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Diatom distribution of surface sediment in the Bering Sea and Chukchi Sea

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Abstract Diatoms from surface sediment samples in the Bering and Chukchi seas were analyzed to reveal the distribution patterns and their relationship with the ocean environment. A low abundance was found to the north of the Arctic Sea Ice Minimum (ASIMin), indicating that diatom growth is strongly inhibited by perennial sea ice. Between the ASIMin and the Arctic Sea Ice Maximum (ASIMax) which experiences seasonal sea ice, the sea ice related diatoms (mainly *Fragilariopsis oceanica* and *Fragilariopsis cylindrus*) were dominant, thereby confirming that sea ice is an important influencing factor. The *Chaetoceros* resting spores were more abundant in the Chukchi Sea, which corresponds well with the active phytoplankton distribution in the water column, and is possibly attributed to the stronger hydrodynamic conditions present in the Bering Sea. The abundances of *Chaetoceros* resting spores were the lowest on the northeast Bering Shelf, possibly because of lower water depth, stronger coastal currents, river influx, coarser particle sizes and stronger winds and bottom currents. The Arctic Diatom Group (dominated by *Bacterosira bathyomphala*, *Thalassiosira antarctica* v. *borealis* and *Thalassiosira antarctica* resting spores) was more abundant in the Bering Basin and the areas central of and to the north of Chukchi Plateau, while the Coastal Benthic Diatoms (including *Paralia sulcata* and *Delphineis surirella*) were mainly found on the northeast Bering Shelf and nearby Cape Lisburne in the Chukchi Sea. *Thalassiosira nordenskioeldii* was found to be the most abundant around the Bering Strait, while *Neodenticula seminae* was only found in the Bering Sea and mainly distributed in the Bering Basin, indicating its close correlation with the Pacific waters.

Keywords **Bering Sea, Chukchi Sea, surface sediment, diatom**

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1 Introduction

The high-latitude oceans are considered to be the most important sinks for biogenic silica. The contents of biogenic silica in the surface sediments are > 55% in the Bering Sea and the Okhotsk Sea. In contrast to the equatorial regions of the Pacific Ocean where a large portion of the accumulated biogenic silica consists of radiolarian skeletons, the biosiliceous components in the sediment of high-latitude oceans are dominated by diatom cell walls. Diatoms are one of the most important marine phytoplankton and have significant influence on marine ecosystems. Diatoms are widely used in Quaternary Paleoceanography to reveal the paleoenvironmental changes of the past because of their sensitive response to environmental variables, widespread distribution and high abundance in ocean sediment.

The Arctic diatoms have been studied since the mid 19th century. Early research reported diatom occurrences in the Arctic marginal seas[1-7]. During recent decades, diatom distributions and their paleoecologic and paleoceanographic significances were studied in the Barrents Sea, the Kara Sea, the East Siberia continental shelf[8-9], the Laptev Sea[10-11], the Nordic Sea[12] and marginal seas in the high-latitude northern Pacific, such as the Okhotsk Sea and the Bering Sea[13-14]. On the basis of the aforementioned research, the paleoceanographic changes in the Arctic were then reconstructed using sediment diatoms[12,14-15]. Most of the research on sediment diatoms mentioned above focused on the eastern Arctic, while few studies were carried out in the western parts of the Arctic, such as the Chukchi Sea.

The purpose of this paper is to analyze the distribution

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of sea surface sediment diatoms in the Chukchi Sea and the Bering Sea, to determine the relationship between the distribution and the oceanographic environment. For this purpose, diatoms from surface sediment samples retrieved during the 2nd and 3rd Chinese National Arctic Research Expeditions (CHINARE-Arctic) were identified and analyzed in detail.

2 Oceanographic setting

The Bering Sea, which is the largest marginal sea in the northern Pacific, is surrounded by the Alaska Peninsula, the Aleutian Archipelago, Kamchatka Peninsula and Siberia. The Bering Shelf, located in the northeast Bering Sea, is seasonally covered by sea ice, while the deep basin in the southwestern region of the Bering Sea is rarely influenced by sea ice[16]. The Alaskan Stream, which is an extension of the Alaskan Current flowing westward along the Aleutian Island in the subarctic Pacific, enters into the Bering Sea mainly through the Amchitka Pass and the pass west of Attu Island in the eastern Aleutian Islands. Much of the Pacific water masses entering the Bering Sea exit though the passes in the region of the Aleutian Islands, such as the Kamchatka Strait and the Near Strait. A large-scale anticlockwise circulation of surface water is recognized along the continental slope and the Aleutian Island region in the Aleutian and Kamchatka basins. Along the Bering Shelf, there are at least three clockwise surface water circulation patterns recognized[17].

The Bering Strait acts as the Pacific gateway to the Arctic Ocean and all Pacific waters found in the Arctic must cross the Chukchi Sea to reach the Arctic Ocean shelf-break at ca. 73°N. The Chukchi Sea with a water depth of ~50 m is typical of the Arctic marginal seas in that it is seasonally ice-covered. During winter, polynyas form along the coast of the Chukchi Sea; during summer, buoyant boundary currents of riverine origin have been found on the eastern and western margins. As a shallow sea, even its depths are within reach of the influence of the atmosphere and it is influenced by the autumn and winter atmospheric storms carried north though the Bering Strait on the storm tracks[18]. The broad northward flow in the southern Chukchi Sea appears topographically steered into three main branches: One east of Hanna Shoal, which feeds into Barrow Canyon; one west of Herald Shoal feeding into Herald Valley; and one between the two shoals, referred to as the Central Channel flow.

The Bering Sea is called “The Sea of Silica” because of its high content of biogenic opal in the sediment[19]. Surface sediment diatom distributions have been studied by Sancetta[13-14], with most of the samples collected from the Aleutian and Kamchatka basins and a few from the Bering Shelf. Being fed by nutrient-rich Pacific waters from the south, the Chukchi Sea is one of the most productive areas of the world’s oceans[18]. In addition, the seasonally changed sea ice can initiate diatom blooming during the ice melting period. Research of surface sediment diatoms in the Eurasian arctic seas showed great number of diatoms in the western Chukchi Sea[20], while sediment diatoms from the eastern Chukchi Sea have not as yet been studied.

3 Materials and methods

The uppermost 0–2 cm surface sediment samples were collected for diatom analysis by box corer and Multi-corer during the 2nd and 3rd CHINAREs-Arctic, which were carried out during July to September in 2003 and 2008. A total of 57 samples from the Bering Sea, the Chukchi Sea as well as the Beaufort Sea and the Canadian Basin were analyzed (Figure 1).

The cleaning of sediment samples and the preparation of permanent mounts for light microscopy followed an improvement of the routine method established at the Alfred Wegener Institute[21]. Freeze-dried subsamples (~1 g) of sediment were treated with ~10% Hydrochloric (HCl) and 30% Hydrogen peroxide (H_2O_2), and heated on an electric hot plate to remove the calcite and organic matter. Distilled water was then added after completion of the reaction and then gently removed by latex tubes after a settling time of ~10 h. This washing process was repeated 4–5 times until all acid and a portion of the clay were removed. The remaining sediment was diluted to ~50 mL, and then 1–5 mL (according to the diatom content) diluted and homogeneously mixed sediment was drawn by a quantified pipette. This sediment sample was then diluted to ~20 mL and ~2 mL of gelatin solution was then added, and subsequently gently decanted into a petri dish fixed with two quadrate cover slips. After a settling time of ~24 h, the water was removed from the petri dish using a strip of absorptive paper. After the material had completely dried, the cover slips were transferred onto permanently labeled slides, and mounted with Naphrax (d*n*=1.73).

4 Results and discussion

4.1 Influence of sea ice on diatom distribution

Few diatoms were found in 24 samples (shown as hollow circles in Figure 1) of the 57 surface sediment samples. These 24 samples are all retrieved to the north of 73°N in the Chukchi Sea, where the abundances of marine phytoplankton in the water column (mainly diatoms) have also been found to be declining[22]. As shown in Figure 1, most of the 24 samples were taking from the north of the Chukchi Slope with a larger water depth. However, abundance of diatoms was also low at station R15, characterized by relatively shallow water (174 m), while the diatom abundance was high at station S24 characterized by water depth of 2 346 m. This shows that water depth is not a good explanation for the extremely low diatom content to the north of 73°N.

As is shown in Figure 1, the 24 sediment samples with less diatom abundance are all located in the northern region of the Arctic Sea Ice Minimum (ASIMin: the median ice extent for September from 1979 to 2010, from the National Snow and Ice Data Center). To the south of the ASIMin, diatoms are abundant in the surface sediment (the solid circles). This indicates that the growth of diatom is strongly inhibited by the perennial sea ice covering in the Arctic Ocean.

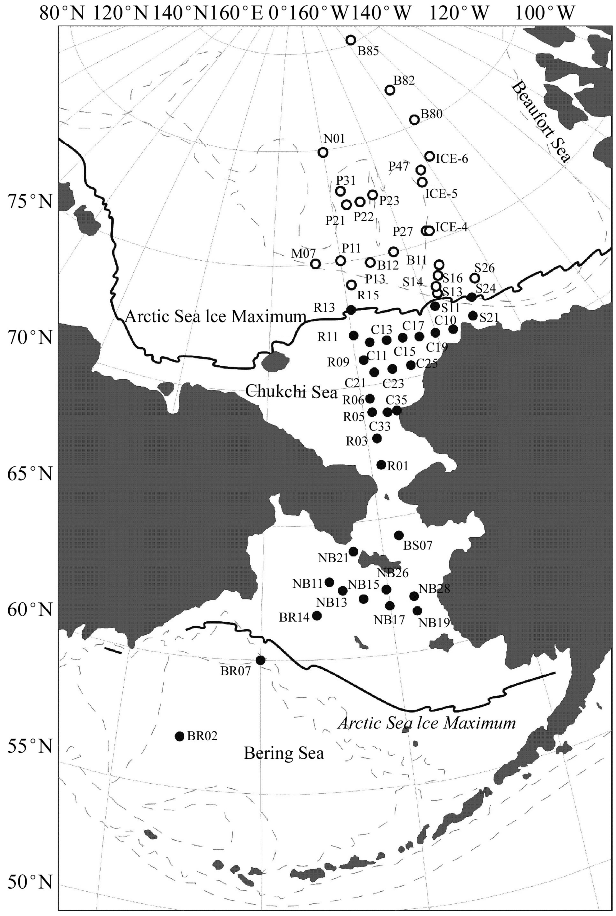

Figure 1 Location of sites in the study area (solid circles represent samples rich in diatom abundance, and hollow circles represent samples with low diatom abundance).

4.2 The main diatom species and their distribution patterns

4.2.1 *Chaetoceros* resting spore

Globally, the diatom genus *Chaetoceros* is one of the most common and abundant among marine phytoplankton. However, a low abundance of *Chaetoceros* is found in deep-sea sediments because they are weakly silicified and dissolved quickly, especially easily fragmented by predators[23-24]. Compared with *Chaetoceros* vegetable cells, the resting spores are more readily preserved in sediment. The *Chaetoceros* resting spores are commonly found in the high-latitude seas of the Northern Hemisphere, with extremely high content (~90%) in some areas[25].

The *Chaetoceros* resting spores were abundant in both the Bering Sea and the Chukchi Sea, with percentages ranging between 5%–70%, and in half of the samples, they constituted > 50% (Figure 2). The abundances of *Chaetoceros* resting spores in the Chukchi Sea were higher than in the Bering Sea, except at site C35 nearby Cape Lisburne, with a percentage composition of 19%. On the Bering Shelf, the *Chaetoceros* resting spores were relatively less abundant, with the lowest percentages of 5% at the site NB19.

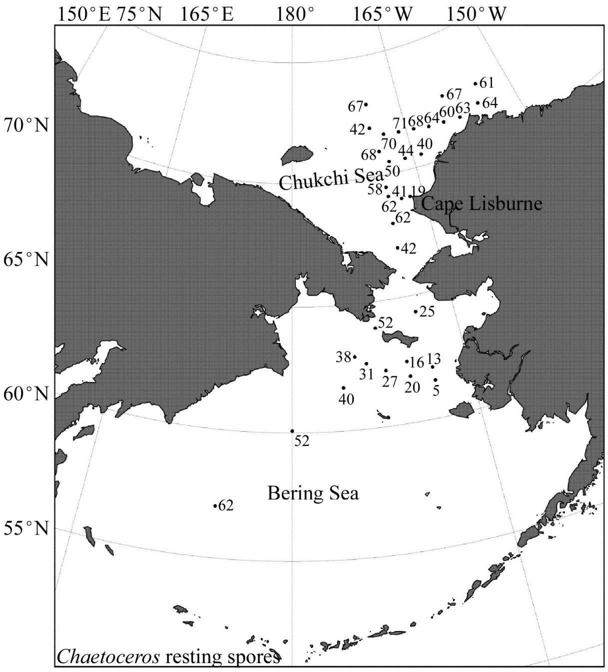

Figure 2 The distribution of *Chaetoceros* resting spores in the Bering Sea and the Chukchi Sea (numbers show the percentages of *Chaetoceros* resting spores).

Previous studies showed that *Chaetoceros* (including *Ch. socialis*, *Ch. subsecundus*, *Ch. compressus* and *Ch. furcellatus*) are the predominant species of phytoplankton in the Chukchi Sea, and the composition of *Chaetoceros* in the sediment notably decrease in the Bering Sea[22], which might be the main reason for the discrepancies in the abundance of *Chaetoceros* in the Chukchi Sea and the Bering Sea. *In situ* investigation during the Chinese Arctic Expedition showed that the color of sediment in the Bering Sea is lighter than that of the Chukchi Sea, and the sediment grain size is relatively coarser in the Bering Sea, which indicates different hydrodynamic forces acting in these two areas. The fine-grained sediment with a high content of organic matter (including the small *Chaetoceros* resting spores) will be more readily transported in the relatively dynamic Bering Sea[26].

This study found that *Chaetoceros* resting spores are less abundant on the Bering Shelf and the Bering Strait with relatively higher productivity than in the deep basin[27], which is inconsistent with that shown by Sancetta[14], who showed that the abundance of *Chaetoceros* resting spores is closely related with high productivity in the Bering Sea. Sancetta[14] also emphasized that the spores are small and light, and are probably easily removed by winnowing and then deposited in nearby basins. Thus, sandy or silt sediments may lack *Chaetoceros* spores, even though high productivity may be occurring in the surface waters. Wang and Chen[28] found that the preservation of siliceous organisms in the Bering Sea will be influenced by many factors, such as the water depth, water temperature and salinity and input of terrigenous matter. The diatoms might be dissolved and broken down more readily on the shallow and low-salinity Bering Shelf, which also assimilates a considerable amount of coarser terrigenous particles.

Chaetoceros resting spores are usually excluded when calculating percentages of other species, as they are always too abundant and dilute the variation information of other diatom species in the high-latitude seas. Therefore, in this study, the percentages of other diatom species were also calculated excluding the *Chaetoceros* resting spores to remain consistent with previous works.

4.2.2 Sea ice diatoms

Fragilariopsis is one of the most popular diatom groups in the polar waters. *F. oceanica* and *F. cylindrus*, which are closely associated with the sea ice, were commonly found in the Arctic and the neighboring seas. Hasle[29] summarized many of the reported occurrences of *F. oceanica* in the plankton, most of which showed it as being common along the Arctic coasts, in water temperatures ranging between -1℃–3℃. Yang et al.[22] found *F. oceanica* to be one of the dominant diatom species among the phytoplankton in the Chukchi Sea, while this species became the second most important species in the Bering Sea. Sancetta[14] showed that the abundance of *F. oceanica* was relatively higher in the Chukchi Sea and then along the east coast of Kamchatka, with lower abundances found on the eastern part of the Bering Shelf, and especially low abundances found in the deep Bering Basin, the Okhotsk Sea and the North Pacific. *F. cylindrus* is one of the few bipolar species, occurring in the Antarctic as well as in the Arctic, which is often found in the pack-ice and is also common in the plankton. Previous works indicated higher content of this species in sediment, occurring mainly in the northern part of the Bering Shelf, while rarely found along east coast of Kamchatka and usually absent in the deep basins of the Bering Sea and in the northern Pacific. It is easy to conclude that both *F. oceanica* and *F. cylindrus* have a preference for sea ice and relatively low sea surface temperature, with higher abundances found in higher latitudes.

Fossula arctic and *Pauliella taeniata* are also typical sea ice related diatom species found in the Arctic, although with relatively lower content in sediment. These two species together with *F. oceanica* and *F. cylindrus* are combined as a Sea Ice Diatom Group for discussion in this study. In this study, the percentages of the Sea Ice Diatom Group ranged between 16%–71% (excluding the *Chaetoceros* resting spores), with average value of 50%. Figure 3 shows that the Sea Ice Diatoms are abundant in the Chukchi Sea and on the Bering Shelf, while the contents of this diatom group are relatively low in the deep Bering Basin. As is shown in Figure 1, the sites BR07 and BR02 in the deep basin are characterized by low percentages of Sea Ice Diatoms and are the only two sites located to south of the Arctic Sea Ice Maximum (ASIMax). The relatively low abundance of the Sea Ice Diatom Group can be explained by rare influence by sea ice in the deep Bering Basin, while this diatom group dominated the surface sediment diatoms in areas strongly influenced by seasonally changing sea ice.

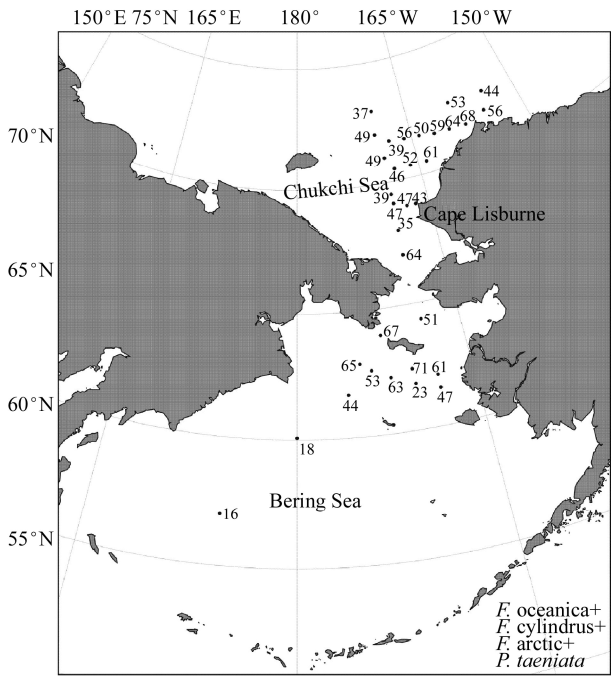

Figure 3 The distribution of the Sea Ice Diatom Group in the Bering Sea and the Chukchi Sea (numbers show the percentages of the Sea ice diatoms excluding *Chaetoceros* resting spores).

4.2.3 The Arctic diatoms

Bacterosira bathyomphala, *Thalassiosira antarctica* v. *borealis*, *Thalassiosira antarctica* resting spore, *Porosira glacialis* and *Dentonula confervaceae* resting spores are often found in the cold waters of the North Hemisphere high latitude seas and are usually called the Arctic Water Diatoms in previous works. Compared with the Sea Ice Diatoms, the Arctic Water Diatoms prefer ice free waters. *B. bathyomphala* and *T. antarctica* are the main species of the Arctic Water Diatom Group in the Bering Sea and the Chukchi Sea[14,30].

B. bathyomphala was commonly found in the Nordic Sea, the Greenland coastal area, the Okhotsk Sea and the Bering Sea. Sancetta[14] found that *B. bathyomphala* was relatively abundant on the southern part of the Bering Shelf compared with the abundance in the deep basin, the northern part of the Bering Sea and the Chukchi Sea. *T. antarctic* is bipolar distributed, and Fryxell et al.[31] distinguished between *T. antarctic* var. *antarctica* from the Southern

Hemisphere and *T. antarctic* v. *borealis* from the Northern Hemisphere. Sancetta[14] reported the presence of rare vegetative valves of *T. antarctic* v. *borealis*, and there appeared to be two morphotypes of *T. antarctic* v. *borealis* resting spores: One smaller, more highly arched with areolae irregularly radial; the other larger, less convex with areolae more regularly radial and sometimes almost fasciculate. The findings from this study appear to indicate that the second morphotype is closer to the vegetative cell of *T. antarctic* v. *borealis*. The resting spore is usually heavily silicified, more readily preserved and more abundant in sediment than the vegetative cells. *T. antarctic* v. *borealis* and its resting spores are widely distributed in the Laptev Sea[10-11], the Labrador Sea[32] and the Nordic Seas[12,33]. In work of Sancetta[14], the contents of resting spores were low on the Bering Shelf, with relatively higher abundance found on the western and central Bering Shelf than the eastern Bering Shelf and the Aleutian Basin, while abundance was relatively rich in the Komandorsky Basin.

The percentage of the Arctic Water Diatom Group in this study varied from 1% to 25% (Figure 4). The highest abundance occurred in the deep Bering Basin, while the lowest value was found on the east Bering Shelf (NB 19), with higher content on the western part of the Bering Shelf than the eastern part. The Arctic Water Diatoms is abundant in the northern Chukchi Sea, while less abundant in the southern part and the eastern part close to Alaska. This indicates that the distribution of the Arctic Water Diatoms Group is strongly influenced by the coastal waters. This diatom group is relatively less abundant in areas apparently influenced by the coastal current.

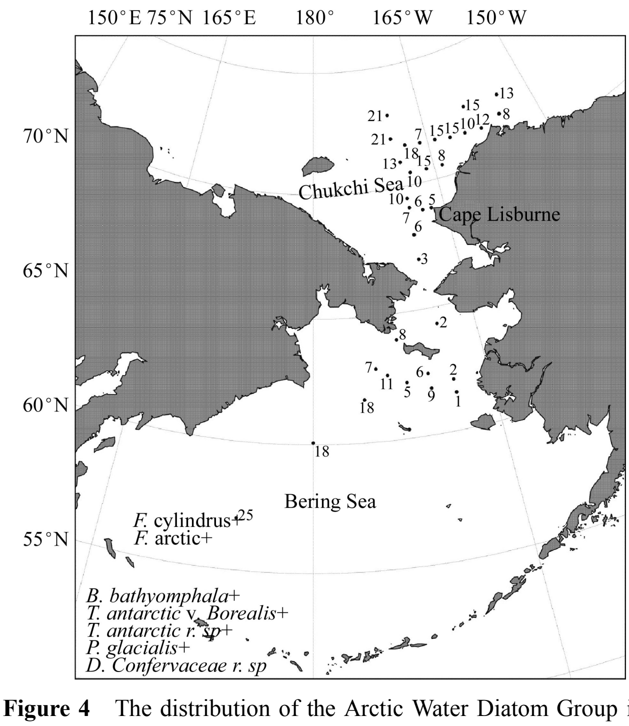

Figure 4 The distribution of the Arctic Water Diatom Group in the Bering Sea and the Chukchi Sea (numbers show the percentages of the Arctic diatoms excluding *Chaetoceros* resting spores).

4.2.4 Coastal benthic diatoms

Paralia sulcata may be a cosmopolitan diatom species. It is a typical bottom form, but fairly common among coastal plankton, and it is therefore regarded as tychoplankton. The habitat of genus *Delphineis* is shallow coastal water over sandy shores, mud and sand flats. It is usually attached to sand grains or other particles, but may be stirred up in turbulent water and thus, become part of the plankton[30]. *Delphineis surirella* is usually found within cold to temperate waters. Given that both species prefer similar environmental conditions, *P. sulcata* and *D. surirella* have been combined as the Coastal Benthic Diatoms Group for discussion in the present work.

It is shown that the highest percentages of the Coastal Benthic Diatoms appear on the Bering Shelf, especially on the eastern part of the shelf (Figure 5). In addition, they are abundant within the area close to the Lisburne Cape in the Chukchi Sea (Figure 5). The content of this group is relatively low in the Bering Basin, the Bering Strait and the northern Chukchi Sea. This demonstrates that the coastal benthic diatoms are mainly distributed in areas with shallower water and influenced strongly by the Alaskan coastal current.

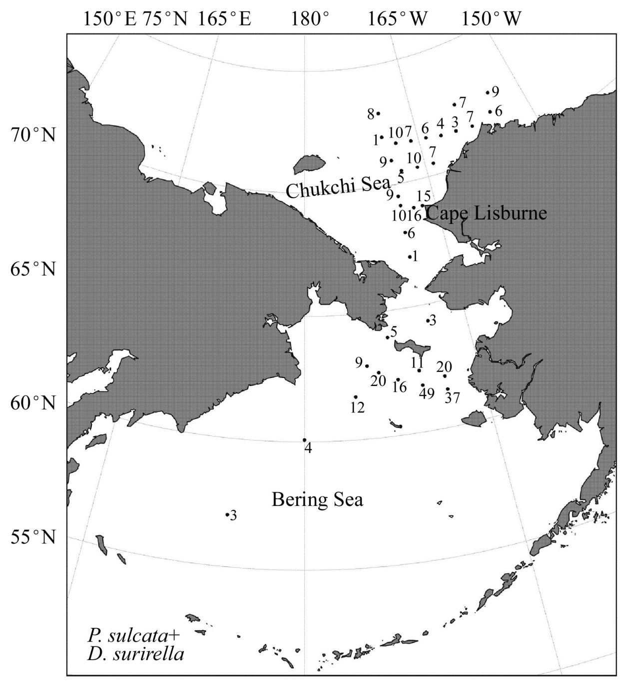

Figure 5 The distribution of the Coastal Benthic Diatoms Group in the Bering Sea and the Chukchi Sea. (numbers show the percentages of the Coastal benthic diatoms excluding *Chaetoceros* resting spores).

4.3.5 *Thalassiosira nordenskioeldii*

Thalassiosira nordenskioeldii is generally reported in the high-latitude seas of the Northern Hemisphere. It is the most common diatom species of the Arctic neritic algal bloom during ice melting in spring[34-36]. Passche[34] remarked that the presence of this species is a characteristic of the very early spring in the Arctic, with water temperature < 3–5℃. Cremer[11] pointed out that an under-ice and ice edge bloom of *T. nordenskioeldii* always follows an initial sea-ice bloom of ice diatoms during ice melting during spring and early summer. In this study, it is shown that *T. nordenskioeldii* is fairly abundant within an area nearby the Bering Strait, with a highest sediment composition of 41%, while showing an extremely low sediment content on the Bering Shelf (Figure 6). The reason for especially high sediment content of *T. nordenskioeldii* nearby the Bering Shelf is not clear at this stage.

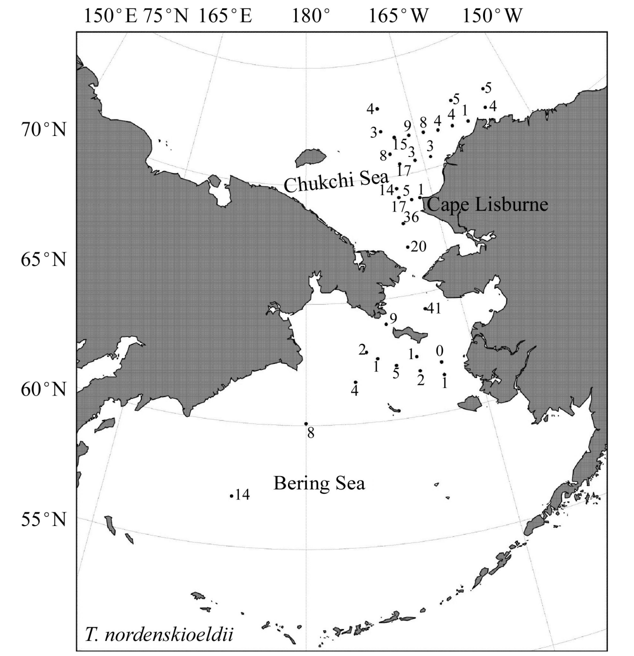

Figure 6 The distribution of *T. nordenskioeldii* in the Bering Sea and the Chukchi Sea (numbers show the percentages of *T. nordenskioeldii* excluding *Chaetoceros* resting spores).

4.2.6 *Neodenticula seminae*

Neodenticula seminae is a typical plankton diatom species in the high-latitude area of the northern Pacific, mainly distributed to the north of 42°N. It is commonly found in high abundance in the northeast Pacific and the Bering Sea. Within the Bering Sea, Sancetta[14] found this species to be mainly distributed in the southwest deep basin, with abundance decreasing sharply in the northwest Bering Shelf, and especially low occurrences in waters shallower than 1 000 m. The results of this study indicate that *N. seminae* only occurs in the Bering Sea, mainly in the deep basin (Figure 7), which corresponds well to the previous work of Sancetta[14] and indicates that *N. seminae* is closely related with the Pacific waters and somewhat restricted by water depth.

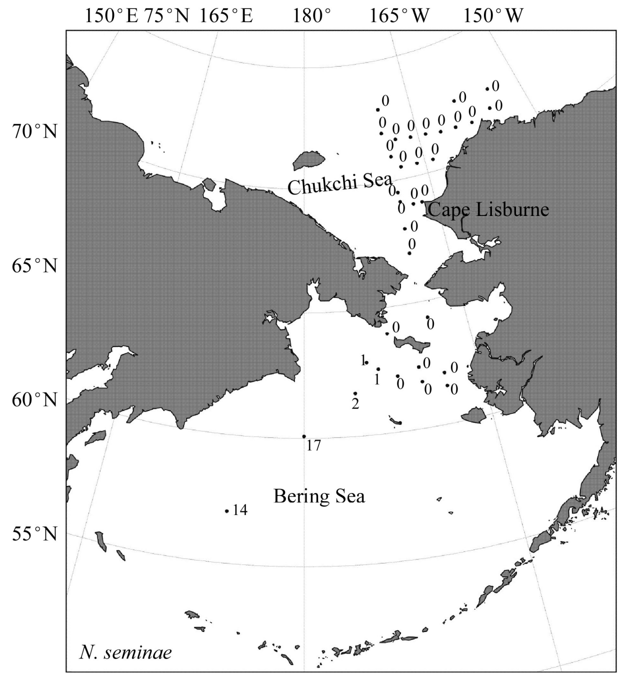

Figure 7 The distribution of *Neodenticula seminae* in the Bering Sea and the Chukchi Sea (numbers show the percentages of *N. seminae* excluding *Chaetoceros* resting spores).

5 Conclusion

The distribution of surface sediment diatoms in the Bering Sea and the Chukchi Sea was studied using surface sediment samples retrieved during the 2nd and 3rd CHINAREs-Arctic, and the main findings are as follows:

(1) Sea ice is an important influencing factor for the diatom distribution in the Arctic and neighboring Seas. Diatom growth is remarkably restricted in areas to the north of the ASIMin, which is strongly influenced by sea ice all year around. In the area between the ASIMin and the ASIMax under the strong influence of seasonally varying sea ice, species from the Sea Ice Diatoms Group are the predominant species of the surface sediment diatom flora.

(2) The *Cheatoceros* resting spores are more abundant in the Chukchi Sea than in the Bering Sea, which may be explained by stronger hydrodynamic conditions within the Bering Sea. The extremely low abundance of *Chaetoceros* resting spore on the northeast Bering Shelf might be related with the shallower water depth, stronger influence of the Alaskan coastal current and riverine input, the coarser particle grains, and transport by wind and bottom currents.

(3) The Arctic Water Diatoms are mainly distributed in the deep Bering Basin and in the central and northern regions of the Chukchi Sea. The Coastal Benthic Diatoms are abundant on the northeast Bering Shelf and within the area close to the Lisburne Cape in the Chukchi Sea; The coastal neritic diatom *Thalassiosira nordenskioeldii* is mainly found in high abundance in the region nearby the Bering Strait, while *Neodenticula seminae* is mainly distributed in the Bering Basin, showing a close correlation with the Pa-

cific waters.

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