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Distribution of biogenic particulate matter in the surface waters of the Bering Sea basin, winter 1993

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Abstract: Biogenic silica (BSi), particulate organic carbon (POC) and nitrogen (PON) and chlorophyll *a* (Chl *a*) of surface waters were measured in the Bering Sea basin from January through March 1993. BSi concentration varied extraordinarily among stations (0.01–0.59 μM) and was relatively high in the central region. POC and PON concentrations showed variations of several fold among stations (2.28–11.38 μM for POC and 0.36–2.11 μM for PON), and were relatively high in the eastern region. The regional variations of POC and PON concentrations reflected that of Chl *a* concentration, whereas the same results were not found for the BSi concentration. Extraordinary variation was found in the BSi/POC atomic ratio (<0.01–0.21), and values above average (>0.070) were observed in the central region. Values higher than 0.13, the typical atomic ratio of cellular silicon to cellular carbon for culture diatoms, were also found. In contrast, POC/PON atomic ratios were roughly uniform (mostly 4–10) and the average was 6.7. The present results show a possibility that diatoms with high silicon demand occur in the Bering Sea basin in winter. In addition, I also compared the characteristics of biogenic particulate matter with those in the summertime Bering Sea basin and in the wintertime Antarctic Ocean.

key words: Bering Sea basin, winter, biogenic silica (BSi), particulate organic carbon (POC), BSi/POC atomic ratio

Introduction

Many studies regarding the characteristics of biogenic particulate matter have been conducted in the Antarctic Ocean (Smith and Nelson, 1985; Nelson and Smith, 1986; Nelson *et al.*, 1989; Tréguer *et al.*, 1990; Leynaert *et al.*, 1991, 1993; Cota *et al.*, 1992; Shiomoto and Ishii, 1995). High atomic ratios of biogenic silica (BSi) to particulate organic carbon (POC) (BSi/POC ratio), 0.3–0.65, compared with the typical atomic ratio of cellular silicon to cellular carbon for culture diatoms (average: 0.13; Brzezinski, 1985), were commonly observed from spring through autumn, whereas low values (<0.06) were observed in winter. Atomic ratios of POC to particulate organic nitrogen (PON) (POC/PON ratio) were roughly equal to the Redfield ratio (6.6) from spring through autumn (seasonal average: 5.9–7.8) and slightly higher than the Redfield ratio in winter (average: 10.2) (Cota *et al.*, 1992). High BSi/POC ratios are mostly attributed to silicon-rich diatoms which uptake dissolved silicon in higher proportion than other elements in the Antarctic Ocean (Tréguer *et al.*, 1990); low ratios are due to the dominance of non-silicerous phytoplankton species (Leynaert *et al.*, 1993).

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Little is known about the characteristics of biogenic particulate matter in the Bering Sea. Banahan and Goering (1986) reported a BSi/POC ratio of 0.16, which is slightly higher than the typical value for culture diatoms, over the eastern Bering Sea shelf. Shiomoto and Ogura (1994) observed non-siliceous characteristics (BSi/POC ratios: 0–0.04) in biogenic particulate matter in the surface waters affected by continental shelf water, and silicon-rich characteristics (BSi/POC: 0.18–0.35) in biogenic particulate matter, repeatedly in the Bering Sea basin in summer. On the other hand, POC/PON ratios (average ± SD: 6.8 ± 1.6, n=20) were nearly equal to the Redfield ratio in all waters. Accordingly, the characteristics of the biogenic particulate matter in the Bering Sea basin can be considered similar to those in the Antarctic Ocean in summer. Moreover, diatoms, which are possibly characterized by high silicon demand, are significant primary producers in the Bering Sea basin in summer, as in the Antarctic Ocean. Measurements of BSi as well as POC and PON reveal the significance of diatoms as primary producers in the polar and subpolar seas.

BSi, as well as POC and PON concentrations, of surface waters were measured in the Bering Sea basin in winter 1993. In this paper, comparing with the previous study data in the summertime Bering Sea basin and in the wintertime Antarctic Ocean, the similarities and differences of the characteristics of biogenic particulate matter are revealed between summer and winter in the Bering Sea basin and between the Bering Sea basin and Antarctic Ocean in winter.

Materials and methods

This study was conducted during a cruise of the R/V *Kaiyo Maru* of the Fisheries Agency of Japan in the Bering Sea from January through March 1993 (Fig. 1). Seawater samples were collected from the surface with a plastic bucket at around noontime. For analyses of BSi, 0.5-l of seawater was filtered immediately after collection through a 47

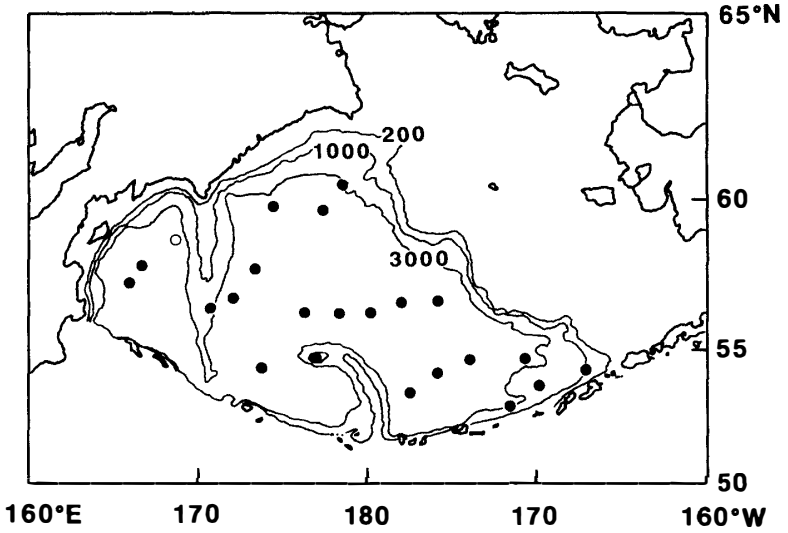

Fig. 1. Location of sampling stations in the Bering Sea basin in winter 1993. Numbers indicate the depth in meters. Samples for correcting POC and PON were collected at the station indicated by an open circle.

mm Nuclepore filter (0.6 μm pore size). For analyses of POC and PON, 1-*l* of seawater was filtered through a 47 mm Whatman GF/F filter (precombusted at 450℃ for 4 hr). For analyses of chlorophyll *a* (Chl *a*), 0.5-*l* of seawater was filtered through a 47 mm Whatman GF/F filter. All filters were stored at -20℃ until analysis ashore.

BSi analysis was performed using the NaOH (0.2 N) digestion method of Paasche (1973). The resulting solutions were analyzed with dissolved reactive silicate using a Bran and Luebbe Traccs 800 Auto Analyzer. Blanks in filters and attack reagents accounted for 7.5–100% (average $\pm$ SD: 31 ± 28%) of the sample values for BSi. Analytical precision for BSi was reported to be 7% as the coefficient of variation, by using Antarctic samples in which diatoms are abundant as they are in the Bering Sea (Shiomoto and Ishii, 1995). Each filter for POC and PON determinations was dried in a vacuum dessicator after elimination of inorganic carbon remaining on the GF/F filter by fuming with HCl. POC and PON concentrations were measured simultaneously using a Hitachi 026 CHN analyzer. Corrections for background levels of carbon and nitrogen in filters and absorption of dissolved organic matter were made by substrating values: 4.88 μM for POC and 0.20 μM for PON. These values were averages of triplicate measurements from a second filter placed beneath the primary filter at the station shown by the open circle in Fig. 1. Chl *a* concentrations were determined by the fluorometric method with a Hitachi F-2000 fluorophotometer, after extraction by 90% acetone (Parsons *et al.,* 1984). The fluorophotometer was calibrated with commercially prepared Chl *a* from Wako Pure Chemical Industries, Ltd. (Tokyo).

Surface temperature and salinity were measured with a thermometer and with a Guildline Autosal Salinometer, respectively. Nutrient concentrations were determined immediately using a Bran and Luebbe Auto Analyzer II. Subsurface temperture and salinity were measured with a Neil Brown CTD MK II.

Results

Temperature, salinity and nutrients

Surface temperature indicated a high-east and low-west trend (Fig. 2a). Surface salinity was nearly uniform in the western and central regions, and relatively low in the eastern region (Fig. 2b). Surface nitrite+nitrate, silicate and phosphate concentrations were nearly uniform in the western and central regions, and relatively low in the eastern region (Fig. 2c, d, e). Water with relatively high temperature, low salinity and low nutrient concentrations was found in the eastern region. This was considered to be water from the Alaskan Stream (Shiomoto *et al.,* 1999).

Distribution of biogenic particulate matter

BSi concentrations varied considerably among stations, ranging from 0.01 to 0.59 μM (Fig. 3a). The average was 0.27 μM (Table 1). Relatively high BSi concentrations exceeding the average were more frequently observed in the central and eastern regions than in the western region. POC and PON concentrations were in the ranges of 2.28 and 11.38 μM and of 0.36 and 2.11 μM, respectively (Fig. 3b, c). POC and PON concentrations showed variations of several fold among stations, but still were more uniform among stations than BSi concentration. The averages were 4.31 μM for POC

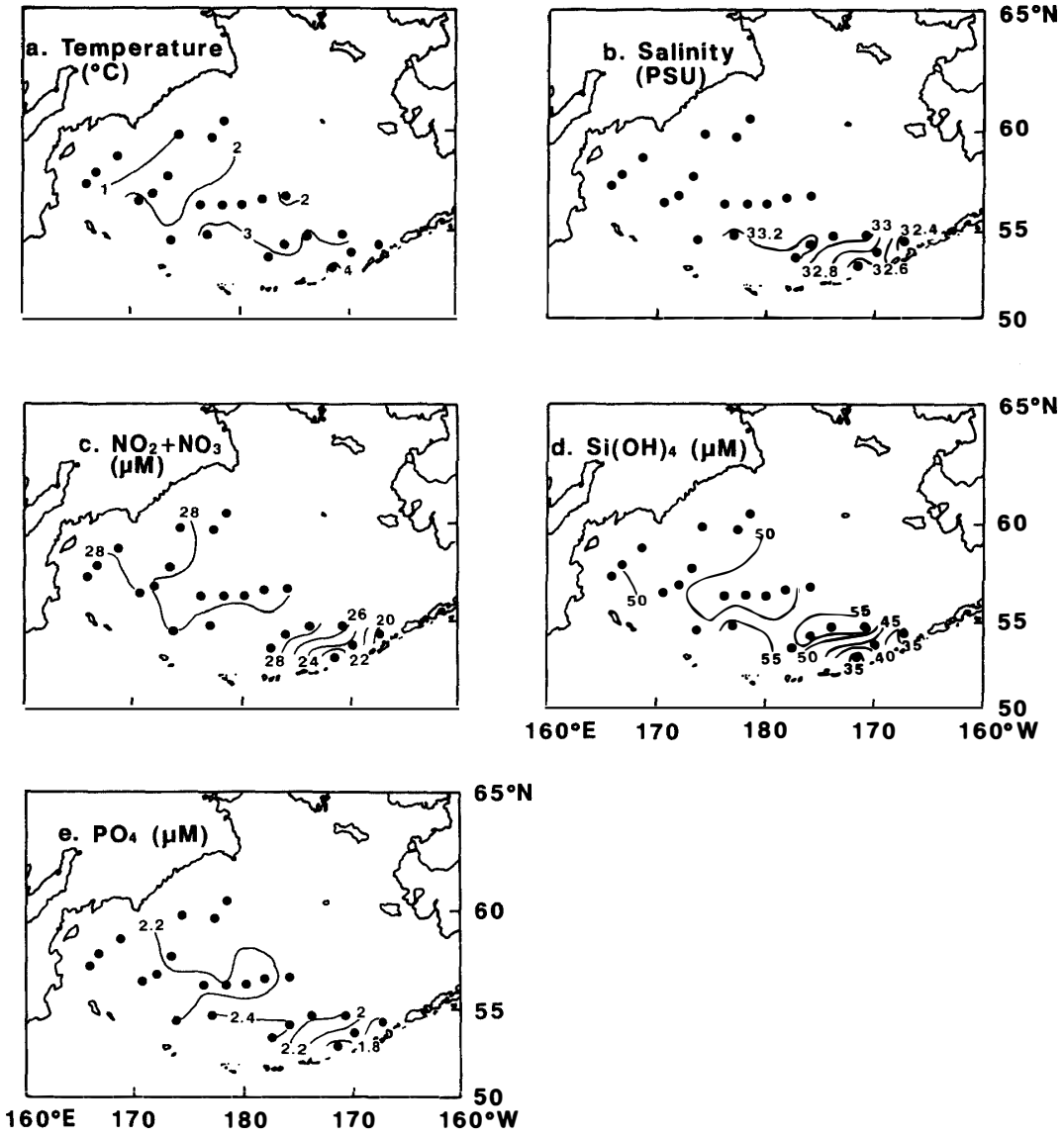

Fig. 2. Regional variations of temperature (a), salinity (b), and nitrite + nitrate (NO_2+NO_3; c), silicate ($Si(OH)_4$; d) and phosphate (PO_4; e) concentrations at the surface.

and 0.69 μM for PON (Table 1). Relatively high values for both POC and PON, exceeding the averages, were mostly observed in the eastern region (Fig. 3b, c). Chl *a* concentrations showed variations of several fold among stations, ranging from 0.12 to 0.70 $\mu g\ l^{-1}$ (Fig. 3d). The average was 0.33 $\mu g\ l^{-1}$ (Table 1). The Chl *a* concentration was more uniform among stations than BSi concentration. Relatively high Chl *a* concentrations exceeding the average were mostly observed in the eastern region (Fig. 3d). These results are similar to those for POC and PON.

Significant linear relationships were observed between POC and Chl *a* concentrations, and between PON and Chl *a* concentrations, whereas no significant relationship was found between BSi and Chl *a* concentrations (Fig. 4). Regional variations of POC and PON concentrations represented that of the phytoplankton biomass.

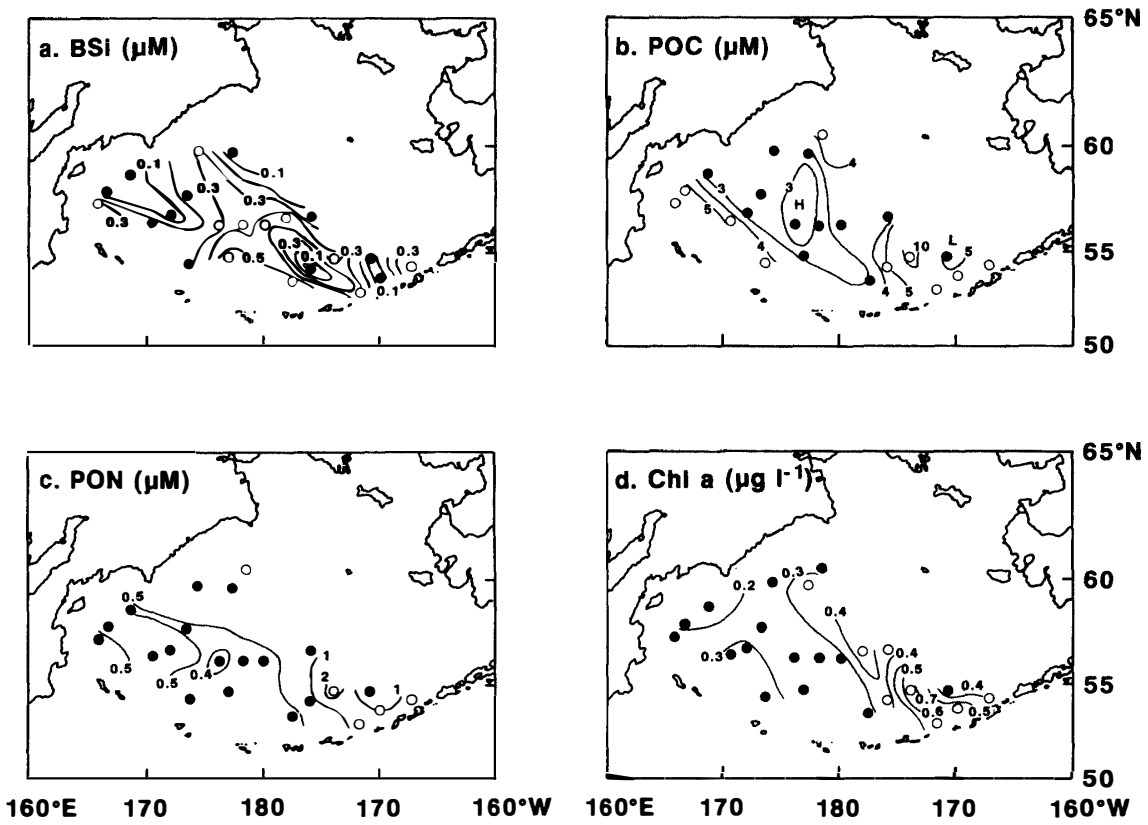

Fig. 3. Regional variations of biogenic silica (BSi; a), particulate organic carbon (POC; b), particulate organic nitrogen (PON; c) and chlorophyll *a* (Chl *a*; d) concentrations at the surface. Open circles indicate stations with values exceeding the averages. Ranges and averages are shown in Table 1.

Table. 1. Particulate matter and chlorophyll *a* concentrations and composiotion of particulate matter at the surface in the Bering Sea basin in winter 1993.

	Range	Maximum/ minimum	Average ± SD	Number of data
BSi (μM)	0.01–0.59	59	0.27 ± 0.18	22
POC (μM)	2.28–11.38	5.0	4.31 ± 2.07	22
PON (μM)	0.36–2.11	5.9	0.69 ± 0.39	22
Chl *a* (μg l^{-1})	0.12–0.70	5.8	0.33 ± 0.14	23
BSi/POC (atomic ratio)	<0.01–0.21	>21	0.07 ± 0.061	21
POC/PON (atomic ratio)	3.5–12.1	3.5	6.7 ± 2.2	22
POC/Chl *a* (weight ratio)	103–364	3.6	168 ± 62	22

Moreover, the Spearman rank correlation was not significant between BSi and Chl *a* concentrations (r_s = 0.063, $P > 0.7$), though the correlation was significant between POC and Chl *a* concentrations (r_s = 0.47, $P < 0.05$), and between PON and Chl *a* concentrations (r_s = 0.70, $P < 0.005$).

Composition of biogenic particulate matter

The atomic ratios of BSi to POC (BSi/POC ratio) showed extraordinary variation

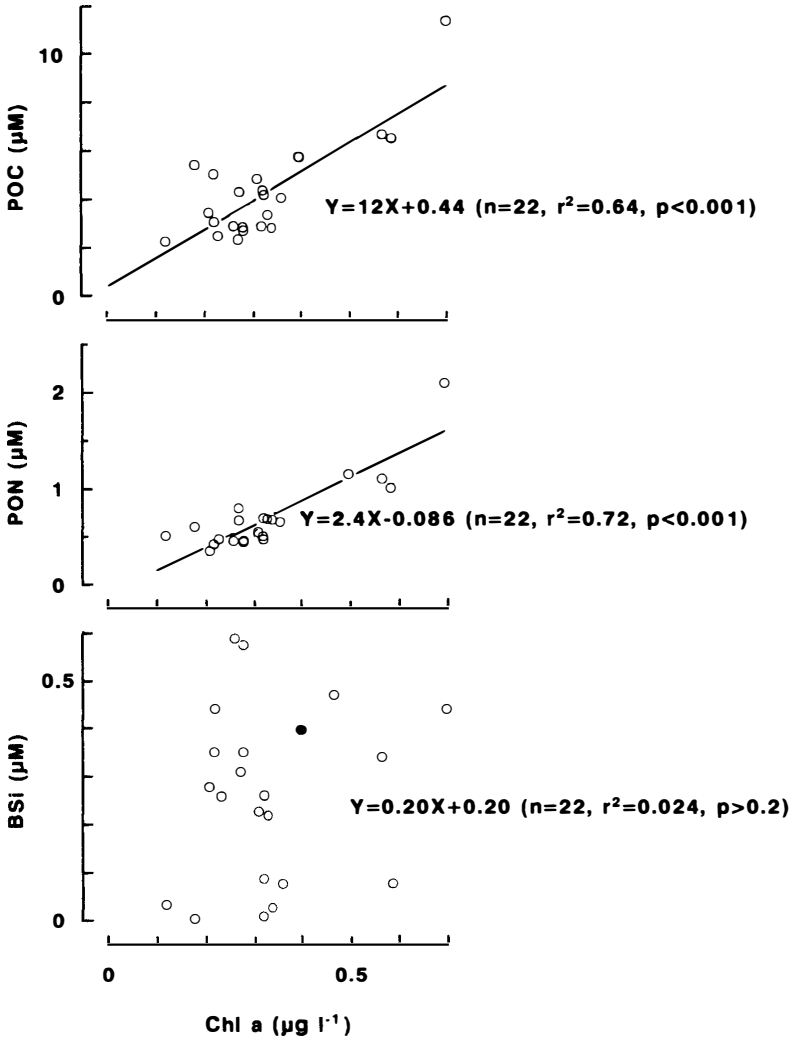

Fig. 4. Relationship between Chl *a* concentration and biogenic particulate matter (POC, PON and BSi) concentrations.

among stations, ranging from <0.01 to 0.21 (Fig. 5a). The average was 0.070 (Table 1). Relatively high values exceeding the average were observed in the western and central regions, particularly frequently in the central region. The atomic ratio of POC to PON (POC/PON ratio) was in the range of 3.5 to 12.1, mostly in the range of 4 to 10 (Fig. 5b). The POC/PON ratio was more uniform among stations than the BSi/POC ratio. The average was 6.7 (Table 1), almost equal to the Redfield ratio (C/N atomic ratio: 6.6; Redfield *et al.*, 1963). The weight ratio of POC to Chl *a* (POC/Chl *a* ratio) was in the range of 103 to 367, mostly in the range of 100 to 200. The average was 168 (Table 1).

Discussion

The results showed that biogenic particulate matter was more silicon-rich in the central region than elsewhere (Fig. 5a). BSi concentrations were relatively higher in the central region (Fig. 3a), whereas POC and PON concentrations were not especially low in

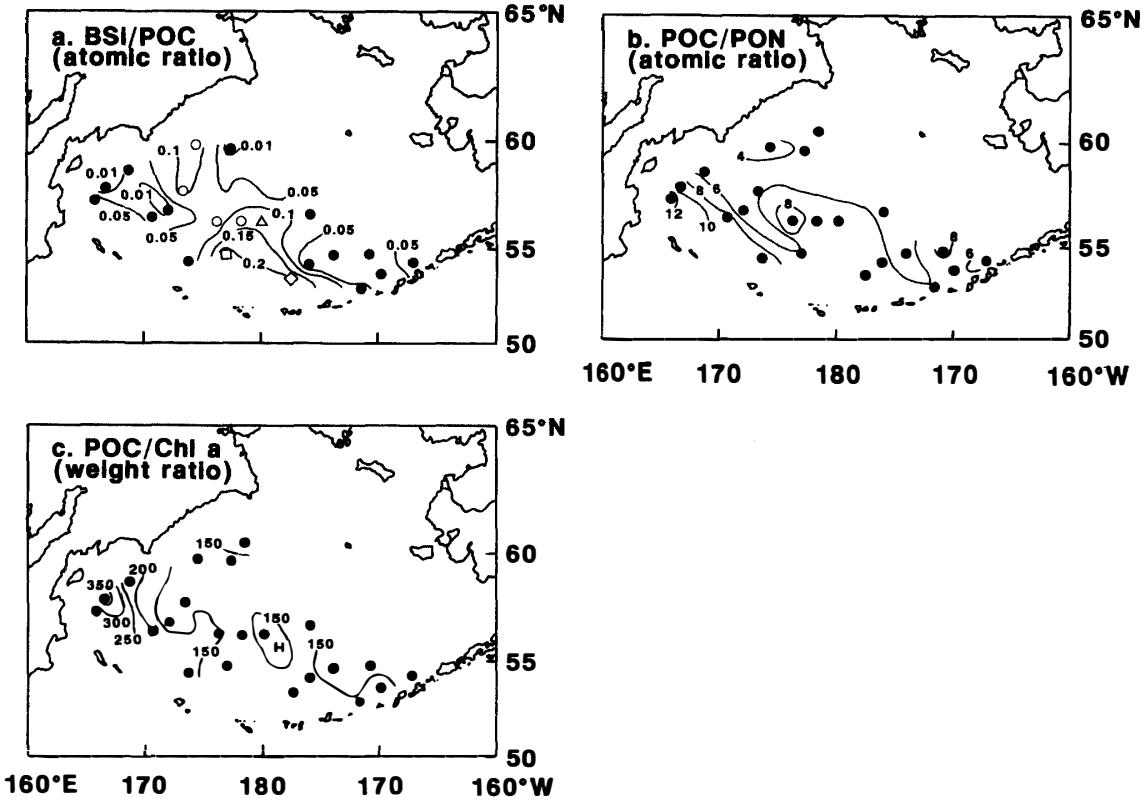

Fig. 5. Regional variations of BSi/POC (a), POC/PON (b) and POC/Chl *a* (c) at the surface. In Fig. 5a, open symbols indicate stations with values exceeding the averages. △ : BSi/POC=0.14 ; ◇ : BSi/POC=0.20; □: BSi/POC=0.21. Ranges and averages are shown in Table 1.

the central region (Fig. 3b, c). The presence of silicon-rich biogenic particulate matter was attributed to the high BSi concentration. Studies previously conducted in spring through autumn show that diatoms make up the basis of the deep basin phytoplankton community; the cell density of diatoms varies regionally (Motoda and Minoda, 1974; Sukhanova *et al.*, 1999). Diatoms contain silicon as well as carbon and nitrogen, and thus probably contribute greatly to the distribution of BSi in the Bering Sea basin. Consequently, there is a possibility that the diatom cell density varies regionally even in winter and diatom cells are relatively abundant in the central region; needless to say, this possibility should be confirmed by observations.

Brzezinski (1985) assessed the variation in the atomic ratios of cellular silicon to cellular carbon among 27 species of marine diatoms in culture grown in the following conditions: nutrient repletion, non-light limited (180–200 μEin m^{-2} s^{-1}), 18:6 h light:dark (LD) cycle and constant temperature of 19°C. The cell volume spanned three orders of magnitude, whereas the cellular silicon to cellular carbon ratios ranged from 0.04 to 0.43 with the vast majority of species having ratios between 0.04 and 0.17. The mean ± 95% confidence intervals of the ratio was 0.13 ± 0.04. Moreover, Brzezinski (1985) reviewed an abundance of literature and suggested that interactions among environmental variables (light intensity, photoperiod, temperature, nutrient limitation, species differences) do not produce cellular silicon to cellular carbon ratios beyond the factor of the two- to threefold

range. The variables have no pronounced effect on the ratio. The mean ratio, 0.13, is thus considered to be a typical value for marine diatoms grown in different conditions.

BSi is mostly made up of diatoms in the Bering Sea basin (see above), whereas POC consists of other phytoplankton as well as diatoms. Thus, the atomic ratio of cellular silicon to cellular carbon in diatoms is higher than the BSi/POC ratio. BSi/POC ratios exceeding 0.13 were found at the three stations in the central region (BSi/C: 0.14, 0.20 and 0.21) (Fig. 5a). The atomic ratios of silicon to carbon for diatom cells can exceed 0.13 even in the case of BSi/POC<0.13. Consequently, the atomic ratios of silicon to carbon for diatom cells were definitely higher than 0.13 at least at the three stations. High BSi/POC ratios exceeding 0.13 have been more frequently reported in summer, suggesting a high silicon demand for diatoms (Shiomoto and Ogura, 1994). There is a strong possibility of the occurrence of such diatoms even in winter. However, the relatively high Chl *a* concentrations were not found in the region where the relatively high BSi/POC ratios were observed (Figs. 3d, 5a), suggesting an insignificant contribution of diatoms to phytoplankton biomass and hence an unimportance of diatoms as primary producers throughout the Bering Sea basin in winter. Moreover, the ratio of average BSi concentration to average Chl *a* concentration in winter (0.27 μM/0.33 μg l^{-1}) was remarkably lower than that in summer (5.52 μM/0.80 μg l^{-1}) (Table 2), suggesting that diatoms contribute less to phytoplankton biomass and hence are less important primary producers in winter than in summer.

Table 2. Avarages of particulate matter and chlorophyll *a* concentrations and atomic ratios of particulate matter.

	Bering Sea basin in winter[a]	Bering Sea basin in summer[b]	Antarctic Ocean in winter[c]
BSi (μM)	0.27	5.52	0.26
POC (μM)	4.31	29.0	5.2
PON (μM)	0.69	4.79	0.51
Chl *a* (μg l^{-1})	0.33	0.80	0.12
BSi/POC (atomic ratio)	0.07	0.18	0.05
POC/PON (atomic ratio)	6.7	6.5	10.2

a: Present study.

b: Cited from Shiomoto and Ogura (1994). The data were obtained at the surface of the stations located between 55°46′N–57°42′N and 177°57′E–177°57′W. The number of data is 16.

c: Cited from Cota *et al.* (1992). The data were obtained in the upper 150 m in the marginal ice zone in the Weddell-Scotia Sea.

As described in the Introduction, the characteristics of biogenic particulate matter in the Bering Sea basin and the Antarctic Ocean are similar, that is, silicon-rich in summer. In winter, average BSi/POC ratios are somewhat higher in the Bering Sea basin than in the Antarctic Ocean (Table 2). BSi/POC ratios exceeding 0.1 are rare in the wintertime Antarctic Ocean (Cota *et al.*, 1992; Leynaert *et al.*, 1993). In contrast, higher BSi/POC ratios (0.14, 0.19 and 0.21) exceeding the average of culture diatoms (0.13) were observed in the Bering Sea basin even in winter (Fig. 5a). The ratios of 0.10–0.13 were also found at the additional three stations. Thus, if anything, biogenic particulate matter in the Bering Sea basin in winter is possibly characterized by being more silicon-rich than in

the Antarctic Ocean. On the other hand, average Chl *a* concentration was higher in the Bering Sea basin than in the Antarctic Ocean in winter, whereas average BSi concentrations were almost equal in both regions (Table 2). The ratio of BSi concentration to Chl *a* concentration was lower in the Bering Sea basin (0.27 μM/0.33 $\mu g\ l^{-1}$) than in the Antarctic Ocean (0.26 μM/0.12 $\mu g\ l^{-1}$). This suggests that the contribution of diatoms to phytoplankton biomass is smaller and hence diatoms are less important primary producers in the Bering Sea basin than in the Antarctic Ocean in winter.

Future problems include elucidating the role of diatoms which possibly contribute to silicon-rich biogenic particulate matter in the Bering Sea basin in winter.

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