DISTRIBUTION OF RADIOLARIA IN SURFACE SEDIMENTS AND ITS RELATION TO THE OCEANOGRAPHY OF THE ICELAND AND GREENLAND SEAS

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In order to depict the distribution of radiolarians in the sea-floor of the Greenland and Iceland Seas, 31 surface sediment samples were analyzed. Three radiolarian assemblages were defined through Q-mode factor analysis and the importance of each species in each biofacies, was determined by means of a graphic multivariate analysis. The first assemblage (factor 1) is called 'Arctic Water' because it dwells in the Arctic Surface Water (ASW). Assemblage 2 inhabits Subarctic Water along the Arctic Front, while assemblage 3 is associated with the Subpolar Water along the Polar Front. *Amphimelissa setosa* (Cleve) is the most prominent species in sediment samples below Arctic Surface Water, whereas *Botryocyrtis platycephala* (Petrushevskaya) and *Cycladophora davisiana* (Ehrenberg) are more prolific below Subarctic Water. *Lithelius spiralis* (Haeckel) and *Artobotrys borealis* (Cleve) predominate below Subpolar Water and represent the coldest radiolarian province in the study area.

Keywords: Radiolaria distributions; Oceanography; Iceland Sea; Greenland Sea.

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INTRODUCTION

Radiolarians principally inhabit the open ocean and therefore possess an extended geographical distribution. However, relative to other micropaleontological groups, there are few studies about its biogeography. In spite of this, radiolarians are a well used tool in paleoceanography. Because of their extended geographical and stratigraphical distributions, it is possible to delineate present zoogeographical provinces, to reconstruct paleoenvironmental conditions and finally the climatic-oceanographic past (e.g. Sachs 1973; Morley 1980; Molina-Cruz 1977, 1988, 1991; Jansen & Bjørklund 1985).

The Iceland and Greenland Seas (Fig. 1) are ice covered during most of the year. This characteristic makes access to this area difficult, and limits the studies of the polycystine radiolarian zoogeography (Petrushevskaya & Bjørklund 1974; Goll & Bjørklund 1985). Thus, the sediment samples collected by the R/V *Polarstern* during the cruise *ARK-VII* in 1990, have given us a new opportunity to define the distribution of radiolarian assemblages in the surface sediments of the Iceland and Greenland Seas, using statistical strategies. Coupling the distribution of radiolarian assemblages with oceanographic features observed in the study area, it was possible to infer the environmental requirements of species occurring prominently in common biofacies.

OCEANOGRAPHIC SETTING

The study area is defined by the parallels 68° and 78° N and the meridians 10° E and 20° W. The principal geographic areas defined in this region are the Greenland and the Iceland Seas, which are bounded by the Greenland coast to the west and the Norwegian Sea to the southeast. The Iceland and Greenland Seas belong to the Arctic zone (Fig. 1). Thus, these show in general low sea-surface temperatures ($t < 5$ °C) and are periodically covered with sea-ice. When the seasonal ice-cover draws back, the oceanic currents are better developed (Fig. 2) and determine the distribution of water masses. This in turn, gives rise to environmental habitats and ultimately to the sedimentological character of the region (Kellogg 1976; Swift 1986).

Sea-surface temperature distribution in the Iceland and Greenland Seas varies seasonally. As is expected, this is greater during the summer than during the winter, when the ice-cover is more extensive (Gathman 1986). During summer, the sea-surface has a temperature gradient from approximately 0 to 9° C (Fig. 3), while in winter the maximum temperature is approximately 5° C. The summer sea-surface temperature distribution is related to the dynamics of the superficial currents; particularly the Norwegian Current, since this carries heat from more temperate regions (the northeastern Atlantic) to the eastern Iceland and Greenland Seas (see Figs 2, 3). In consequence,

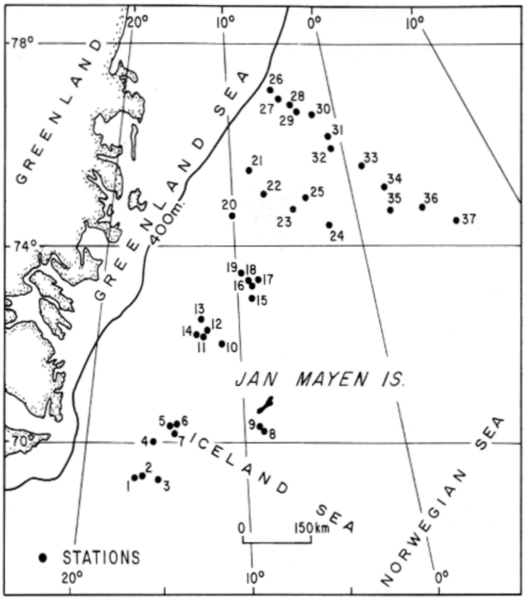


Fig. 1. Study area and sediment sample locations.

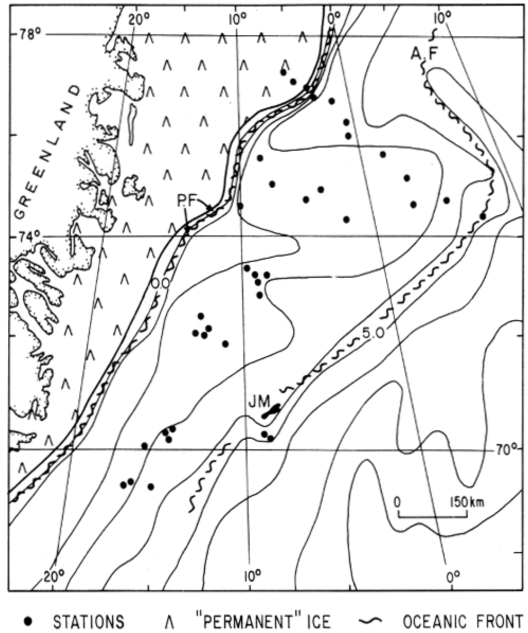


Fig. 3. Summer sea surface temperature distribution (° C) in the Iceland and Greenland Seas (JOHANNESSEN 1986). P.F. denotes the Polar Front and A.F. the Arctic Front.

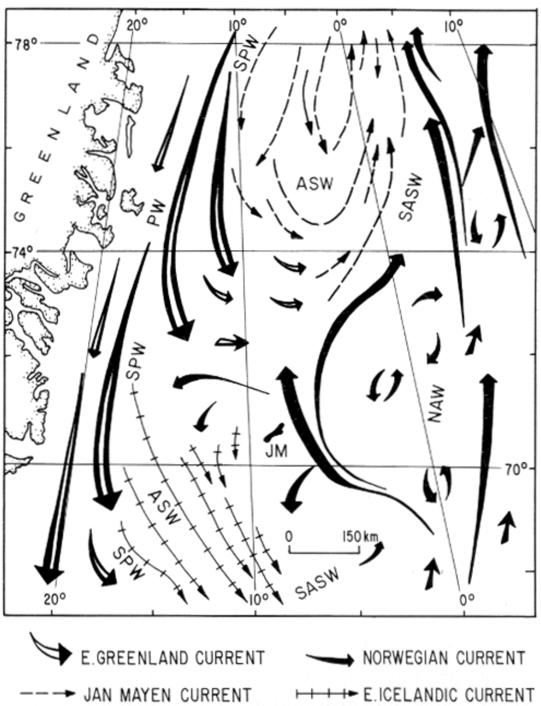


Fig. 2. Sea surface currents and location of surface water masses in the Iceland and Greenland Seas (after JOHANNESSEN 1986 and SWIFT 1986). PW = Polar Water, SPW = Subpolar Water, ASW = Arctic Surface Water, SASW = Subarctic Water, NAW = North Atlantic Water. JM denotes the Jan Mayen Island.

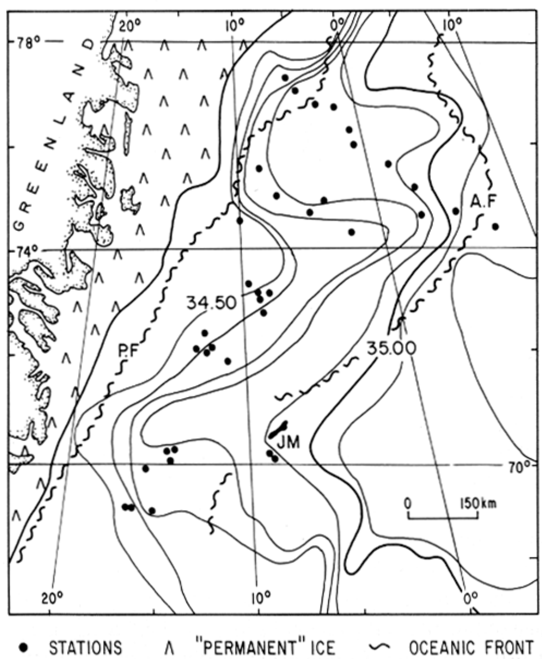


Fig. 4. Summer sea surface salinity distribution (psu) in the Iceland and Greenland Seas (JOHANNESSEN 1986). P.F. denotes the Polar Front and A.F. the Arctic Front.

sea-surface temperature distribution shows lower values along the East Greenland coast (approximately -1° C) and increases gradually eastward (Fig. 3).

In the Iceland and Greenland Seas, the variability of sea-surface salinity is less tangible than the variability of sea-surface temperature (Figs 4 and 3, respectively). Salinity is lower along the Greenland coast (approximately 34.0 practical salinity units (psu)) and gradually increases towards the east (to 35.0 psu), where the Norwegian Current flows (see Figs 2, 4). According to Swift (1986), sea-surface salinity maintains a constant distribution during the whole year; however, some locations in the Greenland and Iceland Seas may be saltier during summer, due to influence of the North Atlantic Water (NAW).

Coupling distributions of sea-surface temperature (Fig. 3) and salinity (Fig. 4), as well as local currents (Fig. 2), it is possible to identify, within the Iceland and Greenland Seas, the following five water masses: 1) Polar Water (PW; $-1.5 < t < 1°$ C; $30.0 < S < 34.0$ psu), 2) North Atlantic Water (NAW; $5 < t < 9°$ C; $S > 35.0$ psu); 3) Arctic Surface Water (ASW; $2 < t < 5°$ C; $34.5 < S < 34.9$ psu), 4) Subpolar Water (SPW) or Arctic Intermediate Water (AIW; $1 < t < 3°$ C; $34.3 < S < 34.6$ psu) and 5) Subarctic Surface Water (SASW; $t \approx 5 \pm 1°$ C; $34.9 < S < 35.1$ psu). Polar Water and North Atlantic Water represent the regional extremes in temperature and salinity. Thus, depending on contribution-volumes, the mixing of these two gives rise to the other three water masses: a major contribution of Polar Water gives rise to Subpolar Water, a major contribution of North Atlantic Water gives rise to Subarctic Water and, more or less the same contribution-volume of Polar Water and North Atlantic Water gives rise to Arctic Surface Water (see Johannessen 1986).

Frequently, the meeting of water masses produces oceanic fronts which are particularly marked by thermal gradients. In the area studied, the most important fronts are: the Polar Front and the Arctic Front (Fig. 3). The Polar Front, also known as East Greenland Front (Johannessen 1986), is confined to the region of the permanent sea-ice. This front is defined where the Polar Water blends with the less cold Arctic Surface Water carried by the Jan Mayen Current and the East Icelandic Current. (see Figs 2 and 3 and Hurdle 1986; Swift 1986). The Arctic Front is principally defined towards the northeast of Jan Mayen Island (Figs 3, 4). This front controls the expansion of the sea-ice during winter (Johannessen 1986). Ice transported across the Arctic Front melts due to a relatively higher temperature of the water masses that originate from lower latitudes and are carried north by the Norwegian Current. It is therefore evident that the Arctic Front separates the Arctic and the North Atlantic provinces.

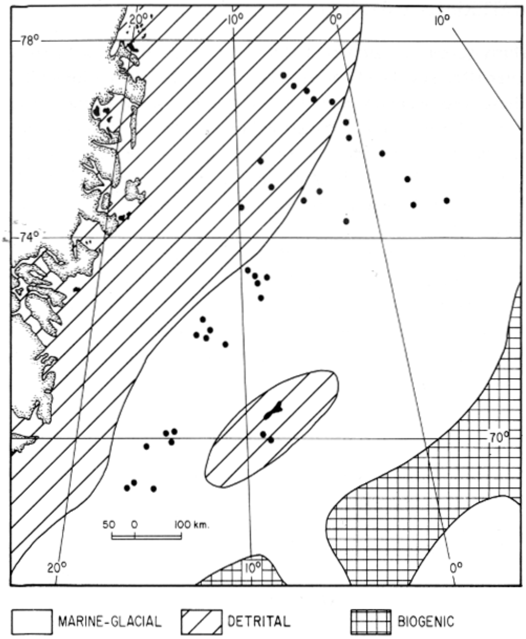


Fig. 5. Distribution of surface sediments (after Kellogg 1976 and Paetsch & al. 1992).

The radiolarian remains studied here, have been deposited in three types of superficial sediments (Fig. 5): 1) detrital-terrigenous, 2) marine glacial-terrigenous and 3) biogenic (Kellogg 1976). The terrigenous material has been classified as 'detrital-terrigenous' and 'marine glacial-terrigenous' because it is convenient to make reference to its form of input. Detrital-terrigenous sediments result from terrestrial weathering, other than glacial erosion, and are distributed principally by turbidity currents once entering the sea. These terrestrial derived sediments are distributed principally over the continental shelf and slope (Mienert & al. 1992; Henrich & al. 1989; Paetsch & al. 1992). The marine glacial-terrigenous sediments are produced by glacial erosion and then transported by icebergs. Upon melting, icebergs liberate the terrigenous material derived from continental erosion (Kellogg 1976; Kennett 1982; Paetsch & al. 1992). Consequently, this terrigenous material accumulates principally between the Polar Front and the Arctic Front zone, where most of the iceberg melting takes place.

The input of biogenic material is related to the productivity of superficial temperate waters. Therefore, its higher accumulations are found on the eastern side of the Arctic Front. This is composed principally of foraminifer, coccolith and diatom remains (Kellogg 1976; Paetsch &. al. 1992; Koc Karpuz & Schrader 1990).

MATERIALS AND METHODS

Thirty-seven top-samples of sediment cores, collected with a box corer (Reineck 1963), were analyzed micropaleontologically. These cores were taken by the R/V *Polarstern* during the cruise *ARK-VII* (1990) and deposited at the Core Laboratory of the University Christian Albrechts of Kiel, Germany. The geographical location of each core is shown in Fig. 1 and listed in Table 1. Since only 31 sample-locations contain radiolarians, we based our study on these.

In order to separate the radiolarians from the sediment samples, the carbonates and organical material were removed by using hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2), respectively. Furthermore, the samples were sieved through a 40 µm mesh screen, in order to concentrate the radiolarian remains.

Table 1. Sample locations. *Deposited at the Core Laboratory of the Christian Albrechts University of Kiel, Germany.

Stn	Core*	Latitude	Longitude	Depth (m)
1	21842-5	69°27.780' N	16°31.490' W	983
2	21843-1	69°28.110' N	16°22.930' W	943
3	21846-3	69°26.517' N	15°17.775' W	1427
4	21852-1	70°15.220' N	15°49.430' W	1105
5	21855-1	70°36.043' N	14°36.812' W	1855
6	21856-2	70°38.480' N	14°27.130' W	670
7	21857-1	70°28.820' N	14°30.380' W	908
8	21864-1	70°18.954' N	08°39.175' W	458
9	21865-1	70°32.288' N	08°49.546' W	204
10	21873-1	72°18.020' N	11°18.160' W	2109
11	21874-1	72°29.413' N	12°36.360' W	509
12	21875-7	72°32.830' N	12°15.260' W	2376
13	21876-1	72°48.440' N	12°46.350' W	2592
14	21877-1	72°28.710' N	13°04.340' W	2649
15	21878-2	73°15.100' N	09°00.940' W	3038
16	21880-3	73°32.800' N	09°04.770' W	333
17	21882-1	73°35.520' N	08°23.800' W	3169
18	21886-3	73°32.290' N	09°05.220' W	260
19	21892-1	73°44.050' N	09°37.520' W	3125
20	21893-1	74°52.060' N	10°06.570' W	3245
21	21894-7	75°48.830' N	08°15.480' W	1992
22	21895-9	75°24.800' N	07°18.600' W	3358
23	21898-6	74°59.140' N	04°57.940' W	3595
24	21900-7	74°31.680' N	02°20.120' W	3538
25	21901-1	75°56.560' N	03°44.370' W	3588
26	21902-3	77°25.650' N	05°45.910' W	422
27	21903-1	77°16.620' N	05°01.260' W	1182
28	21904-1	77°05.140' N	03°59.280' W	1795
29	21905-1	76°55.130' N	03°23.010' W	1761
30	21906-1	76°50.520' N	02°09.000' W	2990
31	21908-1	76°19.250' N	01°04.340' W	2497
32	21909-1	76°06.340' N	01°00.330' W	2488
33	21910-1	75°37.000' N	01°19.000' E	2448
34	21911-1	75°03.500' N	02°58.500' E	2326
35	21912-7	74°29.070' N	02°54.500' E	3727
36	21913-1	74°29.070' N	05°24.430' E	2857
37	21914-4	73°58.030' N	07°39.860' E	1793

Each micropaleontological slide was prepared with approximately 0.5 grams of the non-carbonate material (> 40 µm), following Moore's technique (1973) and Molina-Cruz (1978) and Roelofs & Pisias (1986) indications. This technique allows sediment particles to settle down randomly on the slide; thus reducing the possibility of biasing in their countdowns (Sachs 1973).

In this study, the relative abundances (percentages) of 17 species, listed in Table 2 and shown in Fig. 7, were estimated. In general, these comprise 75 % of the total radiolarian population found in the studied area. In order to define the geographical distribution of the species, their relative abundance was contoured (Fig. 6). However, here only the distributions of the species with higher mean-percentages (M) and occurrence-frequencies (F) are shown, since we will concentrate our discussion on these.

The ecological significance of the species distribution was complemented through the study of radiolarian assemblages, which were defined using Q-mode factor analysis of 17 species, listed in Table 2 (Press 1972). Q-mode factor analysis is a mathematical technique well known in biogeographical studies (e.g. Sancetta 1979; Molina-Cruz 1984; Koc Karpuz & Schrader 1990). It is frequently used to measure the similarity between samples as a function of their faunistic contents. In this analysis, the similarity between samples is expressed through a convenient number of 'latent' variables denominated factors.

The factor loadings for each sample location (Table 3) were contoured on maps (Fig. 8). Because the distribution of each factor occupies a specific environmental zone, these are considered as radiolarian assemblages, each inhabiting an identified ecological region.

Usually in the factor analysis modelling technique, the affinity of each species for each factor is determined numerically by the factor scores matrix (e.g. Pisias 1986). In spite of that, in this study, it has been carried out through a graphic multivariate analysis. This allows observation of details of the affinities which are not easily seen through the factor analysis (Molina-Cruz & Martinez-Lopez 1994). It was possible because the numerical system was defined with only three factors. The graphic multivariate analysis follows four steps: 1) the factor loadings for each sample-location are standardized to 100 % (Table 3); 2) the standardized values are located in a ternary diagram (triangle), as used by Shepard (1954) for sediment analysis; 3) at these locations, the relative abundances (%) of the species under question are noted correspondingly and 4), these are contoured. The distribution depicted for a particular species within the triangle, shows graphically its affinity with each one of the factors (see Fig. 9).

RESULTS AND DISCUSSION

Around 45 radiolarian species are known in the Iceland and Greenland Seas (Petrushevskaya & Bjørklund 1974; Swanberg & Eide 1992). However, only about half of them are frequently present on a micropaleontological slide. Therefore, in this study, we have identified only seven species (of four families) of Spumellaria and ten species (of seven families) of Nassellaria. In general, these species comprise 78 % of the total radiolarian population found in the studied area (Table 2) and are not difficult to identify.

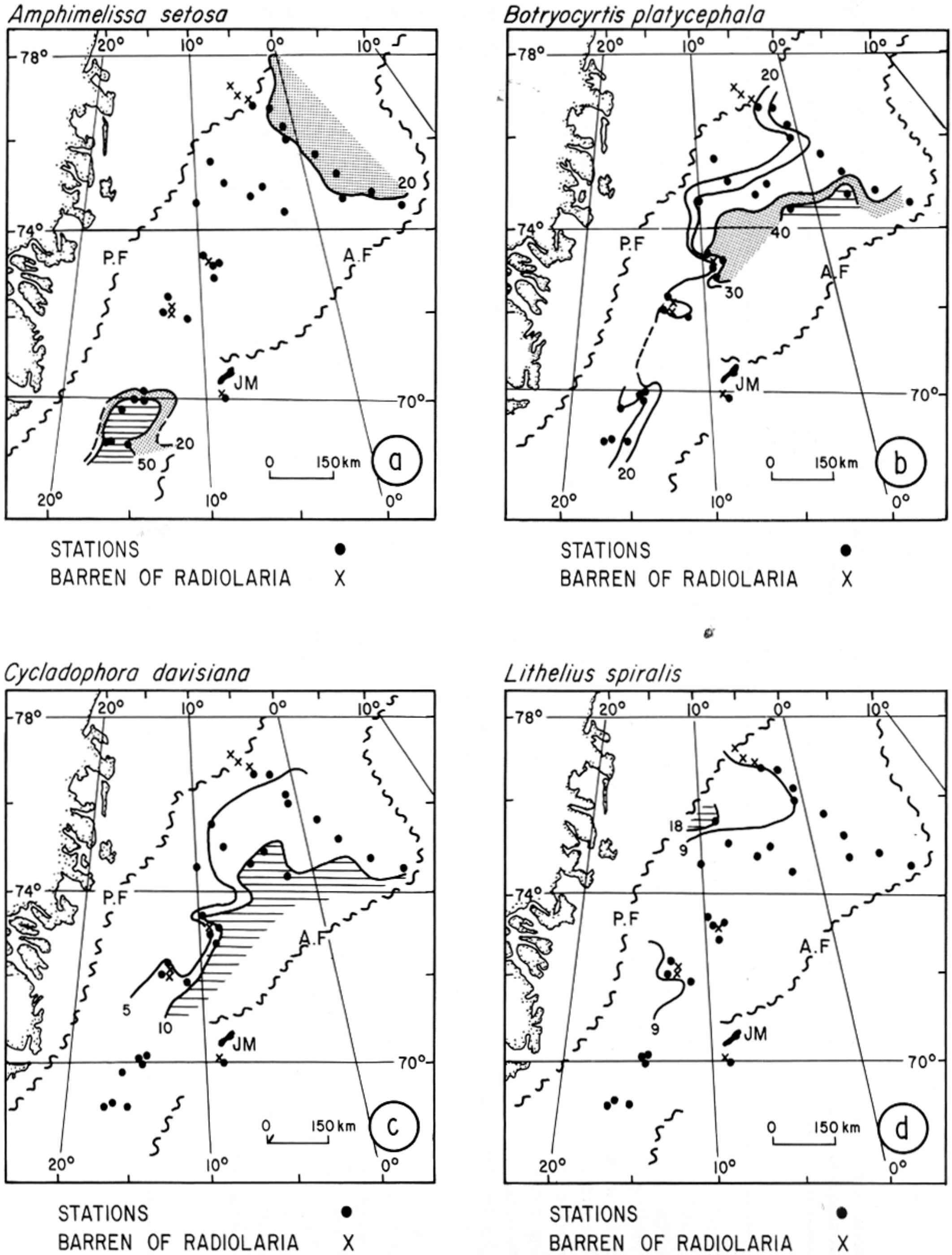


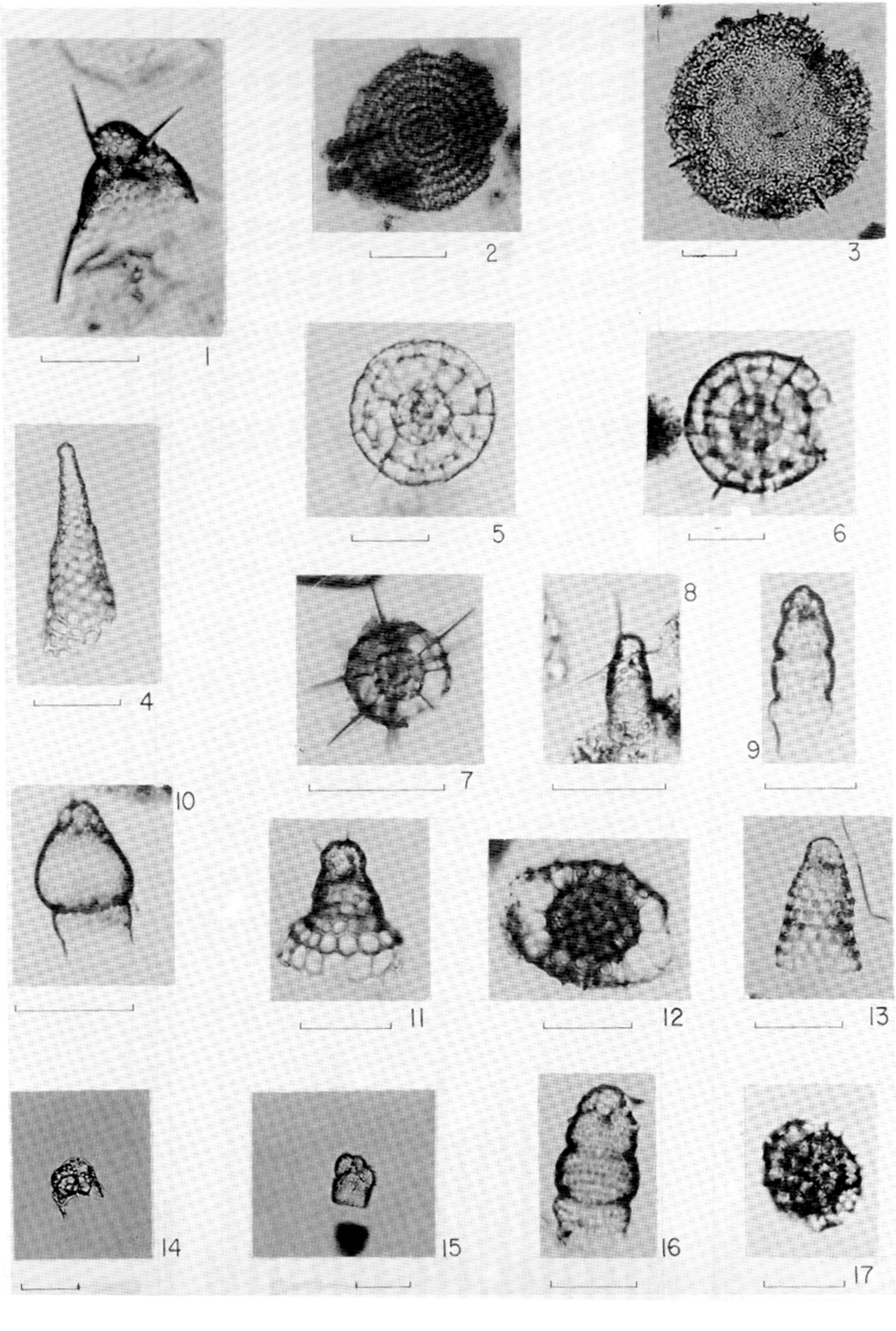
Fig. 6. Radiolarian species distribution in the surface sediments of the Iceland and Greenland Seas. The number of the isolines represent percentages, relative to the total radiolarian population. P.F.= Polar Front, A.F.= Arctic Front.

Table 2. Radiolarian species relative abundance (%).*In these stations the species percentages were not evaluated because radiolarians are scarce. M = Mean abundances (percentages). F = Ocurrence frequencies(%); i.e. percentage of samples where the species was recorded. x denotes presence of the species.

			STATIONS																	
	M	F	1	2	3	4	5	6	7	8	*9	10	*11	12	13	14	15	16	17	*18
NASELLARIA																				
Amphimelissa setosa (Cleve)	23.82	100	50.50	60.68	44.32	51.79	44.59	29.52	51.46	45.42	x	8.76		1.23	6.25	7.18	13.58	42.59	11.90	x
Artobotrys borealis (Cleve)	2.83	100	1.01	0.31	0.23	2.28	3.61	2.86	1.67	6.67		6.96		7.41	2.08	6.08	2.47	3.70	0.96	x
Artostrobus annulatus (Bailey)	0.33	35.48	0.00	0.93	1.86	0.00	0.00	0.00	0.00	0.00		0.00		0.00	1.67	0.00	0.62	0.00	0.00	
Artostrobus jørgenseni Petrushevskaya	1.16	83.37	1.26	0.00	3.02	1.63	0.66	0.88	1.04	0.83	x	1.80		0.00	0.83	0.55	1.85	0.00	0.64	
Botryocyrtis platycephala (Petrushevskaya)	24.13	96.77	11.31	12.69	17.17	15.64	18.69	17.62	14.58	5.00		21.65		18.52	21.25	22.65	35.80	0.00	36.66	
Cornutella profunda (Ehrenberg)	0.38	38.71	0.00	0.00	0.23	0.00	0.33	0.22	0.21	0.00		0.00		4.94	0.00	0.00	0.31	0.00	0.00	
Cycladophora davisiana (Ehrenberg)	6.21	96.77	1.26	0.93	1.39	0.98	0.66	0.66	0.00	0.42		6.96		3.70	5.00	8.84	8.33	0.93	13.50	
Lithomelissa setosa (Jørgensen)	0.12	19.35	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00		0.00	0.42	0.00	0.62	0.00	0.00	
Lithomitra lineata (Ehrenberg)	0.57	51.61	0.00	7.12	0.93	0.33	0.00	1.10	0.42	0.42		0.26		0.00	0.00	0.00	0.31	2.78	0.00	
Pseudodictyophimus gracilipes (Bailey)	6.90	96.77	13.07	0.00	10.67	10.42	8.20	6.61	9.79	5.83	x	7.99		4.94	5.42	1.66	7.10	10.19	4.50	x
Not identified	9.06	91.8	5.53	2.17	3.25	1.30	10.16	4.63	5.42	3.75	x	7.47	x	11.11	14.17	15.47	9.26	7.41	7.40	x
SPUMELLARIA																				
Chromyechinus borealis (Cleve)	2.83	93.55	8.79	3.72	7.66	6.19	0.66	3.08	4.58	0.83	x	2.84		2.47	2.92	3.87	1.54	2.78	0.96	
Echinomma leptodermum (Jørgensen)	2.46	74.19	0.00	3.10	3.02	3.26	0.00	14.32	1.88	4.17		4.38		0.00	3.75	3.87	0.93	0.00	3.22	x
Larcospira minor (Jørgensen)	0.18	22.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00		0.00	0.00	0.00	0.00	0.00	0.00	
Lithelius spiralis (Haeckel)	5.25	96.77	0.50	1.55	1.16	0.00	1.31	2.42	2.08	7.08	x	14.69		25.93	9.58	11.05	4.32	3.70	3.54	
Phorticium clevei (Jørgensen)	0.98	77.42	0.00	0.00	0.00	0.33	0.33	1.98	0.00	0.00		1.80		0.00	1.25	1.66	0.62	0.00	1.61	
Spongotrochus glacialis (Popofsky)	0.64	80.65	0.00	0.31	0.46	0.33	0.00	1.10	0.63	0.42		0.52		2.47	0.83	0.00	0.31	0.93	1.29	
Stylodictya validispina (Jørgensen)	0.03	9.68	0.00	0.31	0.00	0.33	0.00	0.00	0.00	0.00		0.00		0.00	0.00	0.00	0.00	0.00	0.00	
Not identified	12.24	94.5	6.28	6.19	4.64	5.21	10.82	13.00	6.25	19.17	x	13.92	x	17.28	24.58	17.13	12.04	25.00	13.83	x
Radiolarians counted			398	323	431	307	305	454	480	240	29	388	2	181	240	181	324	108	311	13

Table 2. (continued)

	STATIONS																		
	19	20	21	22	23	24	25	*26	*27	*28	29	30	31	32	33	34	35	36	37
NASELLARIA																			
Amphimelissa setosa (CLEVE)	12.96	11.68	7.63	13.21	16.09	10.94	15.76			x	9.60	28.57	21.95	12.50	25.81	29.42	12.08	27.78	12.67
Artobotrys borealis (CLEVE)	2.54	1.71	2.29	1.89	1.30	1.51	0.54			x	6.40	1.43	3.24	5.92	1.16	0.62	0.24	3.63	2.67
Artostrobus annulatus (BAILEY)	0.00	0.85	0.00	0.00	0.00	0.00	0.54				0.80	0.48	0.00	0.00	1.40	0.62	0.00	0.43	0.00
Artostrobus jørgenseni PETRUSHEVSKAYA	0.00	0.85	0.76	0.94	4.35	1.89	1.09				0.00	1.43	2.00	0.66	1.63	1.65	1.69	1.28	0.67
Botryocyrtis platycephala (PETRUSHEVSKAYA)	35.49	31.05	10.69	26.42	33.04	40.75	34.24				21.60	32.86	33.67	20.39	31.63	33.13	46.14	27.78	20.00
Cornutella profunda (EHRENBERG)	0.00	0.00	2.29	0.00	0.00	0.38	0.00				1.60	0.00	0.25	0.00	0.00	0.00	0.48	0.00	0.67
Cycladophora davisiana (EHRENBERG)	9.86	13.11	6.87	6.13	10.43	10.57	15.76				4.00	4.76	8.23	7.89	8.37	6.79	12.32	6.62	7.33
Lithomelissa setosa (JØRGENSEN)	0.28	0.28	1.53	0.00	0.00	0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lithomitra lineata (EHRENBERG)	0.56	0.28	0.00	0.47	0.43	0.00	0.00				0.00	0.00	0.00	0.00	1.16	0.41	0.00	0.64	0.00
Pseudodictyophimus gracilipes (BAILEY)	5.92	6.84	3.82	10.38	5.22	8.30	2.72				6.40	6.67	9.73	11.18	6.28	6.79	4.11	6.62	6.67
Not identified	9.30	11.97	10.69	13.68	10.00	9.06	7.07				11.20	10.48	8.48	11.18	12.33	11.73	10.14	10.47	13.33
SPUMELLARIA																			
Chromyechinus borealis (CLEVE)	1.69	3.13	8.40	1.89	1.30	1.89	1.09	x			2.40	0.95	2.00	0.00	1.40	1.03	0.00	2.35	5.33
Echinomma leptodermum (JØRGENSEN)	3.38	1.42	9.16	1.42	2.17	1.89	0.00				2.40	2.38	0.75	3.29	1.16	0.00	0.00	0.85	0.00
Larcospira minor (JØRGENSEN)	0.28	1.14	0.00	1.89	0.00	0.00	0.00				0.00	0.00	0.00	0.00	0.47	0.41	0.97	0.43	0.00
Lithelius spiralis (HAECKEL)	3.10	2.85	18.32	0.47	1.74	1.51	1.63				9.60	1.90	1.75	15.79	2.09	0.41	0.72	1.28	10.67
Phorticium clevei (JØRGENSEN)	0.28	0.85	3.05	1.89	1.30	0.38	2.17		x	x	0.80	0.95	0.25	1.97	0.47	0.82	0.24	0.64	4.67
Spongotrochus glacialis (POPOFSKY)	0.28	0.28	0.76	1.89	0.43	0.38	2.17			x	0.00	0.48	0.75	0.66	0.00	0.00	0.72	0.21	1.33
Stylodictya validispina (JØRGENSEN)	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00
Not identified	14.08	11.68	13.74	17.45	12.17	10.57	15.22			x	23.20	6.67	6.98	8.55	4.65	6.17	9.90	8.97	14.00
Radiolarians counted	355	351	131	212	230	265	184	1	1	13	125	210	401	152	430	486	414	468	150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On basis of the species mean abundance (M) and frequency of occurrence (F) (Table 2), it is possible to observe that the radiolarian population in the studied area includes at least eight dominant species. These are: *Amphimelissa setosa* (CLEVE,1899), *Botryocyrtis platycephala* (PETRUSHEVSKAYA, 1967), *Cycladophora davisiana* (EHRENBERG, 1862), *Lithelius spiralis* (HAECKEL, 1860), *Artobotrys borealis* (CLEVE,1899), *Chromyechinus borealis* (CLEVE, 1899), *Echinomma leptodermum* (JØRGENSEN, 1900) and *Pseudodyctiophimus gracilipes* (BAILEY, 1856).

Amphimelissa setosa has the highest abundance in the region studied. Southwest of Jan Mayen Island, *A. setosa* represents 59 % of the radiolarian population and North of 74° N reaches 20 % of the population. In general, *A. setosa* distribution is confined between the isotherms 3.0 and 5.0° C and the isohalines 34.5 and 35.0 psu (see Figs 3, 4, and 6A). Therefore, it is suggested that the distribution of *A. setosa* is related to the distribution of Arctic Surface Water (ASW) and in consequence this species is commonly observed in sediments below the Jan Mayen and East Icelandic Currents (Fig. 2) (PETRUSHEVSKAYA & BJØRKLUND 1974; MOLINA-CRUZ 1991).

The high abundance of *A. setosa* in the surface sediments of the Iceland and Greenland Seas, is coherent with its capture in plankton hauls. In these, the relative abundance of *A. setosa* has been up to 69 % (SWANBERG & EIDE 1992).

The second most abundant species in the sediment samples was *Botryocyrtis platycephala*. Its highest abundance (40 %) was found at the northeastern part of the study area (Fig. 6B). This observation is important because this species had previously been reported with only low abundance in this region (< 2 %) (PETRUSHEVSKAYA 1967). Because the predominance of its abundance is observed relatively near the Arctic Front (see Figs 3, 4, and 6B), it is suggested that *B. platycephala* inhabits prominently the Subarctic Water, which is produced by mixing of Arctic and North Atlantic Waters at the Arctic Front.

Similar to *B. platycephala*, the highest abundance of *Cycladophora davisiana* was found near and parallel to the Arctic Front (Fig. 6C); particularly where the Arctic Water, carried by the Jan Mayen Current, mixes with the North Atlantic Water, carried by the Norwegian Current, and forms Subarctic Water (Fig. 2).

In the Iceland and Greenland Seas, the frequency of occurrence of *C. davisiana* is usually between 5 and 10 %; thus greater than in most parts of the Holocene ocean (MORLEY & HAYS 1983). Assuming that the sediment samples studied here are not older than the Holocene, such a 'high' abundance of *C. davisiana* may represent: (1) major production of this species in the studied area and consequently larger test input to the sea floor or (2) less test input of other species. Inhabiting the subsurface of cold water masses, *C. davisiana* has a habitat which is less affected by climatic changes (e.g. water freezing and ice melting) than the habitat of the surface species (MORLEY 1980; MORLEY & HAYS 1983; BJØRKLUND & CIESIELSKI 1994). Therefore, it is probable that the input of surface species tests to the sea floor be more intermittent than the input of *C. davisiana* tests and in consequence, the relative abundance of the last increased.

Added to the effects of productivity, discussed above, it is possible that dissolution of fragile species contributes to the relatively higher frequency of occurrence of robust species such as *C. davisiana* and *B. platycephala* .

Both *Lithelius spiralis* and *Artobotrys borealis* have similar geographical distributions, with only the distribution of *L. spiralis* being shown here (Fig. 6D). The major abundance of these species is observed in the northwest of the study area, where temperatures are generally less than 3.0° C. In this region, the water mass that is produced by the melting of continental ice (Polar Water), mixes with Arctic Surface Water. It is therefore inferred that *L. spiralis* and *A. borealis* are associated with Subpolar Water.

No clear patterns were found in the distributions of *Chromyechinus borealis*, *Echinomma leptodermum* and *Pseudodyctiophimus gracilipes*. However, it is observed that these species show their higher abundances where the Arctic Surface Water is present.

It has been argued that the radiolarian dominant species distributions (Fig. 6) are influenced mostly by the presence of particular water masses. However, it is also known that stochastic fluctuations, such as dissolution and depositional variations also influence these distributions. In spite of this, the influence of particular stochastic fluctuations on the dominant species distributions are not analyzed in this study, due to lack of elements. Nevertheless, the effect of stochastic variations on the dominant

Fig. 7: (1) *Pseudodictyophimus gracilipes* (BAILEY); from station 1. (2*) Stylodictya validispina* JØRGENSEN; from station 35. (3) *Spongotrochus glacialis* POPOFSKY; from station 3. (4*) Cornutella profunda* EHRENBERG; from station 12. (5-6) *Cromyechinus borealis* (CLEVE); from station 1. (7) *Echinomma leptodermum* JØRGENSEN; from station 35. (8) *Artostrobus annulatus* (BAILEY); from station 20. (9) *Lithomitra lineata* (EHRENBERG); from station 3. (10) *Artobotrys borealis* (CLEVE); from station 15. (11) *Cycladophora davisiana* (EHRENBERG); from station 15. (12) *Phorticium clevei* (JØRGENSEN); from station 15. (13) *Artostrobus jørgenseni* PETRUSHEVSKAYA; from station 1. (14-15) *Amphimelissa setosa* (CLEVE) from station 1. (16) *Botryocyrtis platycephala* (PETRUSHEVSKAYA); from station 15. (17) *Larcospira minor* (JØRGENSEN); from station 4. Bars represent 50 mm, respectively.

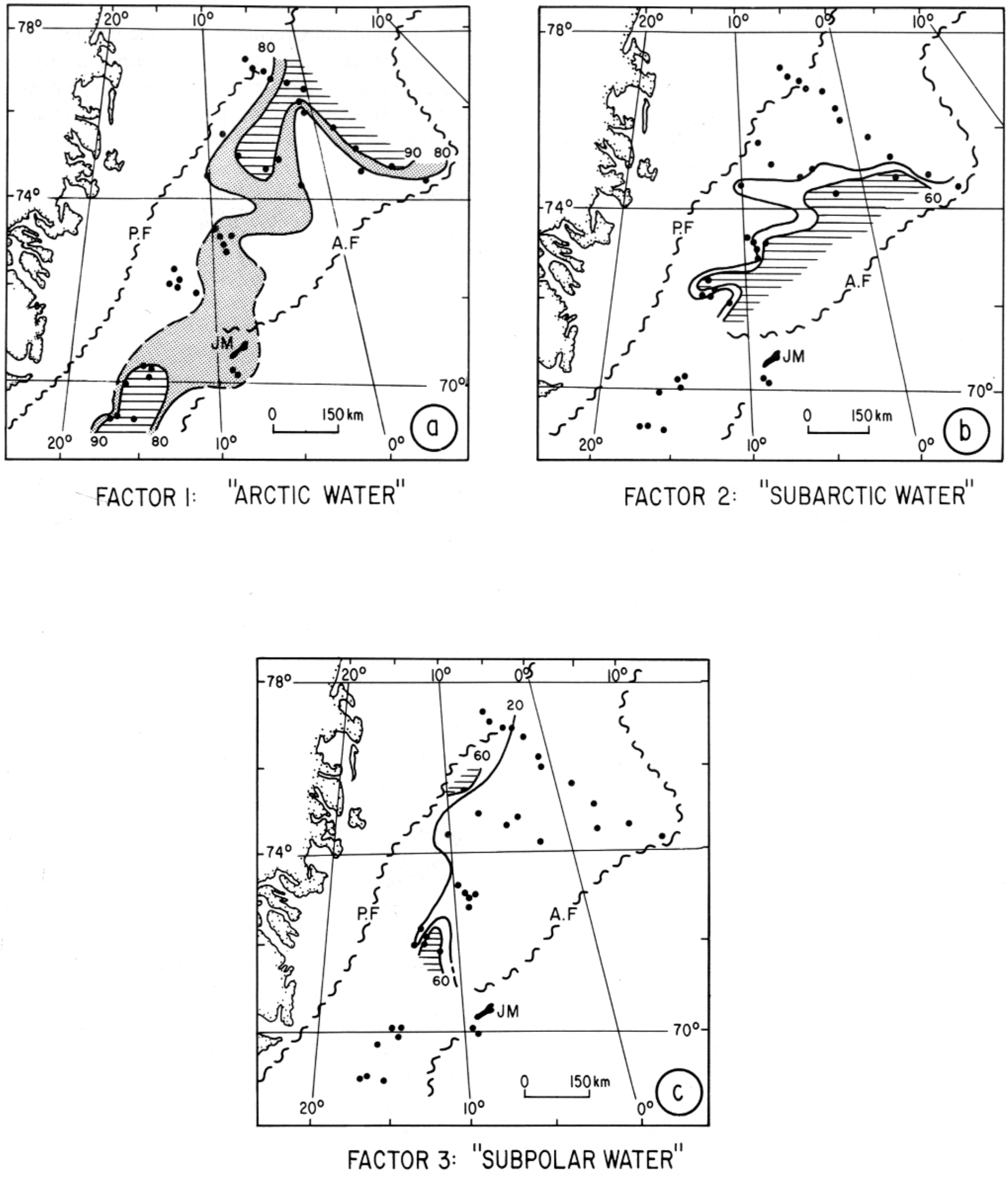

Fig. 8. Radiolarian assemblages (factors) distribution in the surface sediments of the Iceland and Greenland Seas. The number of the isolines represent factor loadings (x 100). P.F. and A.F. as in Fig. 6.

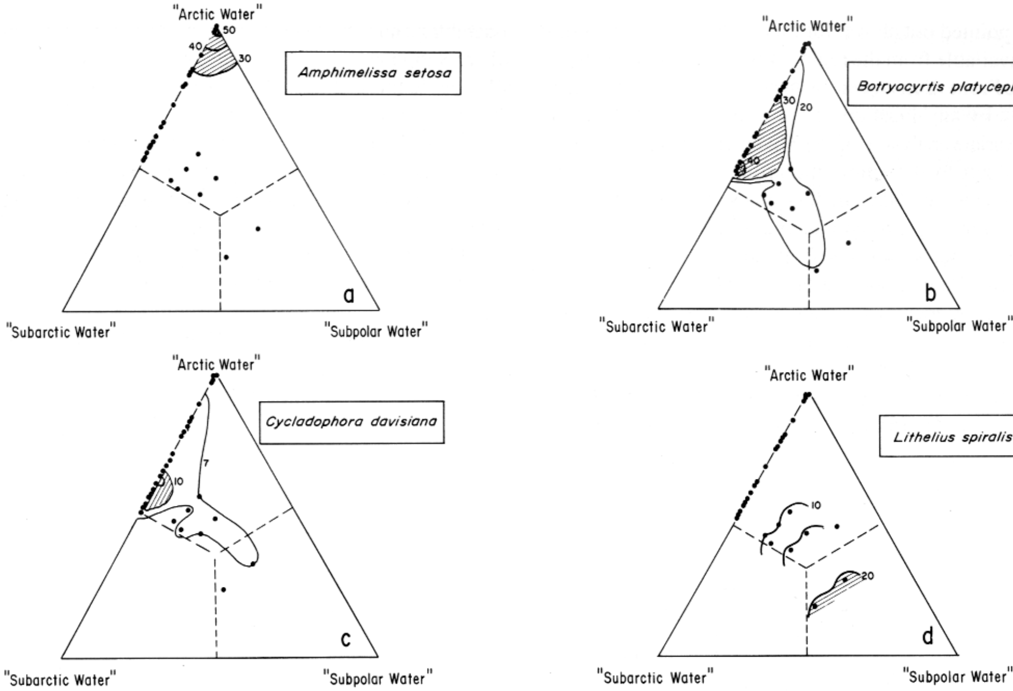

Fig. 9 Graphic multivariate analysis of four radiolarian species which occur in the Iceland-Greenland Sea (see text). The contours within each triangle represent percentages of the species, relative to the total radiolarian population.

species distributions, becomes evident each time these are compared with the distribution of a regional radiolarian assemblage, defined through factor analysis (e.g. compare Figs 6A and 8A). It is assumed that the observable differences between both distributions result from the fact that the effect of stochastic variations shows more on a single-species distribution than on an assemblage distribution, defined through Q-mode factor analysis. This mathematical procedure 'buffers' the signals of the stochastic variations (Sachs 1973). In consequence, the distribution of radiolarian assemblages, defined through Q-mode factor analysis, is analyzed below.

Assemblages distribution

The Q-mode factor analysis carried out in this work yielded three factors (Fig. 8 and Table 3), which explain the majority of the variance (97.4 %). Nevertheless, it must be noted that the region where factor 1 lies, was better sampled than the other ones (Fig. 8). In consequence, factor 1 was mathematically better defined than the other 2 factors. Factor 1 shows factor loadings greater than 0.9, while the other two factors do not show factor loadings greater than 0.60 (see Table 3). This effect, caused by bias in the sampling, is evident in the triangular diagram employed in the graphic multivariate analysis (Fig. 9), since most of the samples are located in the area of factor 1. The area of factor 3 contains only two samples and factor 2 none. In spite of this, the geographical distributions of the factors (Fig. 8) show biogeographical significance.

Factor 1 explains 72.95 % of the total variance and because it is distributed principally where the Arctic Surface Water occurs (see Figs 8A and 2), it has been called 'Arctic Water'. Its higher values are observed southwest of Jan Mayen Island and north of 74° N. In the first region, the Arctic Surface Water flows in the East Icelandic Current, while in the second region, it is transported by the cyclonic gyro of the Jan Mayen Current (Fig. 2). The graphic multivariate analysis (Fig. 9A) points out that *Amphimelissa setosa* is the most prolific species associated with factor 1 ('Arctic Water').

Factor 2 represents 20.73 % of the total variance. Because its distribution (Fig. 8B) is contiguous and parallel with the Arctic Front, where Subarctic Water is formed (see Fig. 2), this has been called 'Subarctic Water'.

As pointed out above, for this study there are no samples available from the region influenced directly by the Arctic Front. Consequently, factor 2 was not represented clearly by any location in the triangles of the graphic multivariate analysis (Fig. 9). Given this inconvenience, it is difficult to determine the affinity of species to the Subarctic Water. Nevertheless, analyzing the ‘affinity triangles’ for *B. platycephala* and *C. davisiana* (Fig. 9B and 9C, respectively), it is observed that, in some way, the Subarctic Water influences their distribution, because, although these species occur abundantly in the Arctic Water zone, their major concentrations show a tendency to be displaced towards the Subarctic Water zone.

Factor 3, named here ‘Subpolar Water’ (Fig. 8C), is poorly defined (variance 3.71 %). However, this radiolarian assemblage appears to be contiguous to the Polar Front, where Subpolar Water is formed. The species with major affinities to this factor are *Lithelius spiralis* (Fig. 9D) and *Artobotrys borealis*.

The distributions of the radiolarian assemblages defined in this study, in general, correspond with the distributions of diatom assemblages defined by Koc Karpuz & Schrader (1990). However, there are some differences: the distribution of the ‘Sea-ice’ diatom assemblage corresponds to the distribution of the ‘Subpolar Water’ radiolarian assemblage, but the distribution of the ‘Arctic’ diatom assemblage, comprises the distributions of the ‘Subarctic’ and ‘Arctic’ radiolarian assemblages.

Table 3. Normalized varimax rotation matrix and standarized factor loadings.

	Factor loadings			Standarized factor loadings		
Stations	Factor 1	Factor 2	Factor 3	% Factor 1	% Factor 2	% Factor 3
1	0.874	0.000	0.031	96.6	0.0	3.4
2	0.851	0.000	0.019	97.8	0.0	22.2
3	0.931	0.000	0.000	100.0	0.0	0.0
4	0.910	0.000	0.007	99.2	0.0	0.8
5	0.950	0.000	0.002	99.8	0.0	0.2
6	0.901	0.000	0.049	94.8	0.0	5.2
7	0.906	0.000	0.044	95.4	0.0	4.6
8	0.812	0.000	0.207	79.7	0.0	20.3
10	0.700	0.579	0.410	41.4	34.3	24.3
12	0.310	0.599	0.654	19.8	38.3	41.8
13	0.714	0.656	0.212	45.1	41.5	13.4
14	0.686	0.645	0.256	43.2	40.6	16.1
15	0.822	0.559	0.000	59.5	40.5	0.0
16	0.755	0.000	0.146	83.8	0.0	16.2
17	0.770	0.608	0.000	55.9	44.1	0.0
19	0.810	0.570	0.000	58.7	41.3	0.0
20	0.749	0.571	0.000	58.2	41.8	0.0
21	0.436	0.331	0.694	29.8	22.7	47.5
22	0.859	0.437	0.000	66.3	33.7	0.0
23	0.858	0.472	0.000	64.5	35.5	0.0
24	0.757	0.627	0.000	54.7	45.3	0.0
25	0.815	0.497	0.000	62.1	37.9	0.0
29	0.791	0.534	0.242	50.5	34.1	15.4
30	0.973	0.186	0.000	84.0	16.0	0.0
31	0.928	0.343	0.000	73.0	27.0	0.0
32	0.755	0.439	0.415	46.9	27.3	25.8
33	0.963	0.235	0.000	80.4	19.6	0.0
34	0.972	0.175	0.000	84.7	15.3	0.0
35	0.745	0.623	0.000	54.5	45.5	0.0
36	0.987	0.123	0.000	88.9	11.1	0.0
37	0.838	0.419	0.524	55.5	27.7	16.8
% Variance	72.945	20.726	3.713			
Σ Variance	97.380					

CONCLUSIONS

Although in this study it was not possible to measure any of the stochastic variations in the sediment samples (dissolution, dilution, differential age, etc.), it is evident that these influence the geographic distributions of single species. This influence however, is 'buffered' within the distribution of radiolarian assemblages if these are defined through Q-mode factor analysis. This analysis shows that approximately 78 % of the radiolarian population in the area may be grouped in three differential assemblages. As in other regions of the ocean, the distributions of these assemblages correspond principally to the presence of particular water masses. In accordance with this fact, the three identified radiolarian assemblages have been called: factor 1: 'Arctic Water', factor 2: 'Subarctic Water' and factor 3: 'Subpolar Water'.

There are approximately eight dominant species of radiolarians in the Iceland and Greenland Seas; however, only five show significant affinity with the presence of particular water masses: *Amphimelissa setosa* is the most evident species in the Arctic Surface Water, while *Botryocyrtis platycephala* and *Cycladophora davisiana* are in the 'Subarctic Water'; in consequence, under the Arctic Front. *Lithelius spiralis* and *Artobotrys borealis*, showing major affinity with the Subpolar Water, represent the coldest radiolarian province.

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