

Radiolarians in the Nordic Seas and Arctic Ocean: Distribution, abundance, preparation and taxonomy

Radiolaria: Definition

Radiolaria are single-celled marine eukaryotes, also some colonial forms, existing from the Cambrian (ca. 530 million years) to Recent. Thus, radiolarians are one of the longest ranging groups of fossil microorganisms. The founders of radiolarian taxonomy were two German scientists, C.G. Ehrenberg (1795-1876) and E. Haeckel (1834-1919). Ehrenberg described more than 70 genera and 500 species, while Haeckel contributed more than 700 genera and 4,000 species. Haeckel's (1887) system is the basis of some modern taxonomic systems. One proposed by Riedel (1967) is the most commonly used: kingdom Protista, phylum Sarcomastigophora, subphylum Sarcodina, class Actinopoda, subclass Radiolaria, superorder Polycystina, and orders Spumellaria (SiO_2)/Nassellaria (SiO_2)/Phaeodaria ($\text{SiO}_2 + \text{organic compound}$). In this scheme, Acantharia (SrSO_4) and Heliozoa (SiO_2) also are assigned to the class Actinopoda but in separate subclasses. This system is mainly based on skeletal material and general morphology, as well as internal cellular structures. New phylogenomic studies show that this Haeckelian system is artificial (not representing evolutionary relationships) and new systems based on molecular genetic data establish more natural relationships among the six supergroups of eukaryotes as proposed by Cavalier-Smith (2002, 2003). The first description of living colonial forms, such as *Sphaerozoum fuscum*, was made by Meyen (1834). Since then we have recorded about 2,500 high rank taxa (genera/subgenera) and 15,000 species, of which 800 to 1,000 are currently living in the oceans (Suzuki and Aita, 2011).

Taxonomic Position of Radiolaria

Today, molecular work on radiolarians is an active field of research, and the taxonomical scheme is constantly adjusted as new data are made available. Cavalier-Smith (2003) suggested the following system: kingdom Protozoa, subkingdom Biciliata, phylum Retaria, and subphylum Radiozoa, with classes Acantharea, Polycystinea, and Sticholonchea, a system that has not stabilized and is under development. The Phaeodaria are no longer included in the general category of "Radiolaria" (previously in the phylum Retaria), but placed in phylum Cercozoa. The Radiolaria 18S rDNA phylogeny trees presented in recent publications are rather similar to each other and suggest a polyphyletic status for the polycystines but are limited by using only the 18S gene. By contrast, Krabberød et al. (2011), using both 18S and 28S rDNA, show that Spumellaria group with Nassellaria, thus suggesting they form a

natural phylogenetic group (Figure 1).

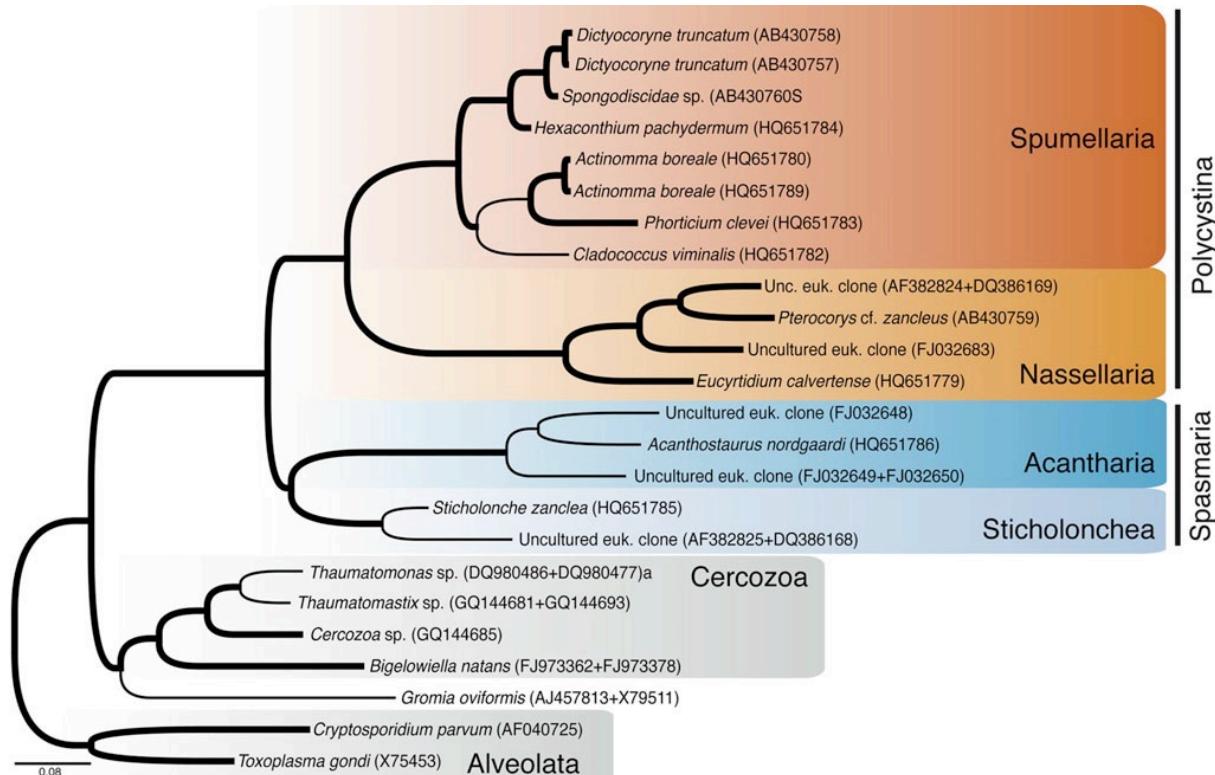


Figure 1. A phylogenetic tree of Radiolaria using the 18S and 28S rDNA genes. Thick branches are well supported with maximum likelihood bootstrap value higher than 95 and Bayesian posterior probability higher than 0.95 (modified from Krabberød et al. 2011).

Their data provide a more convincing monophyletic status for the polycystines (Spumellaria together with Nassellaria), as well as a close relation between Acantharea and Sticholonchea, a group given the name Spasmobia (Cavalier-Smith, 1993). In contrast, when only 18S rDNA is used, Acantharea branch with Spumellaria. These results show that combining the 18S and 28S rDNA genes may greatly improve the resolution of the radiolarian phylogeny. For those being curious about the development of radiolarian taxonomy based on DNA studies, visit also Suzuki and Aita (2011); Suzuki and Not (20??). [More about taxonomy below.](#)

Description of purpose of this GBIF-entry.

On the basis of sediment samples recovered on the *Meteor* Expedition in the South Atlantic, Pratje (1951) found the abundance of radiolarians to range from zero to 5% **sediment weight** in the region between 5° and 60° S. He found the abundance to be essentially in accord with that of diatoms and sponge spicules, and concluded that a direct relationship exists between the biomass of the water column and the concentration of biogenous opal in the underlying sediments. The surface samples from selected gravity cores, essentially from the Lamont-Doherty Earth Observatory (Columbia University, New York), was used to present **three geographical data sets as outlined by** Goll and Bjørklund (1971, North Atlantic; 1974, South Atlantic), and Bjørklund et al. (1998, Nordic Seas). To collect marine deep sea sediments are now very expensive and surface sediment samples from gravity or trigger weight core tops are not easily available. Therefore, the intention with this contribution is to present my

quantitative distribution data of radiolarian skeletons in the Atlantic sector of the World Ocean, from the Antarctic continent in the south to the Arctic Ocean in the north. The gross distribution as presented herein do provide three data sets of detailed information of the number of *radiolarian skeletons/g dried sediment*, from the three regions mentioned above. These numbers define zoogeographical radiolarian provinces which essentially are in harmony with oceanographic fronts, submarine bathymetry and do also reflect ecological provinces and borders.

I have studied radiolarians in high northern latitudes since 1969 and my results of the radiolarian distribution in surface sediment samples are summarized herein (<http://nhm2.uio.no/radiolaria/>). Essentially three areas of study will be encountered herein:

- 1) The north Atlantic (333 samples (Red stations on map “[View North Atlantic Ocean](#)”) used in Goll and Bjørklund, 1971).
- 2) The south Atlantic (456 samples (**Yellow** stations on map “[View South Atlantic Ocean](#)”) used in Goll and Bjørklund, 1974).
- 3) The Nordic Seas and Arctic Ocean (479 samples (**Blue** stations no fauna lists, **Green** stations with fauna lists, in “[View Norwegian Sea and Arctic Ocean](#)”) used in Cortese et al., 2003, and Bjørklund and Kruglikova, 2003).

The cores in the papers by Goll and Bjørklund, 1971; 1974) only show the coordinates and water depth in addition to the actual number of radiolarians/g dried sediment counted and calculated. These data might be of interest for the general radiolarian student in the first attempt to locate an area where radiolarians are abundant in the sediments, and/or where they are rare/absent. As large areas in both the North and South Atlantic Ocean have areas where opal preservation is poor, the abundance numbers from the North and South Atlantic may give a good hint to areas where radiolarian numbers are high. This might be a good guideline when requesting material for radiolarian studies from the different core libraries providing sediment samples.

The cores used in the Bjørklund and Kruglikova (2003) study, and the way they are presented herein, is unique. All stations appearing in **green** indicate that these stations have information on the total number of species counted and the relative percent value for each species. Species information is further linked to www.Radiolaria.org, for description and picture support.

SAMPLE PREPARATION:

It is essential to know the procedure how the radiolarians have been separated from the total sediment. I therefore chose to present a discussion of the different methods commonly used. As a start we can say that the best way to get optimal results is to work on new core material, meaning that the core has not been opened and dried out in the core library/archive.

Method by Goll and Bjørklund (1971): NORTH ATLANTIC

All samples are surface sediment samples (topmost 1-2 cm of gravity cores or Trigger Weight cores), representing the accumulation of radiolarians for the last two or three decades. Only at a few places have the tops of piston core samples been used (where gravity cores were missing). All these samples have been taken from the Lamont-Doherty Earth Observatory's core library. The cores have all been opened and therefore the sediment was dry.

Goll and Bjørklund (1971) decided to estimate the number of individual radiolarian specimens in standard radiolarian preparations from 333 sediment samples from the North Atlantic (“[View North Atlantic Ocean](#)”). The sample preparation techniques used by us were those employed by Riedel (1959) with the exception that the bulk samples were dried and weighed before disaggregation. The sieve used in the preparation of all of our samples (mesh number 325 with 44µm openings) is finer than those used by most other radiolarian specialists (normally 63 µm), and retains many small specimens that would be lost on coarser sieves. Tests indicate that only small and broken fragments of radiolarians are lost through the 325-mesh sieve.

After the prepared residue had been thoroughly suspended in 30 ml of water, a one-tenth aliquot was extracted with a pipette and transferred to a standard microscope slide. The total number of radiolarians in the aliquot was estimated by the expedient of counting random fields. All observed radiolarian skeletons, whether complete or fragmentary, were counted in order to minimize subjectivity. Therefore, repeated counts of separate aliquots of the same residue yielded a variance of approximately 5%. This figure is regarded as insignificant compared with the systematic errors inherent in this double approximation technique. Our analyses give values for abundance in terms of the number of radiolarian specimens larger than 44 µm per gram of dried bulk sediment. Petrushevskaya (1967, text-fig. 6) used similar abundance terminology to describe Antarctic sediments. We conclude that our values probably are within 10% of the true abundance of radiolarians. This level of accuracy is sufficient for our purposes of comparing large-scale changes in radiolarian abundances over vast distances across the sea floor.

Method by Goll and Bjørklund (1974): SOUTH ATLANTIC

All samples are surface sediment samples (topmost 1-2 cm of gravity cores or Trigger Weight cores), representing the accumulation of radiolarians for the last two or three decades. Only at a few places have the tops of piston core samples been used (where gravity cores were missing). All these samples have been taken from the Lamont-Doherty Earth Observatory's core library. The cores have all been opened and therefore the sediment was dry.

As in our previous investigation, we have produced counts of the frequency of radiolarian skeletons retained on a #325 sieve (44-micron mesh openings) per gram of dry bulk sediment also for the South Atlantic (“[View South Atlantic Ocean](#)”). Both whole specimens and broken fragments have been counted in order to reduce the subjectivity of these values. However, the technique for estimating these values has undergone certain revisions since the previous publication of Goll and Bjørklund (1971), and it is advisable to provide a detailed explanation

of the entire process. Samples volumes were approximately two centimeters thick (taken from a quarter of the core), ranging in weight from 2.1 to 15.6 grams. The samples were cut from as close to the top of the core as possible, always from the upper ten centimeters of 456 gravity and piston cores, and a smear slide was made from each bulk sample. Each of the samples was placed in an aluminum weighing tray, dried at 90°C. for 24 hours, allowed to cool in a desiccator and weighed. The samples were transferred to beakers containing 7-8% hydrogen peroxide and allowed to react at room temperature for 24 hours in order to prevent excessive effervescence. Each sample was then ultrasonically vibrated for fifteen seconds with a probe type Artek Sonic 300 Dismembrator, washed on a #325 mesh sieve, treated with hydrochloric acid, and sieved again. This concluded the cleaning process for all but the most recalcitrant clay samples, which required a repetition of the peroxide beakers containing 7-8% hydrogen peroxide and allowed to react at room temperature for 24 hours in order to prevent excessive effervescence. Each sample was then ultrasonically vibrated for fifteen seconds with a probe type Artek Sonic 300 Dismembrator, washed on a #325 mesh sieve, treated with hydrochloric acid, and sieved again. This concluded the cleaning process for all but the most recalcitrant clay samples, which required a repetition of the peroxide-ultrasonic vibration treatment once more.

Radiolarian counts were based on slides made of one five-hundredth aliquots of the washed residues. These aliquot slides were made by filling each beaker with 100 ml. of water, ultrasonically vibrating the beaker until a uniform suspension was obtained, and withdrawing 0.2 ml, with an MLA precision pipette. The contents of the pipette fraction were dried on a slide and mounted in Caedax. The remaining residue was allowed to settle in the beaker. A thickly strewn slide was made of this material for faunal analysis, and any remaining residue was stored in glass vials.

Because we have used a smaller initial aliquot than in our previous investigation (1/500 compared to 1/10), all radiolarians on each slide were counted. We conclude that a complete count of a smaller aliquot is more precise because a second order approximation is eliminated. In the past we had to estimate the number of specimens on the large-aliquot slides by counting random fields, which adds significant nonsystematic error. Moreover, counting errors tend to multiply on slides containing many specimens. By counting all of the specimens on more thinly strewn slides, both of these sources of error are eliminated.

The accuracy of these numbers is difficult to judge. Certainly, our values for number of specimens greater than 44 microns per gram of bulk sediment is significantly lower than the true value in untreated sediment. A variable and unmeasurable quantity of finely particulate skeletal fragments are present in many of these samples. Substantial amounts of breakage can be expected during treatment with peroxide and ultrasonic vibration. Other specimens are lost in the various transfer operations from beaker to beaker, beaker to sieve, and during pipetting. It is not now possible to measure the extent of these errors, but we have endeavored to treat all the samples uniformly.

Two tests were made to determine the precision of these frequency counts. In the first test, ten consecutive runs were made of flow-in material from core V14-62. A ten-centimeter section

of flow-in (sediment entering the bottom of the core tube after maximum penetration) was disaggregated in a weak hydrogen peroxide solution and stirred in order to assure homogeneity. The suspension was allowed to settle in a large flat pan and was dried to hardness. The resulting cake of sediment was broken into ten subsamples ranging in weight from 2.83 to 3.76 grams, and aliquot slides were prepared for each sample by the process described above. The results of this test are shown in table 1. This test indicates reasonably good precision for our technique, when radiolarians are relatively abundant sedimentary components. Lower repeatability is expected in samples with fewer radiolarians.

TABLE 1: Precision tests for Radiolaria frequency counts

Test 1. Ten consecutive runs from V14-62 flow-in

Sample number	Bulk sediment weight	Radiolaria/gram
1	2.93	72.300
2	2.83	72.700
3	3.65	50.200
4	3.04	64.800
5	3.07	60.800
6	3.74	61.700
7	3.28	57.300
8	3.30	56.300
9	3.76	55.700
10	3.65	53.400

Mean value 60.500

Standard deviation 7.100

Test 2. Sixteen core tops from a two-degree square bounded by latitudes 28 and 30° S and by longitudes 29 and 31° W

Core designation	Water depth	Radiolarla/gram
V20-219	3.092	2.720
V20-220	3.601	3.380
RC11-30	2.479	2.200
RC11-31	2.481	4.400
V22-50	3.566	1.080
V22-52	4.361	5.100
V22-56	3.734	2.700
V22-57	9.299	1.340
V22-58	3.442	4.780
V22-59	3.440	540
V22-61	3.493	1.900
V22-62	3.042	870
V22-63	2.722	1.760
V22-64	2.273	3.840
V22-67	2.361	480
V22-68	2.274	360

Mean value 2.200 Radiolaria/gram

Standard deviation 1.390

In the second test, we chose samples with low radiolarian frequencies. Here we have attempted to determine the natural frequency variability in surface sediments. Sixteen gravity core tops were used from a small square area two degrees on each side on the northern slope of the Rio Grande Rise (Table 2). The high standard deviation for this sample set indicates both poor repeatability for low frequency counts and high variability between closely spaced samples. This variability may be the result of the lack of synopticity of our samples. Sediment reworking processes remove true surface material from some sites, depending on topographic position and bottom current velocity. In other cases, the absolute surface sediment may be lost during coring. Frequency counts below 5000 radiolarians per gram of bulk sediment are recorded for regions where silica solution is very high, and local geochemical modifications in sedimentary regime may produce large variability in biogenous silica content of closely spaced samples. Yet despite these factors which may have contributed to our poor results, it seems reasonable to attribute much of the blame for this high standard deviation to low precision for frequencies below 5,000 radiolarians per gram.

Method by different authors: NORDIC-SEAS and ARCTIC OCEAN [Bjørklund et al. 1998, Dolven et al., Cortese et al. 2003, Bjørklund and Kruglikova 2003]

In the Nordic Seas all samples collected by “R/V Vema” was fresh (wet) trigger weight core tops. Almost all other cores were from older dry collections. The preparation technique used was essentially as described in Goll and Bjørklund (1974) and outlined above.

Which preparation technique is the best?

There has been a discussion about the accuracy of different counting techniques. During the CLIMAP program Ted C. Moore, Jr. (Moore, 1973) described a new quantitative slide making method. His abstract is as follows:

A technique has been devised by which fine, hydrodynamically heterogenous grains may be mounted on a microscope slide in such a way that their distribution on the slide is random. The grains are settled from a well-mixed suspension onto the microscope slide where they are held in place by a thin film of gelatin. This technique allows the investigator to use any part of the slide as a representative subsample, and obviates the need for repeated splitting of samples and the counting of a very large number of grains.

Moore’s technique is from a theoretical point of view probably more accurate than the Goll and Bjørklund (1974) technique, but it is quite more time consuming and the accuracy gained is probably not of any practical significance. If the samples are poor in opal microfossil remains the Goll and Bjørklund (1974) method will decant most of the radiolarians, but the Moore (1973) technique will get a more correct number of the radiolarian number, but most

of the settled particles on the slide will be sand, and you will have to count a high number of slides to get a reliable number for statistical purposes.

Abundance numbers such as radiolaria/g dry sediment or radiolaria/g CaCO₃ free sediment is of general interest to map the general occurrence, both in the recent surface sediments as well as down core (through time). Therefore it is of interest to learn to know is the area barren for opal microfossils or in which concentrations do they occur? Goll and Bjørklund used four categories: 1) Barren; 2) 0-1,000 radiolaria/g; 3) 1,000-10,000 radiolaria/g and 4) >10,000 radiolaria/g. These four categories depict major oceanographic areas or boundaries defining different ecological or oceanographic conditions. To use a tedious and more accurate counting technique would probably not have improved our basic purpose, to map the general radiolarian distribution in the Atlantic Ocean's surface sediments.

Abelmann (1988) found it tedious and time consuming and reported: "Freeze-drying clayey sediment samples prior to their disaggregation, rather than oven-drying, has been found effective in reducing the number of steps in the preparation process." This technique definitely speeds up the preparation time as successive drying and washing steps are avoided.

Itaki and Hasegawa (2000) arrived at the same conclusion but pointed out a new aspect with the preparation technique used and the end product, how many radiolarians are recovered, or said differently, how many radiolarians are destroyed during the sample preparation? Itaki and Hasegawa (2000) pointed out in their abstract: "*Radiolarian concentration and faunal composition are compared between pairs of dried and wet sub-samples from 24 samples in sediment cores from the Japan Sea, in order to evaluate the alteration of radiolarian assemblages during the sample-drying process. Radiolarian shell count is reduced by nearly half after oven drying at 50°C as well as at ambient room temperature. In contrast, the shell count is unchanged by freeze drying. The reduction in radiolarian test count is probably caused by contraction and consolidation of the sediment. The reduction in shell count is species-specific and results from the capacity of the shell to resist crushing owing to sediment contraction. Faunal composition definitely is altered by the drying process, especially in assemblages dominated by fragile species. The original faunal composition can be reconstructed from the observed faunal composition in dried material, based on the shell-strength of major species in a sample.*"

Itaki and Hasegawa (2000) pointed out "*We clarified two points regarding dried vs. non-dried samples, as follows: (1) the number of radiolarian shells decreases markedly (48% on average), and (2) the faunal composition changes due to differential robustness among species, when sediment samples are dried.*"

If these results are to be applied in our Atlantic Ocean studies the radiolarian numbers are also underestimated and should be doubled. The most important thing would be the fact that radiolarian tests are subjective to selective dissolution. The retrieved radiolarian faunal assemblages based on dry sediment samples can be strongly affected and delicate species or individuals can be strongly underrepresented or worst, totally missing.

However, at present there is nothing to do about this problem other than keep this in mind: Radiolarian numbers can be underrepresented by an average 48% and fauna composition can be underrepresented due to destruction of species with delicate shells.

RADIOLARIA DISTRIBUTION IN THE NORDIC SEAS AND ARCTIC OCEAN

Definition of area

The investigated area is located in the Atlantic sector of the world's oceans. It includes the Nordic Seas and the Arctic Ocean. See the link

<https://www.ngdc.noaa.gov/mgg/bathymetry/arctic/images/ibcaoposter.pdf> for details of bathymetry: names of oceans, basins and ridges. The Nordic Seas includes the following seas and basins:

- 1) the deep Greenland Sea, located to the west of Knipovich- and Mohn Ridges, and to the north of Greenland-Jan Mayen Ridge;
- 2) the shallow Iceland Sea is located north of Greenland Iceland ridge to the south, east of Greenland, south of Jan Mayen Fracture Zone and west of the Jan Mayen Ridge; and
- 3) the deep Norwegian Sea to the north of Iceland-Faeroe Ridge, east of Jan Mayen-, Mohn- and Knipovich Ridges, west of Norway, the Barents Sea and Svalbard. The Norwegian Sea is divided in two deep basins, Norway Basin to the south and Lofoten Basin to the north of Jan Mayen Fracture Zone.

The Arctic Ocean is defined as the deep sea area north of the American and Eurasian continental shelves. The transarctic Lomonosov Ridge separates the Arctic Ocean into a Eurasian and Amerasian part, each of them with two deep basins. The Eurasian basin is divided by the Gakkel Ridge, the Amundsen Basin to the north of the ridge, and the Nansen Basin to the south. In the Amerasian Basin the Makarov Basin is located to the south of the Lomonosov Ridge, and is separated from the Canada Basin by the Alpha-Mendeleev Ridges.

Oceanic setting: Arctic Ocean and Nordic Seas.

The waters of the central part of the Arctic Ocean are characterized by four water masses ([Aagaard et al., 1991](#); [Rudels et al., 1994](#)):

- 1) The Arctic surface water (0°C at ca. 200 m) is the most variable and heterogeneous. This is because of the latent heat of freezing and thawing; brine addition from ice freezing; freshwater addition by rivers, ice melting, and precipitation; and great variations in insolation

and energy flux as a result of sea-ice cover. The water temperature may vary over a range of 4°C and salinity from 28 to 34 psu.

(2) Warmer Atlantic water everywhere underlies Arctic surface water from a depth of about 200-900 m. As this water cools it becomes so dense that it slips below the surface layer on entering the Arctic Basin through the Fram Strait. Its temperature is about 1-3°C as it enters the basin, but it is gradually cooled, so by the time it spreads to the Beaufort Sea, where it still makes up a considerable part of the entire water mass, it has a maximum temperature of 0.5-0.6°C. The salinity of the Atlantic layer varies between 34.5 and 35 psu.

(3) Bottom water extends beneath the Atlantic layer to the ocean floor. This is colder than the Atlantic water (below 0°C) but has the same salinity.

(4) An inflow of Pacific water can only be observed in the Amerasian Basin, not in the Eurasian Basin. This warmer and fresher water mixes with colder and more saline water in the Chukchi Sea, where its density enables it to flow as a wedge, all the way to the north pole, sandwiched between the Arctic surface water and Atlantic water. The Pacific water, by the time it reaches the Canadian Basin, has a temperature range of 30.5 to 30.7°C and salinity between 31.5 and 33 psu.

The Norwegian Sea is characterized by the Norwegian Current, the extension of the warm North Atlantic Current, is characterized by salinities above 34.9 psu and temperatures above 7°C. When entering the Norwegian Sea at the Faeroe-Shetland Channel the temperature is about 9°C and it cools off to about 3°C west of Svalbard. The loss in heat is released to the surrounding environments. One branch of the Norwegian Current enters the Barents Sea, while the other branch passes through the Fram Strait where it enters the central part of the Arctic Ocean.

The Greenland Sea is characterized by its sea-ice cover and being the site for considerable deep water formation. The Greenland- and Iceland Seas are nourished by the East Greenland Current, cold water from the Arctic Ocean. Gyres of the warm Norwegian Current mixes with the East Greenland Current in the Greenland- and Iceland Seas where it cools and sinks to the bottom. This bottom water is returned to the North Atlantic as a bottom water current across the Iceland-Faeroe Ridge as well as over the Greenland-Iceland Ridge. The temperature profile show that the deep layers in the Greenland Sea has become significant warmer at 2000 m depth from January 1986 to 2016, an increase from about -1.25°C to -0.7°C.

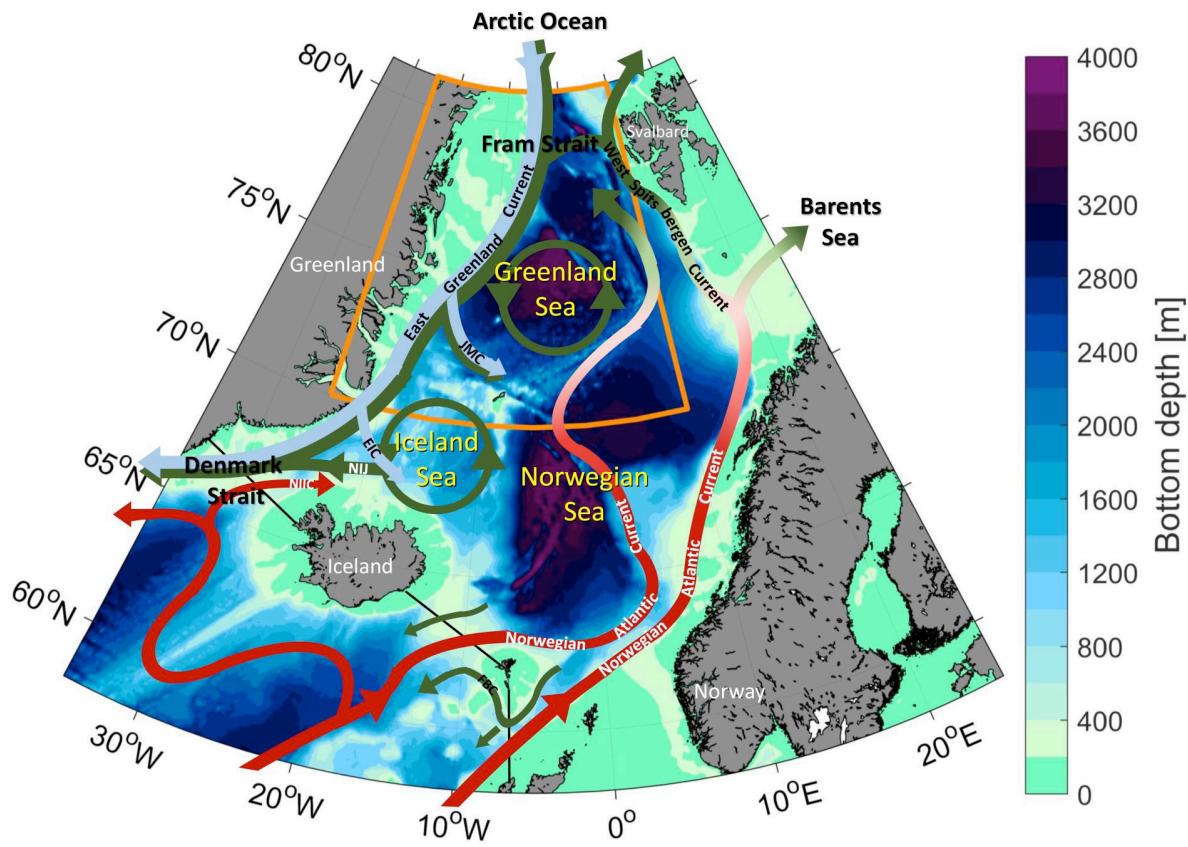


Figure 2: Bathymetry of the Nordic Seas (in colors) including schematics of the general circulation. Red colors indicate inflow of warm Atlantic Water while dark green colors indicate cold and dense waters. Fresh surface water is shown in light blue. (Source: https://www.uib.no/sites/w3.uib.no/files/attachments/ailin_bakstad_0.pdf)

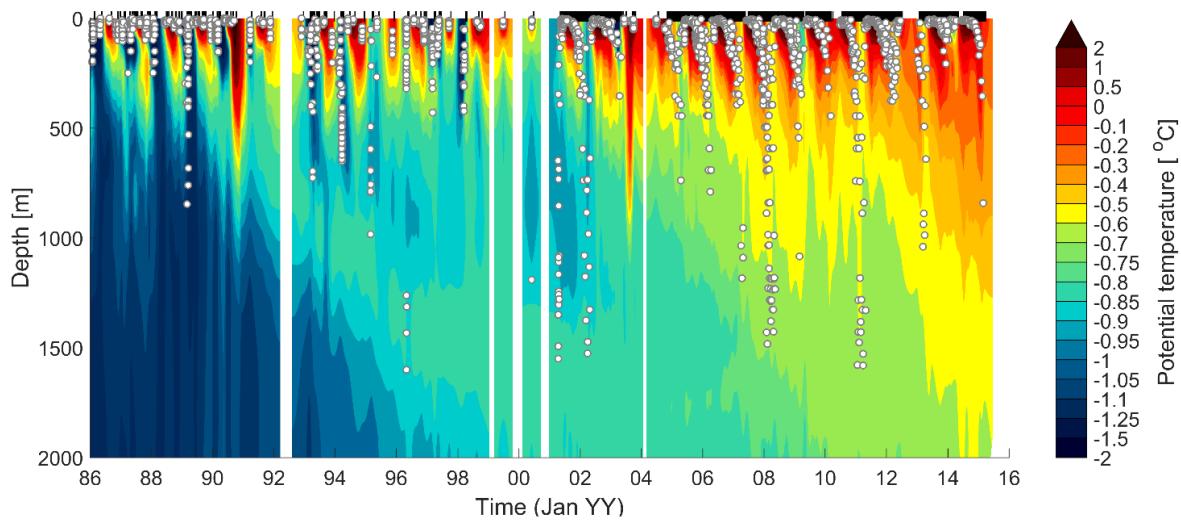


Figure 3: Evolution of potential temperature from January 1986 to 2016, showing a gradual warming. (Source: https://www.uib.no/sites/w3.uib.no/files/attachments/ailin_bakstad_0.pdf)

The World's Conveyor Belt

The Nordic Seas represents an area of great importance in the development of the World's Conveyor Belt as defined by Broecker (1991). The ocean conveyor gets its “start” in the

Norwegian Sea, where warm water from the Gulf Stream heats the atmosphere in the cold northern latitudes (Figure 2 and 4). This loss of heat to the atmosphere makes the water cooler and denser, causing it to sink to the bottom of the ocean. As more warm water is transported northwards, the cooler water sinks and moves southwards to make room for the incoming warm water. This cold bottom water flows south of the equator all the way down to Antarctica. Eventually, the cold bottom waters return to the surface through mixing and wind-driven upwelling. The conveyor belt encircles the globe and have had significant changes in intensity between glacial and interglacial times (Figure 4).

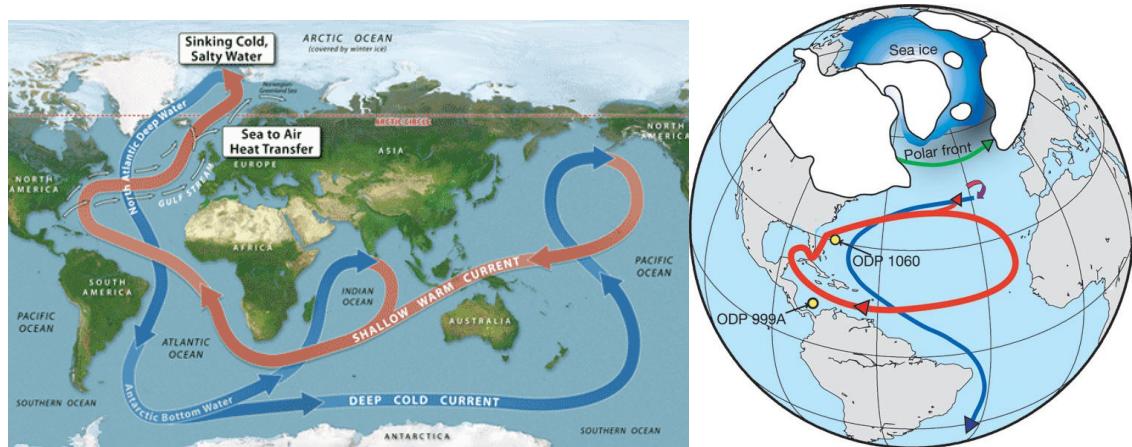


Figure 4. Diagram illustrating the major surface and deep water circulation components of the ocean that combine to form the Global Conveyor Belt during warm interglacial periods (left). Main deep water production is in the Greenland-Iceland Seas. (Credit: [The M Factory © Smithsonian Institution](#)). To the right is shown that the main area of deep water production during cold glacial periods has now shifted southwards to about 45°N.

As seen in the figure above the main surface currents in the North Atlantic are changing considerably between Glacial and interglacial conditions, also causing great north-south fauna migrations. The North Atlantic Current (Gulf Stream) is not a stable current but is dependent on meteorological conditions such as wind stress as well. The inflow of warm Atlantic water to the Norwegian Sea continues into the Arctic Ocean and circumnavigates this cold water basin as a subsurface current, located between 200-900 m. The volume of the inflowing warm water to the Arctic Ocean varies, and so does the temperature. With increasing volume there is also an increase in temperature. Likewise the attached micro-fauna, such as radiolarians, from more southern latitudes, even of a tropical-subtropical origin, are transported to more northern latitudes, even as far as north of Spitsbergen (see discussion below).

First occurrence of modern radiolarians in the Nordic Seas.

Based on fossil assemblages radiolarians first occurred in The Nordic Seas during the end of the Pleistocene (last glacial period) during the warm interval Bølling-Allerød, preceding the cold Younger Dryas (Jansen and Bjørklund, 1985). During the main Pleistocene, the ecological conditions in the Nordic Seas were harsh and most of the area had a solid sea-ice cover. During Bølling-Allerød the sea surface became seasonally ice-free with productive seasons. During main glacial times we do not know for sure if radiolarians were present in the

water column in the Nordic Seas or not. There is no trace of radiolarians, or other siliceous microfossils, in the sediments. This might be a result either of lack of silica producing organisms in the water column or the siliceous skeletal elements have effectively been dissolved. The Nordic Seas Pleistocene radiolarian assemblage is assumed rather similar to the present day conditions in the Arctic Ocean and the cold-water neighboring seas, rather limited or absent.

During the Bølling-Allerød only a handful of species occur, dominated by *Amphimelissa setosa* and *Cycladophora davisiana*. During the Younger Dryas, the ecological conditions returned to an almost glacial setting, and the two mentioned species became even more dominant.

After the Younger Dryas the hydrological conditions in the Nordic Seas changed dramatically. The cold (0-1°C) arctic Younger Dryas water was on the Younger Dryas/Holocene border (12.9 cal ka BP) replaced by warm (6-12°C) Atlantic water (Figure 5). This change in water masses caused an increase in sea temperature at 200 m from just 0-1°C in late Younger Dryas to between 5-6°C (CABFAC/MAT techniques) and 10-12°C (WA-PLS technique) in early Holocene Preboreal time (Bjørklund et al., in press).

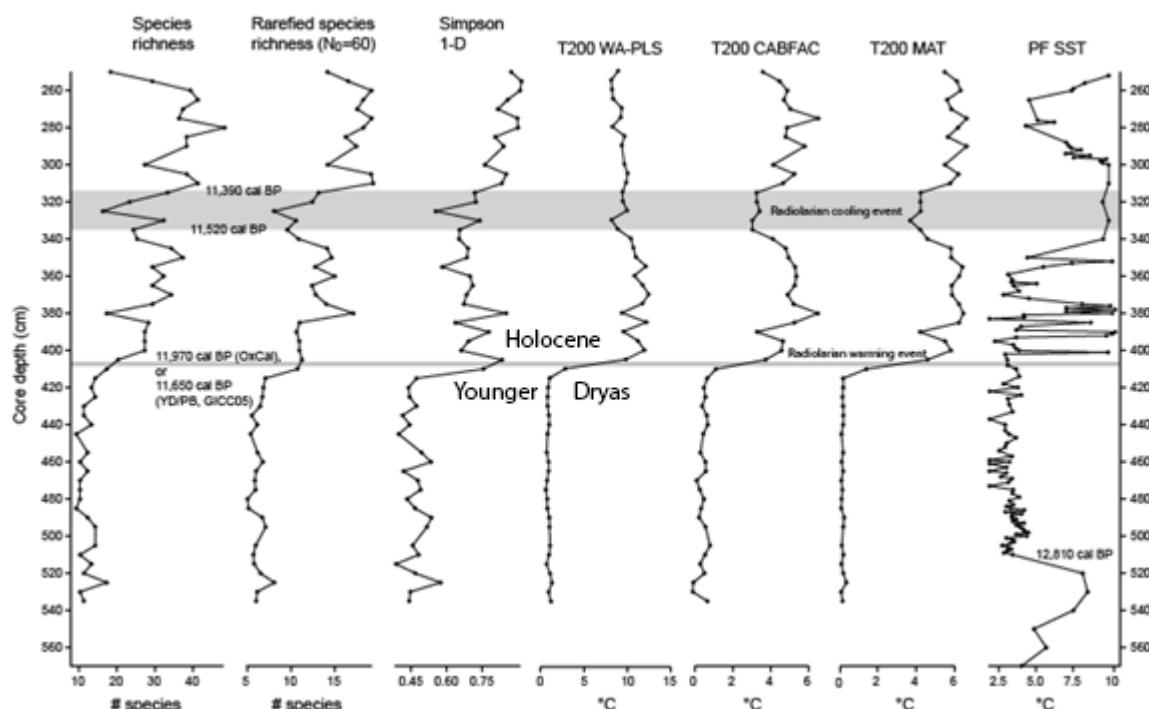


Figure 5. Parameters derived from the radiolarian faunas in the JM99-1200 core. Species richness is the observed number of species. Rarefied species richness is standardized to a small sample size $N_0=60$. The Simpson index D is a measure of numerical dominance of a few species, and conversely $1-D$ is a measure of evenness. The reconstructed paleotemperatures at 200 m water depth are shown for the WA-PLS, CABFAC and Modern Analog Technique (MAT) methods. The reconstructed sea surface temperature based on planktic foraminifera (Ebbesen & Hald 2004) is included for comparison. (From Bjørklund et al., in press).

This increase in temperature took place over a very short period of time, probably only a couple of decades. This abrupt change in the atmosphere's decreased loading of crustal and

sea salt at the termination of the Younger Dryas (Mayevski, et al. (1993), takes also place over a short period of <20 years.

History and route of migration and recruitment of Nordic Seas-Arctic Ocean radiolarians

The Arctic Ocean radiolarians have two possible ways of radiolarian recruitment, either from the North Pacific via the Bering- and Chukchi Seas or from the North Atlantic via the Norwegian Sea. During the Pleistocene (last glaciation) the Bering Strait was dry land and the Arctic Ocean had at that time only one waterway connection with the North Atlantic, through the Fram Strait.

The Arctic Ocean is receiving inflow of sea-water from the North Pacific as well as from the North Atlantic (Figure 6). Most recent radiolarian studies report that the radiolarian fauna in the Arctic Ocean is of an Atlantic affinity. So far we have no proof and no reports demonstrating that Pacific radiolarian species has colonized and gotten established in the Arctic Ocean. Blueford (1983) listed the 10 most common species in the Bering Sea surface sediment samples (numbers counted): *Stylochlamydium venustum* group (3914), **Spongotrochus glacialis** group (1934), *Tholospyris borealis* (212), **Lithomitra arachnea** (52), *Prunopyle antarctica* (51), *Spongurus pylomaticus* (49), *Stylatractus pyriformis* (42), *Pterocanium korotnevi* (39), **Rhizoplegma boreale** (39), and *Carposphaera* sp indet A (37), where only the bold underlined species are present in both the Nordic Seas and the Bering Sea. *Stylochlamydium venustum* group is a subphotic species (Itaki and Takahashi, 1995), and should be expected as a good candidate to be transported and to establish itself in the Arctic Ocean. *Tholospyris borealis* is another candidate, also present in the Bering Sea. So far we have no proof or traces of them being present in the Arctic Ocean. All plankton studies of radiolarians in the shallow Bering Sea and Chukchi Sea report that these samples are barren for radiolarian skeletons. Radiolarians from the north Pacific and southern parts of the Bering Sea will need a long time to travel over the shallow shelves of the northern Bering Sea and Chukchi Sea, a travel that is too rough for them to survive. The lack of living radiolarians in the Chukchi Sea is taken as evidence that no Pacific radiolarian species has successfully recruited the Arctic Ocean to establish sustainable populations.

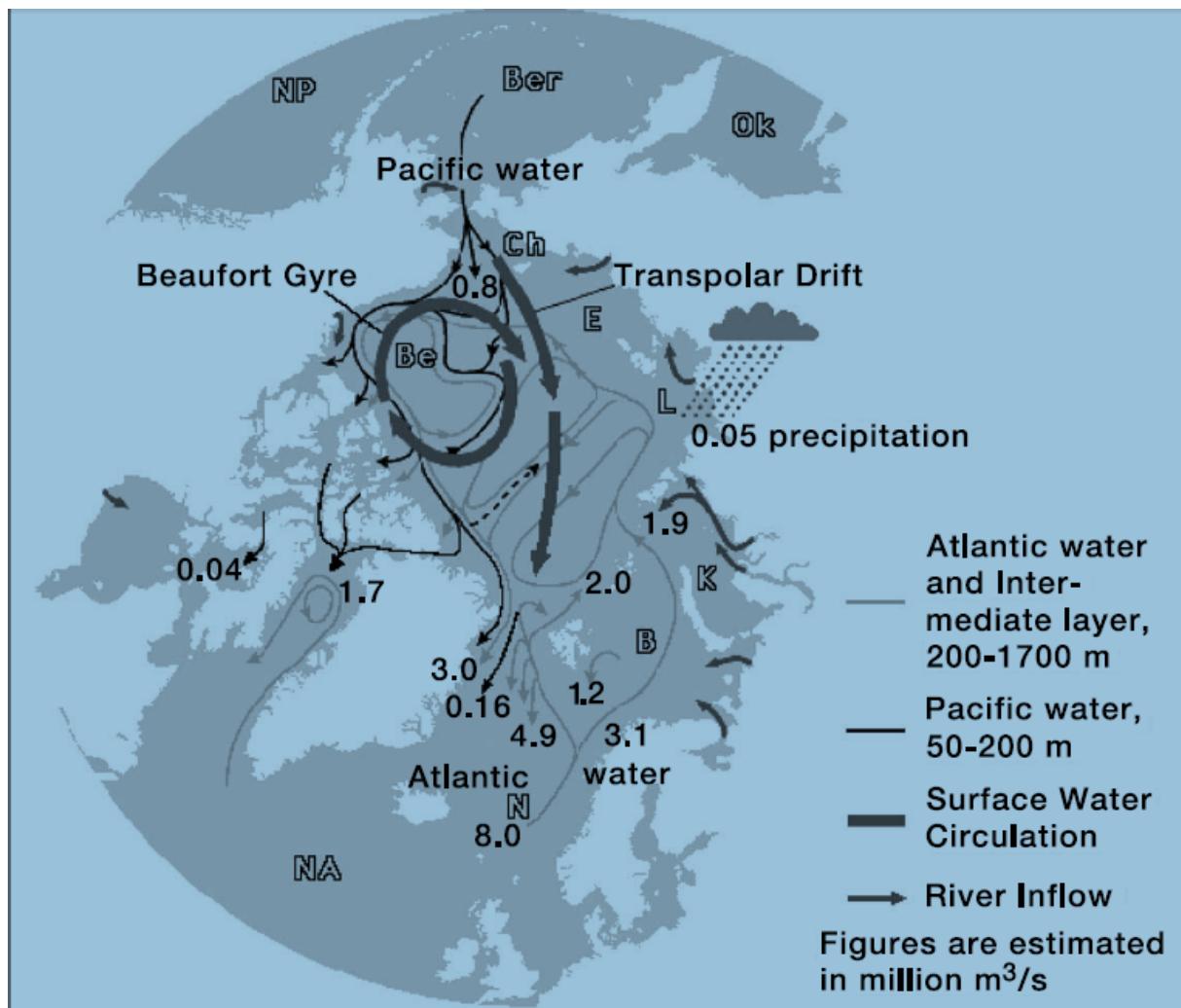


Figure 6. Map showing the circulation patterns of the different water masses in the Arctic Ocean. Abbreviations: NA, North Atlantic; N, Norwegian Sea; B, Barents Sea; K, Kara Sea; L, Laptev Sea; E, East Siberian Sea; Ch, Chukchi Sea; Be, Beaufort Sea; Ber, Bering Sea; Ok, Okhotsk Sea; NP, North Pacific. Map modified after AMAP 1998 (<http://grid2.cr.usgs.gov/geo2000/english/i186.htm>).

History of radiolarian research in the Nordic Seas

The first report on radiolarians from the Nordic waters was made by Cleve (1899), Jørgensen (1900, 1905) and Schröder (1909, 1914).

Cleve (1899) reported on 29 polycystine taxa from the Swedish Expedition to Spitsbergen in 1898. From the western and northern coasts of Norway, Jørgensen (1900, 1905) reported on 43 and 42 species and forms, respectively. However, some of his taxa may be regarded as different growth stages so the taxa list in Jørgensen (1900) is probably too high.

Swanberg and Bjørklund (1987b) reported on 46 taxa in plankton samples from Sognefjord and Hardangerfjord, collected during three different sampling periods.

It was demonstrated by Bjørklund (1974) and Swanberg and Bjørklund (1986, 1987b) that about 60 species of polycystine radiolarians thrive in the neritic coastal and landlocked environments of Norwegian fjords. This number is therefore assumed to represent an average of the species normally found in these fjords.

Bjørklund et al. (1998) reported on 75 taxa based on the study of 63 surface sediment samples in the Nordic Seas, while Cortese et al. (2003) increased the number of taxa to 114 based on 160 surface samples. This higher number of taxa is a result of some stations from the area south of Iceland was also included.

Bjørklund and Kruglikova (2003) studied surface sediment samples from the Arctic Ocean, recognizing 31 polycystine taxa from the surface sediments, all of them are also found in the Nordic Seas. It is evident that there is a significant reduction in the polycystine radiolarian diversity in the Arctic Ocean compared to the Nordic Sea. The opal preservation in the Arctic Ocean proper is probably a major factor controlling the low diversity, as here the silica dissolution is high. Furthermore the fact that large parts of the Arctic Ocean is covered with permanent sea-ice, at least part of the year, the biological production under the sea-ice is strongly reduced.

Bjørklund et al. (2012) studied, in addition to the surface sediment samples, 7 plankton samples from the area north-east of Spitsbergen. These samples were collected between 16th and 28th August 2010, and we recognized 145 taxa therein. We found that 98 taxa had an affinity to more southern latitudes, even of a tropical to subtropical origin. We interpreted this as a result of an extreme 7,5° C Atlantic warm water plume in 2009, that carried these exotic species this far north. In other words, the fauna composition in the water column is strongly influenced by the origin and changing volume, pulsations, in the major current systems. The normal temperature west of Spitsbergen is about 3,5°C. It is evident that a doubling of the temperature indicates that there has been a drastic change in the volume of inflowing warm Atlantic water to the Arctic Ocean. A tremendous amount of heat (energy) is entering the Arctic Ocean, energy that is also participating in heating the Arctic Ocean, Sea-ice is probably also melted from below, not only from the atmosphere above.

Sediment occurrence of radiolarians in the different basins in the Nordic Seas.

Svetlana B. Kruglikova and Kjell R. Bjørklund have for many years been working closely on the radiolarian distribution in the different basins in the Nordic Seas. Based on all our quantitative radiolarian data it is clear that the radiolarian show great differences in their distribution patterns. The Greenland Sea is generally barren for radiolarians in the surface sediments, while the Iceland Sea has the highest recorded number of 170.000 radiolarians/g carbonate free sediment. Or could the value be the double, according to Itaki and Hatewara (2000)? Here the fauna has a dominance of cold water radiolarians. The Norwegian Sea, with its Norway Basin in the south, has also a rich and diverse radiolarian fauna of a warm water category. The Lofoten Basin is also recognized by its warm water components but the

radiolarian numbers are strongly reduced, as opal preservation here is not optimal due to slumping from the continental shelf off Northern Norway. The Barents Sea is shallow and radiolarian occurrence in these sediments is barren to low. Only west off Novaya Zemlya is there an area where radiolarians regularly can be found. In the Fram Strait radiolarians are strongly reduced in number compared to the Lofoten Basin, both what species and specimens are concerned. Another factor, preservation is a problem in this area which may play a role in selective dissolution of thin shelled specimens.

It is evident that the distribution of radiolarian species strongly depicts the structure and nature of the water masses in which they live. This is not only evident for the different species distribution patterns, but even more interesting, even at a higher taxa level, such as the family level, can the different oceans and basins be classified and recognized, as shown below:

Iceland Sea (Iceland Plateau)

The structure of high rank (family) associations change with ecology and water masses. As can be seen from Figure 7 the Iceland Sea (also called Iceland Plateau) the family Cannabotryidae (79%) is dominant, whith Actinommidae (10%) and Eucyrtidiidae (9%) of an almost equal value.

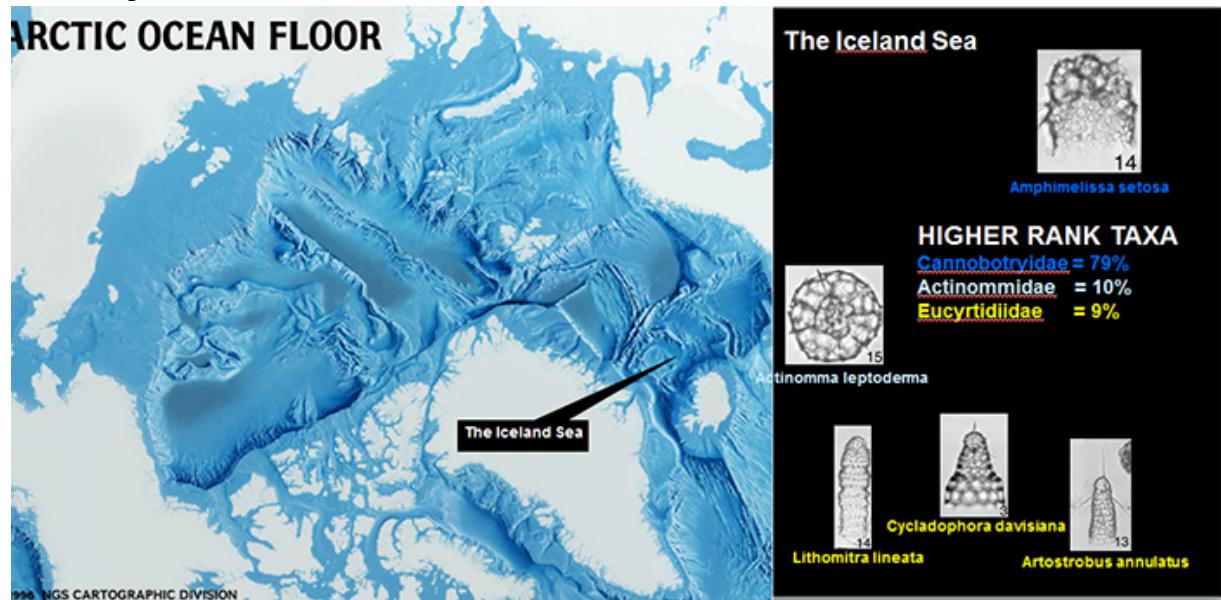


Figure 7. Iceland Sea: Radiolaria distribution by family.

Barents Sea

In the shallow Barents Sea an almost identical picture is obtained. Also here the Cannabotryidae (77%) is the dominant family. Both the Barents Sea and the Iceland Sea are characterized by cold water of an Arctic origin. The families Plagianthidae (20%) and Spongodiscidae (1%) follows as shown in Figure 8.

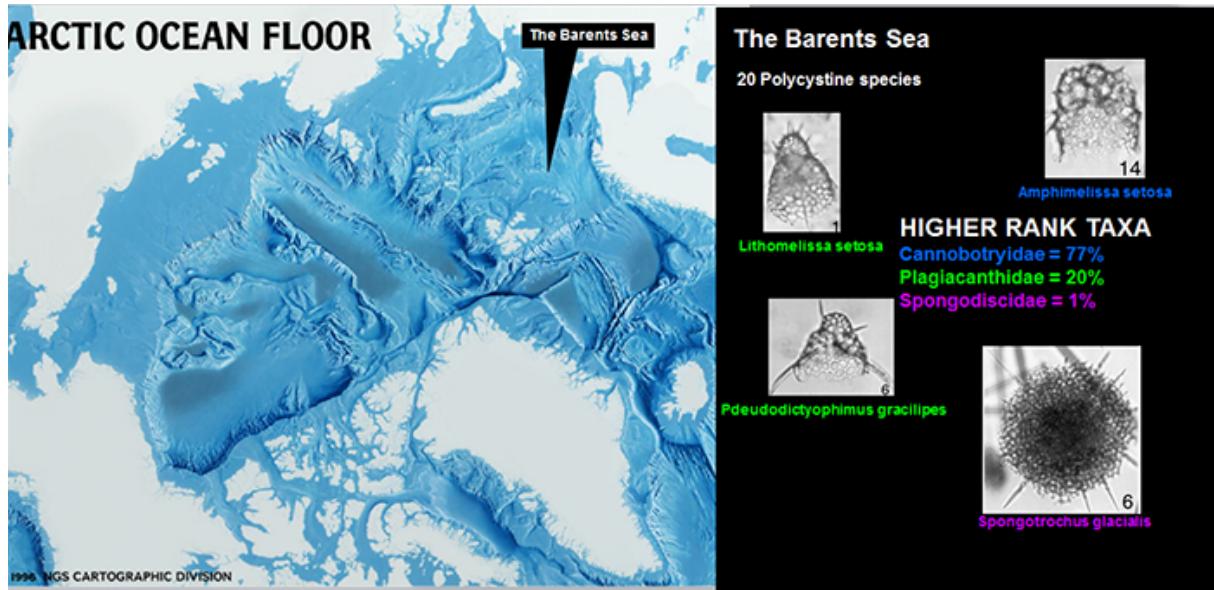


Figure 8. Barents Sea: Radiolaria distribution by family.

Norwegian Sea

In the Norwegian Sea we have a much more homogenous distribution of the three most common families where Plagiacthidae (44%) is the dominant family, with Eucyrtidiidae (20%) and Actinommidae (16%) of almost the same value, Figure 9. It is worth noticing that Eucyrtidiidae is only recorded in low numbers in the cold water provinces like Iceland and Barents Seas.

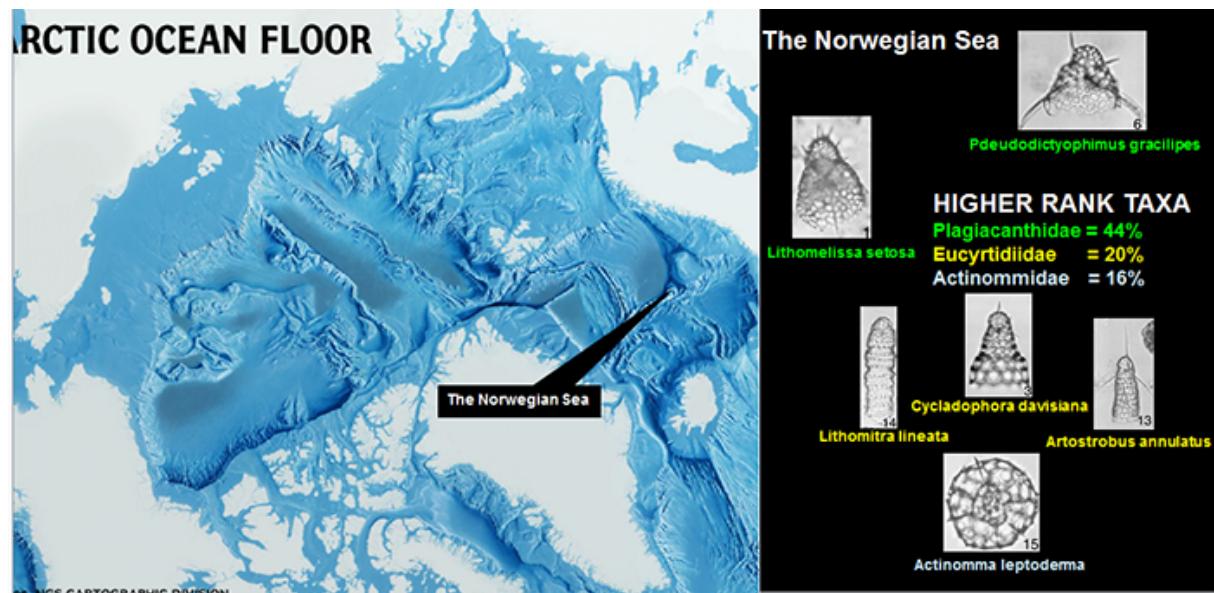


Figure 9. Norwegian Sea: Radiolaria distribution by family.

Fram Strait

All the previous provinces discussed are characterized by a dominance of species from order Nassellaria. As we are moving northwards the assemblages are drastically changing character. In the Fram Strait, on the entrance to the Arctic Ocean, the Actinommidae (59%) are now the

dominant family, with Lithelidae (12%) and Pylonidae (8%) ranking next, Figure 10. All three families counting for 79% of the fauna, belong to the order Spumellaria. The majority of the missing per cent value is due to the fact that many skeleton remains could not be identified to species and are only classified as either unidentified Spumellaria and Nassellaria, numbers that are included when family per cent values are calculated. The Actinommidae have a rather large and robust skeleton compared to most of the Nassellaria species, and are therefore less susceptible to dissolution.

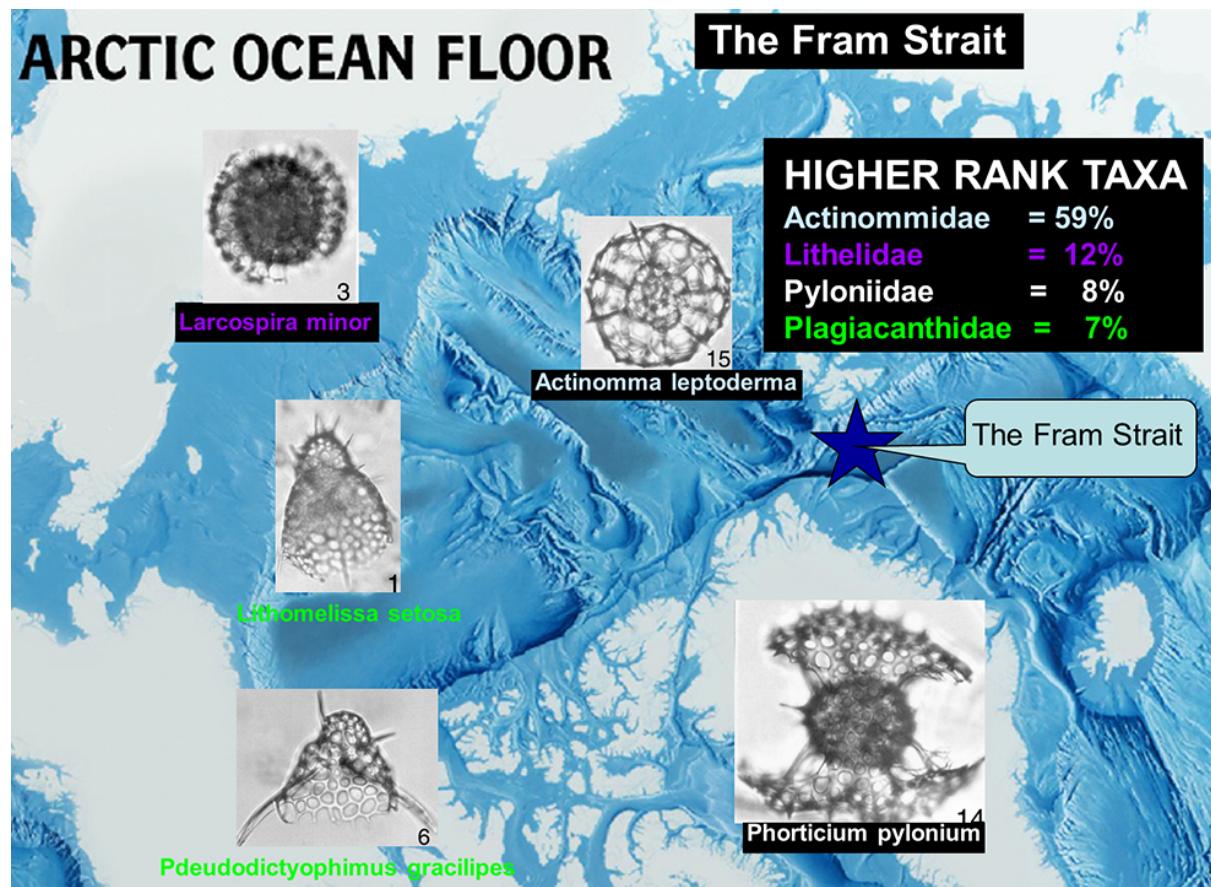


Figure 10. Fram Strait: Radiolaria distribution by family.

Arctic Ocean

Nansen Basin

The inflow of warm Atlantic water from the Norwegian Sea enters the Nansen Basin through the Fram Strait. In the Nansen Basin Actinommidae (83%) totally dominate the fauna, followed by Eucyrtidiidae (4%) and Lithelidae (1%), Figure 11. In the Nansen Basin the warm Atlantic water flows along the Eurasian shelf and make a bend when it meets the shallow Laptev Sea. In the Laptev Sea there are only traces of radiolarians both in the shallow and deeper stations. However, Plagiacanthidae are seen more often there than Actinommidae.

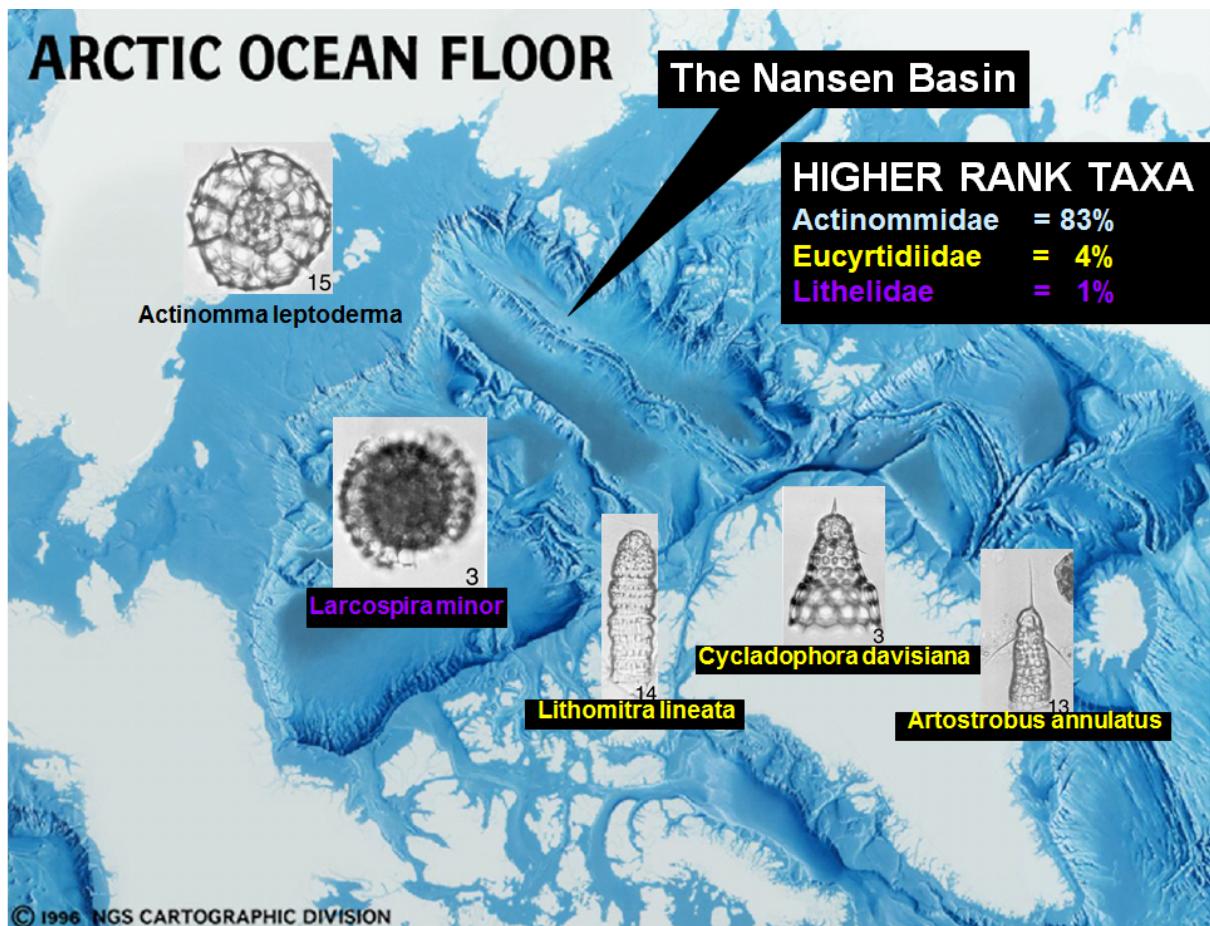


Figure 11. Nansen Basin: Radiolaria distribution by family.

Amundsen Basin

The Amundsen Basin has almost a monospecific Actinommidae (94%) assemblage with only traces of Plagiocanthidae (1%) and Eucyrtidiidae (1%), Figure 12. The Sea-ice is here found all through the year, and the biological production is low.

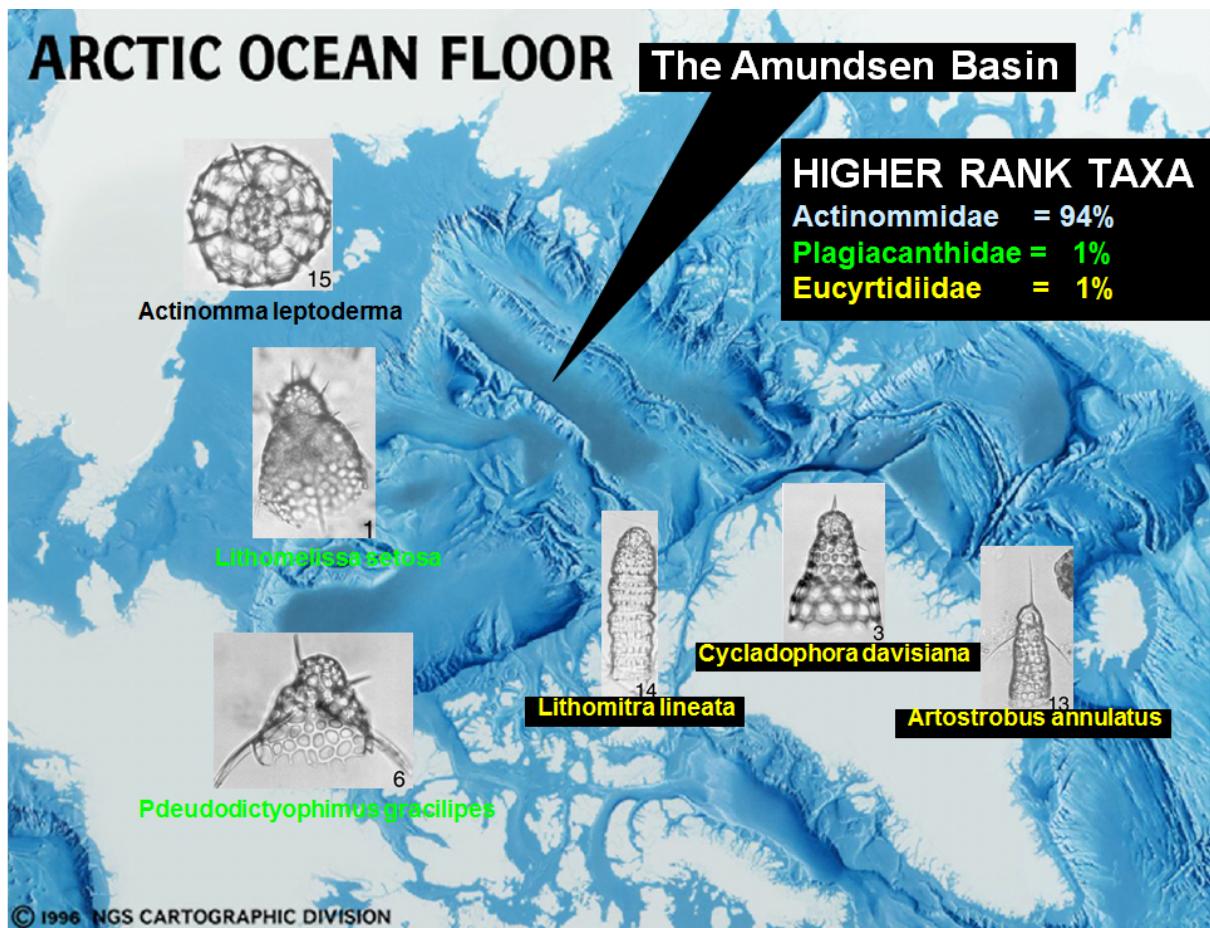


Figure 12. Amundsen Basin: Radiolaria distribution by family.

Makarov Basin

In the Makarov Basin still Actinommidae (75%) dominates the fauna, with Eucyrtidiidae (12%) and Plagiocanthidae (7%) being more present, Figure 13. Why this sudden increase in Nassellaria occur, is not understood, but can be a result of better ecological conditions in this basin or that opal skeletons are better preserved here.

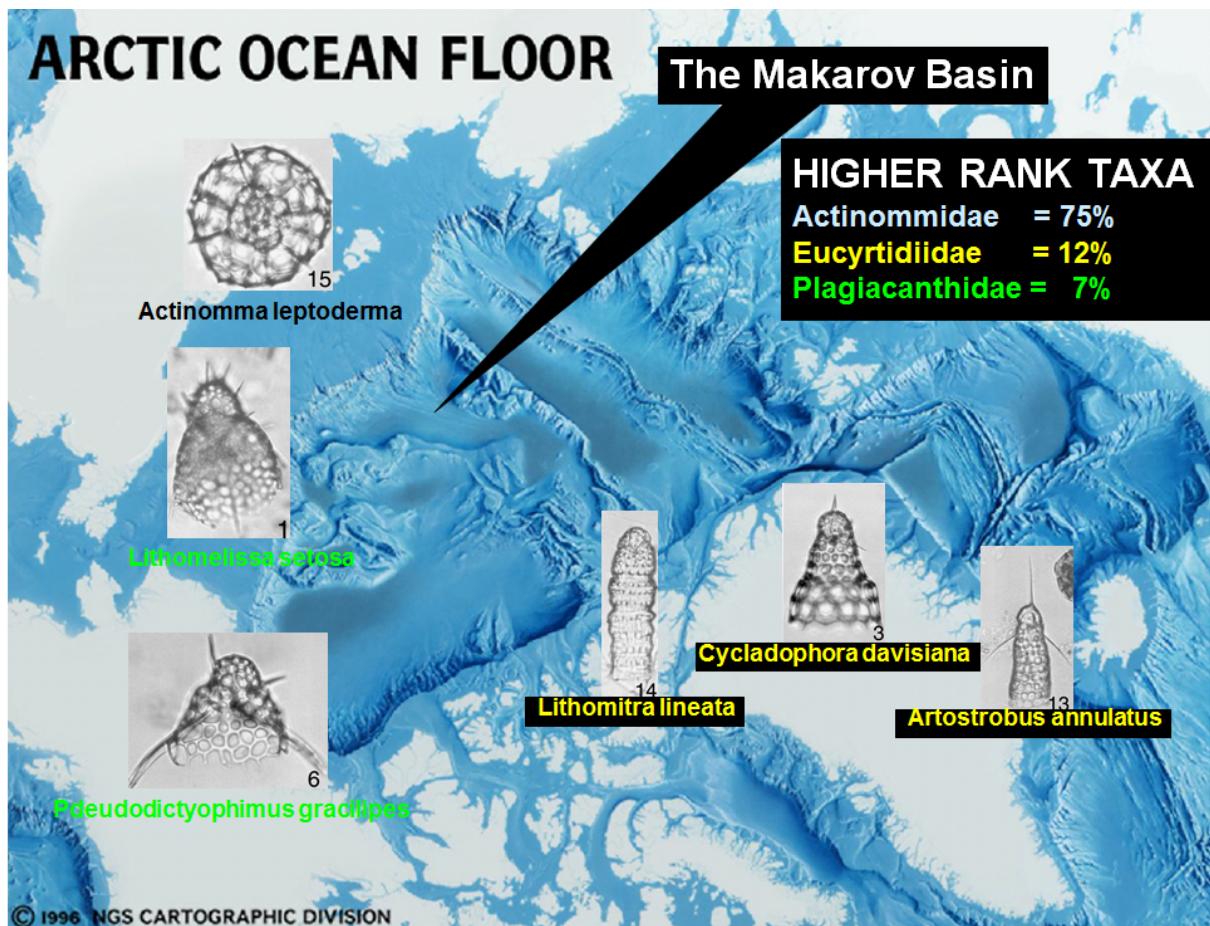


Figure 13. Makarov Basin: Radiolaria distribution by family.

Practical use of species number

Radiolarians in the Greenland- and Iceland Seas are strongly influenced by the East Greenland Current, originating in the Arctic Ocean and are therefore characterized by its cold-water fauna where *Amphimelissa setosa* is the dominant species, but a certain mix of Atlantic fauna elements are also present. Generally, in the Iceland Sea the number of species is normally in the range of 24 species or less. The sedimentation rate in the Iceland Sea is low and radiolarians are only present in the upper about 0-24 cm (Molina-Cruz, 1991). The radiolarian occurrence here may show up to 170,000 radiolarians/g CaCO³ free sediment (Bjørklund et al., 1998).

Norway Basin, southern part of the Norwegian Sea, is underlying the warm Atlantic Current and show the highest number of recorded numbers of radiolarian species. Generally the stations in the Norwegian Sea are characterized with a specie number of 28 or higher. Bjørklund et al. (1998) plotted the number of species at each station in their dataset (Fig. 14). It is evident that most of the Atlantic domain is represented by high species numbers (>28), while most of the Polar and Arctic domains are represented by lower species numbers (<24). The contour lines for 24 and 28 species roughly enveloped the position of the Arctic front, an important oceanographic feature in the study area, which is located in the middle of the gradient of species number. The number of species could therefore give a rough estimate of

the position of the predominant water masses and oceanographic features, such as the Arctic Front, in the Norwegian–Iceland Seas in the geological record.

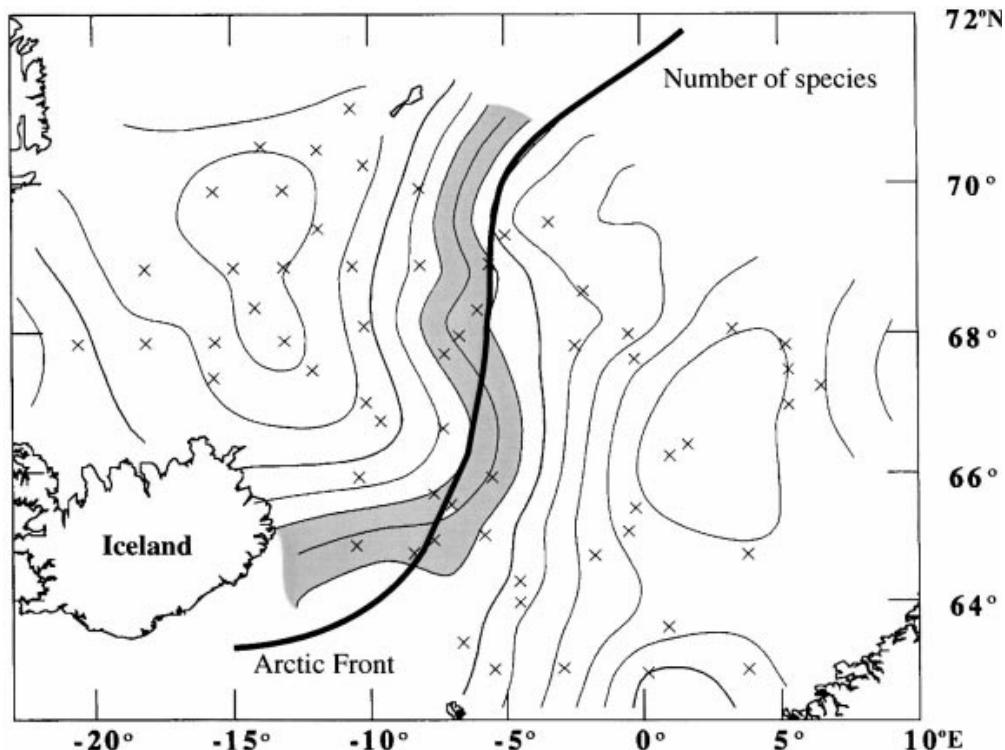


Figure 14. Distribution of the number of radiolarian species in the GIN Seas. The area enveloped by the 24 and 28 species number isolines (shaded) and the position of the Arctic front are shown. Increment between isolines = 2; heavy line increment = 10. From Bjørklund et al. (1998, Fig 16).

Radiolarian Taxonomy

This paper is based on several hundred surface sediment samples from the Nordic Seas (Iceland, Greenland, and Norwegian Seas), the Arctic Ocean, as well as a handful of plankton samples from the area north east of Spitsbergen. The aim is to make a list of all known Radiolaria (Spumellaria + Nassellaria + Entactinaria) species that we have identified. The higher rank taxonomy is unclear, especially since most of the taxonomy is based on skeletal recognition. The framework of morphologic radiolarian taxonomy was made by Ernst Haeckel (16th February 1834-9th August 1919) who in 1887 published his famous Challenger Report where Haeckel himself authored numerous generic and specific names. His system included 739 genera and 4318 species, of which 3508 new species were described (Aita et al. (2009), of this number 2775 were new polycystine species).

Later on, many authors have done minor or major revisions of Haeckel's system; major revision was made by De Weaver et al. (2001). They suggested, based on morphological studies that the order Entactinaria should be extended also to include recent forms such as genera Joergensenium, Gonosphaera, Cleveiplegma, Hecalonche and Hexacontium, with several species found in the Nordic Seas. At present there is a controversy among experts on how to define and where to place the so called “living Entactinaria”. Herein we will follow the suggestion by De Weaver et al. (2001) for some “living Entactinaria” species as their

taxonomic position has not been finalized by any DNA analysis. “Living Entactinaria” in our present Norwegian Sea and Arctic Ocean deals with species within the following genera: *Gonosphaera* (G. primordialis Jørgensen, 1900), *Cleveiplegma* (*Rhizoplegma boreale* (Cleve, 1899)), and *Joergensenium* (J. rotatile Bjørklund, Dumitrica, Dolven and Swanberg, 2008). These have been addressed to Entactinaria exclusively based on morphological characters on the inner shell being different from in regular Spumellaria. De Weaver et al. (2001) also included genera *Hexalonche* and *Hexacontium* among the “living Entactinaria”, but this is still under debate and has not been settled yet. Based on morphology species from both *Hexalonche* and *Hexacontium* has now been DNA analyzed and our DNA studies of *Hexacontium pachydermum* clearly place this species in the Spumellaria group (Yuasa et. al., 2009). Susuki and Not (2015 Green Book), based on DNA studies, found that the members of the “living Entactinaria”, in this case *Hexacontium*, did not make a separate and well defined clade, but grouped well in between the established Spumellaria clade.

We have therefore adapted the taxonomy by De Weaver et al. (2001) for the genera *Joergensenium*, *Gonosphaera*, and *Cleveiplegma*, while we have still included the *Hexalonche* and *Hexacontium* to belong to the Spumellaria, until their taxonomic position is properly settled.

Kjell R. Bjørklund and Svetlana B. Kruglikova have been working for many years on the radiolarian fauna in the Nordic Sea and Arctic Ocean. We have in our study (Bjørklund et al., 2012) recognized 145 taxa and have in the following used the high rank orders as follows:

RHIZARIA

Order Collodaria

Family Collosphaeridae

Family Sphaerozoidae

Order Entactinaria

Family Centrocytidae

Family Quinquecapulariidae

Order Nassellaria (9 families present)

Family Artostribiidae

Family Trissocyklidae

Family Carpacaniidae

Family Lycnocaniidae

Family Pterocoryidae

Family Cannobotryidae

Family Eucyrtidiidae

Family Plagiacanthidae

Family Sethophormididae

Order Spumallaria (9 families present)

Family Strbloniidae

Family Pyloniidae

Family Sponguridae

Family Artiscidae

Family Litheliidae

Family Phacodiscidae

Family Spongodiscidae

Family Porodiscidae

Family Actinommidae

CERCOZOA

Order Phaeodaria (7 families present)

Family Porospathidae

Family Coelodendridae

Family Medusettidae

Family Lirellidae

Family Cannosphaeridae

Family Aulacanthiidae

Family Challengeridae

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and have seen the need for a more uniform taxonomy.

Herein we have made an updated taxonomic list of all the radiolarian taxa that we have achieved during our studies, at present amounting to 145 taxa.

The famous German zoologist, Professor Ernst Haeckel (16th February 1834-9th August 1919), specialized on recent radiolarians and outlined a radiolarian high rank taxonomy as follows:

Kingdom: **Protista** (or **Protoctista**)

Subkingdom: **Protozoa**
Phylum: **Sarcomastigophora**
Subphylum: **Sarcodina**
Superclass: **Actinopodea**
Class: **Polyacystina**
Order: **Nassellaria**
Order: **Spumellaria**
Class: **Phaeodaria**
Class: **Heliozoa**
Class: **Acantharia**

Haeckel himself authored numerous generic and specific names and in his large monograph of 1887 his system included 739 genera and 4318 species, of which 3508 new species were described (Aita et al. 2009), of this number 2775 were new polyacystine species.

Major revision of this system was made by De Weaver et al. (2001). During the last two decades DNA studies have been undertaken on quite a number of radiolarian species in an attempt to test if the Haeckelian taxonomic scheme do reflect the same groups as obtained by molecular analyzes.

Susuki and Aita (2011) summarized the DNA studies and suggested the following system based on available literature:

Supergroup: **Rhizaria**
Group: **Cercozoa**
Order: **Phaeodaria**
Group: **Radiolaria**
Order: **Collodaria**
Order: **Nassellaria**
Order: **Acantharia**
Order **Spumellaria**
Order: **Entactinaria**
Order: **Taxopodia**
Group:

We have at present used the high rank system as outlined by

