment, and thus low salinities have been inferred (Polyak et al., 2003). It is inconceivable that the organic $\delta^{13}\text{C}$ signature of the riverine plankton, as a likely food source for the river-proximal foraminifers, has changed since the early Holocene (Bauch and Polyakova, 2003). However, it could well be that also other processes, such as those induced via methanogenesis (cf. Kennett et al.,

2000; Rathburn et al., 2000), add up to the low calcite $\delta^{13}\text{C}$ signature found in the organic-rich sediments close to the Lena Delta (Mueller-Lupp et al., 2000).

Another possible effect on the calcite $\delta^{13}\text{C}$ signature could be attributed to abiotic environmental factors. Recently, carbon fractionation and, to a smaller extent, oxygen isotope fractionation, were found to depend partly on the carbonate chemistry of the ambient water, at least for planktic foraminifers (Spero et al., 1997; Bauch et al., 2002). Because this so-called carbonate ion effect has an inorganic nature (Zeebe et al., 1999), it should also apply to benthic species. However, no information exists on the carbonate pore water chemistry, such as alkalinity, at our sites, making an evaluation of this effect impossible at present.

7. Conclusions

By comparing stable oxygen isotopes in the benthic foraminifers *Elphidiella groenlandica*, *Haynesina orbiculare* and *Elphidium excavatum* forma *clavata*, a large negative offset from equilibrium calcite is observed for the latter in the river-proximal environmental setting near the Lena Delta. The observation made for $\delta^{18}\text{O}$ fractionation of *E. e. clavata* is accompanied by extreme offsets between shell $\delta^{13}\text{C}$ and $\delta^{13}\text{C}_{\text{DIC}}$ of the bottom water, altogether implying that isotopic fractionation in *E. e. clavata* is highly sensitive when it comes to a freshwater-influenced environment. As a commonly abundant species on Arctic shelves, down-core isotope measurements of *E. e. clavata* are often used to reconstruct environmental changes since the last glaciation. Because the shallow Siberian shelves are regions of large coastline migrations during times of glacial–interglacial eustatic sea-level rise, sediment cores, which today are located in a more stable marine environment, were once, e.g., in the last late glacial and early Holocene, exposed to much fresher conditions due to increased river influence and enhanced deglacial runoff. Our finding indicates that, when interpreting carbon and oxygen isotope records of *E. e. clavata*, the vital effects of this species need to be considered. This is particularly important when further quantitative evaluations, e.g., paleosalinity and paleotemperature estimates, are being directly derived from the isotope data. For investigating proglacial and profluvial Arctic

shelf environments, it seems more advisable to rely on *E. groenlandica* and *H. orbiculare* as these two species appear to reflect oxygen isotopes of the ambient water with a constant offset in both a seasonally, highly variable river-influenced environment and a relatively stable marine setting. The comparison of the $\delta^{13}\text{C}$ calcite values in all three species seems to imply that, when a strongly depleted $\delta^{13}\text{C}$ signature is noted in *E. e. clavata*, this observation may be indicative for the likely coexistence of a vital effect in $\delta^{18}\text{O}$ of this species. When such a case becomes evident from sediment records, it is particularly recommendable not to rely solely on the oxygen isotopic record of *E. e. clavata* but to also consider the $\delta^{18}\text{O}$ values from the other species for further verification.

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Appendix A. Faunal Reference

Elphidiella groenlandica (Cushman, 1933)
(Pl. 2, Fig. 8)

Elphidium groenlandicum: Knudsen, 1971, p. 275,
pl. 12, Figs. 1–8; pl. 21, Figs. 1–3.

Elphidiella groenlandica: Loeblich and Tappan,
1953, p. 106, pl. 19, Figs. 13, 14.

Elphidium excavatum (Terquem) forma *clavata*
(Cushman, 1944) (Pl. 2, Figs. 6, 7).

Appendix A (continued)

Elphidium clavatum Cushman: Loeblich and
Tappan, 1953, p. 98, pl. 19, Figs. 8–10; Knudsen,
1971, pl. 11, Figs. 10–13; pl. 20, Figs. 5–8.
Elphidium excavatum (Terquem) forma *clavata*
Cushman: Feyling-Hanssen, 1972, pls. 1, 2.
Haynesina orbiculare (Brady, 1881)
(Pl. 2, Figs. 1–3).
Elphidium orbiculare: Loeblich and Tappan, 1953,
p. 102, pl. 19, Figs. 1–4.
Protelphidium orbiculare: Knudsen, 1971, p. 289,
pl. 14, Figs. 8–10; pl. 24, Figs. 6–8.

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