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OCCURRENCE AND DISTRIBUTION OF THE PLANKTONIC FORAMINIFER *NEOGLOBOQUADRINA PACHYDERMA* WITHIN ANNUAL AND PERENNIAL SEA ICE OF THE EASTERN PART OF LÜTZOW-HOLM BAY, ANTARCTICA

Atsuo IGARASHI[1], Hideki NUMANAMI[2], Yasutaka TSUCHIYA[3] and Mitsuo FUKUCHI[4]

[1]*Institute of Geology and Paleontology, Graduate School of Science, Tohoku University, Sendai 980–77*
[2]*Laboratory of Biology, Tokyo Kasei Gakuin University, 2600 Aihara, Machida-shi, Tokyo 194–02*
[3]*Shimoda Marine Research Center, University of Tsukuba, 5–10–1, Shimoda 415*
[4]*National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: Annual and perennial sea ice cores, collected regularly for a period of one year at four fixed stations and one time each at 10 other stations in the eastern part of Lützow-Holm Bay, were investigated to elucidate characteristics of vertical distribution and abundance of planktonic foraminifers within sea ice.

At Station A–5, situated about 3 km east of Syowa Station, the planktonic foraminifer *Neogloboquadrina pachyderma* with cytoplasm is present mainly within sections between 20 and 40 cm from the top of the cores. At Station A-2, located near Syowa Station, they are restricted predominantly to the lowermost 50 cm sections of the cores. At Station D, located about 20 km west of Syowa Station, they are distributed maximally within sections between 210 and 244 cm from the top of the cores.

Considering the vertical distribution of foraminifers within sea ice and the time of freezing of sea ice, the main time of foraminiferal incorporation is estimated to be from mid-April to mid-May, that is, from austral late autumn to early winter. The foraminifers may probably become congregated in the uppermost part of the water column in order to feed on abundant diatoms during spring and summer. Until the onset of ice formation from late April to mid-May, they may still remain there and are likely to be accidentally incorporated into the sea ice.

1. Introduction

The occurrence of planktonic foraminifers in sea ice has been known since the first report by CARSOLA (1953) who found adult tests of *Globigerina pachyderma* (EHRENBERG) [presently called *Neogloboquadrina pachyderma* (EHRENBERG)] in sea ice taken from the Bering Sea. In the Antarctic marginal sea, there have been four studies as described below.

LIPPS and KREBS (1974) made the first discovery of a large number of juveniles belonging to the same species from sea ice near the shore of the Antarctic Peninsula. They suggested two possibilities: that the foraminifers might have been trapped in sea ice and killed as the ice froze solid, or they might have actually been alive in the ice interstices with the ice serving as a protective nursery or refuge for foraminifers.

Thereafter, the focus of studies shifted to the question of whether the species lived in sea ice or, if they lived, what might have prompted their entrance into the ice. SPINDLER and DIECKMANN (1986) reported the vertical distribution and abundance change of *N. pachyderma* in sea ice cores from 12 stations along the eastern coast of the Weddell Sea. They provided evidence that more *N. pachyderma* per unit volume lived in sea ice than in the underlying water column. Their study also indicated that small tests of dead juveniles predominated in the upper sections of the sea ice cores whereas large living individuals mainly occurred in the lower sections, owing probably to their migration toward the bottom of the ice. SPINDLER *et al.* (1990) and DIECKMANN *et al.* (1991) reported the quantitative distribution of *N. pachyderma* in the sea ice and in the underlying water column at many stations from the coast to the edge of offshore sea ice of the Weddell Sea. They revealed that sea ice contained approximately the same numbers of foraminifers per unit volume as, or more foraminifers than, the underlying water column, and that a high yield of foraminifers was generally associated with granular ice which originated from frazil ice. From this observation, they suggested that the foraminifers usually became incorporated into the ice when it was being formed dynamically and that the incorporation possibly represented an overwintering strategy whereby they were able to survive and grow in the ice because of ice's higher algal biomass content in winter than the water column.

From these results, a presumption was made that after incorporation into sea ice, foraminifers are alive in the ice interstices and that the season of incorporation is autumn to early winter when the ice is formed or grows dynamically. But sea ice was sampled only once per station; therefore, practical sampling of sea ice throughout the year and analyses of foraminifers in them in relation to vertical growth and decay of the ice will be necessary in order to confirm the above assumed season of their incorporation into sea ice.

Under the aegis of the Sea Ice Ecology and Flux Study program of the 33rd Japanese Antarctic Research Expedition (JARE-33, 1991–1993), the authors had an opportunity to stay at Syowa Station in Antarctica for a period of 13 months, from January 1992 to January 1993. During our stay, we collected sea ice cores regularly at four fixed stations. Also, cores were taken once each from 10 additional stations in the eastern part of Lützow-Holm Bay. This paper presents data on the vertical distribution and abundance of foraminifers within annual and perennial sea ice cores at the four fixed sampling stations. Then the paper discusses the time of incorporation of foraminifers into the sea ice and evaluates why such incorporation occurs. The paper also reports the occurrence and abundance of foraminifers in ice cores taken at various other geographical locations within the Bay.

2. Materials and Methods

Sea ice samples used for this study were collected from 14 stations in the eastern part of Lützow-Holm Bay, Antarctica (Figs. 1 and 2). All the sea ice cores were collected by using an 8 cm diameter electric ice auger.

At Station A-5, situated about 3 km east of Syowa Station (Fig. 2), sea ice cores were collected 12 times in total at intervals between about two weeks and one month from early June to late December 1992 (Table 1). At this station, a block of sea ice measuring about 50×50×50 cm was also obtained when a square hole of about 130×130 cm size was cut on 4 June 1992.

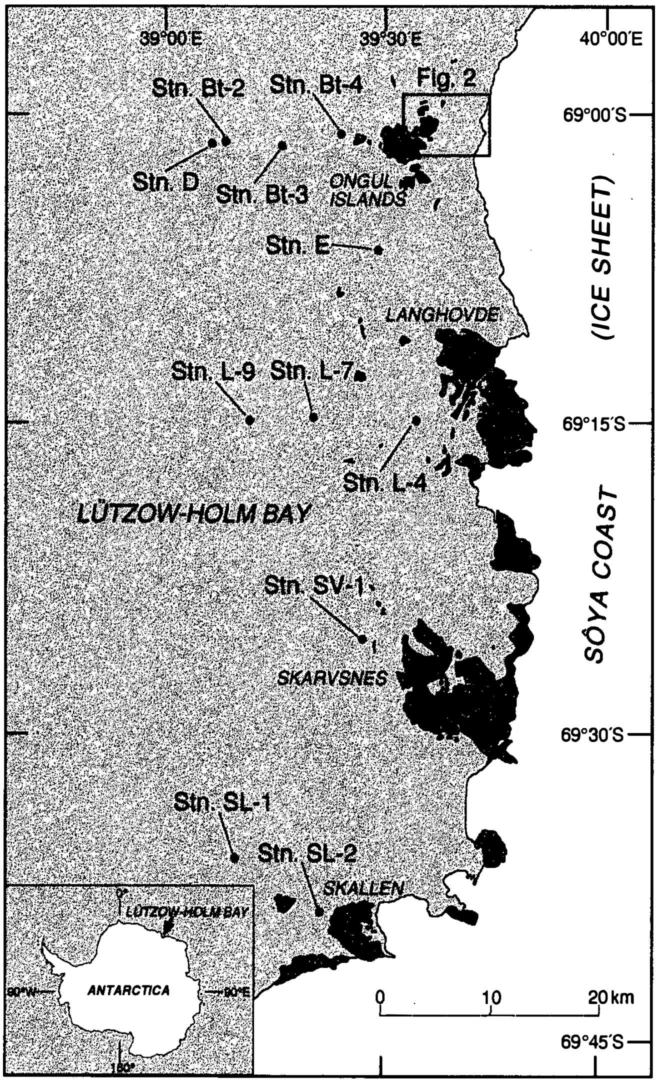

Fig. 1. Map of the east coast of Lützow-Holm Bay showing sampling sites.

At Stations A-2 and C, located near Syowa Station (Fig. 2), cores were collected 18 times in total at the same intervals as those of Station A-5 from late March 1992 to late January 1993 (Tables 2 and 3).

At Station D, located about 20 km west of East Ongul Island (Fig. 1), cores were taken four times in May, August, October, and December in 1992 (Table 4). The lowermost 55 cm of the core collected on 24 October was lost.

In addition to these, cores were collected only once at 10 stations in the eastern part of Lützow-Holm Bay from September to November in 1992 (Fig. 1, Table 4).

The ice at Station A-5 was annual; sea ice was broken and the sea surface became exposed by a strong wind on 12 February 1992, and then the open water began to refreeze at the beginning of March. On the contrary, ice at Stations A-2, C, and D was perennial; it has remained frozen since April 1989, April 1985, and June 1988, respectively (KOKURITSU KYOKUCHI KENKYUJO, 1986, 1987, 1988, 1989, 1990, 1991, 1992). The ice at 10 other stations was also all perennial; it has remained frozen since 1987 or 1988 (KOKURITSU KYOKUCHI KENKYUJO, 1988, 1989, 1990, 1991, 1992).

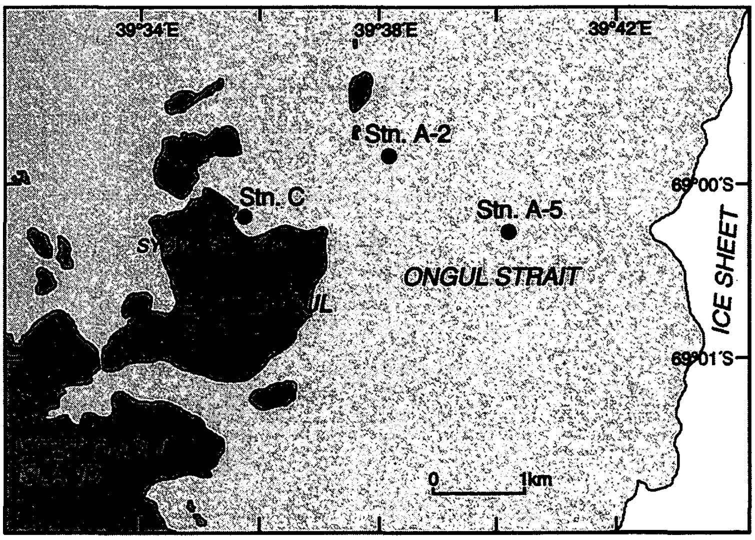

Fig. 2. Map of the environ of Syowa Station showing sampling sites.

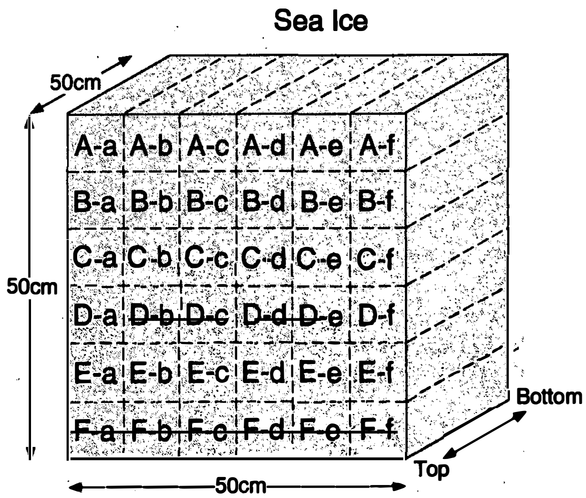

Fig. 3. Illustration of a block of sea ice collected at Station A-5 on 4 June 1992. Broken lines show cutting lines.

All these ice cores and the ice block were brought back to Japan frozen at about −20℃. In the laboratory, the ice cores were described as to their characteristics and then cut into 10 cm sections from the bottom. The block of ice was cut vertically into thirty-six square pillars measuring about 8×8×50 cm (Fig. 3). After describing the characteristics of the ice, each pillar was also cut into 10 cm sections. Sections were then thawed; each yielded about 300 to 480 m*l* of meltwater. With regard to the meltwater from Stations A-5, A-2, C, and D, their salinities were recorded by means of an electric salinometer. Then several milliliters of solution of Rose Bengal stain, whose concentration was about 2 g per liter, was added to each sample of meltwater, and the water was let alone for a day in order to determine if foraminifers contained cytoplasm or were empty tests. The waters were then sieved through about 10 μm-opening filter papers. After filter papers were dried, foraminifers were picked up with the use of an optical microscope.

3. Results

3.1. Station A-5

At this station, since the sea surface began to refreeze early in March, ice continued to grow until early November when the thickness of 114 cm was attained. Late in November, ice thickness decreased once to 104 cm, and the ice began to thicken until late December, reaching as much as 117 cm in thickness (Table 1).

Ice was opaque throughout its entire length owing to the inclusion of numerous minute air bubbles. Ice texture in the upper part of the cores was mixed columnar/ granular, and that of the middle to the lower part was columnar on the whole (Figs. 5 and 6). The zone of ice texture shift occurred generally within an interval from 20 to 40 cm downcore depth. The lowermost 2 cm of the cores was usually porous with parallel ice crystals.

All the specimens recovered from the station had a thin-walled trochospiral test with 4–5 chambers per whorl and the large last chamber spherical to ovate in shape. They are all assigned to *Neogloboquadrina pachyderma* (Fig. 4). Most of the specimens were sinistrally coiled. A greater proportion of individuals showed a distinct coloration by Rose Bengal (Table 1). The largest diameter of 62 specimens measured ranged

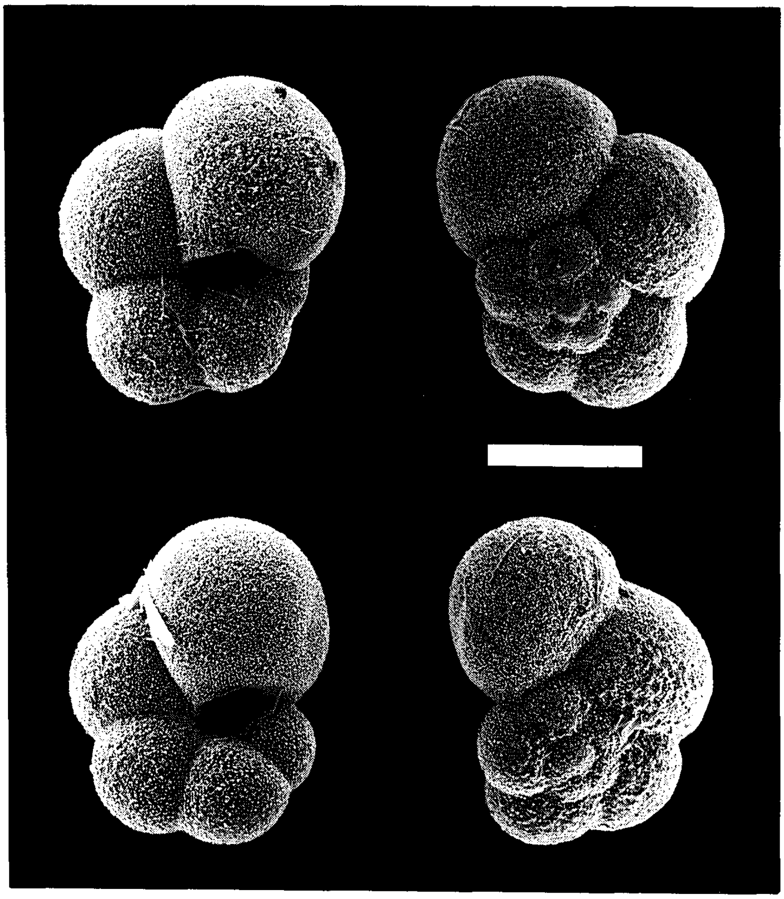

Fig. 4. Neogloboquadrina pachyderma *(EHRENBERG) recovered from sea ice at Station A-5. Scale bar = 100 μm.*

Table 1. Data for sea ice cores at Station A-5, Ongul Strait, Lützow-Holm Bay. Latitude 69°00′ 18″S, longitude 39°40′ 06″E, and water depth 679 m.

Collection date	Ice core length (cm)	Salinity range (psu)	Foram. yield. section from the core top (cm)	Melt. water volume (ml)	Number of foraminifers: Rose Bengal stain: Positive: Sinistral	Positive: Dextral	Negative: Sinistral
04.06.92	50	0.7–5.1	0–10	11504	4	0	0
			10–20	17824	1	0	0
			20–30	18436	147	4	0
			30–40	18904	42	0	0
			40–50	18378	4	0	0
15.06.92	62	3.8–6.1	22–32	420	2	0	0
			32–42	393	1	0	0
29.06.92	70	3.4–5.5	20–30	423	1	0	0
13.07.92	72	3.1–9.7	—	—	0	0	0
28.07.92	83	3.4–7.8	23–33	400	7	0	0
24.08.92	90	3.3–8.1	30–40	375	20	0	0
17.09.92	97	2.3–4.8	17–27	372	1	0	0
05.10.92	106	2.4–6.2	26–36	373	25	2	0
			36–46	394	2	0	0
			76–86	422	1	0	0
20.10.92	110	2.5–5.3	10–20	369	0	0	1
			20–30	380	2	0	0
09.11.92	114	2.4–7.2	34–44	391	3	0	0
25.11.92	104	2.8–5.6	14–24	374	1	0	0
11.12.92	110	3.2–4.8	20–30	398	2	0	0
25.12.92	117	2.4–5.8	17–27	339	1	0	0
			27–37	383	8	0	0

between 111 and 317 μm, and their mean value was 207 μm. These specimens are applicable to neanic and adult individuals.

The numbers of specimens per core were from one to 30 for 11 of the 12 cores, with the exception of the one collected on 13 July (Table 1). For the block of ice collected on 4 June, their numbers were 151 per 18436 m*l* of meltwater at 20 to 30 cm intervals and 42 per 18904 m*l* at 30 to 40 cm intervals, although other sections contained only one or four individuals in 11504, 18378 and 18904 ml of meltwater, respectively (Table 1).

The maximal distribution of *N. pachyderma* was largely restricted to a 10 to 46 cm section from the core tops for the 11 cores (Fig. 5). In the block of ice, they were distributed throughout the entire thickness, and their dominant occurrence was noted in a section between 20 and 40 cm from the core top (Fig. 6). Such distributional features indicate that foraminifers were present mainly within the section between 20 and 40 cm from the core top regardless of difference of samples.

The section between 20 and 40 cm included few diatoms, although several circular diatoms were contained in the upper 20 cm sections of several cores and the lowermost 10 cm section of cores collected on 25 November and 11 December contained comparatively abundant diatoms (Fig. 5).

The salinity of the ice ranged from about 2 to 10 psu throughout the cores, and no particularly high value occurred in the section between 20 and 40 cm as compared with

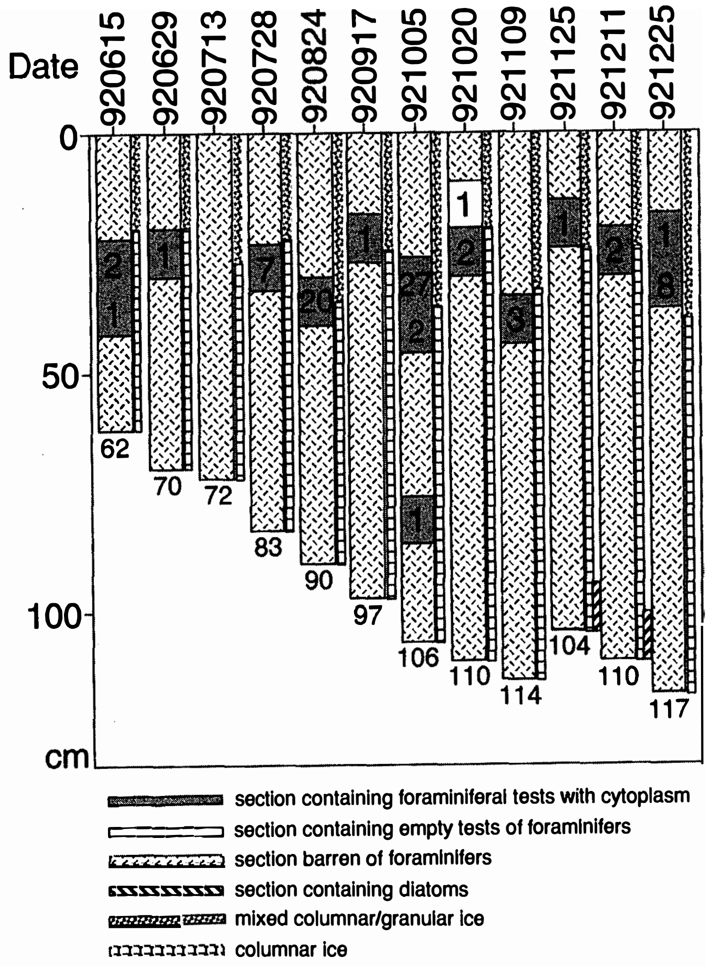

Fig. 5. Columns of sea ice cores collected at Station A-5 between 15 June and 25 December of 1992, showing sections which yielded foraminifers. Numbers on and under each column denote the number of foraminifers and core length, respectively.

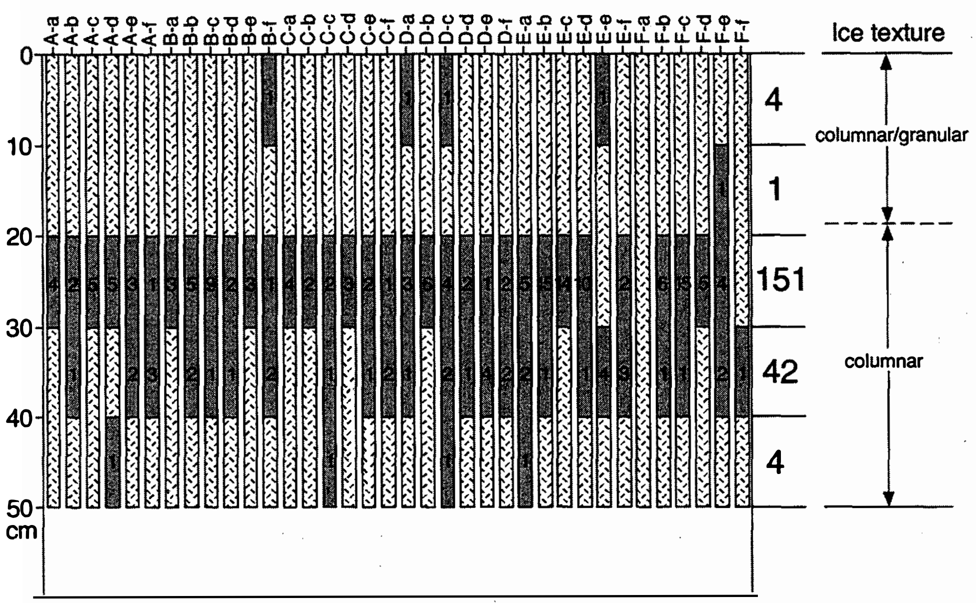

Fig. 6. Thirty-six square columns cut out of a block of sea ice collected at Station A-5 on 4 June 1992, showing square pillars which yielded foraminifers. Numbers on and beside each column denote the number of foraminifers.

other sections.

3.2. *Station A-2*

Ice thickness at this station was nearly 150 cm until late April, but at the beginning of May it increased markedly to 182 cm. Since then, the thickness fluctuated between about 160 to 190 cm until early January of the following year when it grew rapidly to 205 cm (Table 2).

Ice was generally translucent with many relatively large air bubbles in the upper core sections and gradually became opaque toward the bottom owing to the increase of numerous minute air bubbles. The upper part of the ice cores had a mixed columnar/granular texture. The uppermost part particularly had a granular texture on the whole. The ice texture of the middle to lower part of the cores was columnar. The lowermost 2 cm of all the cores obtained after 8 May was porous with parallel ice crystals.

All specimens obtained at the station were morphologically the same as those of Station A-5, which are assigned to *N. pachyderma*. Almost all the tests were sinistrally coiled. Two to 39 individuals per core were obtained from 17 among the 18 cores, with the exception of one collected on 11 April (Table 2). The largest diameter of 117 specimens measured ranged from 143 to 444 μm, and their mean value was 257 μm. These specimens are regarded as neanic and adult.

Tests bearing cytoplasm began to appear after 8 May, and they continued to occur until 20 January of the following year (Table 2, Fig. 7). They were restricted to the lowermost 30 cm section of the cores until 20 October, and after that they were distributed within the lowermost 50 cm sections (Fig. 7). The amount of empty tests was much less than those of tests with cytoplasm. Empty tests occurred generally in the section above that containing tests with cytoplasm, but in the cores taken on 9 and 20 of January, they were present within the same, or sections below, those containing tests with cytoplasm (Fig. 7).

Comparatively abundant diatoms were recovered from the lower sections of all the cores taken at this station, although the middle and the upper sections included few diatoms. They occurred in the lowermost 10 cm sections of the cores taken on 24 March and 11 and 25 of April, but their abundance increased markedly in the lowermost 10 cm section of the core on 8 May. Since then, they occurred within the lowermost 30 cm section until 18 September and thereafter within the lowermost 50 cm until 20 January of the following year (Fig. 7). A few or several copepod specimens usually occurred together with diatoms. These sections containing diatoms or copepods mostly coincided with the sections that yielded foraminifers with cytoplasm.

The salinity of the ice ranged between 0 and 5.2 psu throughout the examined cores, and it tended to increase gradually toward the bottom. The salinity of the lowermost 10 cm section increased from 1.3 psu on 25 April to 2.8 psu on 8 May and even higher to 3.6 psu on 1 June. Thereafter, it fluctuated between 3 and 5 psu level. This time of increase, between April and May, coincided with the first appearance of foraminifers with cytoplasm.

3.3. *Station C*

Ice thickness fluctuated between 185 and 217 cm until the middle of September, and

Table 2. Data for sea ice cores at Station A-2, Ongul Strait, Lützow-Holm Bay. Latitude 68°59′51″S, longitude 39°38′08″E, and water depth 159 m.

Collection date	Ice core length (cm)	Salinity range (psu)	Foram. yield. section from the core top (cm)	Melt. water volume (ml)	Number of foraminifers		
					Rose Bengal stain		
					Positive		Negative
					Sinistral	Dextral	Sinistral
24.03.92	149	0.0–2.2	79–89	388	0	0	3
			89–99	418	0	0	1
11.04.92	156	0.0–2.2	—	—	0	0	0
25.04.92	153	0.0–1.9	123–133	421	0	0	1
			143–153	333	0	0	1
08.05.92	182	0.0–2.8	162–172	393	1	0	0
			172–182	306	8	0	0
01.06.92	182	0.0–3.6	132–142	420	0	0	1
			172–182	373	8	0	0
15.06.92	176	0.1–3.7	156–166	399	3	0	0
			166–176	371	1	0	0
29.06.92	181	0.0–4.1	161–171	428	2	0	0
			171–181	357	1	0	0
13.07.92	176	0.0–3.8	156–166	440	3	0	0
			166–176	361	1	0	0
28.07.92	162	0.1–3.4	142–152	369	5	0	0
			152–162	357	9	0	0
01.09.92	183	0.0–4.3	153–163	460	5	0	0
			163–173	393	12	1	0
			173–183	384	10	0	0
18.09.92	183	0.0–4.5	143–153	327	0	0	1
			173–183	340	3	0	0
20.10.92	182	0.0–5.2	152–162	396	5	0	0
			162–172	392	3	0	0
09.11.92	170	0.1–4.5	130–140	397	5	0	0
			140–150	372	2	0	0
24.11.92	188	0.1–4.4	148–158	387	2	0	0
			158–168	398	2	0	0
			168–178	397	3	0	0
			178–188	381	2	0	0
11.12.92	167	0.3–4.5	127–137	379	0	0	2
			137–147	401	1	0	0
			157–167	358	1	0	0
25.12.92	173	0.4–4.4	143–153	388	2	0	0
			153–163	389	5	1	0
			163–173	356	1	0	0
09.01.93	165	0.2–3.2	105–115	386	0	0	1
			115–125	368	22	0	0
			125–135	378	11	1	0
			135–145	398	3	0	0
			145–155	362	0	0	1
20.01.93	205	0.0–3.3	175–185	432	2	0	3

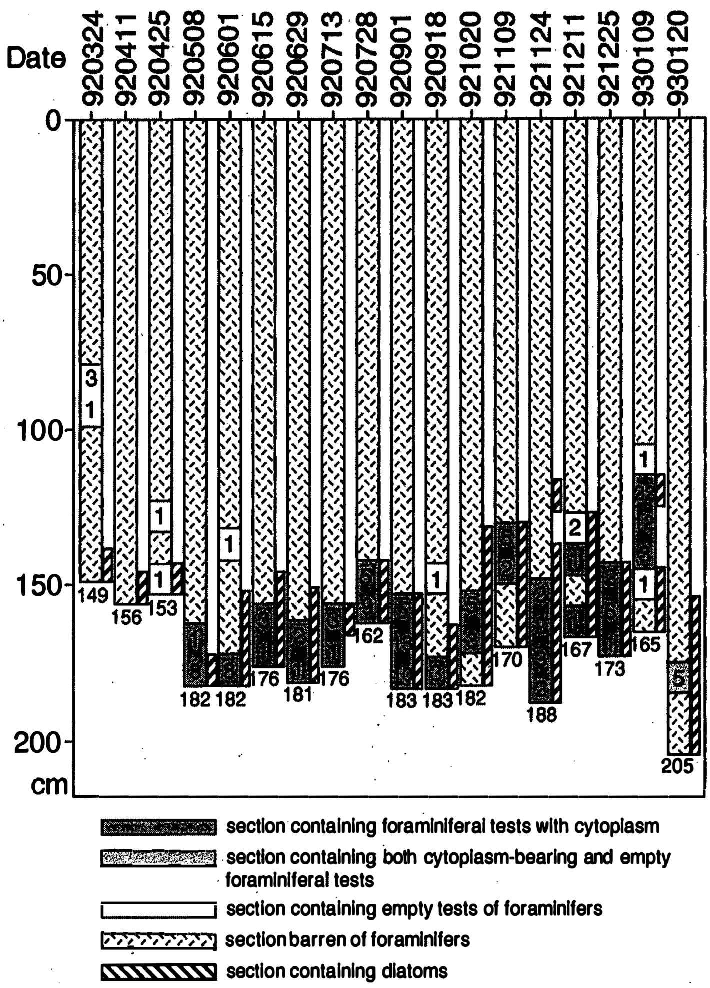

Fig. 7. Columns of sea ice cores collected at Station A-2 between 24 March 1992 and 20 January 1993, showing sections which yielded foraminifers. Numbers on and under each column denote the number of foraminifers and core length, respectively.

thereafter it began to increase until late December when it reached 261 cm at this station. In January, the ice thickness once decreased to 227 cm but increased markedly to as much as 280 cm (Table 3). The character of ice cores was nearly the same as that at Station A-2.

The amount of foraminifers contained in cores taken at this station was quite less than those from Stations A-5 and A-2. Five out of 18 cores each contained one individual assignable to *N. pachyderma* (Table 3). All the individuals were sinistrally coiled and they were morphologically similar to those from Stations A-5 and A-2. Three among the five individuals bearing cytoplasm occurred in the lowermost 20 cm, whereas two empty tests were found in the 107 to 117 cm and 145 to 155 cm sections from the core top (Fig. 8). The largest diameter of the five specimens measured ranged from 143 to 254 μm, and their mean value was 200 μm. These individuals are considered to be neanic and adult ones.

Diatoms were contained in the middle to lower parts of all the cores, and they were relatively abundant in the lower parts. No particularly high content of diatoms was

Table 3. Data for sea ice cores at Station C, Kita-no-ura Cove, Lützow-Holm Bay. Latitude 69°00′ 11″S, longitude 39°35′ 45″E, and water depth 31 m.

Collection date	Ice core length (cm)	Salinity range (psu)	Foram. yield. section from the core top (cm)	Melt. water volume (ml)	Number of foraminifers	
					Rose Bengal stain	
					Positive	Negative
					Sinistral	Sinistral
24.03.92	204	0.0–1.9	—	—	0	0
11.04.92	200	0.0–2.4	—	—	0	0
25.04.92	207	0.0–2.8	—	—	0	0
08.05.92	185	0.0–3.0	145–155	419	0	1
01.06.92	193	0.1–2.7	—	—	0	0
18.06.92	200	0.1–3.3	190–200	348	1	0
29.06.92	189	0.0–4.0	179–189	325	1	0
14.07.92	214	0.0–3.5	—	—	0	0
28.07.92	196	0.0–4.8	—	—	0	0
01.09.92	217	0.0–4.2	107–117	315	0	1
18.09.92	187	0.0–5.6	—	—	0	0
21.10.92	234	0.0–4.1	214–224	384	1	0
09.11.92	252	0.1–6.1	—	—	0	0
25.11.92	260	0.0–8.0	—	—	0	0
11.12.92	254	0.0–4.6	—	—	0	0
25.12.92	261	0.2–4.8	—	—	0	0
09.01.93	227	0.1–4.3	—	—	0	0
20.01.93	280	0.0–4.3	—	—	0	0

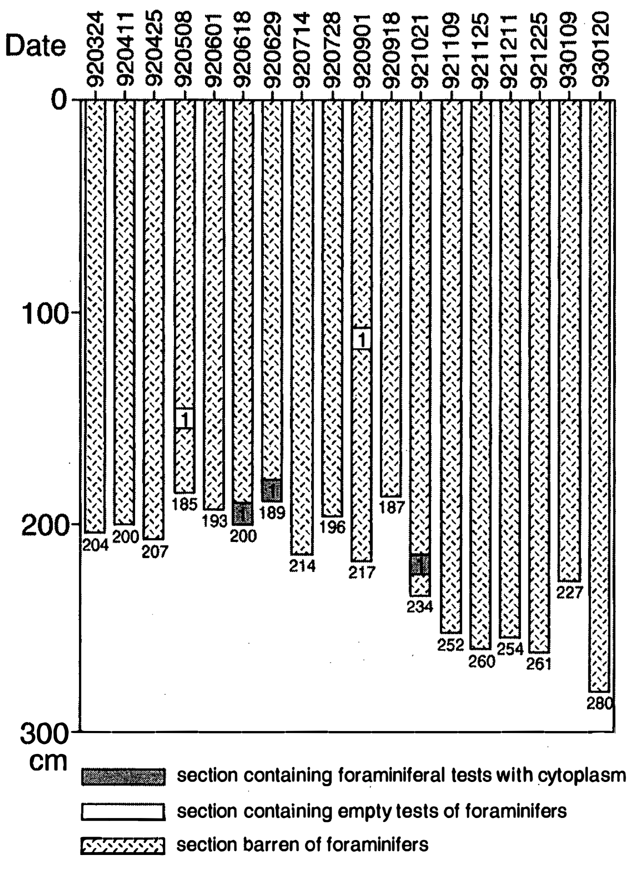

Fig. 8. Same as Fig. 7 except for Station C.

associated with the core section that yielded foraminifers.

The salinity of ice ranged from 0 to 8 psu throughout the core sections and tended to increase gradually toward the bottom. The value did not increase particularly in the section that contained foraminifers.

3.4. *Station D*

Ice thickness on 21 May was 220 cm. Then it increased to 245 cm on 17 August and still more to 310 cm on 24 October. It decreased to 284 cm on 20 December (Table 4). The character of ice cores was similar to that found at Stations A-2 and C.

Two to seven specimens of *N. pachyderma* per core were obtained from all four cores (Table 4). All the tests were sinistrally coiled. All the specimens were morphologically similar to those from other stations. The total of 10 foraminifers with cytoplasm occurred in sections between 210 and 244 cm from the core top in every core (Fig. 9). Seven empty tests occurred within the same or slightly higher section that contained tests with cytoplasm (Fig. 9). The largest diameter of 12 specimens measured

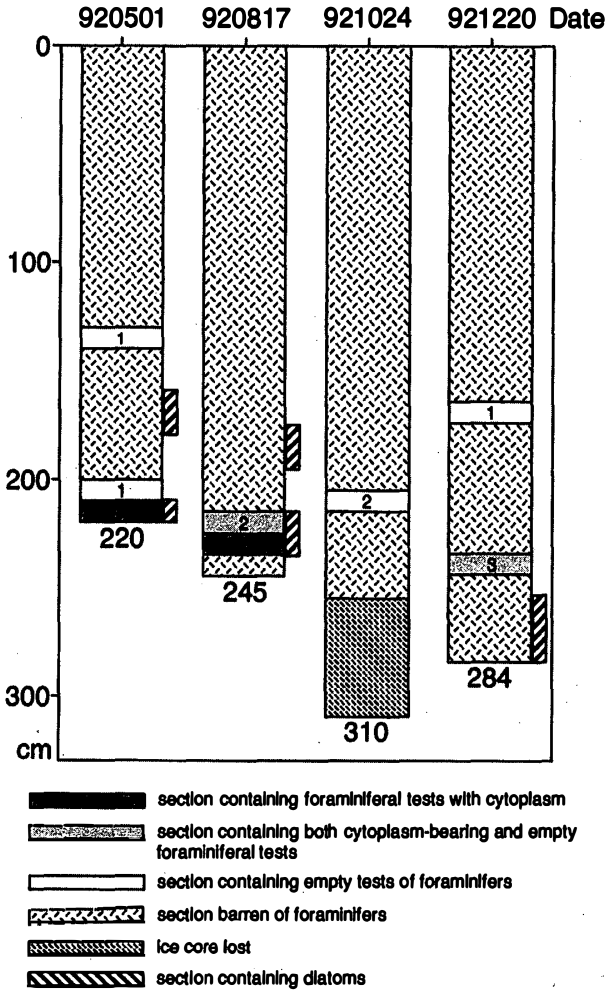

Fig. 9. Same as Fig. 7 except for Station D between 21 May and 20 December of 1992

Table 4. Data for sea ice cores at other stations of eastern part of Lützow-Holm Bay.

Station	Latitude	Longitude	Water depth (m)	Collection date	Ice core length (cm)	Salinity range (psu)	Foram. yield. section from the core top (cm)	Melt. water volume (ml)	Number of foraminifers, Rose Bengal stain, Positive: Sinistral	Positive: Dextral	Negative: Sinistral
D	69°01′25″S	39°06′00″E	232	21.05.92	220	0.0–4.5	130–140	346	0	0	1
							200–210	394	0	0	1
							210–220	329	5	0	0
				17.08.92	245	0.0–5.2	215–225	406	1	0	1
							225–235	406	2	0	0
				24.10.92	310	0.0–3.7	205–215	355	0	0	2
				20.12.92	284	0.0–5.9	164–174	340	0	0	1
							234–244	397	2	0	1
Bt-2	69°01′14″S	39°07′30″E	233	13.11.92	324	—	184–194	401	0	0	1
							294–304	367	5	0	0
Bt-3	69°01′30″S	39°15′46″E	173	17.11.92	297	—	—	—	0	0	0
Bt-4	69°00′50″S	39°23′35″E	52	18.11.92	221	—	71–81	379	0	0	2
							81–91	391	0	0	2
							101–111	343	0	0	1
E	69°06′18″S	39°29′42″E	245	26.11.92	175	—	105–115	383	0	0	2
L-4	69°14′44″S	39°34′16″E	251	14.10.92	145	—	—	—	0	0	0
L-7	69°14′42″S	39°20′03″E	488	16.10.92	175	—	95–105	380	16	3	0
L-9	69°14′48″S	39°11′33″E	497	15.10.92	216	—	186–196	482	0	0	1
SV-1	69°25′30″S	39°26′13″E	487	28.09.92	174	—	—	—	0	0	0
SL-1	69°36′06″S	39°08′41″E	393	26.09.92	189	—	129–139	393	0	0	2
SL-2	69°38′37″S	39°20′25″E	405	26.09.92	207	—	—	—	0	0	0

ranged from 183 and 349 μm, and their mean value was 277 μm. These specimens are applicable to neanic and adult individuals.

Diatoms were included in the lower part of the cores (Fig. 9). The sections that yielded foraminifers did not necessarily contain abundant diatoms.

The salinity of the ice ranged between 0 and 5.9 psu throughout the cores. As a rule, it had a tendency to gradually increase toward the bottom.

3.5. *Other stations*

Ice thickness tended to increase from the eastern edge toward the center of the bay (Table 4). Ice textures of ice cores were mostly the same as those of Stations A-2, C, and D.

At the three stations, located west of the Ongul Islands, foraminifers assignable to *N. pachyderma* were obtained from Stations Bt-2 and Bt-4. Five tests with cytoplasm occurred within the 20 to 30 cm section from the bottom at Station Bt-2. One empty test occurred in the 130 to 140 cm section from the bottom at Station Bt-2, and five empty tests in the 110 to 120 cm and the 130 to 150 cm sections from the bottom at Station Bt-4 (Table 4). This distributional pattern was similar to that of Station D located near Station Bt-2. All the tests examined were sinistrally coiled.

At Station E, located south of the Ongul Islands, two empty sinistrally coiled tests of *N. pachyderma* were collected from a 60 to 70 cm section from the bottom (Table 4).

From the two out of three stations located west of Langhovde, namely Stations L-7 and L-9, the foraminifers were recovered. Nineteen tests with cytoplasm, among which 16 were sinistrally coiled, occurred within a 70 to 80 cm section from the bottom at Station L-7. One sinistrally coiled empty test was contained in a 20 to 30 cm section from the bottom at Station L-9 (Table 4).

Among the three stations in the southeastern part of the bay, only two empty sinistrally coiled tests were obtained from a 50 to 60 cm section from the bottom at Station SL-1 (Table 4).

All these specimens were morphologically the same as those mentioned before.

Compared with Station A-5 and A-2, these stations tended to yield empty tests in a high proportion. At the stations, the abundance of foraminifers per core was similar to that in the fixed Stations A-5, A-2, and D. No distinct pattern of changes in the foraminiferal abundance occurs toward the center of the bay from the eastern edge.

4. Discussion

At Station A-5, the main foraminifera-yielding section was between 20 and 40 cm from the core top. As judged from the ice growth rate from the beginning of refreezing of the sea surface early in March up to 50 cm in thickness early in June, foraminiferal incorporation into sea ice is presumed to have occurred mainly between mid-April and mid-May. At Station A-2, it is assumed that, when the ice thickness rapidly increased from late April to early May, foraminifers became incorporated into the sea ice. This assumption is made both from the first appearance time of foraminifers with cytoplasm as mentioned before and from the rapid increase time of ice thickness. The timing of rapid increase of ice coincided with the first appearance time of porous and parallelcrystallized ice texture in the lowermost 2 cm section and with the time of salinity increase in the lowermost 10 cm section. At Station D, the incorporation of foraminifers into sea ice is presumed to take place during May, judging from the depth of sections bearing foraminifers with cytoplasm. The observation at Station Bt-2, located near Station D, also supports a similar conclusion.

In summary, the principal time of foraminifera incorporation in the eastern part of Lützow-Holm Bay is estimated to be mid-April to mid-May, that is, from the austral late autumn to early winter. At other times, few foraminifers incorporated. This estimate of incorporation time agrees with DIECKMANN *et al.* (1991), who stated that foraminifers enter the sea ice as an overwintering strategy.

So far as this study is concerned, it is questionable if it can be assumed that after their incorporation foraminifers would survive and grow in the ice by utilizing diatoms as their food (SPINDLER and DIECKMANN, 1986; DIECKMANN *et al.*, 1991). It is suggested in this study that foraminifers did not survive and grow in the ice.

One reason is that the ice type of foraminifera-yielding sections in this study is mostly columnar ice, which is the product of well-ordered growth of parallel ice crystals at the ice-water interface (DIECKMANN *et al.*, 1991). In contrast, the ice type of foraminifera-yielding sections in previous studies is chiefly granular ice, which is formed by accumulation of irregularly shaped frazil ice crystals (SPINDLER *et al.*, 1990) and has porosity that offers more space to be utilized by organisms for settlement than that of columnar ice (SPINDLER *et al.*, 1990; DIECKMANN *et al.*, 1991). These different ice types of foraminifera-yielding sections indicate that the ice observed in this study had no interstices or brine channels in which foraminifers could survive. This indication is supported by the fact that the number of individuals per unit volume of columnar ice examined in this study is much less (average number of *N. pachyderma* per liter for the block of sea ice collected at Station A-5 is 2.4) than those from the granular ice studied by SPINDLER *et al.* (1990) and DIECKMANN *et al.* (1991) (average numbers of *N. pachyderma* per liter for whole samples are 100.7 and 87, respectively).

Furthermore, another reason is that abundant diatoms are not necessarily included in sections that yield foraminifers. At Stations A-2, C, and D, almost all sections that contained foraminifers with cytoplasm yielded diatoms, but their amount was not necessarily large. At Station A-5, few diatoms were little included within such sections. These facts suggest that even if live foraminifers were incorporated in the sea ice, they could not obtain ample food such as diatoms.

If this is the case, why does the incorporation of foraminifers into the ice occur during the austral late autumn and early winter? The vertical distribution of *N. pachyderma* in the water column in the study area has yet to be investigated. In the sea ice region around Syowa Station, ice algae productivity at the lowermost part of the sea ice reaches its maximum during October and November (WATANABE and SATOH, 1987; WATANABE, 1990). After that, by the reduction of ice algae from the base of sea ice, phytoplankton productivity in water column under sea ice increases abruptly and reaches a maximum during late January and early February (HOSHIAI, 1969; FUKUCHI *et al.*, 1984; SATOH *et al.*, 1986; WATANABE, 1990). Furthermore, BÉ (1969) found that in winter, that is, from June through September, the upper 100 m of water around Antarctica was comparatively barren of plankton, including foraminifera, and that the bulk of plankton populations inhabit deeper waters between 250 and 1000 m. He also indicated that *N. pachyderma* occurred most abundantly during spring, summer, and autumn, that is, from early October to late April, which coincided with the period of high phytoplankton production, whereas the low concentration of *N. pachyderma* prevailed from late autumn to winter, from May to September.

These facts suggest that foraminifers are concentrated in the uppermost part of the water column in order to feed on abundant diatoms thriving there during spring and summer. When ice formation begins in early autumn, between late April and mid-May, the foraminifers that became neanic to adult individuals still remain there, thereby accidentally being incorporated in the sea ice. Then as winter sets in, the uppermost part of the water column becomes barren of foraminifers due to their downward migration. This explains the absence of foraminifers in the sea ice that grew after mid-May as observed at Stations A-5 and D.

The reason why fewer foraminifers contained in cores taken at Station C than those from Stations A-5 and A-2 seems to be that the water depth at Station C (31 m) is much shallower than depths at Stations A-5 and A-2 (679m and 159 m, respectively).

5. Conclusions

Annual and perennial sea ice cores were collected regularly during a period of one year from four fixed stations, supplemented by one-time collection from 10 other stations, all in the eastern part of Lützow-Holm Bay, in order to investigate the vertical distribution and abundance of foraminifers within the sea ice.

At Station A-5, situated about 3 km east of Syowa Station, cytoplasm-bearing planktonic foraminifers of the species *Neogloboquadrina pachyderma* were present mainly within ice core sections between 20 and 40 cm from the core top. At Station A-2, located near Syowa Station, they were largely restricted to the lowermost 50 cm sections of ice cores. At Station D, located about 20 km west of Syowa Station, they were distributed maximally within core sections between 210 and 244 cm from the core top. At Station C, the quantity of foraminifers in ice cores was quite small compared with that at Stations A-5 and A-2. At 10 other stations, the abundance of foraminifers per core was similar to that at four other fixed stations. No distinct pattern of changes in the foraminiferal abundance occurs toward the center of the bay from the eastern edge.

The ice type of foraminifera-yielding sections was mostly columnar ice. Abundant diatoms were not necessarily found within the sections that yielded foraminifers. From these observations, the ice is interpreted to be not an ideal habitat where foraminifers can maintain vigorous growth.

Considering the depth of foraminifera-yielding ice sections and the freezing time of ice, foraminiferal incorporation possibly occurs during the austral late autumn to early winter, that is, from mid-April to mid-May, whereas few foraminifers are incorporated in other seasons. Foraminifers are possibly concentrated in the uppermost part of the water column in order to feed on abundant diatoms during spring and summer. They still remain there when ice formation starts in early autumn, from late April to mid-May, and they are accidentally incorporated in the sea ice.

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