

Holocene palaeo-oceanography of the northern Iceland Sea, indicated by Radiolaria and sponge spicules

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ABSTRACT: The micropalaeontological analysis of 49 samples, from three box cores collected from the northern Iceland Plateau, indicates that radiolarian and sponge remains are rare in glacial sediments but are common after deglaciation; mostly during the first half of the Holocene. The record trend of the abundance of *Oxycalthrop* sponge spicules is regional in character. Fluctuations in radiolarian abundance, and the first occurrence of each of the species inhabiting the Iceland Sea at present, coincide with changes in oceanographic conditions that occurred during the Holocene. At the Younger Dryas chronozone, the downcore record of *Cycladophora davisiana* (Ehrenberg) depicts a maximum peak, because the sea surface was colder than it has been recently; though still seasonally free of ice-cover. During the Preboreal, Boreal and Atlantic chronozones, *Amphimelissa setosa* (Cleve) was highly abundant, as a consequence of the increase in mixing between the Arctic Water and the North Atlantic Water. During the Subboreal chronozone, the East Icelandic Current became better developed, and initiated the onset of the 'Arctic Front' in the Iceland Sea; as is suggested by the *Lithomitra lineata* (Ehrenberg) record. This 'cooled' environment also allowed an increase in the occurrence of *Artobotrys borealis* (Cleve). The reappearance of *Stylodictya validispina* (Jørgensen) in the Iceland Sea, during the Sub Atlantic chronozone, indicates a larger input of Atlantic Water, via the Norwegian Current.

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Introduction

The Nordic Seas, in particular the Greenland, Iceland and Norwegian Seas, have been the subject of a number of palaeo-oceanographic studies considering the Holocene–Pleistocene boundary, principally during the last decade (e.g. Björklund *et al.*, 1979; Kellogg, 1984; Sejrup *et al.*, 1984). Most of these studies have been carried out in the Norwegian Sea, because it is thought that the palaeo-oceanographic signals become enhanced, owing to the direct influence of the Atlantic surface water mass each time it is introduced (or retreats) via the Atlantic–Norwegian Current.

The major part of these studies have been based on micropalaeontological and isotopic analyses of the calcareous components of the sediments (e.g. Jansen and Erlenkeuser, 1985; Jansen, 1987), even though it has been suggested that an analysis of siliceous components will provide complementary information (Jansen and Björklund, 1985). Consequently, this paper represents a preliminary study of Radiolaria in the northern Iceland Sea, since the last deglaciation, approxi-

mately 10 000 yr BP, and also represents a geographical extension of Holocene palaeo-oceanographic studies towards the southwest of the Greenland–Iceland–Norwegian Sea.

The study is based on three box cores collected from the northern Iceland Plateau, approximately along the parallel 70°N (Table 1 and Fig. 1), in locations that are presently influenced by the East Greenland–Icelandic Current system and by the seasonal formation of sea-ice cover and deep water.

A Holocene chronostratigraphic framework is established by considering the oxygen isotope record ($\delta^{18}\text{O}$) of core GIK 23352-2 (Latitude: 70°01'N; Longitude: 12°25'W) and the stratigraphic position of an ash layer correlated to the Vedde ash layer (age 10 600 yr BP; Mangerud *et al.*, 1984; Sejrup *et al.*, 1989). Within this framework, the chronozones established by Mangerud *et al.* (1974) are shown (see Fig. 3e) with the downcore fluctuations of the absolute abundance of radiolarians and sponge spicules (belonging to the oxycalthrop type (Locker and Martini, 1985; Fig. 2(18)), correlated with the stratigraphic record depicted by the abundance of 'terrigenous input' (particles coarser than 40 μm and free of carbonate). The relative abundance of 13 species of the radiolarian population are shown in Tables 2 and 3.

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Table 1 General core data

Core	Location	Depth (m)	Core length (cm)	Number of samples analysed
23351-4	70° 22' N, 18° 12' W	1679	31	14
23352-2	70° 01' N, 12° 25' W	1822	35	15
23357-2	70° 57' N, 05° 32' W	1735	31	19
P57-7	68° 26' N, 13° 52' W	1620	800	(Sejrup et al., 1989)

Oceanographic setting

The Iceland Sea is located north of Iceland and its boundaries are arbitrarily defined by Greenland, the geographic parallel 71°N and the geographic meridian 6°W (Fig. 1). The area includes the Iceland–Jan Mayen Ridge in the western side and the Iceland Plateau in the eastern side (Perry, 1986). The Iceland Plateau has an average depth of roughly 1750 m.

The Iceland Sea generally has ice-cover in winter, but the East Greenland and the East Icelandic Currents extend into the area in summer with an incursion of the Irminger Current through the Denmark Strait (Fig. 1). The East Greenland Current carries mostly Polar Water (temperature < 1°C; salinity < 34.4 ppm); the Irminger Current, Atlantic Water (temperature > 5°C; salinity > 34.9 ppm); and the East Icelandic Current, Arctic Water (temperature –1°C to 6°C; salinity 34.4–34.9 ppm) (Kellogg, 1976; Johannsen, 1986). The Arctic Water mass is considered as a transitional water because it is formed by mixing of the Atlantic Water mass and the Polar Water mass. However, this mixing is shown as a sharp transitional zone only along the Arctic Front (Hurdle,

1986) (Fig. 1). Thus, it must be noted that it is possible to mix Atlantic Water with Arctic Water or Atlantic Water with Polar Water. A clear meeting of Atlantic Water with Polar Water develops the Arctic Front (Hurdle, 1986).

Material and methods

The three cores analysed in this study (Table 1 and Fig. 1) were collected by the German R/V 'Meteor' during the late summer of 1988. Core 23351-4 is defined as a complex dark diamicton, while cores 23352-2 and 23357-2 consist of brownish sandy mud with scattered dropstones (Hirschleber et al., 1988).

All cores were sampled from top to bottom, in 1-cm thick slabs, every 2 cm. However, core 23357-2 was also sampled every centimetre, from the top down to 8 cm, because it appears to have a reduced sedimentation rate during the last 5000 years. The samples were (dry) weighed, treated with hydrochloric acid and oxygen peroxide and wet-sieved

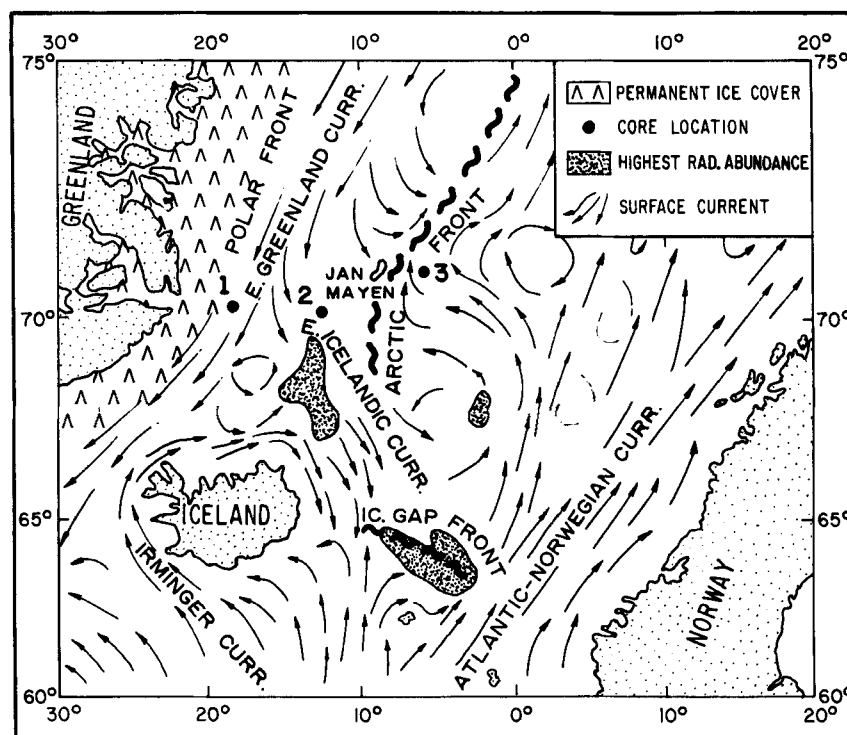


Figure 1 Principal sea-surface oceanographic features and areas of recent sediments with the highest radiolarian abundance (after Goll and Björklund, 1985). The 'oceanic fronts' are depicted according to Hurdle (1986) and Johannsen (1986). The cores used in this study are: (1) Core 23351-4; (2) Core 23352-2; and (3) Core 23357-2.

Table 2 Radiolarian species relative abundance (%) for Core 23352-2^a

Age (× 1000 yr)	Sub-bottom depth (cm)	<i>Amphimelissa</i> <i>setosa</i> (Cleve)	<i>Ariobolus</i> <i>borealis</i> (Cleve)	<i>Ariobolus</i> <i>annulatus</i> (Bailey)	<i>Ariobolus</i> <i>seni</i> (Petrushevskaya)	<i>Cycladophora</i> <i>davisiana</i> (Ehrenberg)	<i>Lithomelissa</i> <i>setosa</i> (Jorgensen)	<i>Lithomitra</i> <i>lineata</i> (Ehrenberg)	<i>Lithomitra</i> <i>platyccephala</i> (?) (Ehrenberg)	<i>Pseudodictyophimus</i> <i>gracilipes</i> (Bailey)	<i>Cromyechinus</i> <i>borealis</i> (Cleve) (4 shells)	<i>Phorticum</i> <i>clevei</i> (Jorgensen)	<i>Spongostochus gla-</i> <i>cialis</i> (Popolsky)	<i>Stylocytha</i> <i>validispina</i> (Jorgensen)	Radiolarians not identified
2.5	0-1	46.9	01.8	02.9	02.3	00.7	01.1	03.6	13.9	05.2	10.9	00.9	00.5	—	09.1
	2-3	54.1	01.2	03.1	01.2	02.3	01.6	00.4	13.3	03.9	04.3	00.8	00.4	—	13.3
	4-5	50.5	02.9	05.1	02.5	01.1	02.1	01.8	14.8	02.1	05.8	—	—	—	11.1
	6-7	50.9	03.9	05.8	01.5	03.4	01.9	01.9	14.3	04.6	05.0	00.4	—	—	06.1
	8-9	53.8	01.2	03.4	03.4	02.5	01.2	03.7	12.5	03.1	03.7	00.9	00.3	—	09.9
	10-11	47.8	01.3	02.5	05.1	01.3	01.7	08.5	14.4	02.5	07.6	—	00.4	—	06.8
	12-13	54.3	00.5	01.4	03.7	02.8	01.8	06.3	12.6	02.8	06.2	—	—	—	07.7
	14-15	50.3	01.1	01.8	01.8	02.5	03.3	04.0	10.5	03.6	07.3	00.7	—	—	12.7
	16-17	63.9	—	00.2	01.5	02.6	01.5	01.7	12.4	01.0	07.7	—	—	—	07.2
	18-19	71.1	—	00.2	01.1	02.1	01.5	02.0	08.8	02.8	07.5	—	—	—	02.6
5	20-21	76.8	—	00.4	00.9	01.8	00.4	01.6	09.0	00.4	05.0	—	—	—	03.2
	22-23	67.7	—	—	02.0	01.5	00.5	01.0	13.6	02.8	06.8	—	—	—	04.0
	24-25	59.0	—	—	01.2	03.8	00.4	00.8	15.6	02.1	11.0	—	—	—	05.8
	26-27	59.2	—	—	—	04.8	—	—	21.3	01.9	03.8	—	—	—	08.6
10	$\bar{x}$	57.6	01.0	01.9	02.0	02.4	01.3	02.6	13.3	02.8	06.6	00.4	00.1	—	07.7

^aGenerally, a minimum of 350 radiolarians were counted in each sample. Mean of the sum of identified species = 92.3**Table 3** Radiolarian species relative abundance (%) for Core 23357-2

Age (× 1000 yr)	Sub-bottom depth (cm)	<i>Amphimelissa</i> <i>setosa</i> (Cleve)	<i>Ariobolus</i> <i>borealis</i> (Cleve)	<i>Ariobolus</i> <i>annulatus</i> (Bailey)	<i>Ariobolus</i> <i>seni</i> (Petrushevskaya)	<i>Cycladophora</i> <i>davisiana</i> (Ehrenberg)	<i>Lithomelissa</i> <i>setosa</i> (Jorgensen)	<i>Lithomitra</i> <i>lineata</i> (Ehrenberg)	<i>Lithomitra</i> <i>platyccephala</i> (?) (Ehrenberg)	<i>Pseudodictyophimus</i> <i>gracilipes</i> (Bailey)	<i>Cromyechinus</i> <i>borealis</i> (Cleve) (4 shells)	<i>Phorticum</i> <i>clevei</i> (Jorgensen)	<i>Spongostochus gla-</i> <i>cialis</i> (Popolsky)	<i>Stylocytha</i> <i>validispina</i> (Jorgensen)	Radiolarians not identified
2.5	0-1	39.3	06.9	00.6	03.4	02.3	01.1	02.9	15.0	05.8	05.2	00.6	—	00.6	16.7
	1-2	35.7	07.5	00.4	02.5	02.1	01.7	06.7	24.7	03.7	01.7	—	—	—	13.0
	2-3	39.4	04.6	00.4	02.7	01.1	01.9	03.4	20.7	09.9	05.0	—	—	00.4	09.9
	3-4	33.3	06.8	01.7	03.4	04.2	01.3	06.4	25.2	04.7	03.4	—	—	—	09.3
	4-5	38.8	08.9	00.7	02.1	03.2	01.8	02.5	13.6	06.5	06.8	01.0	—	—	13.6
	5-6	33.1	09.0	00.9	02.7	01.3	02.3	04.5	21.8	08.6	04.5	00.9	—	—	09.5
	6-7	31.9	03.5	00.7	00.7	02.1	01.4	04.2	17.7	05.6	12.0	06.3	—	—	13.4
	7-8	36.0	04.7	00.9	03.2	02.9	04.2	06.4	20.3	04.7	05.9	00.5	—	00.2	09.6
	8-9	36.0	03.3	00.6	03.3	00.6	00.6	09.3	14.0	06.6	06.0	00.6	—	—	13.3
	10-11	31.7	—	—	01.5	02.3	05.4	05.4	18.6	03.9	04.6	01.5	—	00.7	22.4
5	12-13	33.3	—	01.5	03.1	02.7	03.4	05.5	15.8	06.3	14.3	00.8	—	—	08.7
	13-14	21.6	02.7	—	05.4	07.1	02.7	02.7	10.8	08.1	16.2	00.8	—	—	24.3
	14-15	17.8	—	—	03.6	03.6	—	03.5	17.8	03.6	10.7	—	—	—	39.7
	16-17	—	—	—	—	—	—	—	—	—	—	—	—	—	—
10	$\bar{x}$	30.6	04.1	00.8	02.7	02.6	02.3	04.5	16.9	05.6	06.8	01.1	—	00.5	21.0

^aGenerally, a minimum of 250 radiolarian specimens were counted in each sample. (Below 16 cm sub-bottom, radiolarians are barren.) Mean of the sum of identified species = 79.0

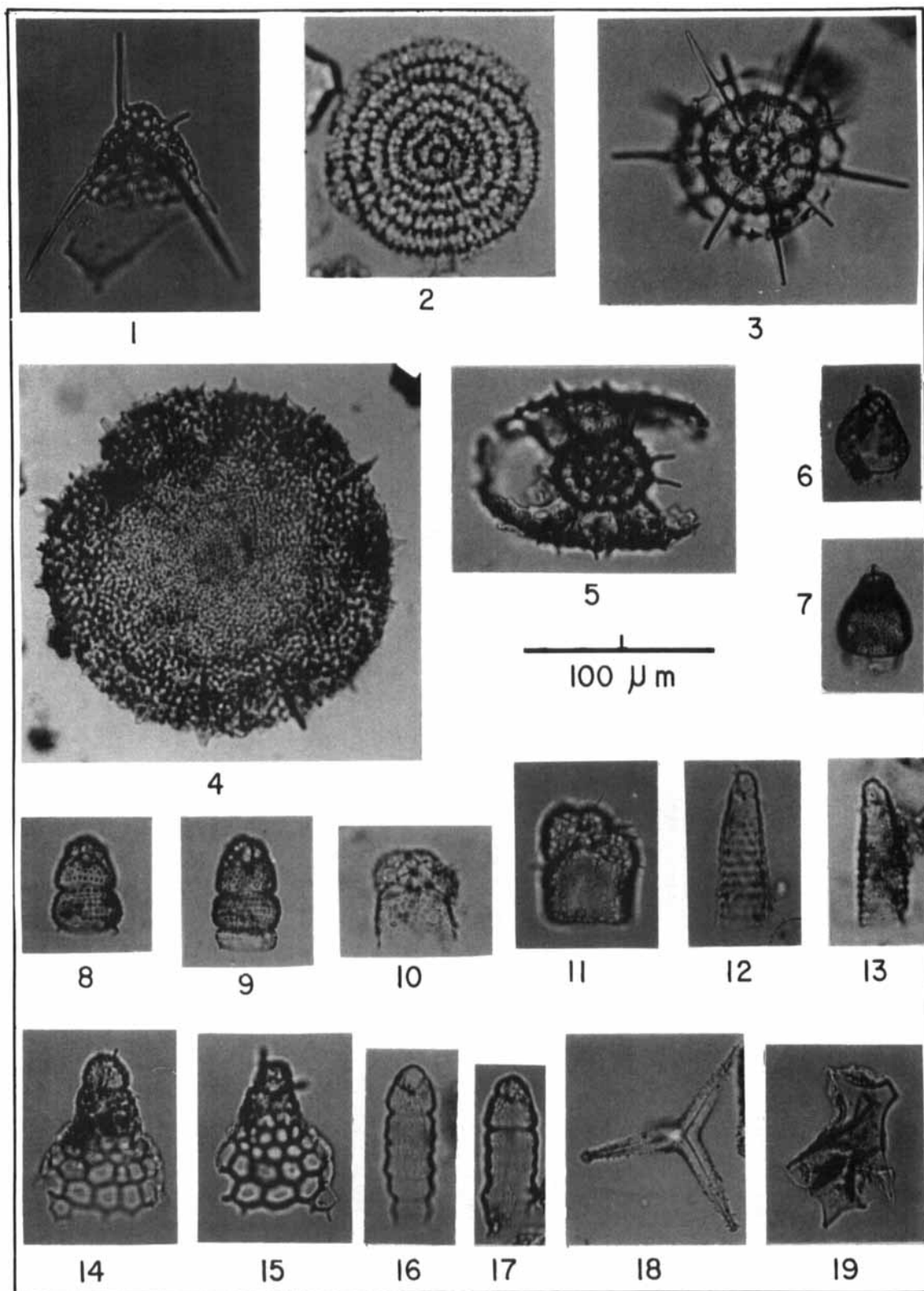


Figure 2 (1) *Pseudodictyophimus gracilipes* (Bailey); from Core 23357-2, sub-bottom depth (s.d.) 3–4 cm. (2) *Stylodictya validispina* (Jørgensen); from Core 23357-2, s.d. 6–7 cm. (3) *Cromyechinus borealis* (Cleve); from Core 23352-2, s.d. 24–25 cm. (4) *Spongotrochus glacialis* (Popofsky); from Core 23352-2, s.d. 10–11 cm. (5) *Phorticium clevei* (Jørgensen); from Core 23357-2, s.d. 5–6 cm. (6 and 7) *Artobotrys borealis* (Cleve); from Core 23357-2, s.d. 3–4 and 5–6 cm, respectively. (8 and 9) *Lithomitra platycephala* (?) (Ehrenberg); from Core 23357-2, s.d. 3–4 and 5–6 cm, respectively. (10) *Amphimelissa setosa* (Cleve); from Core 23352-2, s.d. 10–11 cm. (11) *Amphimelissa setosa* (Cleve); from Core 23357-2, s.d. 3–4 cm. (12 and 13) *Artostrobos annulatus* (Bailey); from Core 23352-2, s.d. 8–9 and 10–11 cm, respectively. (14) *Cycladophora davisiana* (Ehrenberg); from Core 23352-2, s.d. 24–25 cm. (15) *Cycladophora davisiana* (Ehrenberg); from Core 23357-2, s.d. 5–6 cm. (16) *Lithomitra lineata* (Ehrenberg); from Core 23352-2, s.d. 12–13 cm. (17) *Lithomitra lineata* (Ehrenberg); from Core 23357-2, s.d. 3–4 cm. (18) Sponge spicule, Oxycalthrop type; from Core 23352-2, s.d. 10–11 cm. (19) Ash grain; from Core 23352-2, s.d. 25–26 cm.

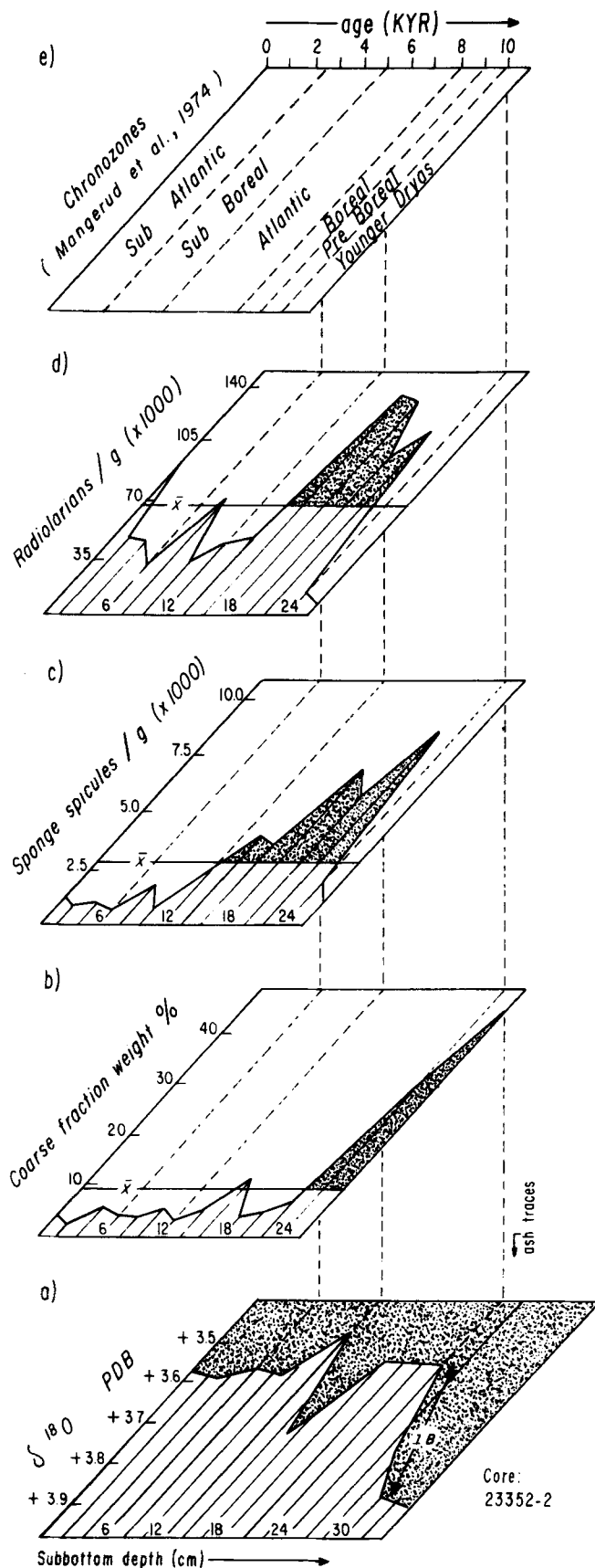


Figure 3 (a) Downcore isotopic record ($\delta^{18}\text{O}$) for Core 23352-2; (b) downcore record of the terrigenous coarse fraction ($>40\ \mu\text{m}$) weight percentage; (c and d) downcore records of the abundance of radiolarian and sponge spicules (Oxycalthrop type), respectively, expressed in terms of individuals per gram (carbonate free); (e) chronozones (Mangerud et al., 1974). Arrow 'I_B' in (a), indicates a glacial termination (Jansen and Veum, 1990). $\bar{x}$ represents the mean occurrence.

through a $40\ \mu\text{m}$ screen. The fraction remaining in the sieve (the coarse fraction) was also dried and weighed giving the weight percentage of the non-carbonate coarse fraction ($>40\ \mu\text{m}$). The values have been plotted in Figs 3–5. A split of this coarse fraction, also weighed, was used to prepare micropalaeontological slides; following the 'settling technique' developed by Moore (1973) and Molina-Cruz (1978).

After identification and counting of the radiolarians and sponge spicules contained in the slides, and knowing the sample weight employed to prepare each slide, the area of the 'settling beaker' base, and the cover slide area, it was possible to estimate the number of radiolarian specimens and sponge spicules present on a $40\ \mu\text{m}$ screen per gram of dry sediment, on a carbonate-free basis; following the Lozano

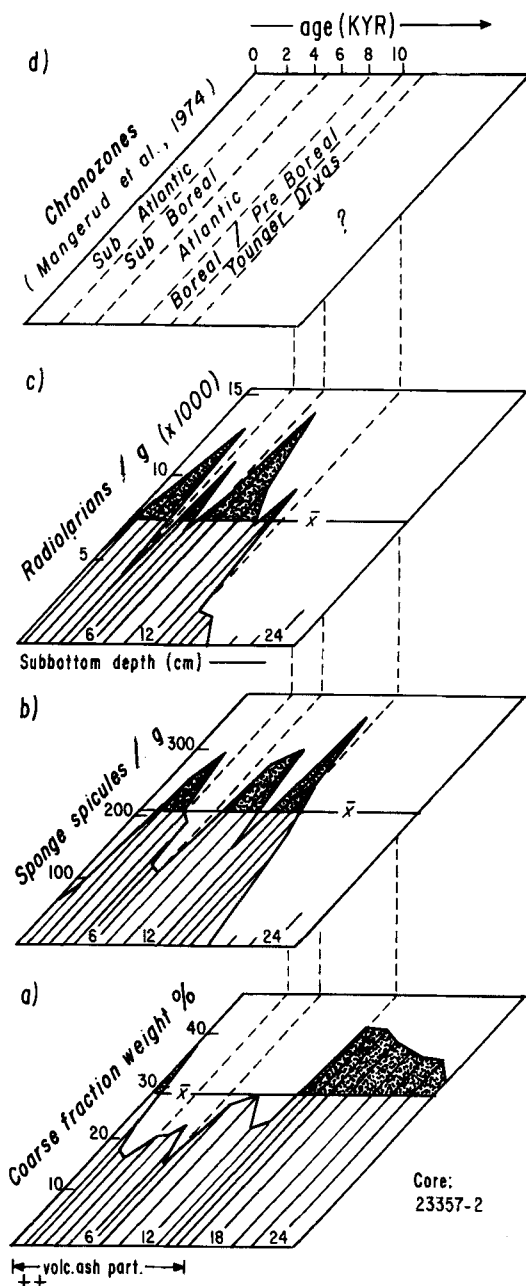


Figure 4 (a) Downcore record of the terrigenous coarse fraction ($>40\ \mu\text{m}$) weight percentage for Core 23357-2; (b and c) downcore records of the abundance of radiolarians and sponge spicules (Oxycalthrop type), respectively, expressed in terms of individuals per gram (carbonate free); (d) chronozones (Mangerud et al., 1974). $\bar{x}$ indicates the mean occurrence.

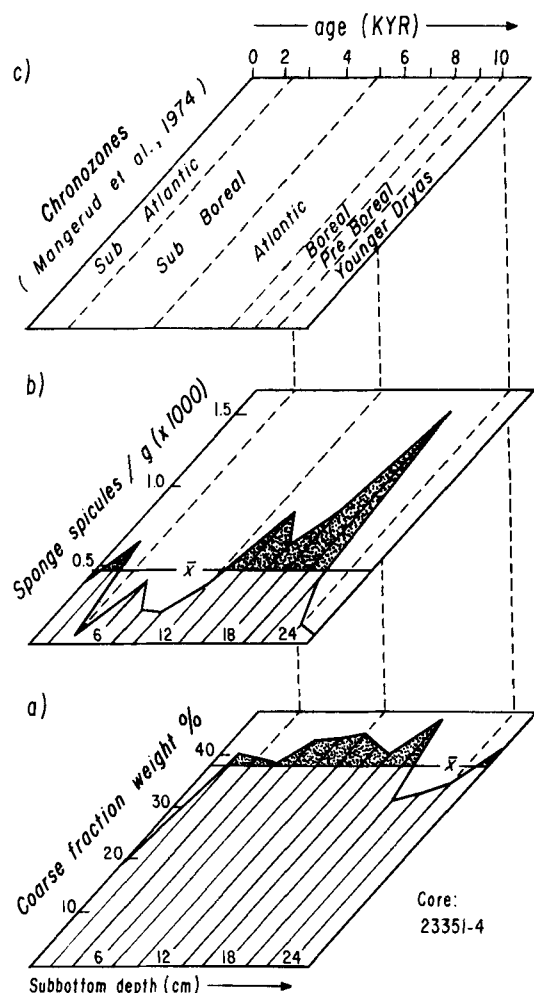


Figure 5 (a) Downcore record of the terrigenous coarse fraction ($>40\ \mu\text{m}$) weight percentage for Core 23351-4; (b) downcore record of sponge spicules (Oxycalthrop type) abundance, expressed in terms of individuals per gram (carbonate free). $\bar{x}$ indicates the mean occurrence.

and Hays (1976) procedure. These values have been plotted downcore in Figs 3–5. The relative abundance (percentage) of the identified species (Fig. 2), as well as some statistics, are shown in Tables 2 and 3, and in Fig. 6.

Results and discussion

Chronostratigraphy and correlation

Chronostratigraphic correlation based on biostratigraphy only is often considered with lack of confidence, because of the transgressive nature and/or local character that is observed by some of the micropalaeontologically recorded events. Consequently, in this study, the biostratigraphical criteria has been combined with isotopic ($\delta^{18}\text{O}$) and tephra evidence.

H. Willkomm and H. Erlenkeuser from the University of Kiel have analysed the isotopic record ($\delta^{18}\text{O}$) of core GIK 23352-2 (Fig. 3a). In this core, located in the middle of the study region (Fig. 1), it is relatively easy to identify the glacial termination: 'I_B', following the criteria indicated by Jansen and Veum (1990). According to these authors, termination 'I_B' occurred approximately between 10 400 and 10 000 years before present (BP); a little after the deposition of the 'Vedde ash layer' (Mangerud et al., 1984; Long and Morton, 1987).

Recently, Sejrup and co-workers (1989), analysing core P57-7, located near core 23352-2 (Table 1), identified the presence of an ash layer (Ash zone A) on the Iceland Plateau, which is correlated with the Vedde ash layer present in western Norway and the Norwegian Sea. They argued consequently, that these ashes represent a major volcanic event that occurred in Iceland about 10 600 years ago, and that they are related in some way to the last major deglaciation (termination 'I_B').

Analysing the micropalaeontological slides of core 23352-2, it is possible to observe the presence of ash grains (Fig. 2(19)) between 25 and 26 cm in the sub-bottom depth. This depth both coincides with that observed for ash zone 'A' in core P57-7 (Sejrup et al., 1989) and with the isotopic ($\delta^{18}\text{O}$) and lithological downcore changes that suggest deglaciation: decrease of $\delta^{18}\text{O}$ values and a large decrease of terrigenous input (Figs 3a and 3b). Thus, it is assumed that these particles represent the Younger Dryas Vedde ash layer event, dated to 10 600 yr BP by Sejrup and co-workers (1989).

Taking the age of this tephra event and the end of termination 'I_B' (10 000 yr), and assuming a constant (linear) sedimentation rate between their stratigraphic position and the present, a time-scale can be established within which the chronozones identified by Mangerud et al. (1974) can be interpolated (Fig. 3e). The downcore changes are discussed with reference to this framework.

According to this 'chronologic framework' (Figs 3a and 3e), in the Iceland Sea, siliceous microfossils become common at the end of termination 'I_B'. Later, at approximately 5000 yr BP, there is a large fluctuation showing a radiolarian and sponge spicule abundance decrease in the record with a minimum at approximately 2500 yr BP. The 5000 yr age for the low abundance radiolarian event age is practically in phase with the Atlantic–Subboreal chronozone boundary (Mangerud et al., 1974; Jansen and Björklund, 1985); around which the diatom productivity and estimated sea-surface palaeotemperature in the Iceland Sea also commenced to decrease (Kok-Karpuz and Schrader, 1990). The peak minimum in radiolarian abundance will be discussed later.

In core 23357-2 (Fig. 4) it was not possible to define the Vedde ash layer datum, because ash grains are common in the upper 16 cm; particularly in the topmost 4 cm. This core is located close to the volcanic island Jan Mayen (Fig. 1) and it is possible that the 'Vedde ash layer event' has been diluted by local events or even did not reach this area. Nevertheless, it is observed that ash particles become more common up core, at the same interval in which the terrigenous (coarse fraction) input decreases and the microfossils appear and rapidly increase in abundance (Fig. 4); as in core 23352-2. The radiolarian and sponge spicules events can be correlated with core 23352-2 up to the 2500 yr BP horizon (Figs 3d and 4c). Above the 2500 yr BP datum a further stratigraphic correlation between the cores is difficult since the radiolarian abundance record of each core becomes somewhat different. It is not clear if the tops of some of the cores are missing, but the interval that represents approximately the last 5000 yr, i.e. the Subboreal and Sub Atlantic chronozones, is shorter in core 23357-2 than in core 23352-2 (compare Figs 3 and 4), and the deposition of a volcanic ash, probably produced in the Jan Mayen Island, has perturbed the biopelagic content of the upper part of core 23357-2.

Core 23351-4 is located at the rise of the continental margin of Greenland (Fig. 1) and consequently receives more ice-rafted terrigenous input than the other cores (compare values in Figs 3b, 4a and 5a). In spite of this, with the exception of the core top, its coarse fraction record does not depict a major drop. Only a slight decrease is observed in the interval

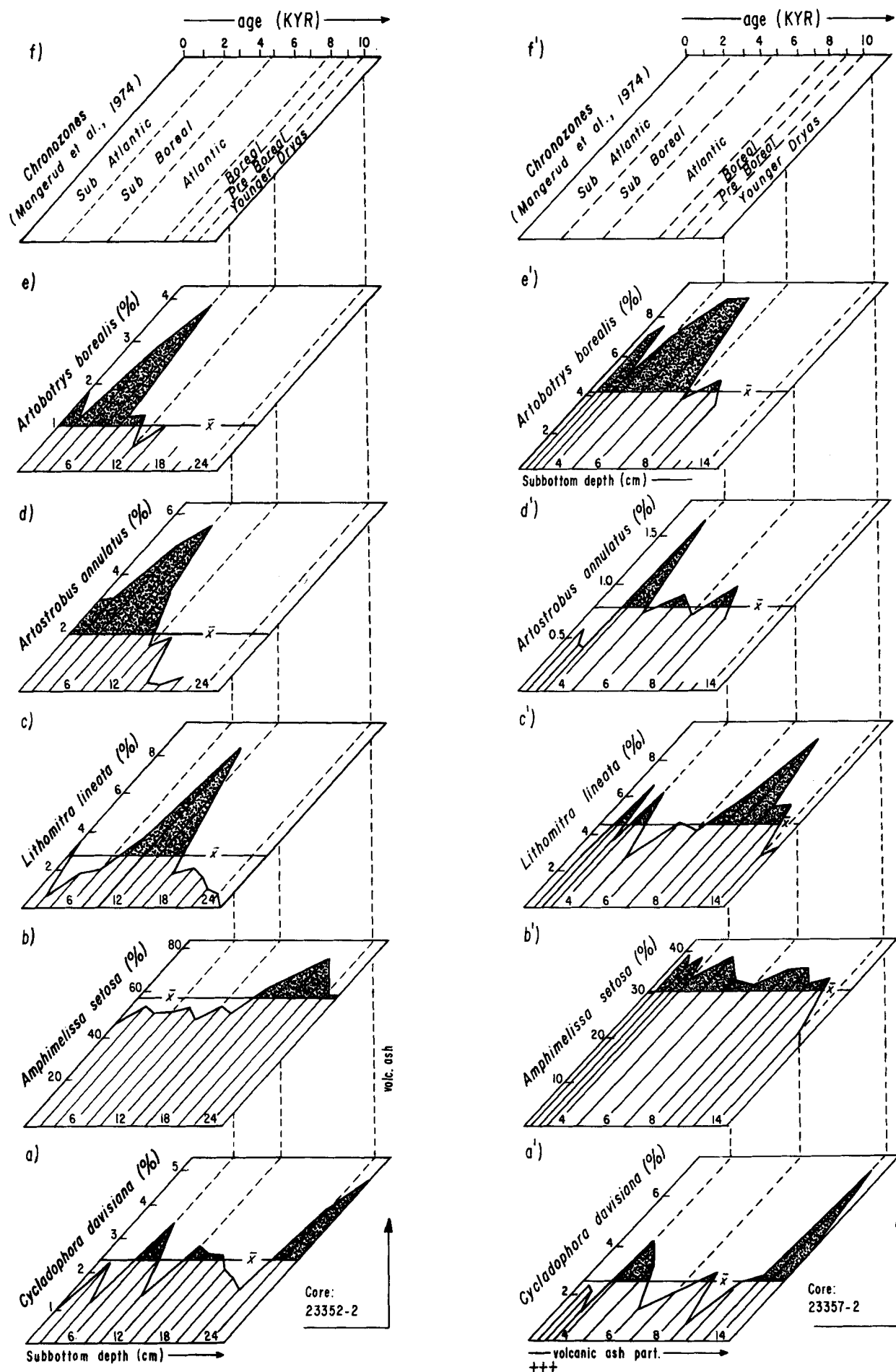


Figure 6 Downcore records of radiolarian species relative abundance, expressed in percentages. (a-e) For Core 23352-2; (a'-e') for Core 23357-2. $\bar{x}$ indicates the mean occurrence.

20–24 cm. This core also lacks a recognisable ash layer and is barren of radiolarians.

Even though the planktonic siliceous microfossils ($> 40 \mu\text{m}$) are almost absent in core 23351-4 (some diatoms occur (rarely) in the interval 20–24 cm, and in the topmost 4 cm) it is possible to find sponge spicules belonging to the *Amphiox* and *Oxycalthrop* type (Locker and Martini, 1985). The *Amphiox* type spicules are by far more abundant than the *Oxycalthrop* type (Fig. 2(18)). However, because there was less doubt in the identification of the latter type, and because they are found consistently down the core (Figs 3c, 4b and 5b), only these are considered in this study. Because of the higher terrigenous input, it may be that core 23351-4 has experienced a higher sedimentation rate than the other cores; however, because the sponge spicule record is similar to those of the other cores (compare pertinent records in Figs 3–5), a tentative 'chronostratigraphic correlation' has been assumed (Fig. 5c).

Calculation of absolute abundances for different variables within the same mathematical process makes the records mutually dependent (Kellogg, 1984). Therefore, this fact must be considered to explain, at least in part, why the radiolarian record and the sponge spicules record trend similarly; i.e. both showing 'high' abundance during the Boreal and Atlantic chronozones and 'low' during the Subboreal and Sub Atlantic chronozones. In spite of this similarity, it is observed that the highest peak of the sponge spicules abundance occurs before the radiolarian peak (see Figs 3c versus 3d and 4b versus 4c).

It is difficult, at this point, to determine if the sponge spicules record is principally influenced by changes, through time, of sponge production or by a dissolution process. Nevertheless, since the sponge-spicules record shows similar trends in several localities of the Iceland Sea (compare Figs 3c, 4b and 5b), and if it is assumed that bottom waters extend regionally, then they are presumed to influence preservation potential of the spicules. If this is true, the stratigraphic record is then a promising tool to study the evolution of bottom-water formation; which commenced in the Nordic Seas about 11 000 yr BP (Jansen, 1987; Jansen and Veum, 1990), within the Younger Dryas event. The first occurrence of sponge spicules is approximately at this time and is more or less concurrent with the drop in input of coarse terrigenous material (see pertinent records in Figs 3–5).

Iceland Sea post-glacial radiolarians

The taxonomical and ecological aspects of the radiolarians inhabiting the Nordic Seas, have been studied recently by Petrushevskaya and Björklund (1974), Björklund (1976), Goll and Björklund (1985), and Björklund and Swanberg (1987). These studies form the basis of the taxonomic framework used here. This framework considers the more abundant species in the Iceland Plateau sediments during the Holocene (Tables 2 and 3 and Fig. 2).

Amphimelissa setosa (Cleve) and *Lithomitra platycephala* (?) (Ehrenberg) are by far the more abundant species in cores 23352-2 and 23357-2, while *Stylodictia validispina* (Jorgensen) is present only in core 23357-2. Because the identification of *Echinomma leptodermum* (Jorgensen) is not consistent, its relative abundance has been included within the unidentified species.

Downcore variations of relative abundance for all the species contained in the Tables 2 and 3 were recorded. However, in this study only species that are believed to be sensitive environmental indicators of Holocene palaeo-

oceanographic events are shown (Fig. 6). The chronostratigraphy described above is used in Fig. 6(f and f'), and the radiolarian records of core 23357-2 have been adjusted accordingly.

During the Younger Dryas event (the Vedde ash is positioned within this chronozone; Mangerud *et al.*, 1984), *Cycladophora davisiana* (Ehrenberg), *A. setosa* (Cleve) and *Lithomitra lineata* (Ehrenberg) were present in the Iceland Sea (Fig. 6). However, only *C. davisiana* is present in significant numbers.

Cycladophora davisiana is a species that commonly lives in the subsurface of relative cool water masses (Morley, 1983; Morley and Hays, 1983). It has been studied particularly because its abundance corresponded with palaeoclimatic records of $\delta^{18}\text{O}$ isotope maxima (Morley, 1980) and it is found most commonly around the glaciation climax suggested by the oxygen isotopic record (Hays *et al.*, 1976; Lozano and Hays, 1976; Molina-Cruz, 1988).

These peaks may represent *C. davisiana* blooms resulting from a decrease in temperature and/or salinity, or they may represent a reduction in abundance of the other species, enhancing the relative flux of *C. davisiana*, or some other factor. Further knowledge is required of the radiolarian ecology and the real flux of each species into the sea-floor sediments. The results in this study favour the second proposition; since the *C. davisiana* peaks correspond with relative low values of radiolaria per gram (compare Figs 6a and 6a' with Figs 3d and 4c respectively). Thus, it is suggested that environmental conditions during climatic cooling are tolerated more by *C. davisiana* than by the other species. This may be partly because its habitat is generally deeper than 200 m (Morley and Hays, 1983) and therefore less exposed to drastic changes in temperature and salinity.

Thus, during the Younger Dryas the *C. davisiana* peak signals a cooling of the Iceland Sea water surface. This was, however, free of a permanent ice-cover since, although cooler, radiolarians were present and the proportion of ice-raft sediments decreased steadily (Figs 3d and 3b).

Above the *C. davisiana* peak, at the end of the Younger Dryas, once the adverse conditions for the development of 'surface species' ended, the radiolarian productivity increased considerably in the Iceland Sea (Figs 3d and 4c); remaining high until approximately 5000 yr BP (approximately the Atlantic–Subboreal boundary).

At present, according to Goll and Björklund (1985), the greatest radiolarian abundance in Iceland Sea sediments is below the area where the Icelandic and Irminger Currents mix (Fig. 1). Thus, if this oceanographic feature was stronger and/or shifted north of its present location in the Early Holocene, this would explain the higher radiolarian abundance in the northern Iceland Sea at that time. Kellogg's results (1984) suggest a strong Irminger Current in the Early Holocene.

Amphimelissa setosa (Cleve) is the dominant species in the high radiolarian abundance zone (up to 90% relative abundance; Jansen and Björklund, 1985; Björklund and Swanberg, 1987). Core 23352-2 is located just north of this zone (Fig. 1), and shows a high *A. setosa* abundance (average 60%) in the Early Holocene, paralleling the record of the total radiolarian abundance (compare Figs 3d and 6b).

The ecological–oceanographic changes, which encouraged the increase in abundance of radiolarians and particularly of *A. setosa*, during the Preboreal, Boreal and Atlantic chronozones, also encouraged sponges to flourish. The spicules and radiolarian record correspond (compare Figs 3c and 3d). It is interesting to note that similar changes occurred in the northeastern North Sea during the Younger Dryas event at approximately 10 300 yr BP (Björklund, 1985). Mixing

conditions, similar to those observed in the Iceland Gap Front (Johannsen, 1986) at present (Fig. 1), may have occurred in the North Sea, but further work will be required to answer this question.

Amphimelissa setosa is also abundant in core 23357-2 (on average 30%); however its record (Fig. 6a') only feebly defines the highest peak of total radiolarian abundance (Fig. 4c). The peak reflects the relative abundance curve of other species; particularly *Lithomitra lineata* (Ehrenberg), *Lithomelissa setosa* (Jørgensen) and *Artostrobos joergenseni* (Petrushevskaya) (only the record of *L. lineata* is shown in Fig. 6). The biogeography of these species is not yet well defined. However, observing that the occurrence of *L. lineata* is relatively abundant in sediments below transitional zones of water masses (Petrushevskaya and Björklund, 1974), it is assumed that they occur mostly in the mixed water that defines the Arctic Front (Hurdle, 1986; see oceanographic setting and Fig. 1). The data from this study support this assumption, since these species are more abundant in the core closest to the Arctic Front (core 23357-2) (compare mathematical means in Tables 2 and 3).

It is suggested therefore that during the period of high radiolarian accumulation (Preboreal, Boreal and Atlantic chronozones), the Arctic Front was already present near to the east of the Jan Mayen Island. It was probably not developed in the eastern Iceland Sea, because the influx of the Irminger Current increased mixing between the North Atlantic water and the Arctic water, thus diluting the Arctic Front, or pushing it towards the northeast (Fig. 1). Note that the Arctic Front is formed by mixing Polar Water and Atlantic Water (see the oceanographic setting).

Around 5000 yr BP (more or less concurrent with the Atlantic-Subboreal boundary), the radiolarian abundance decreased drastically to present-day values (Figs 3d and 4c). This suggests a reduction in the mixing between the Irminger Current (Atlantic Water) and Arctic Water. At this time, the East Greenland-Icelandic Current system probably became well developed, causing in turn, greater input of Polar Water to the Iceland Sea and consequently, the onset of the Arctic Front in the eastern Iceland Sea. Such oceanographic changes, particularly the presence of the Arctic Front in the Iceland Sea, is indicated by highest peaks of *L. lineata*, *L. setosa* and *A. joergenseni*, which shifted time transgressively from the northeast (core 23357-2) to the southwest (core 23352-2) (Fig. 6c and 6c'). Concurrent with the formation of the Arctic Front in the eastern Iceland Sea, *Artobotrysts borealis* (Cleve) and *Artostrobos annulatus* (Bailey) also increase in abundance (Figs 6d, 6d', 6e and 6e').

Artobotrysts borealis is a boreal cold species, which shows greatest abundance under oceanic fronts (Petrushevskaya and Björklund, 1974). Thus, its increase in abundance at the Subboreal chronozone (Figs 6e and 6e'), suggests a higher input of Polar Water to the Iceland Sea at that time, extending the East Icelandic Current with the formation of the Arctic Front in the eastern Iceland Sea. During this time also, *Phortidium clevei* (Jørgensen) and *Spongotrochus glacialis* (Popofsky) were more evident (Tables 2 and 3).

At approximately 2500 yr BP Subboreal conditions were best developed and this is supported by the high relative abundance of *A. borealis* and *A. annulatus*, and by a slight peak in the record of the cold species *C. davisiana* (Fig. 6). Immediately following this, within the Sub Atlantic chronozone, there was a rapid and 'dramatic' drop in the relative abundance of these species (Figs 6d, 6d', 6e and 6e'). This coincides with a rise in microfossil accumulation (best seen in core 23357-2; Figs 3–5), and with the return of higher numbers of *L. lineata* from core 23352-2 to core

23357-2 (Figs 6c and 6c'). Additionally at this time, *Stylodictya validispina* (Jørgensen), which has been reported in Norwegian Sea sediments (Björklund, 1976) and which was absent in core 23357-2 during the Subboreal chronozone, reappears (Table 3). All these environmental features suggest that the input of the Atlantic Water to the Iceland Sea increased again, probably via the Norwegian Current, but in lower proportions than during the Preboreal, Boreal and Atlantic chronozones, as indicated by the radiolarian abundance levels (Figs 3d and 4c).

Conclusions

Whether the chronology and stratigraphic correlation adopted in this study are accepted or not, it is evident that the Radiolaria and sponge (spicules) population expanded on the Iceland Plateau at the end of the Younger Dryas. The trend is repeated in several localities, and suggests at least three palaeosedimentary events: (i) a large increase in opal accumulation shortly after the isotopic termination 'I_g' (ca. 10000 yr BP); (ii) a significant drop in this accumulation about the middle of the Holocene (ca. 5000 yr BP); and (iii) the establishment of present conditions at about 2500 yr BP.

The Iceland Sea was free of ice-cover, at least seasonally, during the Younger Dryas. Under this climatic regime, some Holocene radiolarian and sponge species made their first appearance, albeit in low absolute abundances. At this time, the *Cycladophora davisiana* stratigraphic record shows a peak, which suggests a sea-surface temperature colder than at present. Immediately following this, siliceous microfossil deposition, represented largely by the abundance of *Amphimelissa setosa*, increased greatly as a consequence of increased mixing between Atlantic Water and Arctic Water. Similar oceanographic conditions remained for almost 5000 yr, reaching a maximum near the boundary between the Atlantic and Subboreal chronozones. Shortly after this, the radiolarian and sponge spicule (Oxycalthrop type) population decreased in absolute abundance concurrently with the increased development of the East Greenland-Icelandic Current and the formation of the Arctic Front within the eastern Iceland Sea. These cooler conditions were characteristic of the Subboreal chronozone and encouraged the expansion of several radiolarian species in the Iceland Sea, particularly *Lithomitra lineata* and *Artobotrysts borealis*. During the Sub Atlantic chronozone, the siliceous microfossil abundance increased again, probably because of an increased input of Atlantic Water, although apparently in lower volumes than during the first half of the Holocene.

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