Benthic foraminifera in Hornsund, Svalbard: Implications for paleoenvironmental reconstructions

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Abstract: Modern hydrology of a typical Arctic fjord (Hornsund, SW Spitsbergen, Svalbard) was investigated and compared with commonly used in paleoceanography proxies: benthic foraminiferal assemblages and their stable isotope ($\delta^{18}O$ and $\delta^{13}C$) composition. The benthic foraminifera from Hornsund comprised 45 species and 28 genera. Their spatial variations follow the zonation pattern, resulting from the influence of Atlantic water at the fjord mouth and glacial meltwaters at the fjord head. At the mouth of the fjord, the total number of species and the contribution of agglutinating species were the highest. In the inner part of fjord, the foraminiferal faunas were poor in species and individuals, and agglutinating species were absent. "Living" (stained) foraminifera were found to be common throughout the short sediment cores (~10 cm long) studied. The stable isotope values of $\delta^{18}O$ and $\delta^{13}C$ were measured on tests of four species: *Elphidium excavatum* forma *clavata*, *Cassidulina reniforme*, *Nonionellina labradorica* and *Cibicides lobatulus*. The results confirmed the importance of species-specific vital effects, particularly in the case of *C. lobatulus*. The variability in the isotopic composition measured on different individuals within a single sample are comparable to isotopic composition of the same species test between sampling stations. The temperatures and bottom water salinities calculated from $\delta^{18}O$ values in different foraminifera tests mirrored those recorded for bottom waters in the central and outer fjords relatively well. However, in the case of the inner fjord, where winter-cooled bottom waters were present, the calculated values from $\delta^{18}O$ were systematically higher by about 2°C. The obtained results imply that particular caution must be taken in interpretation of fjord benthic foraminifera assemblages in high resolution studies and in selection of material for isotope analyses and their interpretation in cores from inner fjords or silled fjords, where winter-cooled waters may be present.

Key words: Arctic, Spitsbergen, benthic foraminifera, oxygen and carbon stable isotopes, paleotemperature, fjords.

Introduction

Arctic fjords form unique marine environments being an interface between glaciated land and the ocean with strong hydrological, sedimentological, and biological gradients along the fjord axis (Syvitski and Shaw 1995) and potentially provide a long-term, high-resolution record of environmental changes (Gilbert 2000). The record from western Spitsbergen fjords is of particular interest because they are located near major warm and saline water transport pathways to the Arctic basin, where the North Atlantic Drift forms oceanic fronts on its northern and eastern boundary in the Fram Strait and in the Barents Sea, respectively (Kostianoy *et al*. 2004). One of the greatest advantages and, simultaneously, disadvantages of fjord sedimentary records is inclusion of both marine and terrestrial signals. On the one hand, they increase the amount of information available regarding the two systems, while on the other, the proxies commonly used in paleoceanography must be adapted and calibrated for a specific fjord environment.

To date, paleoenvironmental studies in Svalbard based on sedimentary records from fjords focused mainly on major postglacial changes (Elverhøi *et al*. 1995; Hald *et al*. 2001, 2004; Forwick and Vorren 2009) or on the short-term changes during the last millennium (Zajączkowski *et al*. 2004; Majewski and Zajączkowski 2007; Majewski *et al*. 2009; Szczuciński *et al*. 2009). Few studies applied benthic foraminifera as the main proxy for paleoenvironmental reconstructions (Hald *et al*. 2001, 2004; Majewski and Zajączkowski 2007; Majewski *et al*. 2009) and faced some difficulties in interpreting the foraminiferal stable isotope composition (*e.g.* Hald *et al*. 2004; Majewski *et al*. 2009).

Because, so far, only a few studies have been carried out using benthic foraminiferal assemblages and the oxygen and carbon stable isotope composition of their tests, there is very limited knowledge about their relation to specific subpolar and polar fjord processes. The latter include for instance the seasonal and inter-annual variability of meltwater input and sea ice cover (Węsławski *et al*. 1988; Arnkværn *et al*. 2005; Szczuciński and Zajączkowski in press). Meltwater in glaciated fjords does not directly affect benthic foraminifera because of the buoyancy of the brackish water flow, however, during winter the surface meltwater signal is transferred to the near-bottom layer when the whole water column is mixed by convection and brine removal during formation of sea ice (Svendsen *et al*. 2002). Moreover, the changes in sea ice cover and surface water turbidity influence primary production through control of the euphotic zone thickness (Zajączkowski *et al*. 2010). Those processes may be recorded in the isotopic composition of foraminifera tests. Oxygen isotopic composition mainly reflects the isotopic composition of seawater ("salinity effect") and its temperature. In general, $\delta^{13}C$ mirrors the carbon isotopic composition of dissolved inorganic carbon in the seawater. However, multi-species measurements and the study of recent foraminifera have revealed that the oxygen and carbon stable isotope composition of the calcite tests

of most species exhibit strong deviations from the calcite precipitated in equilibrium with the ambient bottom water (Rohling and Cooke 1999). These deviations are attributed to so-called vital effects, which need to be taken into account and are usually defined by using core top samples and modern hydrological conditions. This approach implies that the available in the literature vital effects for particular species vary a lot (*e.g.* Grossman 1987 and Ivanova *et al*. 2008).

While, the sedimentary record in fjords may be potentially recovered in high resolution, using foraminifera tests in those studies needs to take into account some limitations as well. Mixing of the sediments (mainly due to bioturbation), vertical active penetration of the foraminifera and their favorable habitat depth, *i.e.* many of them live not at the sediment surface but several cm below, are particularly important.

Although, the modern benthic foraminifera were already studied in the Hornsund and appeared to be similar to those in some of the fjords of Svalbard (Hald and Korsun 1997; Mityaev *et al*. 2005; Pogodina 2005; Majewski *et al*. 2009), they were not investigated with respect to their isotopic composition and modern ecological factors. In Svalbard, such a complex study was done only for one single sediment core from outer Isfjorden (Ivanova *et al*. 2008).

The overall objective of this study is to evaluate the reliability of benthic foraminifera as proxies of paleoceanographical changes in the Hornsund fjord, Svalbard. This is assessed through investigations of modern foraminiferal assemblages and their relation to modern hydrological conditions in various basins of the fjord, and secondly by analysing $\delta^{18}O$ and $\delta^{13}C$ in modern foraminiferal tests and comparing temperature estimates from $\delta^{18}O$ using several temperature equations (Shackleton 1974; GEOSECS 1987; Hays and Grossman 1991; Azetsu-Scott and Tan 1997; MacLachlan *et al*. 2007) to measured temperatures in the fjord. Finally, the observations of the foraminiferal habitat depths and local sedimentation conditions are discussed in context of their limitations for high resolution studies.

Study area

Hornsund is a 34 km long and 5–10 km wide fjord located in southern Spitsbergen (Fig. 1). It is divided into several basins separated by deep sills with water depth usually over 100 m. The central basin is more than 250 m deep. The ice-proximal basins are 180 m (Burgerbukta and Samarinvagen), 150 m (Brepollen) and 55 m (Isbjornhamna) deep. According to Beszczyńska-Moller *et al*. (1997), Hornsund is influenced by Atlantic Water (AW) transported with the West Spitsbergen Current (WSC) and Arctic Water (ArW), which mix over the continental shelf forming Shelf Transformed Water (STW, Fig. 1). ArW is less saline than AW, and with the additional input of fresher coastal water the salinity of STW decreases to less than 35 PSU. Sills prevent STW from influencing the innermost fjord basins in their deepest
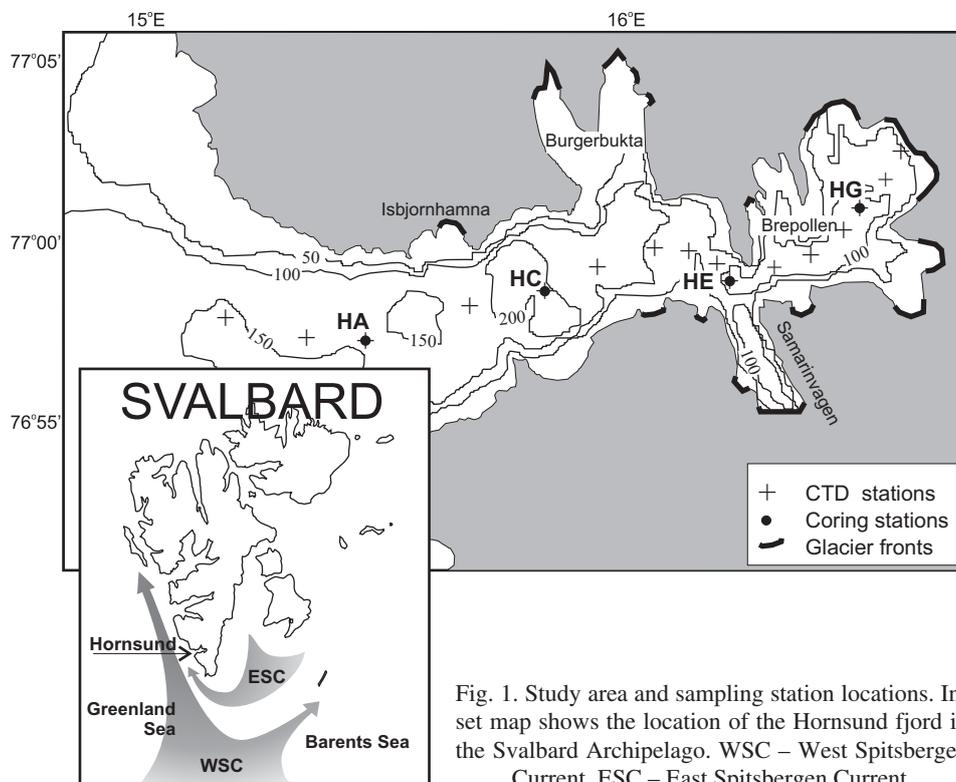
Fig. 1. Study area and sampling station locations. Inset map shows the location of the Hornsund fjord in the Svalbard Archipelago. WSC – West Spitsbergen Current, ESC – East Spitsbergen Current.

parts and winter-cooled water is often recorded near the bottom with temperatures below -0.5°C. Thirteen tidewater glacier fronts form a large part of the inner fjord basin coastline. About 70% of the fjord catchment area is covered by glaciers (Hagen *et al*. 1993). Some of these glaciers have retreated during the last century at a rate of up to 200 m annually (Ziaja 2001; Pälli *et al*. 2003). During that period new bays of Brepollen, Burgerbukta and Samarinvagen were formed, which increased the fjord surface area by more than 20% (Fig. 1). The summer meltwater delivered from the glaciers causes seasonal water stratification and high turbidity of the fjord surface waters. The fjord bottom is covered mostly with glacimarine mud (Görlich 1986; Görlich *et al*. 1987), which has been accumulating recently at rates ranging from 0.5 to 0.7 cm y^{-1} along the fjord central axis (Glud *et al*. 1998; Szczuciński *et al*. 2006). Closer to the tidewater glaciers, the sediment accumulation rate increases to more than 10 cm y^{-1} (Filipowicz 1990).

Materials and methods

CTD profiles were measured in July and August 1999, 2000, and 2002 with an Idronaut 316 and Sensordata 200 probes from R/V *Oceania*. Undisturbed sedi-

Table 1

List of coring stations in the Hornsund fjord

Station	Latitude	Longitude	Water depth [m]	Core length [cm]	Near-bottom temperature [°C]	Near-bottom salinity [PSU]
HA	76.95565 N	15.44898 E	151	8	1.5729	34.7304
HC	76.973983 N	15.85328 E	203	9	1.6317	34.7227
HE	76.980167 N	16.2022 E	106	11	-1.7177	34.636
HG	77.012183 N	16.48675 E	138	26	-1.7453	34.6504

ment cores were retrieved with a Nemisto gravity corer (7 cm internal diameter) in July 2002 at sampling stations located in the central deeps along the axis of the Hornsund fjord (Fig. 1, Table 1). The cores were cut into 1 cm slices onboard of the vessel and were frozen at – 20°C until further analyses in the laboratory.

Prior to the analysis of benthic foraminiferal assemblages, the samples thawed out in temperature of 20°C, than they were weighted. The sediments were treated for 1 h with Bengal-Rose dissolved in alcohol to distinguish between "living" (stained at least one chamber) and dead foraminiferal individuals. Thereafter, the samples were dried, weighted and subsequently wet sieved through a 125 μm sieve. The sediment fraction >125 μm was analysed using a stereo-microscope with magnification up to 130×. Samples with a large quantity of tests were divided using a dry micro-splitter. At least 300 specimens (both, "living" and "dead") were identified and counted in each sample. In case of broken specimens, only the part with aperture was counted. The taxonomy above the species level is used according to Loeblich and Tappan (1987), with few exceptions. The foraminiferal collection is stored at the Institute of Oceanology, PAS in Sopot (Poland).

Foraminiferal species composition was analysed using the orthogonally rotated (varimax), Q-mode Principal Component (PC) method, applied to the data set of total ("living" and "dead") individuals. The commercially distributed statistics package SYSTAT 11 was used for the analyses, and taxa with abundance < 1% of the total assemblage in at least one sample were excluded from the analysis.

Four foraminifera species that are common in the Hornsund fjord were chosen for stable isotope analyses. Three of them are infaunal species: *Elphidium excavatum* f. *clavata* (= *Cribroelphidium excavatum* f. *clavata*), *Cassidulina reniforme*, and *Nonionellina labradorica*. The fourth is an epifaunal species – *Cibicides lobatulus (= Lobatula lobatula)*, which can be used as an indicator of near-bottom environmental conditions (Hald and Korsun 1997; Polyak *et al*. 2002).

The $\delta^{18}O$ and $\delta^{13}C$ analyses were performed separately on stained ("living") foraminifera tests and "dead" (non-stained) specimens. Due to large sizes of the individual foraminifera, one to ten tests were analysed. Measurements of single specimens as well as the whole groups of tests for the same samples were also per-

formed. The isotopes were analysed in the GeoForschungsZentrum in Potsdam (Germany), using a Finnigan MAT 253 mass spectrometer coupled to a Kiel IV carbonate preparation device (ThermoFisher Scientific). The samples were dissolved in 100 % H_3PO_4 at 71°C, and the isotopic composition was measured on released, cryogenic purified CO_2. The data were compared to the isotopic standard NBS-19 and expressed in standard δ notation relative to VPDB. The achieved analytical precision was <0.06‰ for $\delta^{13}C$ and $\delta^{18}O$.

The obtained data on $\delta^{18}O$ and the measured salinities (S) were used to calculate water temperatures. The results were compared with the measured near bottom water temperatures to determine the most representative temperature and salinity equations for the fjord. Three formulae for calculation of $\delta^{18}O_w$ (in water) from salinities were used:

an equation reported for the North Atlantic (GEOSECS 1987)

$$\delta^{18}O_w = (0.558 \cdot S) - 19.256 \tag{1}$$

where S is salinity.

a recently established relationship for Kongsfjorden, a fjord in NW Spitsbergen (MacLachlan *et al*. 2007)

$$\delta^{18}O_w = (0.43 \cdot S) - 14.65 \tag{2}$$

an equation for Kangerlugssuaq Fjord, eastern Greenland (Azetsu-Scott and Tan, 1997)

$$\delta^{18}O_w = (0.69 \cdot S) - 24.18 \tag{3}$$

Paleotemperatures were calculated based on $\delta^{18}O_w$ and $\delta^{18}O_c$ (in calcite foraminiferal tests) with an equation from:

Shackleton (1974), which is a polynomial expansion of the formula by O'Neil *et al*. (1969)

$$T_{°C} = 16.9 - 4.38(\delta^{18}O_c - \delta^{18}O_w) + 0.1(\delta^{18}O_c - \delta^{18}O_w)^2 \tag{4}$$

and its modification by Hays and Grossman (1991)

$$T_{°C} = 15.7 - 4.36(\delta^{18}O_c - \delta^{18}O_w) + 0.12(\delta^{18}O_c - \delta^{18}O_w)^2 \tag{5}$$

Altogether, six solutions (temperatures) were obtained since three $\delta^{18}O_w$ values calculated from equations (1), (2), and (3) were used in equations (4) and (5). The conversion equation of $\delta^{18}O$(SMOW) versus $\delta^{18}O$(PDB) (Coplen *et al*. 1983) is

$$\delta^{18}O \text{ (PDB)} = 0.97002 \ \delta^{18}O \text{ (SMOW)} - 29.98 \tag{6}$$

Because, *N. labradorica* and *C. lobatulus* do not precipitate their tests in equilibrium with $\delta^{18}O_w$, the disequilibrium values of Ivanova *et al*. (2008) of -0.28 and +0.76, respectively, were taken into account during the calculations.
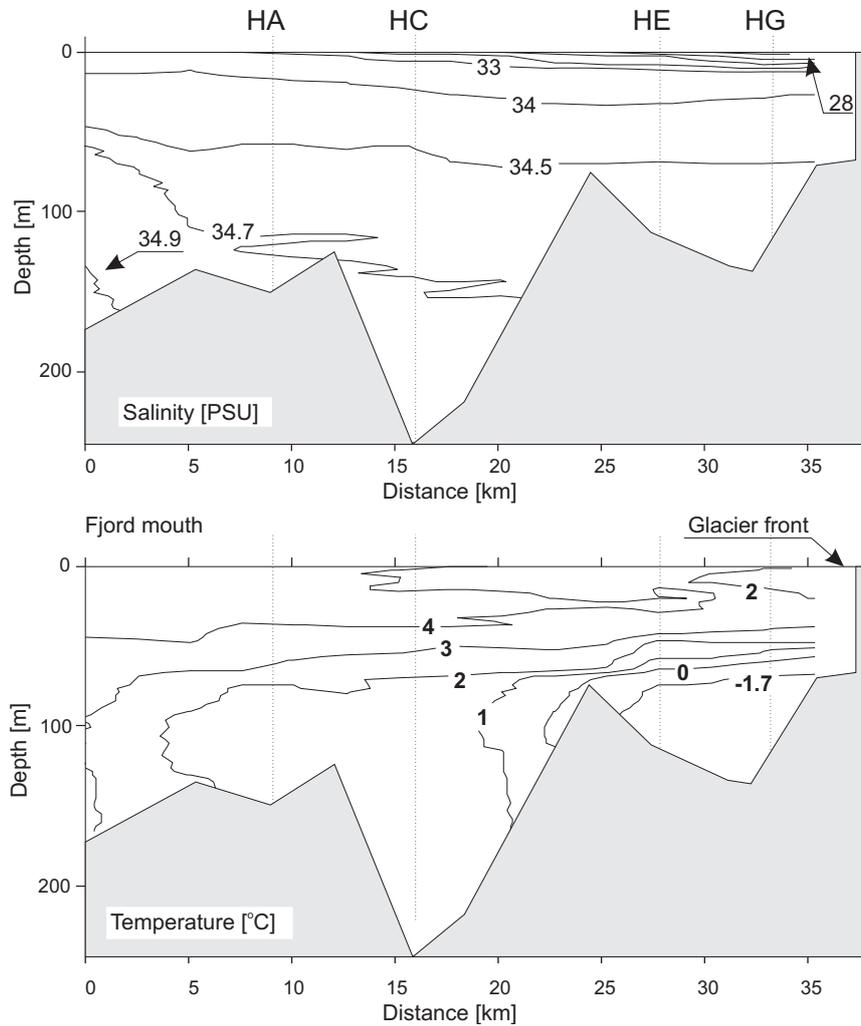
Fig. 2. Salinity and temperature of Hornsund water in July 2002 along the transect from the fjord mouth to the inner basin. For the exact locations see Fig. 1. Vertical lines show location of coring stations.

Results

Hydrology. — During the summer 2002, the brackish surface water was as thick as 20 m at the fjord head and 4 m in the center of Hornsund (Fig. 2). The salinity of fjord head surface water (5 km from glacier fronts) was less than 28 PSU and increased to 34.68 PSU near the bottom (station HG). Water temperature in the inner basins, below a depth of 100 m, was less than 0°C and reached -1.75°C near the bottom. In the fjord center, surface salinity of 32 PSU indicated significant influence of meltwater. The isohaline of 34.7 PSU showed that STW penetrated the fjord up to the central basin in the near-bottom zone. In the deeper part of the fjord mouth, high

Table 2

PC scores and percentage of total variance explained by three factor principal component (PC) analyses performed on the entire ("living" and "dead") foraminifera dataset. The most statistically significant taxa are underlined; scores of accessory species are in bold.

	PC1	PC2	PC3
Percent of total variance explained	50.245	32.948	5.968
Adercotryma glomerata	-0.342	-0.056	0.572
Ammodiscus sp. 1	-0.195	-0.455	-0.080
Ammotium cassis	-0.238	-0.207	-0.128
Astrononion gallowayi	-0.223	-0.348	0.033
Bolivina pseudopunctata	-0.192	-0.441	-0.047
Buccella frigida	0.492	0.796	1.076
Cassidulina obtusa	-0.212	-0.439	-0.00032
Cassidulina reniforme	**2.078**	-0.730	0.630
Cibicides lobatulus	0.179	-0.169	0.512
Cornuspira foliacea	-0.221	-0.388	-0.126
Elphidium albiumbilicatum	-0.179	-0.468	-0.081
Elphidium bartletti	0.113	-0.344	-0.079
<u>***Elphidium excavatum* f. *clavata***</u>	<u>**5.779**</u>	0.792	0.008
<u>***Elphidium excavatum* f. *selseyensis***</u>	-0.711	**2.227**	<u>**5.259**</u>
Elphidium spp.	-0.173	-0.404	-0.204
Elphidium subarcticum	-0.214	-0.378	0.218
Globobulimina auricula	-0.209	-0.442	-0.043
Globobulimina turgida	-0.201	-0.454	-0.060
Hyperammina subnodosa	-0.291	0.426	**-1.278**
Islandiella helenae	-0.226	0.040	-0.120
Islandiella islandica	-0.211	-0.445	-0.021
Islandiella narcrossi	-0.303	-0.083	0.225
Islandiella spp	-0.184	-0.468	-0.077
Labrospira crassimargo	-0.277	-0.153	-0.005
Miliamina agglutinata	-0.232	-0.241	-0.245
Miliamina stalkeri	0.072	-0.425	0.150
Nonion orbiculare	-0.069	-0.548	-0.101
Nonion spp.	-0.193	-0.448	-0.050
<u>***Nonionellina labradorica***</u>	-0.134	<u>**4.403**</u>	**-2.119**
Pyrgo williamsoni	-0.196	-0.412	-0.089
Quinqueloculina arctica	-0.215	-0.309	-0.050
Quinqueloculina seminulum	-0.306	0.553	0.058
Quinqueloculina sp.	-0.199	-0.447	-0.053
Recurvoides turbinatus	-0.952	**3.120**	-0.949
Reophax scorpiurus	-0.243	-0.348	-0.001
Robertina arctica	-0.223	-0.404	-0.055

Table 2 – *continued*.

	PC1	PC2	PC3
Spiroplectammina biformis	-0.179	-0.399	-0.167
Spiroplectammina earlandi	-0.184	-0.396	-0.202
Stainforthia fusiformis	-0.167	-0.400	-0.233
dctlpar*Triloculina frigida*	-0.167	-0.212	-0.146
Triloculina oblonga	-0.041	-0.054	**-1.922**
Verneuilina arctica	-0.209	-0.442	-0.013

water salinity (34.9 PSU) and temperature, reaching more than 1.5°C, indicated the influence of AW. The bottom water temperatures measured during summer seasons of 1999, 2000 and 2002 were in the range of 1.27 to 2.02°C at station HA and 1.37 to 1.88°C at station HC. Winter cooled water existed each year in the inner basin of Brepollen even during late summer, *i.e.* middle of August.

Foraminiferal species composition. — A total of 18879 foraminifera were identified in 54 samples taken from the four cores composed of homogenous glacimarine mud. They represent 38 species from 23 genera (Appendix 1). In the core HG, 23 barren samples were encountered. The counts for all foraminifera (stained and unstained) are presented in Appendix 2.

The foraminiferal fauna, recovered from core HA from the fjord mouth, was of the highest diversity, usually more than 30 species per sample, and abundance of up to 2233 individuals per 10 cm^3. Between 12 and 54% of them were agglutinated taxa. The most abundant species were the two forms of *E. excavatum*: forma *clavata* (15% in sample) and forma *selseyensis* (19% in sample) (Feyling-Hanssen 1972). However, *N. labradorica* and *Recurvoides turbinatus* were also common. *Cassidulina reniforme* (5% in sample) and *Buccella frigida* (6% in sample) were abundant in the deeper part of the HA core (Fig. 3). Over 80% of the recorded foraminifera were found at sediment depths between 3 and 7 cm. Only *N. labradorica* and *R. turbinatus* were particularly abundant in the upper 2 cm of the sediment. "Living" individuals were found in the entire 8 cm long core section (Fig. 4). 100% stained *C. reniforme* and *C. lobatulus* tests were observed at sediment depths of 1–2 cm and 2 cm, respectively. Over 60% of *E. excavatum* f. *clavata* were found stained in the entire sediment core.

Core HC from the fjord center had a relatively diverse foraminiferal assemblage of approximately 20 species of which agglutinated species accounted for 7–30% of the total fauna with maximum relative abundance in the upper part of the core. The number of specimens ranged from 207 to 952/10 cm^3. The most abundant species was *E. excavatum*. However, the number of *E. excavatum* f. *selseyensis* was significantly lower than the number of the most abundant *E. excavatum* f. *clavata* (Fig. 3). The concentration of *N. labradorica* ranged from 17 to 194 specimens/10 cm^3, with the highest values in the upper part of the core. The number of the most abundant ag-
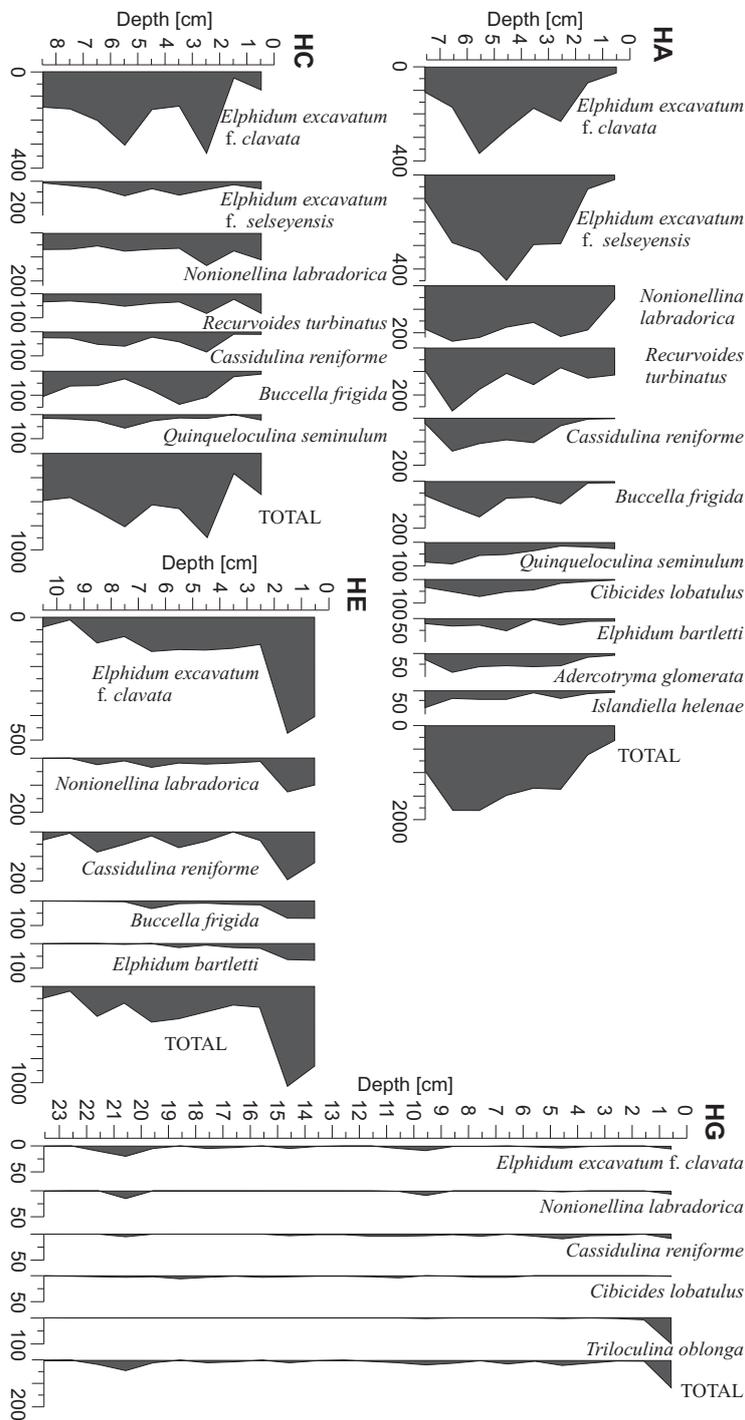
Fig. 3. Occurrences of dominant foraminiferal taxa in the four cores analyzed in number of all foraminiferal specimens per 10 cm^3 of sediment.
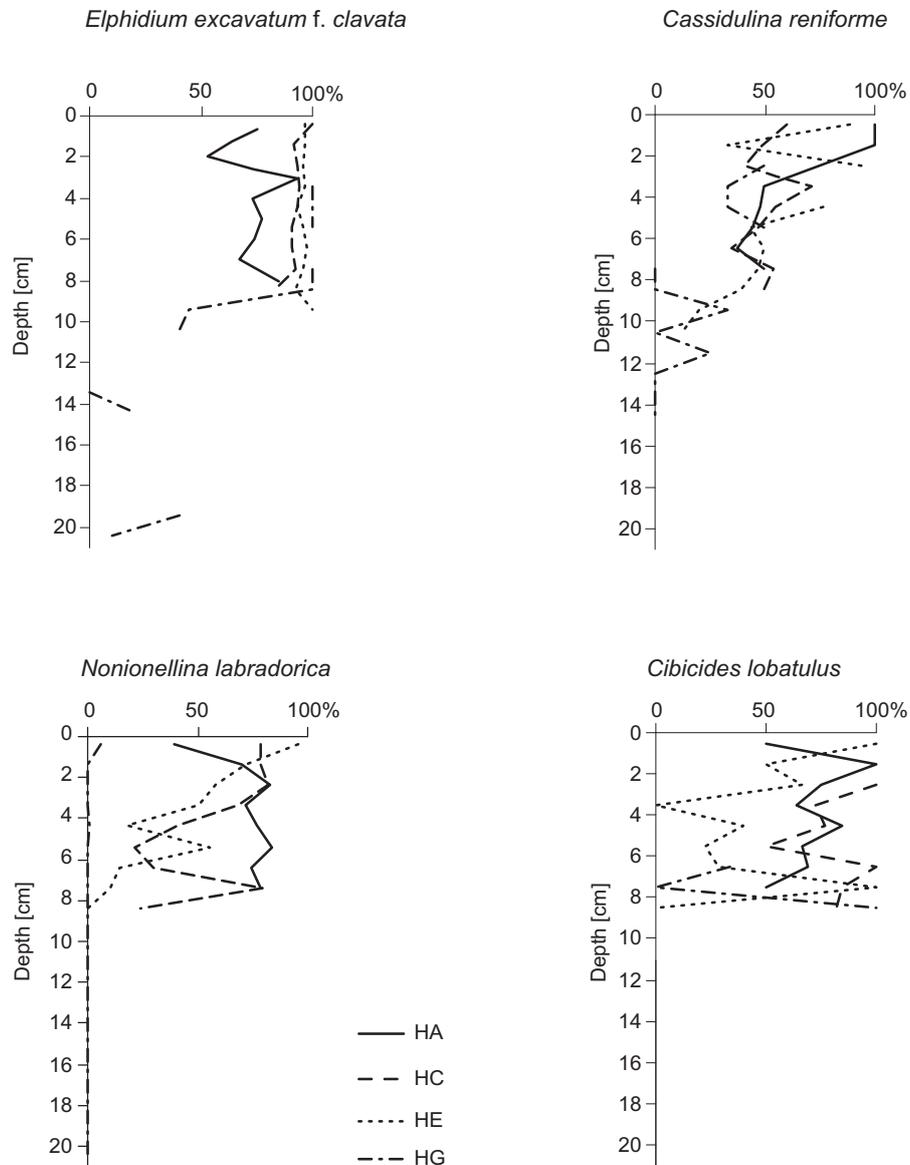
Fig. 4. Distribution of the selected foraminiferal species below the surface of sediment as the percent of "living" (stained) specimens.

glutinated species, *R. turbinatus*, varied from 33 to 117/10 cm^3. More than 90% and 40–60% of tests were stained in the whole sediment core in case of *E. excavatum* f. *clavata* and *C. reniforme*, respectively (Fig. 4).

A decrease in foraminiferal species richness was observed in the core HE from the inner fjord, except of the upper 2 cm, where the number of specimens was still high, *ca.* 1000 specimens/10 cm^3. Down-core the number of specimens decreased

Table 3

Results of stable oxygen and carbon isotopic analyses.
The data are uncorrected for vital effect.

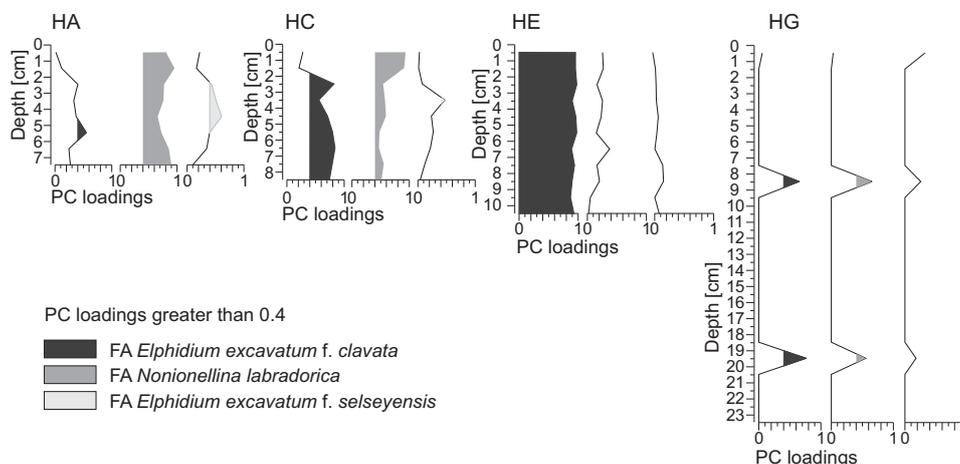| Core	Core depth [cm]	Species	$\delta^{13}C$ ‰VPDB	$\delta^{18}O$ ‰VPDB	Number of specimens in sample	"Living" (L) or "dead" (D) specimens
HA	2	*C. reniforme*	-1.19	3.00	4	L
HA	7	*C. reniforme*	-0.71	3.64	4	D
HC	8	*C. reniforme*	-1.41	3.47	8	L
HC	8	*C. reniforme*	-1.10	3.71	5	D
HE	0	*C. reniforme*	-1.28	3.73	4	L
HE	10	*C. reniforme*	-0.10	4.02	10	D
HA	0	*C. lobatulus*	-0.41	2.70	2	L
HA	0	*C. lobatulus*	0.02	2.06	1	L
HA	7	*C. lobatulus*	1.02	2.34	1	D
HA	7	*C. lobatulus*	1.04	2.36	2	D
HC	0	*C. lobatulus*	0.59	2.25	1	L
HC	8	*C. lobatulus*	0.52	1.72	2	D
HE	10	*C. lobatulus*	0.81	2.92	1	D
HE	10	*C. lobatulus*	1.27	2.61	2	D
HG	6	*C. lobatulus*	1.39	3.09	2	L
HG	22	*C. lobatulus*	1.50	2.68	3	D
HG	24	*C. lobatulus*	1.13	2.78	1	D
HA	0	*E. excavatum*	-2.46	2.94	1	L
HA	1	*E. excavatum*	-2.15	3.03	4	L
HA	1	*E. excavatum*	-1.27	3.46	1	L
HA	7	*E. excavatum*	-1.98	3.19	3	D
HA	7	*E. excavatum*	-1.23	3.25	1	D
HC	0	*E. excavatum*	-2.38	3.25	3	L
HC	8	*E. excavatum*	-1.57	3.5	1	D
HE	0	*E. excavatum*	-1.81	3.83	2	L
HE	10	*E. excavatum*	-1.58	3.81	3	D
HG	0	*E. excavatum*	-2.01	3.31	1	L
HG	21	*E. excavatum*	-0.99	4.31	3	D
HA	0	*N. labradorica*	-1.98	3.83	5	L
HA	7	*N. labradorica*	-2.35	3.80	3	D
HC	0	*N. labradorica*	-2.14	3.81	3	L
HC	8	*N. labradorica*	-2.51	3.98	3	D
HE	0	*N. labradorica*	-1.17	4.28	3	L
HE	8	*N. labradorica*	-1.83	4.28	3	D
HG	0	*N. labradorica*	-2.16	3.91	3	L
HG	20	*N. labradorica*	-2.22	4.09	3	D

Fig. 5. PC loading values for three foraminiferal assemblages in the studied sediment cores. Statistically significant PC loadings (> 0.4) are marked in shades of gray.

to about 100 in 10 cm³. *Elphidium excavatum* f. *clavata* comprised 48% of the specimens, *C. reniforme* 18%, and *N. labradorica* 10%. Agglutinated species like *R. turbinatus* and *Miliamina stalkeri* comprised usually less than 10% of the whole assemblage. Almost all specimens of *E. excavatum* f. *clavata* were stained. More than 50% of stained tests of *C. reniforme* were observed in the samples from 1st, 3rd, 5th and 8th cm of the sediment core. The percentage of stained tests of *N. labradorica* decreased from 96% at the surface to zero at 9 cm, at the bottom of the core. "Living" *C. lobatulus* was observed at the sediment surface as well as 8 cm down-core.

The diversity and abundance of the foraminiferal fauna in the core HG from the fjord head was low with <10 species and <55 specimens in 10 cm³, respectively. Only the surface sediments were richer in foraminifera species with 98 individuals of *Triloculina oblonga*. In the remaining samples, *E. excavatum* f. *clavata* dominated (32%), along with *N. labradorica* (26%), *C. reniforme* (9%) and *C. lobatulus* (3%), (Fig. 3). Stained tests of *E. excavatum* f. *clavata* were found in every sample containing foraminifera in this core. At the depth of 4–9 cm, 100%, and in the layers from 15 and 20 cm, 20% and 45%, were coloured, respectively.

Principal Component Analysis. — The Principal Components explain 89.17% of the total variance of the tested foraminiferal dataset using a 3-factors solution. Each PC is defined by a dominant species and by accessory species. In the following, PC's will be referred as foraminiferal assemblages (FA) named by the taxa with highest PC score values (Table 3, Fig. 5).

The *E. exavatum* f. *clavata* FA explains 50.25% of total foraminiferal variance, with *C. reniforme* as an accessory species. In the second assemblage, *N. labradorica* (32.95%) is the most important, and its two accessory species are *R.*

turbinatus and *E. excavatum* f. *selseyensis*. The third FA explains only 5.97% of total variance. The most important species, *E. excavatum* f. *selseyensis*, is accompanied by three accessory species: *N. labradorica, Hyperammina subnodosa* and *Triloculina oblonga*.

Core HA from the outer fjord has high *N. labradorica* FA values throughout; however, in the middle of the core (3–6 cm) factor loading decrease, and the role of *E. excavatum* f. *selesyensis* FA increases (Fig. 5). The *E. excavatum.* f. *clavata* FA plays a minor role in the mouth of the fjord, but its role increases towards the fjord head and in the core HE it is the single most important foraminiferal assemblage. The central basin of Hornsund (HC core) presents a transitional area where both assemblages of *E. excavatum* f. *clavata* and *N. labradorica* are important, but the *N. labradorica* FA is more significant in the upper 2 cm of the core. The foraminiferal assemblages in the core HG were the least diverse with PC loading values exceeding 0.4 only in two samples at 9 and 20 cm.

Stable isotopes. — Complete data on the oxygen and carbon stable isotope compositions in the foraminiferal tests are presented in Table 3 and Fig. 6. The low δ^{13}C values (-2.5‰VPDB) were measured in *E. excavatum* f. *clavata* and *N. labradorica* tests. Both species had similarly wide ranges of δ^{13}C values from -2.5‰VPDB to about -1‰VPDB. The range of *C. reniforme* overlapped, but was much narrower at -1.5‰VPDB to -0.7‰VPDB. *Cibicides lobatulus* had higher δ^{13}C values from -0.4‰VPDB to 1.5‰VPDB. The widest range in δ^{18}O values was also noted in *C. lobatulus* ranging from 1.7‰VPDB to 3.1‰VPDB. Slightly narrower ranges, but with much higher values, were noted for *E. excavatum* f. *clavata* (δ^{18}O between 2.9‰VPDB and 4.3‰VPDB) and *C. reniforme* (3‰VPDB to

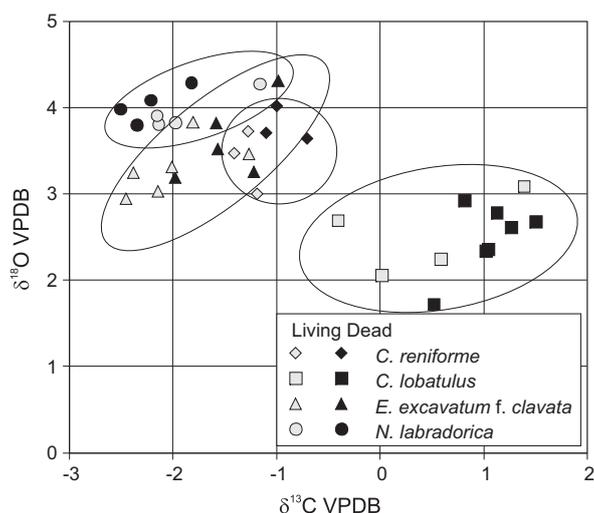Fig. 6. Composition of stable isotopes δ^{13}C and δ^{18}O in foraminifera tests of "living" and "dead" specimens. The data are uncorrected for vital effects. Note the offset for *C. lobatulus*.

4‰VPDB). Although the $\delta^{18}O$ values of *N. labradorica*, were similar (3.8‰ VPDB to 4.3‰VPDB), the variation was much smaller. The diagram in Fig. 6 combines both $\delta^{13}C$ and $\delta^{18}O$ and shows that each species cover specific fields. The fields of *C. reniforme*, *E. excavatum* f. *clavata* and *N. labradorica* partly overlap, while *C. lobatulus* from the same samples has a distinctly different stable isotope composition. Differences between species are much greater than those between "living" or "dead" specimens or between specimens of the same species from various sites.

The comparison of values noted in stained foraminifera tests ("living") and unstained specimens revealed a regular pattern. In most cases, $\delta^{13}C$ values in "living" foraminifera tests were systematically lower than in "dead" tests. In this respect, *N. labradorica* is exceptional since the "living" specimens revealed higher values than the "dead" specimens. The $\delta^{18}O$ values showed no clear differences; however, most of the "living" tests had slightly lower $\delta^{18}O$ values than the "dead" specimens collected from the same samples.

Five samples of *E. excavatum* f. *clavata* and *C. lobatulus* were analysed twice for variable numbers of tests in samples using only one large test in the first measurement and two to five smaller tests in the second. The greatest variations were found within "living" foraminifera. Differences in $\delta^{18}O$ values were as high as 0.6‰VPDB, while those in $\delta^{13}C$ were even as high as 0.9‰VPDB in samples comprised of several smaller tests with lower $\delta^{13}C$ values. Among *E. excavatum* f. *clavata*, variations in the same sample were more than 50% of the total variability revealed by all of the samples of this species.

The different foraminiferal species exhibited variable trends in stable isotope composition along the fjord axis. In the case of *E. excavatum* and *C. lobatulus,* both $\delta^{13}C$ and $\delta^{18}O$ values increased from the fjord mouth to the inner basin. With *N. labradorica*, the values were almost the same and a very slight increasing trend was noted toward the fjord head. *Cassidulina reniforme* also showed an increasing trend in the same direction for $\delta^{18}O$; however, the trend for $\delta^{13}C$ was opposite.

Paleotemperature calculations

The differences in oxygen isotopic composition of the various foraminiferal species from the same locations made it necessary to consider paleotemperature equations separately for each species. Figure 7 presents the actual near-bottom water temperatures and temperatures calculated from stained ("living") foraminifera tests of the four species. There was a 5.6°C difference in the paleotemperatures depending on the combination of equations applied. In general, in the part of the fjord with near-bottom water temperatures above 1°C, some results were very close to the real water temperature. In contrast, the calculated temperatures were in general at least 2°C higher for the inner fjord where basins were filled with winter-cooled waters of -1.7°C (Fig. 7)
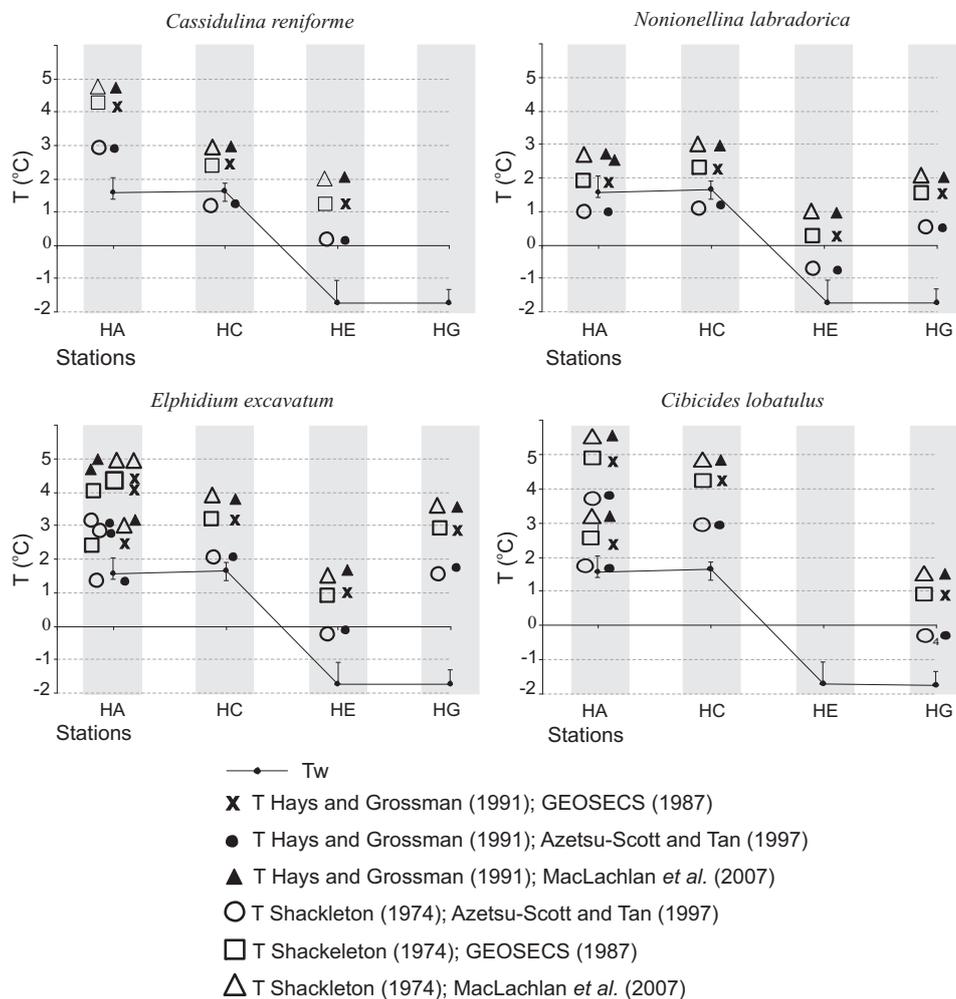
Fig. 7. Comparison between the real measured summer bottom water temperatures (Tw) and temperatures calculated from δ^{18}O values (corrected for vital effects) of "living" foraminiferal tests (T). The error bars show the range of the measured temperatures in the years 1999 and 2000.

For *C. reniforme* in the outer part of the fjord (HA, HC) the combination of equations (3) and (4) gave the best temperature approximation, however, the values for the outer station were almost 2°C higher than those actually measured. For the inner part (HE), also equations (3) and (4) gave the closest approximation although the resulting temperature was over 1.7°C higher than the real water temperature. In general, the calculated temperatures for all the solutions exhibited a decreasing trend from the fjord mouth to the fjord head with an amplitude of about 3°C.

In the case of *E. excavatum* f. *clavata*, in the outer fjord (HA, HC), equations (3) and (4) produced a very good approximation of the measured water temperatures with an accuracy in the order of 0.5°C for some samples. However, in case of

samples from core HA, about 1.5°C warmer temperatures were obtained using the same equations. In the inner fjord (HE, HG), again, the best match was obtained with equations (3) and (4), but the calculated values were almost 2 to 4°C higher in comparison with the real temperatures. In general, the calculated temperatures increased toward the fjord mouth except at the innermost station, and the calculated amplitudes reached 3°C.

Temperatures of bottom waters, obtained from *N. labradorica* tests in the outer fjord using equations (3) and (4), were about 0.5°C lower than the measured temperatures. In the inner fjord, the formula combinations of (3) and (5), as well as (3) and (4) produced results closest to those measured. The temperature trend recorded by *N. labradorica* was very similar to that of *E. excavatum* f. *clavata*.

In the case of *C. lobatulus*, the combination of equations (3) and (4), as well as (3) and (5) gave the best approximation for the outer and inner fjord. The variation from the measured results for the best approximation was in the order of 2°C.

Discussion

Benthic foraminifera are widely used in paleoceanography and paleoenvironmental reconstructions. However, their analyses are often performed on various sizes of foraminifera tests. Scientist studying foraminifera in the Arctic use different size fractions (over 63, 100, 125, 150 μm) for various reasons. The coarse foraminifera fraction (>125 μm) was used in the present study because it made up to 75% of all foraminiferas found in the sediment. Moreover, according to Jennings and Helgadottir (1994) large size classes accelerate analyses and helps avoiding the uncertain identification of juvenile individuals. They concluded that even though their >125 μm data were incomplete, they were more closely related to water masses and provided more useful paleoceanographic information than the >63 μm fraction.

Benthic foraminiferal assemblages as a modern environmental proxy. — Foraminiferal species composition, diversity and abundance revealed a clear zonation in Hornsund fjord that reflects the influence of AW and glacial meltwater (Fig. 2).

The mouth of the fjord (HA), occupied with STW is dominated by *N. labradorica* assemblage (Fig. 5), which may be indicative of an environment with high food supply to the bottom. This interpretation concurs well with Polyak and Mikhailov (1996), who showed that this species is known to feed on fresh phytodetritus and is indicative of high productivity environments. *Recurvoides turbinatus*, an accessory species of the assemblage, was reported by Hald and Korsun (1997) to be positively correlated to higher temperature and salinity. The influence of AW in the outer Hornsund fjord is also indicated by *E. excavatum* f. *selseyensis*, which is considered a boreal form (Feyling-Hanssen 1972; Rodrigues

and Hooper 1982). It is also known as an epifaunal grazer and filter feeder, taking advantage of vigorous bottom currents (Hald and Korsun 1997; Polyak *et al*. 2002), and it is considered a bottom current indicator. The data presented in this paper also show a low number of *I. norcrossi* in core HA, which could be related to episodic occurrences of sea ice (Korsun and Polyak 1989; Steinsund 1994). Highest foraminiferal abundance is found at the 3–6 cm below sediment surface in this setting (Fig. 3) and indicates sufficient oxygen content and food availability (Gooday 2003). It is supported by relatively abundant "living" *C. lobatulus* in the subsurface sediments, which is regarded as epifaunal (Nyholm 1961; Korsun *et al*. 1994) and oxyphylic (Gooday 2003), however, in this study it appears to be more an infaunal species. Ivanova *et al*. (2008) suggested that *C. lobatulus* can penetrate deep in to the sediment if it is detached from the hard substrate and transported down-core by bioturbation.

The center of the fjord (HC) is still influenced by STW. During the summer, however, near-bottom temperatures decreased in comparison with the outer fjord (Fig. 2). The number of species decreases, and the dominant boreal species *E. excavatum* f. *selseyensis* is replaced by the opportunistic *E. excavatum* f. *clavata*, which is well adapted to higher sedimentation rates and unstable environmental conditions (Hald and Korsun 1997). The decline in relative abundance of the *N. labradorica* assemblage indicates lower supply of phytodetritus to the bottom.

In the fjord center, the number of agglutinated specimens decreases in comparison to the fjord mouth, while in the fjord head they almost disappear. Wollenburg and Kuhnt (2000) noted the poor fossilization potential of modern agglutinated foraminifera in the Arctic Ocean due to early diagenesis. However, no increase of damaged test frequency was noted up fjord. Therefore, it seems more likely that the number of the most common agglutinated species (*e.g*. *R. turbinatus* and *H. subnodosa*) is decreasing due to increase in water turbidity (cf. Majewski and Zajączkowski 2007).

The conditions in the inner fjord (cores HE and HG) are glacier proximal, and even in the second half of summer there is winter-cooled water in the near-bottom layer trapped in the inner basin (Fig. 2). Despite the similar hydrological conditions at these two stations, the species composition of benthic foraminifera differs. At a distance of 7 km from the glacier fronts (HE), *E. excavatum* f. *clavata* dominates. The presence of *C. reniforme, N. labradorica*, and *B. frigida* indicate that seasonal STW and sea ice formation have an influence. It is possible that this part of the fjord is balanced by the exchange of AW and glacial meltwater. The importance of STW might be controlled by the magnitude of occasional inflows over the sill. In the HE core, foraminifera were mostly found in the upper 2 cm of the sediment probably related to higher food availability (Gooday 2003). Close to the glacier fronts (HG), the number of foraminiferal individuals and number of species decreases significantly, and agglutinated foraminifera disappear completely. "Living" infaunal species were noted even in the sediments at the depth of 21 cm and

"living" epifaunal *C. lobatulus* were found at 9 cm below the sediment-water inter-ference. Such a deep penetration may be related to the high sediment deposition rates. Although this part of the fjord is covered by fast ice every winter, *I. norcrossi* and *B. frigida* are very rare. This suggests that these species are not tolerat to the high sedimentation rates and high water turbidity, which prevails in the first few kilometers extending from the tidewater glacier fronts where most of the sedi-ments are deposited (Zajączkowski 2008; Szczuciński and Zajączkowski in press). Hald and Korsun (1997) showed that in the inner part of Hornsund the foramini-feral fauna is almost completely dominated by *C. reniforme*, followed by *E. excavatum* f. *clavata*. The data from the present study indicates that *C. reniforme* plays a secondary role closer to the fjord head. This discrepancy could reflect inter-annual fluctuations of foraminiferal species composition in the Hornsund fjord as suggested previously by Pogodina (2005).

Data presented on Fig. 4 shows that penetration depth of the most common foraminifera species reaches up to 21 cm. Frequent occurrences of stained fora-miniferal tests in the deeper sediment layers in all the studied sites show that, tak-ing into account modern sediment accumulation rates, foraminifera living at pres-ent can penetrate up to 20 years old sediment layers.

Application of benthic foraminiferal stable isotopes. — Stable oxygen and car-bon isotope records of benthic foraminifera are widely used in paleoceanographic and paleoclimatic studies (*e.g.* Shackleton *et al.* 1983; Keigwin *et al.* 1994; Ślu-bowska-Woldengen *et al.* 2007; Rasmussen and Thomsen 2009). However, their application is partly limited, particularly by species specific vital effects. The im-pact of vital effects is exemplified on Fig. 6, which combines $\delta^{13}C$ and $\delta^{18}O$ records for particular species. Each species plots in a specific field. This is very likely re-lated to their habitats. *Cibicides lobatulus* prefers living on sediment surface, being attached to gravels, grains, shells, or algae (Nyholm 1961; Korsun *et al.* 1994), while the remaining species are typical sediment dwelling organisms (Hald and Korsun 1997). Thus, *C. lobatulus* is more likely to represent near-bottom wa-ter conditions and the three other species record pore water conditions. The offset of *C. loabtulus* with respect to other benthic foraminifera has been described previ-ously and discussed in the context of using it as a paleotemperature proxy. It is usu-ally suggested that the $\delta^{18}O$ value is corrected by +0.64‰ (Shackleton and Opdyke 1973). However, other corrections have also been suggested, including +0.83‰ (Herguera *et al.* 1992), +0.76‰ (Ivanova *et al.* 2008) or, under specific conditions, no correction at all (Lynch-Stieglitz *et al.* 1999). In the present study, the offset of "living" *C. lobatulus* to the other species varied from 0.2 to as much as 1.8. *Cibicides lobatulus* also revealed systematic offset in $\delta^{13}C$ with values that were heavier by as much as 4‰. This is likely related to the different habitats of the spe-cies studied. Indeed, it is often assumed that infaunal species tend to have lighter $\delta^{13}C$ due to the oxidation of organic matter which causes depletion in the ^{13}C of the sediment pore water (Woodruff *et al.* 1980; Bauch *et al.* 2004). The offset in stable

isotopes values due to vital effect was reported also for *E. excavatum* but it was recorded to be negative (Polyak *et al*. 2003) or both positive and negative (Bauch *et al*. 2004). This effect was not supported by the presented results, nor by Ivanova *et al*. (2008).

Most of the stained foraminiferal tests gave slightly lower $\delta^{18}O$ values than the unstained ones, suggesting that bottom waters had been recently slightly warmer or less saline. However, the hydrological measurements are available for too short period of time to verify this suggestion. Differences in $\delta^{18}O$ and $\delta^{13}C$ for the same samples suggest that test size is very important. Improvements in analytical techniques, notably with respect to sample size, mean that even single foraminiferal test can be used. Using a single test requires the preferential use of larger specimens, and this may produce biased results. For example, the variations observed in the isotopic composition of *C. lobatulus* are much larger than the range of values of the same species analysed with 3 to 9 specimens per sample separated from a 150–700 μm size fraction and analysed in a 3 m long core spanning the last millennium that was collected from outer Hornsund fjord (Majewski *et al*. 2009). Therefore, the usual procedure for obtaining isotopic records consists of making isotopic measurements on a number specimens from a given size range should be followed.

The paleotemperature equations (4) and (5) that were applied use two variables: $\delta^{18}O$ of calcite (measured) and $\delta^{18}O$ of water, which is commonly obtained from its relation to water salinity, as presented in equations: (1), (2), and (3). The only available $\delta^{18}O$ from water measurements in the Hornsund fjord (Damm *et al*. 2005) were conducted at a single, outer fjord station under hydrological conditions that were similar to those observed during the present study. The dense fjord water had a salinity range of 34.5 to 34.7, which is similar to that of the near-bottom water in the present study. Damm *et al*. (2005) measured $\delta^{18}O$ of water (‰ VSMOW) in the range of 0.25 to 0.33, while in the present study the calculated $\delta^{18}O$ of water (in ‰ VSMOW) was in the following ranges: 0.07 to 0.12, 0.24 to 0.28, and -0.28 to -0.21, using equations (1), (2), and (3), respectively. Thus, it seems that the second relationship between salinity and water oxygen isotopic composition, established by MacLachlan *et al*. (2007) in Kongsfjorden in western Spitsbergen should be expected to reflect Hornsund conditions in the most accurate way. However, for temperature calculations, the best fit was found using $\delta^{18}O$ in foraminifera tests and salinity (as a function of $\delta^{18}O$ of water) using equation (3) based on regional mixing line obtained for Kangerlugssuaq Fjord, eastern Greenland by Azetsu-Scott and Tan (1997). Surprisingly, the results obtained by applying a local mixing line from a western Spitsbergen fjord – Kongsfjorden (MacLachlan *et al*. 2007) gave a much poorer fit. This may be the result of the different hydrological setting of the Hornsund fjord in contrast to Kongsfjorden. The STW waters affecting Hornsund are formed from cold, fresher ArW transported by the East Spitsbergen Current and the WSC carrying warm AW. Kongsfjorden is only influenced by the WSC (Węsławski *et al*. 1991).The temperatures calculated from $\delta^{18}O$ in foramini-

feral tests and bottom water salinities mirrored relatively well the measured bottom water temperatures for the outer and central fjord. The differences between results of paleotemperature equations (4) and (5) appeared to be very small, although the first usually gave results closer to the measured temperatures.

However, in the case of the inner fjord, where winter cooled bottom waters are present, the calculated values are systematically about 2 °C higher than the measured water temperatures (Fig. 7). The most likely reason is related to sea ice growth from fresher surface water. The lower salinity in the inner fjord surface water is sustained by meltwater outflow from polythermal tidewater glaciers in fall as well, when air temperatures are below 0°C and sea ice starts to form (Szczuciński and Zajączkowski in press). During sea ice growth isotopically light brines are produced, that subsequently sink and mix with the more saline, subsurface water masses (*e.g.* Bédard *et al*. 1981; Bauch *et al*. 2004). Consequently, the winter-cooled bottom waters are usually not in phase with the regional $\delta^{18}O$ – salinity mixing lines. This is also supported by the results of Damm *et al*. (2005), who measured the isotopic composition of two Svalbard fjords and shelf waters, and found that the dense cold fjord waters may have a slightly heavier $\delta^{18}O$ than fjord subsurface waters, even if they have similar salinities. In conclusion, it is not likely that deep inner fjord basins, which are common among Svalbard fjords, could serve as a reliable source of paleotemperature record.

Temperatures of bottom waters obtained from *N. labradorica* tests in the outer and central fjord using equations (3) and (4) are about 0.5°C lower than the measured by CTD. This findings suggest that *N. labradorica* may calcify during early-summer or during spring primary production, when water temperature is lower. *Cassidulina reniforme*, *E. excavatum* and *C. lobatulus* recorded almost equal or, even 1.5°C higher, temperatures in comparison to near-bottom CTD measurements. It shows that these species calcify their tests during summer when occasionally water temperature may be higher than measured.

Limitations of paleoenvironment reconstructions. — Frequent problem in the studies of paleorecords is partial or even total desintegration of agglutinated foraminifera and dissolution of carbonate foraminiferal tests. The latter was suggested also to occur in Hornsund (Mityaev *et al*. 2005). However, in the present study no trace of those processes was found.

The fjords are particularly promising with regard to high resolution studies because of their high sediment accumulation rates, which presently are in order of 1 to 5 mm per year in the central basins of the fjords of Svalbard (Szczuciński *et al*. 2009) and permit to obtain records with decadal resolution. In particular cases, for instance in Adventfjorden – a branch of Isfjorden, even subdecadal resolution was achieved, because sediment accumulation rates are in the excess of 1 cm per year (Zajączkowski *et al*. 2004, Majewski and Zajączkowski 2007). Normally, however, sites with very high sediment accumulation rates are not very useful because the sedimentation is very variable, so they reflect mostly local conditions and

foraminiferal assemblages are related mostly to local environment, governed by rapid sedimentation and soft bottom and not by general hydrological patterns.

While applying benthic foraminiferal analyses, at least two limiting factors must be taken into account: bioturbation and the real habitat and active penetration depth of foraminifera. The bioturbation causes mixing of the surface layer. The mixing depth, determined using ^{210}Pb radionuclide excess profiles, is variable. For instance, in the central Billefjorden, it was observed to be in order of 1 to 2 cm (Szczuciński *et al*. 2009), in the central basins of Hornsund it was found to be even about 2–4 cm (Szczuciński *et al*. unpublished), and on the continental shelf it may reach thickness of 4 to 8 cm on average (*e.g.* Sommerfield *et al*. 2007). If one assumes mixing depth of 4 cm and sediment accumulation rate of 0.5 cm per year, similar to values found in Hornsund, then we should expect the decadal record to be mixed and averaged.

Apart from bioturbation, it is very important to take into account the favorable habitat depth of particular foraminiferal species. The present study confirmed that some of the species prefers to live at least several cm below the sediment surface, moreover, they may actively penetrate the sediment in search for food and better conditions, *e.g.* oxygen. Furthermore, various species have various habitat depth. In paleoceanographic studies, it is usually not taken into account but in case of sampling intervals ~5 cm it is probably less significant. However, if a high resolution study is to be performed then that factor needs to be taken into account. The actual depth of occurrence of modern foraminifera is also very important for dating. The most common ^{14}C dating is often performed on foraminifera as they accurately record their age but since foraminifera used to live below the sediment surface, the sediment at the same depth will be older than the dated foraminifera.

Conclusions

The major hydrological features of the Hornsund fjord are the inflow of transformed AW into the outer and central fjord basins, and the presence of cold winter-cooled, near-bottom waters and brackish sediment-laden waters near the surface in the inner fjord basins. The major water masses as well as the biological (primary production) and physical (sedimentation, sea ice formation) processes are reflected well by changing benthic foraminiferal assemblages. The outer fjord is dominated by abundant boreal taxa (*N. labradorica* and *E. excavatum* f. *selseyensis* assemblage) with common agglutinated species, whereas the inner fjord is poor in species and is dominated by opportunistic taxa (*E. exavatum* f. *clavata* and *C. reniforme*). The increasing number of *C. reniforme* and agglutinated species could indicate increased STW inflows into the fjord.

The habitat depth of various foraminiferal species is variable and usually the maximum occurrence of modern foraminifera is several cm below the sediment

surface. It should be taken into account while attempting high-resolution paleo-environmental studies.

The analysis of the available paleotemperature equations proved the one by Shackleton (1974) and $\delta^{18}O_{water}$ mixing lines by Azetsu-Scott and Tan (1997) to be the most suitable for Hornsund. The mixing line obtained recently by MacLachlan *et al.* (2007) for Kongsfjorden should not be used for fjords with an ArW component. The stable isotopic composition of benthic foraminifera does not reflect the real water temperature in case of basins filled with winter-cooled waters. The analysis and interpretation of stable isotopes from the sedimentary record of deep fjord basins, where such water masses could form, must be done with caution.

The modern foraminiferal isotopic composition shows clear species-specific vital effects and high variability in specimens from the same samples, which suggests using single species and a larger number of medium sized tests as single samples instead of using single large tests.

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Appendix 1

List of foraminiferal species found in the Hornsund fjord during the survey of 2002

Adercotryma glomerata (Brady, 1978)
Ammotium cassis (Parker, 1870)
Astrononion gallowayi Loeblich and Tapan, 1953
Astrononion tumidum Cushman and Edwards 1937
Bolivina pseudopunctata Höglund, 1947
Buccella frigida (Cushman, 1922)
Cassidulina obtusa Williamson, 1958
Cassidulina reniforme Nørvag, 1945
Cibicides lobatulus (Walker and Jacob, 1798)
Cornuspira foliacea (Philippi, 1844)
Elphidium albiumbilicatum (Weiss, 1954)
Elphidium bartletti Cushman, 1933
Elphidium excavatum f. *clavata* Cushman, 1944
Elphidium excavatum f. *selseyensis* (Terquem, 1875)
Elphidium subarcticum (Weiss, 1954)
Globobulimina turgida (Bailey, 1851)
Hyperammina subnodosa (Brady, 1884)
Islandiella helenae (Feyling-Hanssen and Buzas,1976)
Islandiella islandica Nørvag, 1945
Islandiella narcrossi (Coushman, 1933)
Labrospira crassimargo (Norman, 1892)
Miliamina agglutinata Cushman, 1933
Miliamina stalkeri (Loeblich and Tapan, 1953)
Nonion orbiculare (Brady, 1881)
Nonionellina labradorica (Dowson, 1860)
Pyrgo williamsoni (Sylvestri, 1923)
Quinqueloculina arctica Cushman, 1933
Quinqueloculina seminulum (Linné, 1758)
Recurvoides turbinatus (Brady, 1881)
Reophax scorpiurus (Montfort, 1808)
Robertina arctica (d'Orbigny, 1839)
Spiroplectammina biformis (Parker and Jones, 1865)
Spiroplectammina earlandi (Parker, 1952)
Stainforthia fusiformis (Williamson, 1958)
Stainforthia loeblichi (Feyling-Hanssen, 1954)
Triloculina frigida Lagoe, 1977
Triloculina oblonga (Montagu, 1803)
Verneuilina arctica Höglund, 1947

Appendix 2

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.2478/v10183-010-0010-4