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Millennial-scale paleoceanographic events and implication for the intermediate-water ventilation in the northern slope area of the Bering Sea during the last 71 kyrs

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ABSTRACT

Millennial-scale paleoceanographic changes in the Bering Sea during the last 71 kyrs were reconstructed using geochemical and isotope proxies (biogenic opal, $CaCO_3$, and total organic carbon (TOC), nitrogen and carbon isotopes of sedimentary organic matters) and microfossil (radiolaria and foraminifera) data from two cores (PC23A and PC24A) which were collected from the northern continental slope area at intermediate water depths. Biogenic opal and TOC contents were generally high with high sedimentation rates during the last deglaciation. Laminated sediment depositions during the Early-Holocene (EH) and Bølling-Allerød (BA) were closely related with the increased primary productivity recorded by high biogenic opal and TOC contents and high $\delta^{15}N$ values. Enhanced surface-water productivity was attributed to increased nutrient supply from strengthened Bering Slope Current (BSC) and from increased amount of glacial melt-water, resulting in high C/N ratios and low $\delta^{13}C$ values, and high proportion of *Rhizoplegma boreale* during the last deglaciation. In contrast, low surface-water productivity during the last glacial period was due to depleted nutrient supply caused by strong stratification and to restricted phytoplankton bloom by extensive sea ice distribution under cold climates. Extensive formation of sea ice produces more oxygen-rich intermediate-water, leading to oxic bottom-water conditions due to active ventilation, which favored good preservation of oxic benthic foraminifera species. Remarkable $CaCO_3$ peaks coeval with high biogenic opal and TOC contents in both cores during MIS 3 to MIS 4 are most likely correlated with Dansgaard–Oeschger (D–O) events. High $\delta^{15}N$ and $\delta^{13}C_{org}$ values during D–O interstadials support increased surface-water productivity resulting from nutrients supplied mainly by intensified BSC. During the EH, BA and D–O interstadials, dominant benthic foraminifera species indicate dysoxic bottom-water conditions as a result of increased surface-water productivity and weak ventilation of intermediate-water with mitigated sea ice development caused by strengthening of the Alaskan Stream. It is of note that the bottom-water conditions and formation of intermediate-water in the Bering Sea during the last glacial period are related to the variation of dissolved oxygen concentration of the bottom-water in the northeastern Pacific and to strong ventilation of intermediate-water in the northwestern Pacific. Thus, the millennial-scale paleoceanographic events in the Bering Sea during the D–O interstadials are closely associated with the intermediate-water ventilation, ultimately leading to weakening of North Pacific Intermediate Water.

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1. Introduction

The Bering Sea is a marginal sea in the subarctic Pacific Ocean. Because the Bering Sea is characterized by high surface-water productivity (Springer et al., 1996; Grebmeier et al., 2006), it has a great potential to drawdown atmospheric CO_2 by biological pump process (Kaltin and Anderson, 2005). With respect to paleoproductivity changes in the Bering Sea, Holocene surface-water productivity was higher than during the last glacial period (Nakatsuka et al., 1995; Gorbarenko et al., 2005; Okazaki et al., 2005, 2010; Brunelle et al., 2007; Caissie et al., 2010). Higher surface-water productivity during the Holocene was explained by enhanced nutrient supply from the deep subsurface water by strong vertical mixing (e.g., Nakatsuka et al., 1995) and by strengthened Alaskan Stream injection through the Aleutian passes (e.g., Okazaki et al., 2005). In contrast, low productivity during the last glacial period was likely due to suppression of nutrient supply from the deep subsurface water (Brunelle et al., 2007) and restricted phytoplankton bloom due to the light limitation by extensive sea ice distribution (Tanaka and Takahashi, 2005).

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Several studies in association with millennial-scale Dansgaard–Oeschger (D–O) cycles have been carried out in the northern North Pacific (Kiefer et al., 2002), Santa Barbara Basin (Behl and Kennett, 1996), California continental margin (Hendy and Pedersen, 2005), and Gulf of Alaska (Pride et al., 1999). Based on oxygen isotopes of planktonic foraminifera, Kiefer et al. (2001) reported cooling in the northwestern subarctic Pacific at warm D–O interstadials during Marine Isotope Stage (MIS; Martinson et al., 1987) 3, in contrast to the Atlantic Ocean. However, warming in the Santa Barbara Basin was observed during warm D–O interstadials in synchronous with the Atlantic Ocean (Hendy and Kennett, 2000). In addition, based on bioturbation index in the Santa Barbara Basin, Behl and Kennett (1996) suggested that changes of millennial-scale ventilation were closely related with D–O cycles. Thus, millennial-scale paleoclimate changes are also expected in the Bering Sea.

A few investigations on the millennial-scale paleoclimate changes during the last deglacial period have been recently conducted in the Bering Sea (Cook et al., 2005; Gorbarenko et al., 2005, 2010; Okazaki et al., 2005; Brunelle et al., 2007; Itaki et al., 2009; Caissie et al., 2010; Khim et al., 2010). Most of these studies revealed that a series of dramatic changes of productivity, $CaCO_3$, $\delta^{18}O$ of both planktonic and benthic foraminifera, and sedimentary lithology are synchronous with deglacial events (Bølling-Allerød; BA, Younger Dryas; YD, and Early Holocene; EH) identified in GISP2 $\delta^{18}O$ (Grootes et al., 1993). Unfortunately, most of these previous studies have been carried out in the southern part of the Bering Sea. Gorbarenko et al. (2005) suggested that three $CaCO_3$ peaks during MIS 3 correspond to warm D–O interstadials in the Bowers Ridge of the southern Bering Sea. Although Itaki et al. (2009) reported millennial-scale paleoceanographic events in the northern part of the Bering Sea during the last 61 kyrs, knowledge about millennial-scale paleoproductivity changes and associated paleoceanographic conditions in terms of intermediate-water ventilation has been rarely obtained so far.

In this study, we document geochemical (biogenic opal, $CaCO_3$, total organic carbon (TOC)) and isotope (nitrogen and carbon isotopes of sedimentary organic matters) proxies from core PC24A and microfossil (foraminifera) data from core PC23A collected from the northern slope area of the Bering Sea. We also reconstruct millennial-scale paleoceanographic changes with respect to surface-water paleoproductivity and intermediate-water ventilation during the last 71 kyrs in the Bering Sea.

2. Study area

The Bering Sea is composed of a deep (>3500 m) basin in the southwestern half and broad and shallow (<200 m) continental shelves in the northeastern half. About two thirds of the northeastern continental shelf are covered with seasonal sea ice during the winter, but become ice-free during the summer (Niebauer, 1998). Sea ice generally begins to form in November over the continental shelf, and reaches its maximum in March. Inter-annual variability of sea ice formation mainly depends on winter insolation, atmospheric advection, and position of pressure system (Niebauer, 1998; Katsuki et al., 2009). Sea ice is not formed over the deep basin today.

Surface circulation in the Bering Sea is characterized by a large cyclonic gyre, with the southward flowing Kamchatka Current as a western boundary current and the northward flowing Bering Slope Current (BSC) as an eastern boundary current (Fig. 1; Stabeno et al., 1999). The BSC is formed by northward turning of the eastward flowing Aleutian North Slope Current at the point where water depth becomes about 200 m deep. The circulation system in the Bering Sea is strongly influenced by the Alaskan Stream (i.e., warm North Pacific Ocean water) which flows northward through many passes in the Aleutian Islands Arc (Overland and Pease, 1982; Stabeno et al., 1999). Some part of the Bering Sea water flows continuously northward through the Bering Strait into the Arctic Ocean (Coachman and Aagaard, 1981).

Deep-water circulation in the Bering Sea has not been fully understood. Warner and Roden (1995) reported that in the present-day a little deep-water formation occurred by brine rejection caused by sea ice formation during the winter. Stabeno et al. (1999) suggested that the path of deep-water above 3000 m flows through the Kamchatka Strait from the northwestern Pacific must be northward and eastward, which is located in the westernmost of the Aleutian Islands Arc (Fig. 1). In contrast, deep-water below 3000 m flows southward out of the Bering Sea into the northwestern Pacific through the Kamchatka Strait (Stabeno et al., 1999).

Because nutrient-rich BSC waters and high summer solar insolation create one of the world's most productive ecosystems (Walsh et al., 1989), a local region of very high primary production (i.e., Green Belt) is located along the continental shelf-slope front in the Bering Sea (Springer et al., 1996). Okkonen et al. (2004) reported that high chlorophyll *a* concentrations are associated with clockwise eddy group propagation derived by the BSC. Hydrocasting CTD surveys also revealed that the BSC is highly variable, interspersed with eddies, meanders, and instabilities (Kinder et al., 1975), which can deliver new nutrients to the euphotic zone and stimulate new production. Thus, high surface-water productivity along the shelf-slope area of the Bering Sea is closely related to the strength of the BSC.

3. Materials and methods

Three piston cores (PC23A, PC24A, and PC25A; about 12 km far from each other) were collected from the northern continental slope area in the Bering Sea by R/V Mirai of JAMSTEC during MR06-04 in 2006 (Fig. 1; Table 1). Subsamples for further analyses were obtained on board at about 2.5 cm intervals, after the lithologic description. Sediments of three cores are composed largely of diatomaceous silty or sandy clay with some laminated intervals (Fig. 2).

Because all three cores are located in the same region of very high primary production, the BSC plays a significant role in pumping new nutrients into the euphotic zone. In addition, seasonal sea ice variability is an important factor to alter surface-water properties because three cores are influenced by the southern/southwestern boundary of seasonal sea ice today.

3.1. Geochemical (biogenic opal, $CaCO_3$, and TOC) analyses

Biogenic silica (Si_{BIO}) content was measured using a wet alkaline extraction method modified from DeMaster (1981) and Müller and Schneide (1993) at Pusan National University. The relative error of Si_{BIO} content in sediment samples is less than $\pm 1\%$. The opal content was calculated by multiplying Si_{BIO} content by 2.4 (Mortlock and Froelich, 1989). Total inorganic carbon (TIC) content was measured using UIC CO_2 coulometer (Model CM5014) at Pusan National University. TIC content is used to calculate $CaCO_3$ content as weight percentage by the multiplication of factor 8.333. The analytical precision of $CaCO_3$ content as relative standard deviation is $\pm 1\%$. Total carbon (TC) and total nitrogen (TN) contents were measured by Flash 2000 Series Elemental Analyzer. The analytical precision of both parameters are less than $\pm 0.1\%$ for TC and less than $\pm 0.01\%$ for TN, respectively. TOC content was calculated by the difference between TC and TIC.

3.2. Stable isotope analysis

Sediment samples of core PC24A for stable carbon and nitrogen isotope analyses were measured using the EA-IRMS (Europa Scientific RoboPrep-CN elemental analyzer) at Iso-Analytical Ltd. Untreated sediment powders were used to measure stable nitrogen isotopes, whereas acid treated sediment powders were used to measure stable

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