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Japan Sea planktic foraminifera in surface sediments: geographical distribution and relationships to surface water mass

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Abstract. Modern planktic foraminifera in 51 surface sediments from the Japan Sea, a marginal sea of the western North Pacific, were studied to reveal the relationships between geographical distribution and surface water masses in the Japan Sea. Twenty-four species belonging to 10 genera were identified, of which nine species, namely *Neogloboquadrina incompta*, *Neogloboquadrina pachyderma*, *Globigerina quinqueloba*, *Globigerina bulloides*, *Globigerinoides ruber*, *Neogloboquadrina dutertrei*, *Pulleniatina obliquiloculata*, *Globigerinoides tenellus*, and *Globigerinita glutinata* are predominant. We recognized four geographical distribution patterns of these dominant species that are related to hydrographic conditions in the Japan Sea. The transitional water formed by the mixture between the warm Tsushima Current and cold waters in the Japan Sea is optimal for *N. incompta*, while the distribution of *N. pachyderma* is matched with cold water in the northern Japan Sea. *Globigerina quinqueloba* and *G. bulloides* appear to be associated with less saline, nutrient-rich river water from the Changjiang (Yangtze River), and *G. ruber*, *N. dutertrei*, *P. obliquiloculata*, *G. tenellus*, and *G. glutinata* can be regarded as indicators of Tsushima Current water.

Key words: Japan Sea, planktic foraminifera, surface sediments, Tsushima Current

Introduction

The Japan Sea is a semienclosed marginal sea which is connected with the Pacific and adjacent marginal seas through four shallow and narrow straits with sill depths of less than 130 m. At present, the only oceanic water flowing into the Japan Sea is the warm Tsushima Current, which enters through the Tsushima Strait in the south. The Tsushima Current, transporting heat and salt to the surface water, is one of the most important factors in the hydrography of the Japan Sea. However, during the last glacial period the Tsushima Current did not flow into the Japan Sea because the global sea level was remarkably low. Surface water of the Japan Sea has undergone drastic changes over time, including distinct stratification due to low-salinity surface water during the last glacial maximum and the inflow of the cold Oyashio Current during the period from 15 to 10 kyr BP (Oba *et al.*, 1991, 1995). Corresponding with the changes in surface water, planktic microfossils have significantly changed from the last glacial period to the present time (Oba *et al.*, 1991).

Recently, improved chronology based on accelerator mass spectrometry radiocarbon datings and tephrochronology makes it possible to discuss detailed paleoenvironmental changes during the last 30 kyr (e.g., Kim *et al.*, 2000; Gorbarenko and Southon, 2000; Takei *et al.*, 2002; Ikehara, 2003; Itaki *et al.*, 2004). However, the study of planktic foraminifera has been limited to stable isotope analysis and measurement of the sinistral or dextral coiling ratio of *Neogloboquadrina pachyderma*. The abundance and species composition of planktic foraminifera are useful tools for reconstructing past surface-water hydrography, and it is hoped that detailed study of planktic foraminiferal faunal change will help elucidate the paleoenvironmental history of the Japan Sea.

Investigations of relationships between distributions of living assemblages and environmental factors that provide basic data for inferring past environmental conditions are necessary to produce detailed paleoceanographic reconstructions based on the fossil record. Depth distributions of modern radiolarians or ostracods related to the vertical water structure have been studied using surface sediments and plankton tows from the Japan Sea (Itaki, 2003; Ozawa, 2003). However, data on geographical distributions of planktic foraminifera in Japan Sea surface sediments are limited to the distribution of *N. pachyderma* off Hokkaido (Kitazato, 1978) and preliminary results on species distributions in narrow areas (Oda and Ikehara, 1987, 1988; Oda, 1989, 1991; Oda and Xu, 1992; Domitsu *et al.*, 1999; Tsukawaki *et al.*, 2001). Thus, no comprehensive study of the species distributions of planktic foraminifera in surface sediments across the Japan Sea is available. In this study, we used 51 surface sediment samples systematically collected mainly from the Tsushima Current region in the Japan Sea and examined the relationships between the species distribution of modern planktic foraminifera and the surface water masses.

Oceanographic setting

The Japan Sea is a marginal sea surrounded by the Japanese Islands, the Korean Peninsula, and the Eurasian continent. It contains the Yamato Rise, three deep basins (the Japan, Yamato, and Tsushima basins), and narrow continental shelves (Figure 1). The average and maximum water depths of the sea are 1350 m and 3700 m, respectively. The four straits of Tsushima, Tsugaru, Soya, and Tatarskiy, which connect the Japan Sea with the Pacific, the Okhotsk Sea, and the East China Sea, have shallow sill depths of less than 130 m. Because water exchange between adjacent seas is confined to surface water, deep water below 300 to 400 m depths in the Japan Sea is generally homogeneous, with a low temperature (0°C to 0.5°C), low salinity (34.0‰ to 34.1‰), and high dissolved oxygen content (5.0 to 5.5 mL/L) (Moriyasu, 1972). This deep water is called the Japan Sea Proper Water (Uda, 1934). In the southern part of the Japan Sea, the Japan Sea Proper Water is covered by the warm surface water of the Tsushima Current. The Tsushima Current water is formed by the mixture between the Kuroshio and East China Sea shelf waters (Lim, 1971; Sawara and Hanzawa, 1979). The Tsushima Current enters the Japan Sea through the Tsushima Strait and flows out mainly to the Pacific through the Tsugaru Strait (Figure 1a). The rest flows northward along the western coast of Hokkaido and out to the Okhotsk Sea through the Soya Strait. After passing through the Tsushima Strait, the Tsushima Current is characterized by strong variabilities created by many meanders and eddies. The warm water of the Tsushima Current is cooled by mixing with cold water as it travels through the Japan Sea (Figure 2a, b). In the northern Japan Sea, the Liman Current flows southward from near the Tatarskiy Strait. The boundary between both currents forms a polar front at latitude 39°N to 40°N.

The salinity around the Tsushima Strait, especially in the western channel, decreases rapidly in summer (Figure 2c, d; Ogawa, 1983; Manda *et al.*, 2000). The main source of this low-salinity water is the fresh water of the Changjiang (Yangtze River), whose discharge accounts for about 90% of the total river discharge into the Yellow Sea and the East China Sea (Isobe *et al.*, 2002; Chan and Isobe, 2003).

Material and methods

Surface sediment samples were collected from the central Japan Sea and the southwestern to northeastern parts along the Japanese Islands during cruises of the R.V. *Hakurei-maru* of the Geological Survey of Japan and R.V. *Tansei-maru* of the Ocean Research Institute of the University of Tokyo (Table 1; Figure 1b). A grab sampler was used to collect all samples except for sample No. 19, which was obtained with a multiple-core sampler. The uppermost 1 to 2 cm of surface sediments were used for this study.

The samples were first washed through a 63-μm screen, and the retained particles were dried at 40°C. When planktic foraminifera were relatively abundant, sediments coarser than 63 μm were split into smaller aliquots with a microsplitter. Each sample was then dry sieved through a 125-μm screen. Planktic foraminifera larger than 125 μm were picked out from the aliquots until 100 to 200 planktic foraminiferal specimens had been collected. All these specimens were identified and counted. Foraminiferal assemblages in sediment samples from about 1500 m and deeper were affected by dissolution because the present carbonate compensation depth (CCD) of the Japan Sea is about 2000 m, much shallower than in the open ocean (Ichikura and Ujiié, 1976). We eliminated samples affected by dissolution and examined the foraminiferal assemblages of 51 surface samples for this study.

Results

A total of 24 species belonging to 10 genera were identified in the studied 51 samples (Table 2; Figure 3). The most dominant species, with maximum percentages greater than 50%, were *Neogloboquadrina incompta* and *N. pachyderma*. Secondary predominant

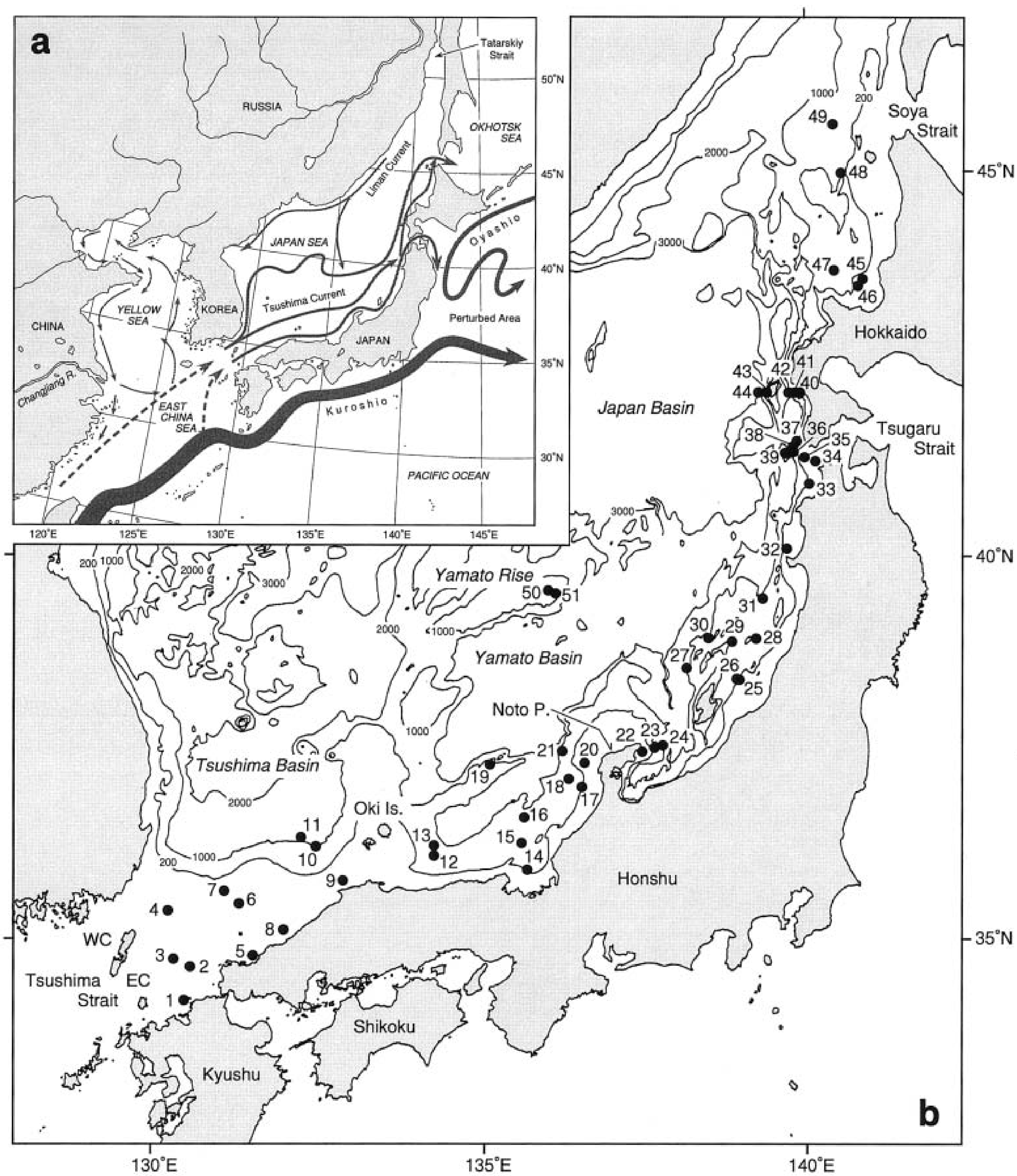


Figure 1. Map (a): Paths of main ocean currents around Japan. Dashed arrows show two hypotheses with respect to the origin of the Tsushima Current. Map (b): Locations of the 51 surface sediment samples (dots) used in this study. WC and EC indicate the western and eastern channels of the Tsushima Strait, respectively.

species, exceeding 30%, were *Globigerina quinqueloba*, *Globigerina bulloides*, and *Globigerinoides ruber*. These five species accounted for 40% to 100% of the planktic foraminiferal assemblage in each sample. Other common species were *Neogloboquadrina dutertrei*, *Pulleniatina obliquiloculata*, *Globigerinoides*

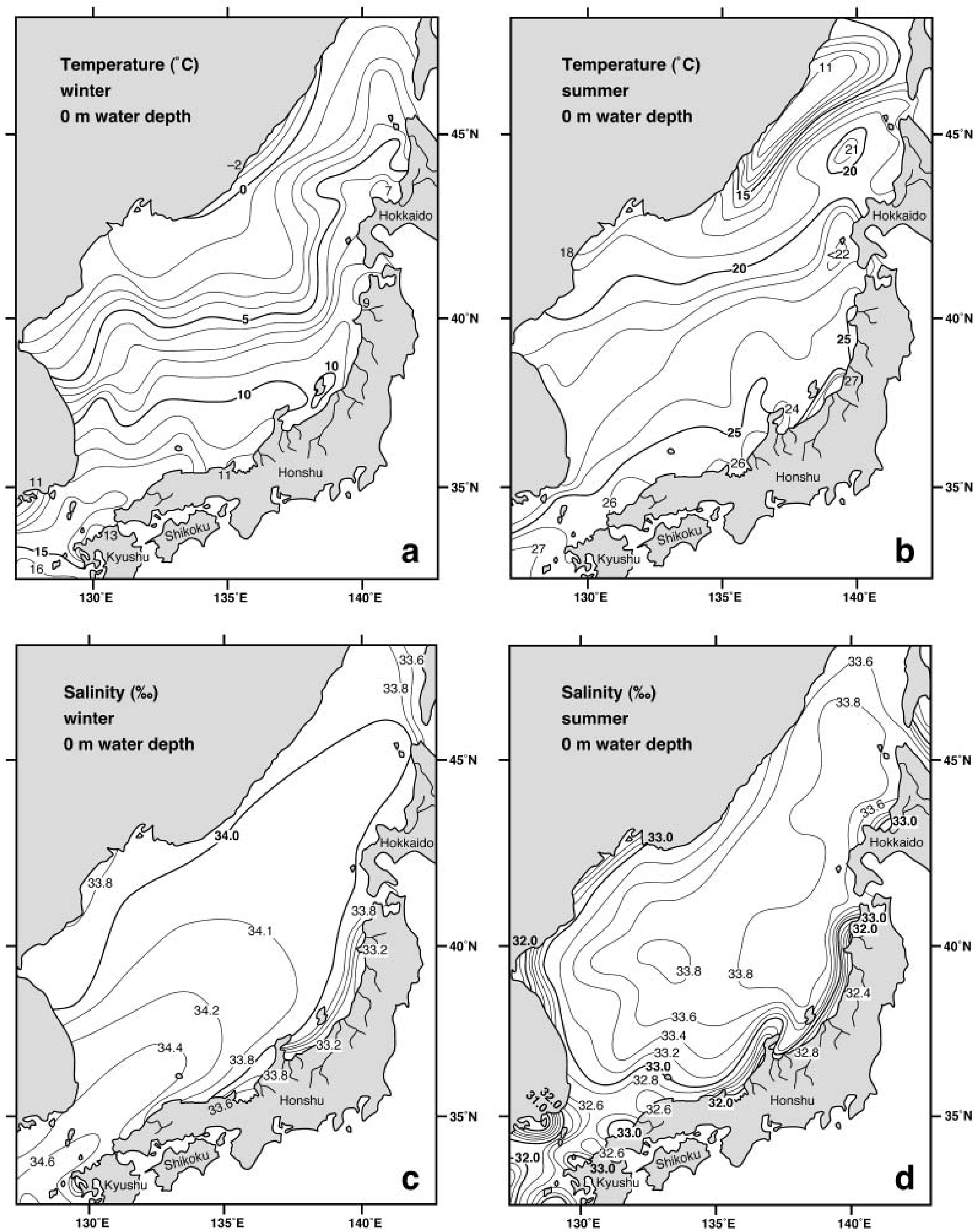


Figure 2. Hydrographic conditions in the Japan Sea in terms of mean values of surface-water temperature and salinity in winter and summer (after Japan Oceanographic Data Center, 1978). Main rivers on the Japan Sea side of Japan are also shown.

Table 1. Locations and water depths of surface sediment samples used in this study.

Sample No.	Cruise	Station	Latitude N	Longitude E	Water depth (m)	Reference
1	GH85-2	57	33˚51.08'	130˚20.86'	49	Ikehara and Kawahata, 1986
2	GH85-2	64	34˚20.39'	130˚23.46'	112	ibid.
3	GH85-2	26	34˚24.95'	130˚09.45'	110	ibid.
4	GH85-2	17	34˚58.82'	130˚05.40'	125	ibid.
5	GH85-2	231	34˚30.98'	131˚21.66'	66	ibid.
6	GH85-2	202	35˚04.66'	131˚09.53'	116	ibid.
7	GH85-2	167	35˚13.50'	130˚56.31'	137	ibid.
8	GH85-2	350	34˚53.93'	131˚49.62'	116	ibid.
9	GH86	65	35˚33.99'	132˚41.94'	126	Ikehara *et al.,* 1987
10	GH86	32	35˚59.87'	132˚18.03'	873	ibid.
11	GH86	273	36˚04.14'	132˚06.02'	1134	ibid.
12	GH86	222	35˚57.97'	134˚12.07'	519	ibid.
13	GH86	223	36˚03.89'	134˚12.04'	769	ibid.
14	GH87-2	138	35˚50.23'	135˚39.49'	218	Katayama and Ikehara, 1988
15	GH87-2	120	36˚10.70'	135˚34.24'	387	ibid.
16	GH87-2	125	36˚32.80'	135˚37.22'	707	ibid.
17	GH87-2	228	36˚54.01'	136˚23.98'	216	ibid.
18	GH87-2	230	36˚59.98'	136˚15.96'	341	ibid.
19	KT95-14	M-1	37˚10.2'	134˚55.2'	1047	Tsukawaki *et al.,* 1997
20	GH88	140	37˚19.41'	136˚29.35'	168	Katayama, 1989
21	GH88	53	37˚30.37'	136˚08.89'	374	ibid.
22	GH88	165	37˚25.04'	137˚23.50'	89	ibid.
23	GH88	168	37˚29.69'	137˚38.96'	703	ibid.
24	GH88	169	37˚31.28'	137˚44.18'	1315	ibid.
25	KT99-14	G-44	38˚22.9'	138˚55.7'	174	Tsukawaki *et al.,* 2001
26	KT99-14	G-43	38˚23.2'	138˚55.0'	202	ibid.
27	KT99-14	G-37	38˚32.4'	138˚05.7'	1456	ibid.
28	GH91	262	38˚55.23'	139˚16.25'	673	Nakajima and Katayama, 1992
29	GH91	238	38˚52.11'	138˚50.99'	736	ibid.
30	GH91	227	38˚55.36'	138˚28.89'	956	ibid.
31	GH91	327	39˚28.39'	139˚21.87'	830	ibid.
32	GH91	408	40˚07.07'	139˚44.91'	73	ibid.
33	GH77-3-2	110	40˚58.1'	140˚07.1'	138	unpublished data (Oda, MS)
34	GH77-3-2	105	41˚14.0'	140˚13.0'	296	ibid.
35	GH77-3-2	247	41˚16.1'	140˚03.8'	252	ibid.
36	GH77-3-2	255	41˚20.1'	139˚51.9'	150	ibid.
37	GH94	1021	41˚27.88'	139˚54.97'	330	Inouchi *et al.,* 1995
38	GH94	1014	41˚23.86'	139˚50.06'	822	ibid.
39	GH94	1002	41˚20.07'	139˚44.91'	536	ibid.
40	GH94	1059	42˚06.08'	139˚57.59'	100	ibid.
41	GH94	1058	42˚05.93'	139˚52.59'	135	ibid.
42	GH94	1057	42˚06.02'	139˚47.40'	939	ibid.
43	GH94	1054	42˚06.09'	139˚22.56'	315	ibid.
44	GH94	95	42˚04.05'	139˚14.90'	2788	ibid.
45	GH96	311	43˚35.98'	141˚00.09'	109	Katayama *et al.,* 1997
46	GH96	306	43˚32.01'	140˚55.01'	118	ibid.
47	GH96	253	43˚40.01'	140˚35.17'	782	ibid.
48	GH98	466	45˚00.03'	140˚44.91'	285	Ikehara *et al.,* 1999
49	GH98	551	45˚34.20'	140˚35.05'	496	ibid.
50	KT99-14	G-18	39˚29.1'	135˚50.6'	777	Tsukawaki *et al.,* 2001
51	KT99-14	G-19'	39˚27.3'	135˚53.7'	1021	ibid.

tenellus, and *Globigerinita glutinata*. The relative abundance (%) distributions of these nine species in the study area are shown in Figure 4.

Neogloboquadrina incompta occurred abundantly (> 70%) in the marginal areas from the Oki Islands to the central part of Hokkaido and decreased to less than 10–20% in the central part of the Japan Sea and around the Tsushima Strait (Figure 4a).

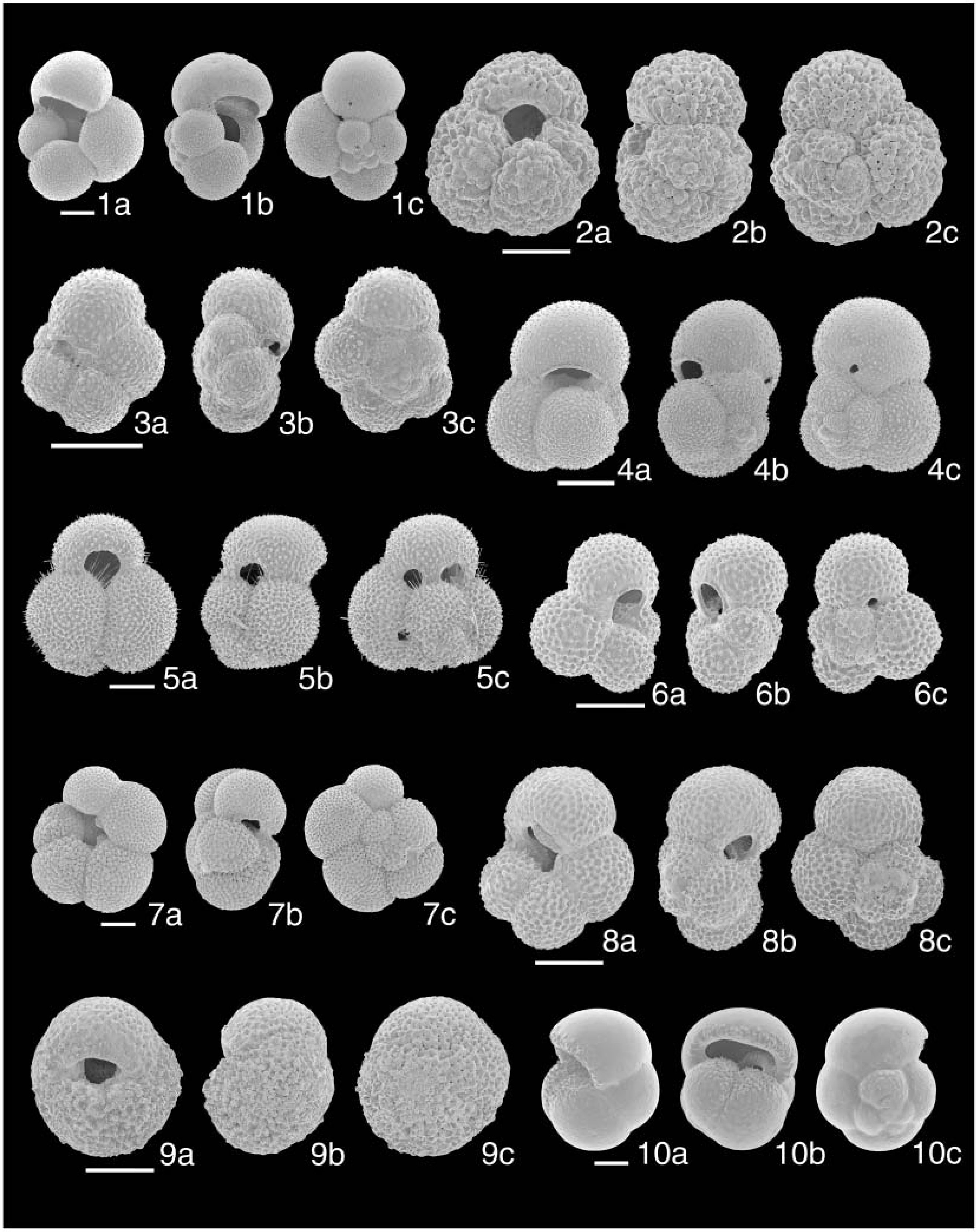
Neogloboquadrina pachyderma was abundant (> 70%) in the central and northern parts of the Ja-

Table 2. Occurrences of all species in surface sediment samples from the Japan Sea.

Species | Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Globigerina bulloides d'Orbigny (thin-walled form)	37	85	68	76	42	55	36	32	10	2	2	1	2	0	0	6	1	0	0	4	0	9	3	0	0	4
Globigerina bulloides d'Orbigny (thick-walled form)	0	0	0	0	0	0	0	0	0	3	0	3	4	0	0	0	1	1	0	0	0	0	1	1	0	0
Globigerina falconensis Blow	8	7	9	0	0	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerina quinqueloba Natland	2	16	3	63	8	10	55	5	0	1	0	3	0	1	4	16	2	2	0	12	0	145	49	7	12	17
Globigerina rubescens Hofker	3	5	5	1	10	5	1	10	3	0	0	0	1	1	0	1	0	1	0	0	0	6	0	0	0	0
Globigerina umbilicata Orr and Zaitzeff	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinella aequilateralis (Brady)	2	0	2	1	1	2	1	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Globigerinella calida (Parker)	0	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinita glutinata (Egger)	0	19	23	12	4	10	5	4	1	0	0	0	2	4	0	3	0	1	0	1	0	9	1	0	0	0
Globigerinita minuta (Natland)	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Globigerinita uvula (Ehrenberg)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinoides conglobatus (Brady)	0	2	2	0	5	1	0	3	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Globigerinoides ruber (d'Orbigny)	40	58	43	19	88	27	18	55	24	4	2	0	8	1	0	6	0	3	1	2	1	21	5	3	3	7
Globigerinoides sacculifer (Brady)	4	3	3	1	2	1	0	6	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Globigerinoides tenellus Parker	10	10	8	1	12	9	2	18	5	0	0	0	2	5	2	0	0	0	0	0	1	25	0	0	3	3
Globorotalia inflata (d'Orbigny)	2	8	14	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neogloboquadrina dutertrei (d'Orbigny)	19	42	36	19	29	28	6	9	10	3	10	0	3	5	1	1	0	1	1	0	0	1	1	0	0	1
Neogloboquadrina incompta (Cifelli)	0	17	8	35	14	35	80	38	57	387	288	327	456	121	182	276	132	294	77	324	159	234	480	95	125	138
Neogloboquadrina pachyderma (Ehrenberg)	0	0	0	0	0	0	3	1	0	15	5	23	13	3	1	7	0	1	4	1	4	11	42	2	0	0
Neogloboquadrina spp.	0	8	3	6	0	2	1	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Orbulina universa d'Orbigny	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pulleniatina obliquiloculata (Parker and Jones)	5	17	28	3	7	19	7	5	2	3	3	0	2	0	1	2	0	0	0	0	0	0	0	0	0	0
Tenuitella anfracta (Parker)	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Tenuitella fleisheri Li	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Tenuitella sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turborotalita aff. *guaymasensis* Matoba and Oda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turborotalita cf. *humilis* (Brady)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
others	4	5	0	1	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total specimens	136	303	257	239	224	214	220	195	116	420	313	357	494	141	192	319	136	305	84	344	165	467	582	108	143	170

Table 2. Continued

Species / Sample No.	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Globigerina bulloides d'Orbigny (thin-walled form)	0	1	1	1	0	0	0	5	28	39	4	6	2	2	1	1	3	0	3	1	0	0	0	0	0
Globigerina bulloides d'Orbigny (thick-walled form)	3	2	0	4	5	3	2	4	4	19	24	32	27	6	6	1	12	11	8	4	14	7	7	17	13
Globigerina falconensis Blow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerina quinqueloba Natland	0	5	14	5	4	50	14	44	20	95	9	12	6	11	20	48	49	51	9	23	0	0	0	0	0
Globigerina rubescens Hofker	0	0	0	1	0	0	0	1	1	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Globigerina umbilicata Orr and Zaitzeff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinella aequilateralis (Brady)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinella calida (Parker)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinita glutinata (Egger)	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0
Globigerinita minuta (Natland)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinita uvula (Ehrenberg)	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
Globigerinoides conglobatus (Brady)	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
Globigerinoides ruber (d'Orbigny)	0	2	5	3	1	12	3	39	5	11	1	6	0	3	0	3	1	2	3	0	0	0	0	0	0
Globigerinoides sacculifer (Brady)	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinoides tenellus Parker	0	0	3	0	1	1	0	3	0	11	0	2	0	0	2	1	2	0	0	0	0	0	0	0	0
Globorotalia inflata (d'Orbigny)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neogloboquadrina dutertrei (d'Orbigny)	0	1	1	0	0	0	0	2	0	7	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
Neogloboquadrina incompta (Cifelli)	272	132	151	86	83	45	205	547	412	461	181	176	145	166	127	152	101	56	229	124	154	15	10	19	27
Neogloboquadrina pachyderma (Ehrenberg)	36	5	5	7	9	0	8	4	25	43	48	33	38	20	21	16	71	42	35	50	54	131	193	125	124
Neogloboquadrina spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Orbulina universa d'Orbigny	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pulleniatina obliquiloculata (Parker and Jones)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tenuitella anfracta (Parker)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tenuitella fleisheri Li	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tenuitella sp.	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turborotalita aff. *guaymasensis* Matoba and Oda	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Turborotalita cf. *humilis* (Brady)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
others	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Total specimens	312	148	181	107	103	113	232	651	495	705	267	269	218	209	180	224	242	162	289	203	222	153	211	161	164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pan Sea and occurred only sparsely (< 10%) around the continental margin of the Japanese Islands (Figure 4b). This species was frequently absent in many samples around the Tsushima Strait.

The occurrence of *G. quinqueloba* increased in two different areas of the Tsushima Strait (> 20%) and marginal areas in the Northwest Japan (10–30%) (Figure 4c).

Globigerina bulloides was abundant (> 20%) around the Tsushima Strait and sporadically common (3–10%) in the central part of the Japan Sea and marginal areas off Hokkaido (Figure 4d). Two forms of this species differing in thickness of chamber wall are distinguished (Figure 3). Samples from southwest of the Oki Islands contained mostly thin-walled forms, while thick-walled forms were abundant in the central part of the Japan Sea and marginal areas off Hokkaido (Table 2).

Globigerinoides ruber showed high abundance (> 20%) around the Tsushima Strait and decreased (> 3%) rapidly around the Oki Islands (Figure 4e).

Neogloboquadrina dutertrei, *P. obliquiloculata*, *G. tenellus*, and *G. glutinata* represented a similar trend to that of *G. ruber*. These species occurred commonly (generally > 9%) around the Tsushima Strait and decreased to less than 3% around the Oki Islands (Figure 4f–i).

Discussion

Two distinct patterns, called here Pattern I and II, can be distinguished from these nine geographical distributions. Pattern I occurs frequently within the Japan Sea and corresponds to the areas of distribution of *N. incompta* and *N. pachyderma*. Pattern II shows a high concentration around the Tsushima Strait and generally decreases northeastward along the Japanese Islands. This pattern also includes distributions of the other seven species. Furthermore, distributional patterns I and II can each be subdivided into two supplementary patterns, Ia and Ib and IIa and IIb, respectively. Pattern Ia, marked by predominance of *N. incompta*, is typical in the southeastern Japan Sea, from the Oki Islands to near central Hokkaido (Figure 4j). Pattern Ib is highly prevalent from the central to northern Japan Sea (Figure 4k) and contains high percentages of *N. pachyderma*. Pattern IIa is highly characteristic of the western channel of the Tsushima Strait (Figure 4l) and consists of predominant *G. quinqueloba* and *G. bulloides*. Pattern IIb occurs frequently in the eastern channel of the strait (Figure 4l) and is characterized by the occurrence of *G. ruber*, *N. dutertrei*, *P. obliquiloculata*, *G. tenellus*, and *G. glutinata*. These four distributional patterns relate closely to the surface water masses (Table 3).

Oceanographic implication of Pattern I

Neogloboquadrina incompta and *N. pachyderma* dominate the modern Japan Sea, suggesting optimal conditions for these species. Pattern Ia corresponds with mid- to downstream regions of the Tsushima Current, where mixing with northern cold water cools the Tsushima Current and numerous meanders and eddies cause great variability. This pattern suggests that *N. incompta* is best suited to the transitional water formed by the mixing of the warm Tsushima Current and cold waters in the Japan Sea. In the western North Pacific off Japan, *N. incompta* shows high abundance in the perturbed area between the Kuroshio and Oyashio fronts and in the cold-water mass near Kuroshio (Takayanagi and Oda, 1983; Oda and Takemoto, 1992). These results are concordant with those of this study.

Pattern Ib is associated with the cold-water region north of the polar front in the Japan Sea. Therefore, *N. pachyderma*, the predominant species in this pattern, may be an indicator of cold water in the northern Japan Sea. This species is a dominant species of cold water in polar and subpolar regions (Bé, 1977) and is regarded as a typical marker of the cold Oyashio Current near Japan (Takayanagi and Oda, 1983; Oda and Takemoto, 1992).

Oceanographic implication of Pattern II

Pattern II correlates with the upstream region of the Tsushima Current. This pattern suggests that the seven associated species are influenced by waters flowing into the Japan Sea through the Tsushima

← **Figure 3.** Selected planktic foraminiferal species in surface sediment samples from the Japan Sea. Specimens of *Globigerina bulloides* exhibit morphological differences in the thickness of chamber walls.
1. *Globigerina bulloides* d'Orbigny (thin-walled form), from sample No. 3. **2**. *Globigerina bulloides* d'Orbigny (thick-walled form), from sample No. 38. **3**. *Globigerina quinqueloba* Natland, from sample No. 6. **4**. *Globigerinita glutinata* (Egger), from sample No. 8. **5**. *Globigerinoides ruber* (d'Orbigny), from sample No. 9. **6**. *Globigerinoides tenellus* Parker, from sample No. 5. **7**. *Neogloboquadrina dutertrei* (d'Orbigny), from sample No. 11. **8**. *Neogloboquadrina incompta* (Cifelli), from sample No. 38. **9**. *Neogloboquadrina pachyderma* (Ehrenberg), from sample No. 49. **10**. *Pulleniatina obliquiloculata* (Parker and Jones), from sample No. 3.
a: umbilical, b: side, c: spiral views, scale bars: 100 μm.

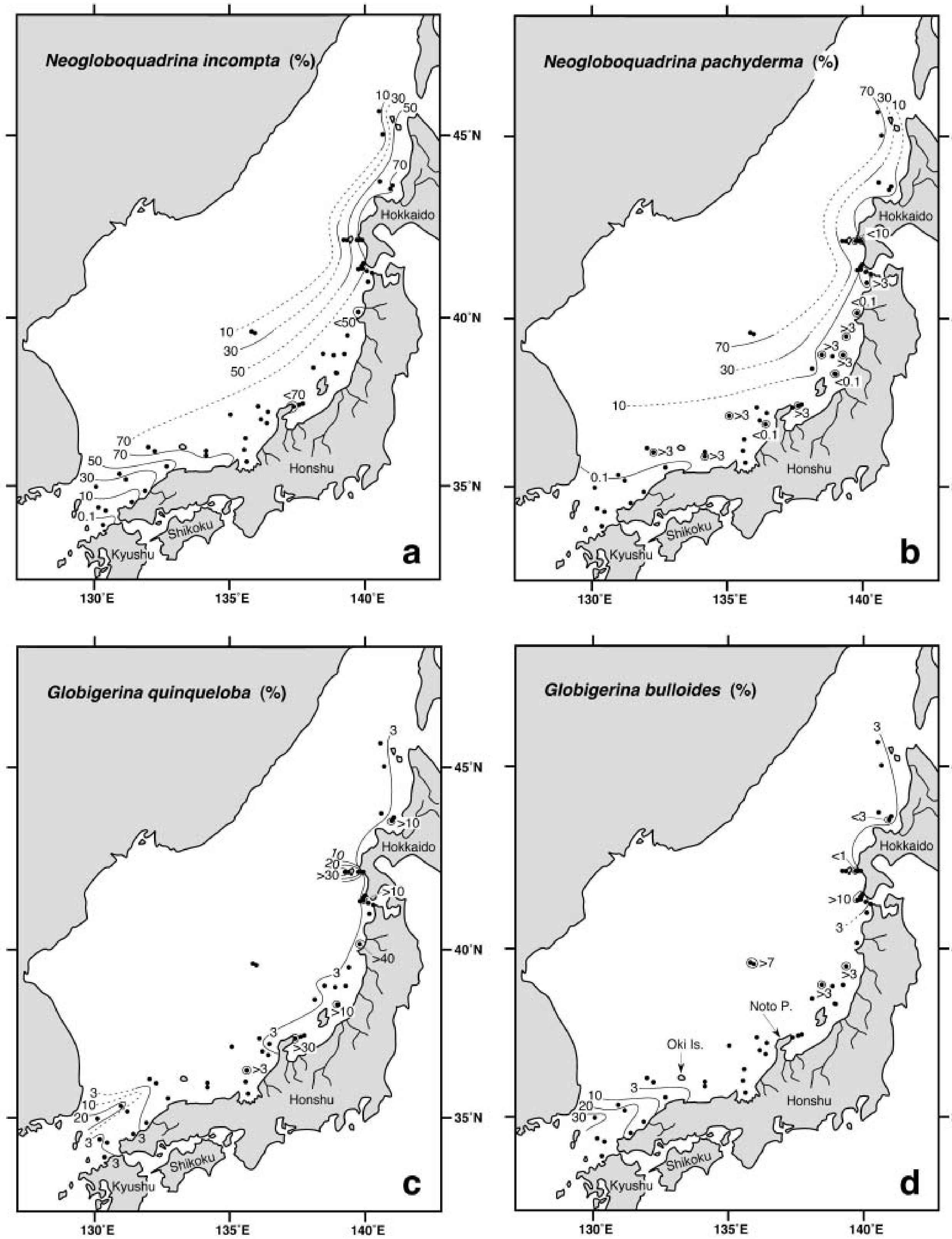

Figure 4. Map (a–i): Distributions of the nine predominant planktic foraminiferal species in surface sediments from the Japan Sea. Values represent % of total count. Map (j–l): Schematic representation of four patterns of Pattern Ia, Ib, IIa, and IIb distinguished from the geographical distributions of nine major species in this study. Main rivers on the Japan Sea side of Japan are also shown.

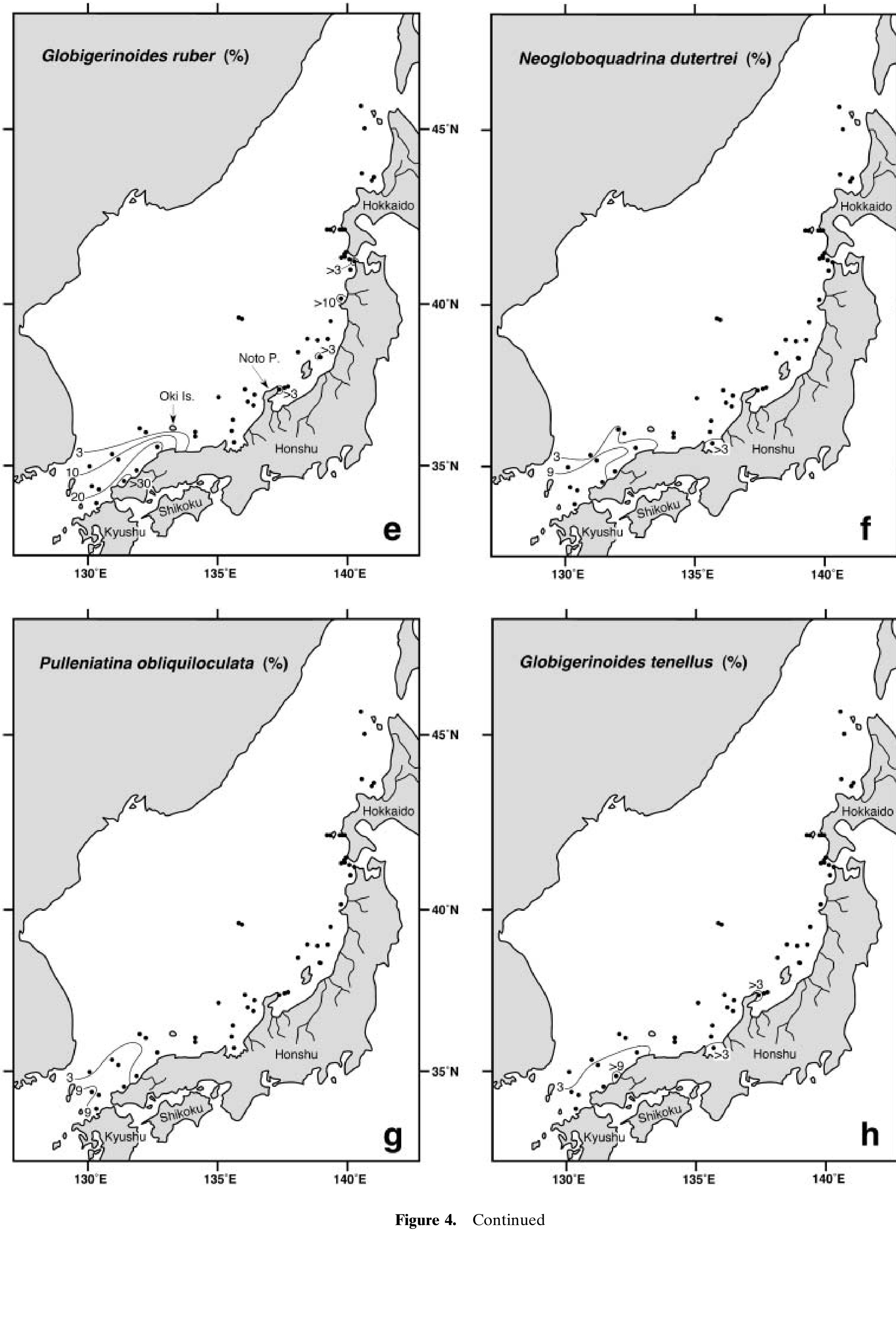

Figure 4. Continued

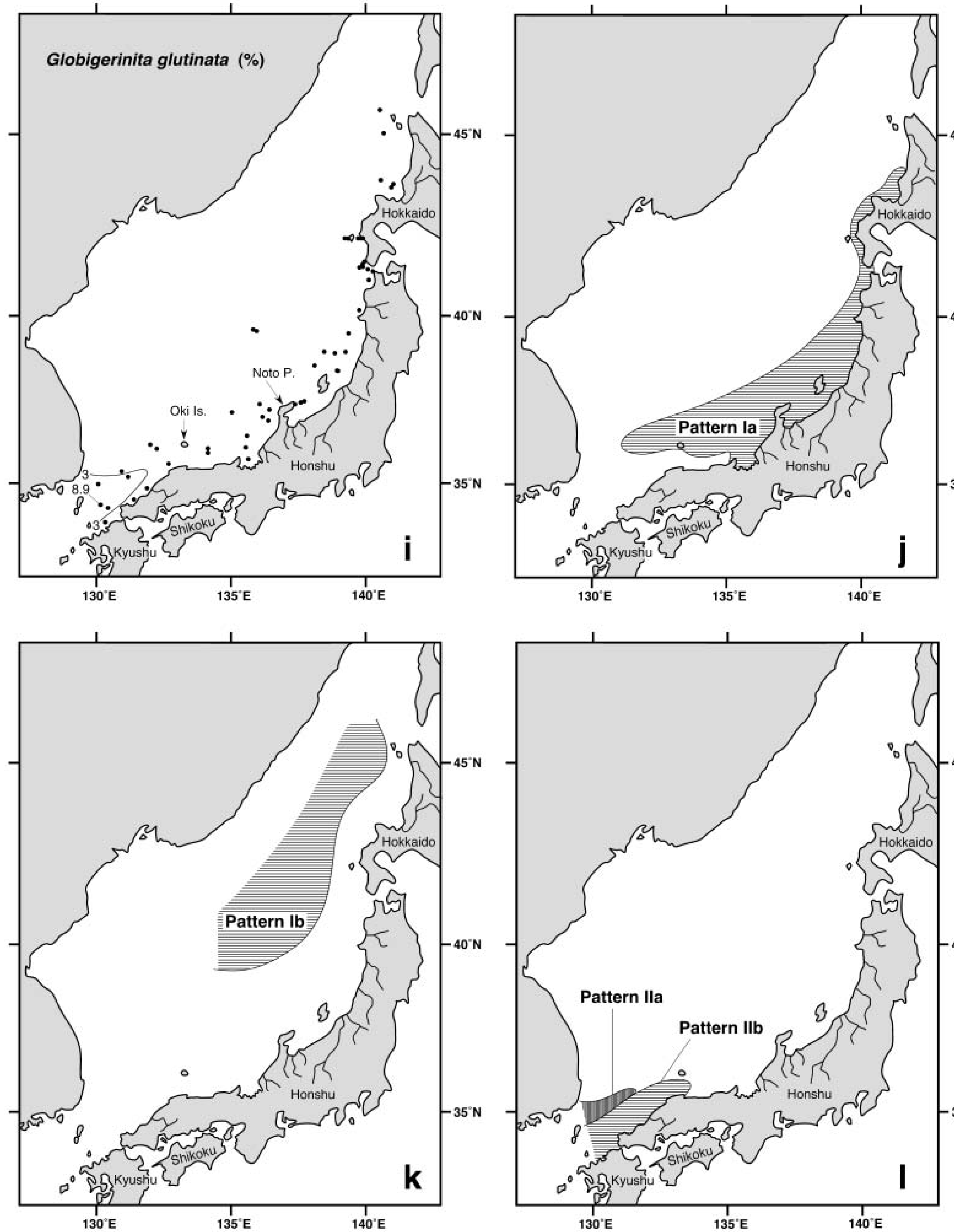

Figure 4. Continued

Table 3. Summary of the relationships between the geographical distributions of nine major planktic foraminiferal species in surface sediments and surface water masses in the Japan Sea.

Species	[pattern]	Geographical distribution	Corresponding surface water mass
Neogloboquadrina incompta (Figure 4a)	[Ia] (Figure 4j)	southeastern Japan Sea (mid- to downstream regions of the Tsushima Current)	transitional water mixed with the warm Tsushima Current and cold waters in the Japan Sea
Neogloboquadrina pachyderma (Figure 4b)	[Ib] (Figure 4k)	central to northern Japan Sea north of the polar front	cold water in the northern Japan Sea
Globigerina quinqueloba *Globigerina bulloides* (Figure 4c, d)	[IIa] (Figure 4l)	western channel of the Tsushima Strait (upstream region of the Tsushima Current)	less-saline and nutrient-rich water from the Changjiang which enters via the East China Sea
Globigerinoides ruber *Neogloboquadrina dutertrei* *Pulleniatina obliquiloculata* *Globigerinoides tenellus* *Globigerinita glutinata* (Figure 4e–i)	[IIb] (Figure 4l)	eastern channel of the Tsushima Strait (upstream region of the Tsushima Current)	Tsushima Current water

Strait, namely, by the Tsushima Current and Changjiang river water that enters via the East China Sea.

Pattern IIa corresponds with the western channel of the Tsushima Strait, where salinity decreases markedly during the summer due to the input of fresh water from the Changjiang transported from the East China Sea. Thus, *G. quinqueloba* and *G. bulloides* may be strongly influenced by less saline and eutrophic water. In the East China Sea, high abundance of *G. quinqueloba* in surface sediments is restricted to areas near the mouth of the Changjiang (Wang *et al.*, 1988; Xu and Oda, 1999). *Globigerina bulloides* occurs abundantly in surface sediments from the continental shelf (Xu and Oda, 1999), where primary productivity is remarkably high due to large amounts of dissolved inorganic nutrients from the Changjiang (Hama *et al.*, 1997). Distributions of both species in the East China Sea also reflect the influence of the less saline and nutrient-rich fresh water from the Changjiang. This is consistent with the distributions of both species in the Japan Sea. *Globigerina quinqueloba* also occurs commonly in the coastal area from the Noto Peninsula to western Hokkaido (Figure 4c). This distribution is probably related to the freshwater input from main rivers along the west coast of Honshu and Hokkaido.

Pattern IIb correlates with the eastern channel of the Tsushima Strait, which is not as strongly affected as the western channel by the fresh Changjiang water. This suggests that the distributions of *G. ruber*, *N. dutertrei*, *P. obliquiloculata*, *G. tenellus*, and *G. glutinata* relate to Tsushima Current water. These five species are widely distributed in tropical and subtropical regions (Bé, 1977; Saito *et al.*, 1981). In surface sediments from the East China Sea, *N. dutertrei* and *P. obliquiloculata* occur abundantly in the path of the Kuroshio Current (Xu and Oda, 1999; Ujiié and Ujiié, 1999) which is the source of the Tsushima Current water. *Globigerinoides ruber* and *G. glutinata* are the main species of the assemblage in surface sediments from the East China Sea (Xu and Oda, 1999) and the predominant species in surface sediments from the Kuroshio area on the margin of the western North Pacific (Oda and Takemoto, 1992). Thus, these five species can be regarded as indicators of Tsushima Current water in the Japan Sea. As *G. ruber* shows high abundance and occurs continuously to its distribution's northernmost edge off central Hokkaido (Table 2), this species is likely the most important indicator of the Tsushima Current in the Japan Sea.

Conclusions

Twenty-four species belonging to 10 genera of planktic foraminifera were recognized in 51 surface sediment samples collected mainly from the Tsushima Current region of the Japan Sea. Four distinct patterns were distinguished from the geographical distributions of nine major species of *N. incompta*, *N. pachyderma*, *G. quinqueloba*, *G. bulloides*, *G. ruber*, *N. dutertrei*, *P. obliquiloculata*, *G. tenellus*, and *G. glutinata*. Comparing distributional patterns and surface water masses in the Japan Sea revealed the following four relationships between planktic foraminiferal assemblages and hydrographic conditions: 1) *N. incompta* appears to be an optimal indicator of transitional water formed by mixing of the warm Tsushima Current and cold waters in the Japan Sea; 2) *N. pachyderma* can be considered an indicator of cold water in the northern Japan Sea; 3) *G. quinqueloba* and *G. bulloides* distributions reflect the strong influence of less saline and nutrient-rich water from the Changjiang which enter via the East China Sea; and 4) *G. ruber*, *N. dutertrei*, *P. obliquiloculata*, *G. tenellus*, and *G. glutinata* can be regarded as indicators of Tsushima Current water. These relationships can be used for a better reconstruction of past conditions in the Japan Sea from the fossil record.

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