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Millennial-scale variations of late Pleistocene radiolarian assemblages in the Bering Sea related to environments in shallow and deep waters

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ABSTRACT

A high-resolution record of the radiolarian assemblage from 60 to 10 ka was investigated using a piston core (PC-23A) obtained from the northern slope of the Bering Sea. Faunal changes based on the 29 major radiolarian taxa demonstrated that the surface and deep water conditions in the Bering Sea were related to the orbital and millennial-scale climatic variations known as glacial–interglacial and Dansgaard–Oeschger (D–O) cycles, respectively. During interstadial periods of the D–O cycles, the assemblage was characterized by increases in the high-latitude coastal species *Rhizoplegma boreale* and the upper-intermediate water species *Cycladophora davisiana*, while the sea-ice related species *Actinomma boreale* and *A. leptodermum* and many deep-water species such as *Dictyophimus crisiae* and *D. hirundo* tended to be reduced. This trend was more apparent in two laminated intervals at 15–13.5 and 11.5–11 ka, which were correlated with well-known ice-sheet collapse events that occurred during the last deglaciation: melt-water pulse (MWP)-1A and MWP-1B, respectively. The radiolarian faunal composition in these periods suggests that oceanic conditions were different from today: (1) surface water was affected by increased melt-water discharge from continental ice-sheet, occurring at the same time as an abrupt increase in atmospheric temperature, (2) upper-intermediate water (ca. 200–500 m) was well-ventilated and organic-rich, and (3) lower-intermediate water (ca. 500–1000 m) was oxygen-poor. Conversely, the sea-ice season might have been longer during stadial periods of the D–O cycles and the last glacial maximum (LGM) compared to the interstadial periods and the earliest Holocene. In these colder periods, deep-water species were very abundant, and this corresponded to increases in the oxygen isotope value of benthic foraminifera. Our findings suggest that the oxygen-rich water was present in the lower-intermediate layer resulting from intensified ventilation.

1. Introduction

Regional climatic variations in the subarctic Pacific and its marginal seas are associated with millennial-scale climatic changes recognized in the Greenland ice-core record known as Dansgaard–Oeschger (D–O) cycles (Tada et al., 1999; Kiefer et al., 2001; Gorbarenko et al., 2005; Sakamoto et al., 2006). Intermediate water ventilation in the North Pacific occurs via North Pacific Intermediate Water (NPIW) at depths of ca. 300–800 m in the present day (Ried, 1965), while NPIW apparently reached as deep as 2000 m during the last glacial period (Keigwin, 1998; Matsumoto et al., 2002). In addition, this water is interpreted to have extended as far as south to the California margin during stadials of the D–O cycles (Behl and Kennett, 1996; Tada et al., 2000). One major modern source area for NPIW formation is the Sea of Okhotsk (Yasuda, 1997), where the formation is closely related to dense water on the shelf, as a result of brine rejection occurring during winter sea-ice production (Kitani, 1973).

Based on the changes in abundance of the intermediate water-dwelling radiolarian species *Cycladophora davisiana*, it has been hypothesized that the Bering Sea might be a source area for glacial NPIW formation (Ohkushi et al., 2003; Tanaka and Takahashi, 2005). Although Khusid et al. (2006) reported faunal abundance changes of benthic foraminiferal tests related to the D–O cycles in a well-dated core from the southern Bering Sea (GC-11), but the benthic foraminiferal record is only representative of seafloor conditions, i.e., 3000 m at the GC-11 core.

Polycyctine radiolarians (hereafter, radiolarians) belong to a planktonic protista group characterized by an opaline skeleton that is one of the major components in deep-water sediments from the subarctic Pacific region. The fossil record of radiolarians is a potential paleoceanographic indicator for surface- and deep-water

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conditions due to the discrete depth habitats of specific radiolarian species. Several previous studies of the late Pleistocene and Holocene radiolarians have been performed in the Bering Sea (Blueford, 1983; Morley and Robinson, 1986; Tanaka and Takahashi, 2005; Wang and Chen, 2005; Itaki et al., 2009). However, these studies have only documented abundance changes for a few species, including *C. davisiana*, and detailed faunal compositions and their temporal changes are therefore not well understood.

In order to reconstruct paleoceanographic conditions through the water column in the Bering Sea, we examined high-resolution changes in the radiolarian assemblage during the late Pleistocene based on a well-dated core (PC-23A) from the northern slope of the Bering Sea. Variations in the abundance of *C. davisiana* and geochemical components including the total organic carbon (TOC), biogenic opal and calcium carbonate ($CaCO_3$) were previously reported from this core (Itaki et al., 2009; Kim et al., 2009). Furthermore, stable oxygen isotope of benthic foraminifera has been measured (Rella et al., submitted). It is expected that the high-resolution record of these proxies will reconstruct the vertical oceanographic conditions from the sea-surface to the seafloor to be revealed by the combined interpretations of radiolarians, geochemical components, oxygen isotope record and lithological facies throughout the core.

2. Oceanographic setting

The Bering Sea, which is surrounded by the Aleutian Islands and the Siberian and Alaskan coasts, is the largest marginal sea in the North Pacific, with a total area of 2.3×10^6 km^2 (Fig. 1). The northeastern area of this sea is shallower than 200 m and forms part of a wide continental shelf, which continues through the Bering Strait into the Chukchi Sea in the western Arctic. Deep basins in the southwestern portion of the Bering Sea reach depths of 3800–3900 m.

The major water exchange between the Bering Sea and the North Pacific is believed to occur between 168°E and 172°E, where the sill depth of the Aleutian Arc is 1589 m (Tomczak and Godfrey, 1994). A significant portion of the Alaskan Stream enters the Bering Sea through this passage, turning east and driving a cyclonic gyre in the deep part of this sea as the Bering Slope Current. A large part of the water carried by the inflow from the Alaskan Stream leaves the Bering Sea as the Kamchatka Current, with some leakage through the Bering Strait.

The water mass structure is controlled by advection of water from the North Pacific and modification of the water properties. Sea surface temperature and salinity in the basin vary seasonally from 2 to 10 °C and from 33 to 33.5 °C, respectively. The entire shelf is generally covered with sea-ice during the winter. In addition, a pronounced temperature minimum (<2 °C) at a depth of 100 m is formed by vertical mixing of the surface-water during winter cooling, while a temperature maximum (ca. 4 °C) at 300 m is maintained by waters from the North Pacific by the Alaskan Stream. Salinity increases rapidly from low surface values to 34 within the upper 300 m. An oxygen minimum zone (OMZ) usually develops between 300 and 1000 m.

"Green Belt" is a term referring to the observation that much of the high primary production in the Bering Sea seems to be concentrated along the shelf break (Springer et al., 1996). Nutrient-rich waters are supplied to the surface from deeper depths via vertical mixing in cyclonic eddies occurring along the Bering Slope Current (Mizobata et al., 2002; Mizobata and Saitoh, 2004).

3. Materials and methods

Piston core PC-23A (17.5 m) was obtained from the northern slope of the Bering Sea (60°09.52′N, 179°27.82′W, water depth 1002 m, Fig. 1) during MR06-04 cruise of the R/V *Mirai* operated by JAMSTEC. The sediment was primarily composed of diatomaceous silty or sandy clays, with some intercalated laminated layers (Fig. 2). An ash layer was identified at a depth of 1.5 m in the core, but its original primary structure was artificially destroyed during piston coring. Therefore, soft sediments around this ash layer might be somewhat disturbed.

In this study, a total of 106 sub-samples (2.2 cm thickness taken at 10–20 cm intervals) of core PC-23A were used for the radiolarian analysis. Analytical procedures have been described in detail by Itaki et al. (2009). Briefly, freeze-dried sub-samples (1–5 g) were weighed and then treated with 15% H_2O_2 and HCl solution to remove the organic matter and the calcium carbonate, respectively. The samples were then wet sieved (45 μm mesh size), after which two types of slides were made from the residue to quantify the abundance (Q-slide) and for the faunal analysis (F-slide). To prepare the Q-slides, all of the residue was transferred to a 100-ml beaker that contained 50-ml of distilled water. The solution was then well mixed, after which a 0.2-ml sample was taken from the suspension using a micropipette and dropped onto a glass slide. The sample was then dried and mounted with

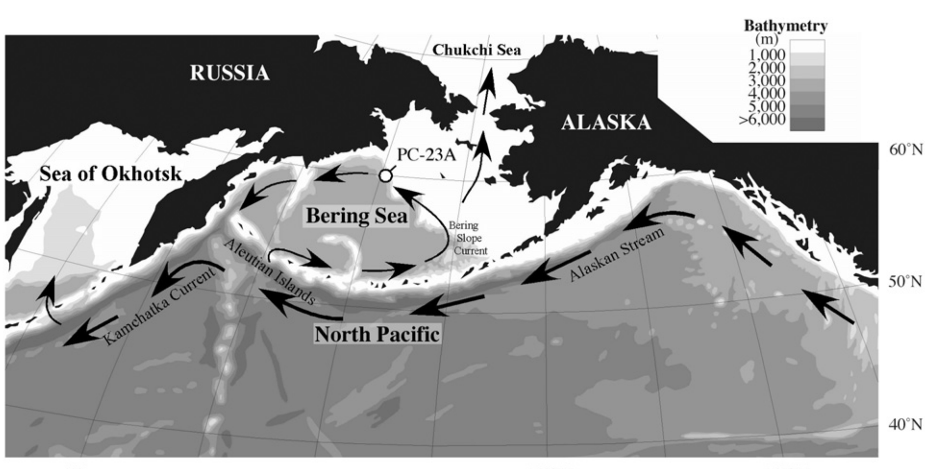

Fig. 1. Map showing the core site PC-23A and bathymetry in the Bering Sea.