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Glacial to deglacial ventilation and productivity changes in the southern Okhotsk Sea

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ABSTRACT

As a source region of North Pacific Intermediate Water, the Okhotsk Sea plays an important role in the ventilation of the North Pacific. To understand the detailed oceanographic changes in this marginal sea since the last glaciation, we studied decadal to centennial scale proxy records from new sediment cores from the southwestern Okhotsk Sea. Glacial to Holocene $\Delta^{14}C$ records of benthic foraminiferal shells suggested enhanced ventilation in the Okhotsk Sea during the early deglacial period between 18 and 15 ka, corresponding to Heinrich Event 1. Although the $\Delta^{14}C$ reconstruction has considerable uncertainties, the Okhotsk Sea may have acted as a source for vigorous ventilation of the subarctic Pacific during this period. $CaCO_3$ preservation events appear to be better explained by the ventilation history of the Okhotsk Sea than by coccolithophores and foraminifera production. $CaCO_3$ preservation started to improve during 18 to 15 ka, and pronounced peaks in the $CaCO_3$ content corresponded to the Bølling–Allerød (15 to 13 ka) and Preboreal (11.5 to 10 ka) warm periods. Diatom and coccolithophore productivity remained low in the Okhotsk Sea throughout the glacial to deglacial periods, different from the situation in the open subarctic Pacific, where high productivity was observed during the Bølling–Allerød period. After the Preboreal period, biogenic opal gradually increased and $\delta^{15}N$ decreased in the southern Okhotsk Sea, suggesting that productivity was enhanced by a relaxation of the nitrate limitation.

1. Introduction

The Okhotsk Sea is a marginal sea in the western North Pacific that is connected to the North Pacific via passes between the Kuril Islands and to the Japan Sea via the Soya and Tartar straits (Fig. 1). The counterclockwise surface circulation of the Okhotsk Sea is a part of the subarctic circulation system of the North Pacific (Dodimead et al., 1963; Favorite et al., 1976). In the Northern Hemisphere, the Okhotsk Sea represents one of the southernmost areas of sea-ice coverage. A large volume of brine, called dense shelf water (DSW), is left behind by the formation of sea ice above the northwestern shelf of the Okhotsk Sea (Martin et al., 1998), and this DSW is a major source of Okhotsk Sea Intermediate Water (OSIW). The outflow of OSIW from the Okhotsk Sea, mainly through the Bussol' Strait, is an important contributor to North Pacific Intermediate Water (NPIW) formation (e.g., Talley, 1991).

During the last glacial maximum (LGM), a well-ventilated water mass called Glacial North Pacific Intermediate Water (GNPIW) was distributed in the upper 2000 m of the North Pacific (Keigwin, 1998; Matsumoto et al., 2002). The ventilation source of GNPIW is not specified, but the subarctic Pacific and its marginal seas (including the Okhotsk Sea) are likely candidates (Matsumoto et al., 2002). The glacial-to-deglacial ventilation history of the Okhotsk Sea is under debate. From the ^{14}C ages of coexisting benthic and planktonic foraminifera, Keigwin (2002) inferred that mid-depth ventilation in the Okhotsk Sea was not greater during the LGM than at present. Subsequently, Ohkushi et al. (2003) inferred from the distribution of *Cycladophora davisiana*, a radiolarian species that lives in well-ventilated intermediate water, that GNPIW was formed not in the Okhotsk Sea but in the Bering Sea. However, abundances of *C. davisiana* in the Okhotsk Sea, particularly the southern Okhotsk Sea, were not low throughout the glacial period (Okazaki et al., 2005a; Itaki et al., 2008). In addition, glacial-to-deglacial ventilation in the western subarctic Pacific showed large variation associated with a major reorganization of the meridional overturning circulation (Ahagon et al., 2003; Sagawa and Ikehara, 2008; Okazaki et al., 2010). Therefore, to understand paleoceanographic changes in the North Pacific realm, an improved understanding of glacial-to-deglacial changes in the ventilation history of the Okhotsk Sea is needed.

At present, the Okhotsk Sea is characterized by high biological productivity during spring and autumn in association with diatom blooms (Sorokin and Sorokin, 1999, 2002). During the last glacial period, however, biological productivity was low in the subarctic Pacific and its marginal seas because of enhanced stratification (e.g., Narita et al., 2002;

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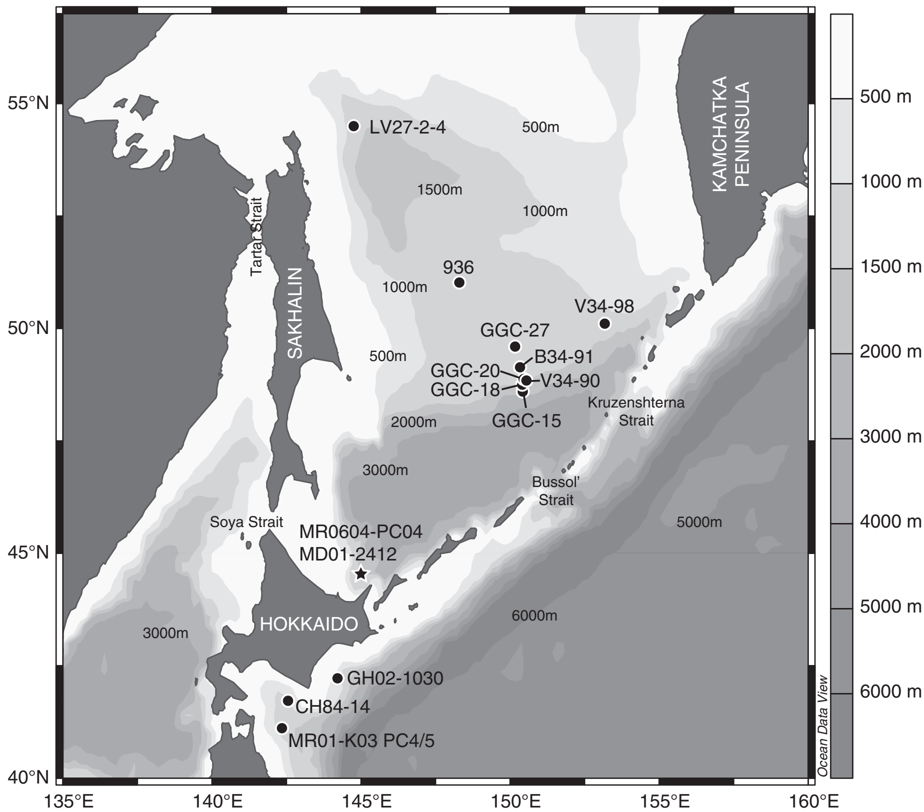

Fig. 1. Locations of sediment core sites MR06-04 PC04 and MD01-2412 (solid star) and of other sediment core sites, described in previous studies, in the Okhotsk Sea and the western subarctic Pacific (solid circles).

Sato et al., 2002; Seki et al., 2004a; Jaccard et al., 2005; Okazaki et al., 2005a,b; Brunelle et al., 2007, 2010; Galbraith et al., 2007; Shigemitsu et al., 2007; Caissie et al., 2010; Kohfeld and Chase, 2011; Iwasaki et al., 2012; Khim et al., 2012). In the Okhotsk Sea, paleoceanographic studies have focused mainly on glacial-to-interglacial scale environmental changes (e.g., Gorbarenko, 1996; Keigwin, 1998; Shiga and Koizumi, 2000; Ternois et al., 2001; Gorbarenko et al., 2002, 2004, 2007, 2010, 2012; Narita et al., 2002; Sato et al., 2002; Okazaki et al., 2003, 2005a, 2006; Seki et al., 2003, 2004a,b, 2005, 2012; Nürnberg and Tiedemann, 2004; Ono et al., 2005; Sakamoto et al., 2005, 2006; Harada et al., 2006, 2008, 2012; Liu et al., 2006; Wang and Wang, 2008; Katsuki et al., 2010; Nürnberg et al., 2011; Iwasaki et al., 2012; Khim et al., 2012). For example, core MD01-2412 from the southwestern Okhotsk Sea has provided a high-resolution, centennial-scale proxy dataset that has revealed rapid environmental changes for the last 120 kyrs in sea-surface temperature and salinity (Harada et al., 2006, 2008), sea-ice coverage (Sakamoto et al., 2006), and biological production (Okazaki et al., 2005a; Ono et al., 2005). Unfortunately, core MD01-2412 has no age control points between 23 and 8 ka, so detailed discussions of deglacial oceanographic changes based on data

Table 1
Locations of sediment cores in the Okhotsk Sea and the western North Pacific used in this study.

Core ID	Latitude	Longitude	Water depth (m)	Reference
MR06-04 PC04A, PC04B	44.53°N	145.00°E	1215	This study
MD01-2412	44.53°N	145.00°E	1225	Sakamoto et al. (2006)
V34-90	48.83°N	150.46°E	1590	Gorbarenko et al. (2002)
V34-98	50.11°N	153.20°E	1175	Gorbarenko et al. (2002)
936	51.02°N	148.31°E	1305	Gorbarenko et al. (2004)
LV27-2-4	54.50°N	144.75°E	1305	Gorbarenko et al. (2010)
B34-91	49.14°N	150.34°E	1227	Keigwin (1998, 2002)
GGC-15	48.61°N	150.43°E	1980	Keigwin (1998, 2002)
GGC-18	48.75°N	150.43°E	1700	Keigwin (1998, 2002)
GGC-20	48.87°N	150.43°E	1510	Keigwin (1998, 2002)
GGC-27	49.60°N	150.18°E	995	Keigwin (1998, 2002)
CH84-14	41.73°N	142.55°E	978	Duplessy et al. (1989)
GH02-1030	42.23°N	144.21°E	1212	Sagawa and Ikehara (2008)
MR01-K03 PC4/5	41.12°N	142.40°E	1366	Ahagon et al. (2003)