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Paleoenvironment changes in the NW Okhotsk Sea for the last 18 kyr determined with micropaleontological, geochemical, and lithological data

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A B S T R A C T

Lithological, geochemical, and micropaleontological data indicate that the Late Glacial of the northwestern Okhotsk Sea (OS) is characterised by severe climatic and environmental conditions with mainly perennial sea ice coverage and low productivity accompanied by weak deep-water ventilation and a temperate formation of the upper Sea of Okhotsk Intermediate Water (SOIW). The age model of the studied core sediments was constructed by AMS ^{14}C dating. The most severe environmental conditions occurred during the period 15.8–14.8 kyr, synchronous with cold Heinrich event 1. Insignificant regional environmental amelioration accompanied by an increase of productivity and ice weakening during summer occurred almost simultaneously with the Bølling–Allerøed (BA) warming. The obtained results distinguished both the Bølling and Allerøed warmings as having different environmental conditions. Oxygen content in the surface sediment was low, as seen from the production of the benthic foraminifera (BF) species. During 12.6–11.1 kyr, synchronous with the Younger Dryas (YD) cold event, the regional environment conditions were cold, but not as severe as the glacial ones. Some climatic warming since the Preboreal has stimulated sea ice melting and surface amelioration during the summer season, which in turn led to a productivity rise and changes in the water column and bottom environment. Some increase in the surface water stratification and the intensified oceanic diatom and surface radiolarian production is parallel with the development of a mesopelagic regime of productivity. The surface sediment condition favours BF abundance and domination by BF species tolerant to oxygen deficiencies. During the Boreal period more stable surface conditions were accompanied by continuously high productivity and an intensifying of its mesopelagic regime.Significant regional climate warming since the Atlantic (9 kyr ago) strongly intensified the summer sea ice melting in the OS, and this created considerable surface environment amelioration with the preferential transport of bacteria and phytodetritus into the SOIW. Further considerable warming of the regional climate from 6 kyr ago contributed to slight sea ice changes, surface water warming, and the enhancement of its stratification; all typical for most of the OS. Along with a high nutrient supply from the Amur River, the NW OS experienced a strong diatom production increase with the maximum amount occurring during the last 3.6 kyr. This changed the productivity type and organic matter export into the water column while increasing the feeding of the "productive" *Plagoniidae* spp. group and decreasing the microbial biomass supply into the upper SOIW. Some sea surface water cooling or saltier conditions at the beginning of the Subatlantic (2.4–1.8 kyr) was followed by its warming or freshening 1.5–1.0 kyr ago, which likely correlated with the Medieval Warm Period. In turn, that probably led to strong surface water stratification, productivity deterioration and considerable changes in the overall NW OS environment. The established sequence of the northwestern OS environmental changes during the Late Glacial–Holocene is related to the Northern Hemispheric climate changes and was likely forced by atmospheric teleconnection in line with the polar circulation index variability.

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1. Introduction

The OS, as a marginal subarctic basin, is a good candidate for Quaternary paleoceanographic research for the following reasons: (1) it is located in the Northern Hemispheric latitudes where the most distinctive Pleistocene paleoclimatic fluctuations took place

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and (2) its paleoenvironment changes were also influenced by climatic changes above the adjacent land and by water exchange with the adjoining Pacific. A high sedimentation rate, extensive sea ice coverage and the presence of numerous and various microfossils in the sediments led to expressive fluctuations of geochemical, lithophysical and paleontological parameters, allowing us to reconstruct a high-resolution paleoceanographic history.

The Late Quaternary study of the OS that took place from 1950 to 1960 (Bezrukov, 1960; Jouse, 1962) was actively renewed at the end of the 1980s and 1990s and at the beginning of the present century by Russian, American, German and Japanese scientists (Gorbarenko et al., 1998, 2002a, 2004; Keigwin, 1998; Khusid, 2000; Shiga and Koizumi, 2000; Barash et al., 2001; Basov et al., 2001; Ternois et al., 2001; Okazaki et al., 2003; Seki et al., 2004; Nürnberg and Tiedemann, 2004; Sakamoto et al., 2005; Itaki et al., 2008). The Late Quaternary chronostratigraphy and main changes in the surface water condition, sea ice history, productivity, and the intermediate and bottom water evolution during the Late Pleistocene and Holocene have been reconstructed. Most of the published paleontological studies of the OS were based on the limited biogenic fossils and paleoenvironmental indicators (Shiga and Koizumi, 2000; Barash et al., 2001; Pushkar and Cherepanova, 2001, 2008; Basov et al., 2001; Okazaki et al., 2003; Matul' and Abelmann, 2001; Itaki et al., 2008), and this lack of data presently hampers a comprehensive overview of the climate and environmental evolution of this very special marginal basin. In addition, the majority of these studies were concentrated in the central and southern parts of the basin.

In the present study the authors studied a sediment core from the northwestern (NW) part of the OS, which has more severe modern sea ice conditions, by using a multidisciplinary approach in order to get a more comprehensive reconstruction. The age model of the studied sediments was reconstructed with AMS ^{14}C data. The resulting complex of isotope—geochemical, lithological and micropaleontological analyses including diatoms, radiolarians and benthic foraminifera (BF) allowed us to define high-resolution changes of the sea ice condition, surface water, water column and surface sediment environment, and the productivity of the NW OS during the last 18 kyr and correlate them with the environmental changes in other parts of the OS and with the global Northern Hemisphere climate changes.

1.1. *Modern hydrology of the study area*

The large-scale surface cyclonic circulation of the OS includes: (1) the warm Western Kamchatka Current carrying Pacific water transformed near the Kurile Islands to the north and the Compensation Kamchatka Current flowing to the south off Kamchatka, (2) currents along the northern seacoast—North Okhotsk Current, and (3) a steady cold East Sakhalin Current that carries cooled, freshened shallow water along Sakhalin Island from its north tip to the south over the shelf area and leaves the Okhotsk Sea through the Bussol' Strait (Fig. 1). In addition it includes the warm and saline water of the Soya Current which inflows from the Sea of Japan and enters the southern part of the Okhotsk Sea through the La Perouse Strait (Fig. 1). According to the physical oceanography, the hydrology of the studied core area was not significantly influenced by the East Sakhalin Current and the Soya Current and was mostly under the effect of the North Okhotsk Current.

The spring and summer heating of the surface water in the OS creates warm surface water (WSW) during the summer season with high temperatures between 5 and 14 °C and a low salinity of 31.5‰ and 33.2‰ (Kitani, 1973; Freeland et al., 1998). At a depth range of 30–40 to 150–200 m, under a thin surface layer of high

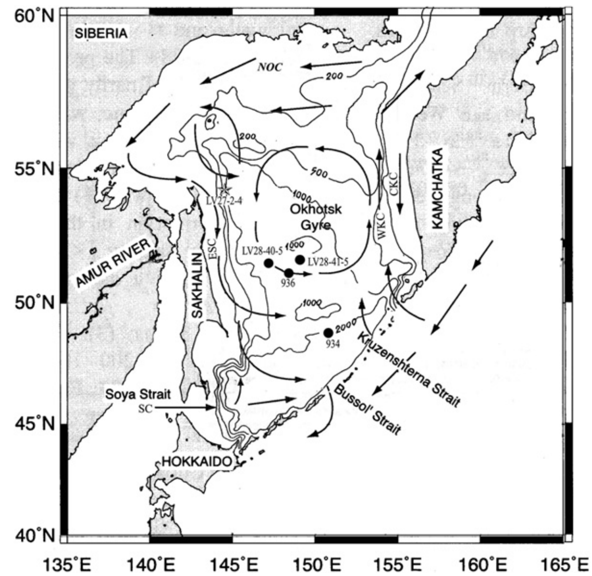

Fig. 1. Location of the investigated core LV 27-2-4 (star) and previously studied cores 934, 936, LV 28-40-5, V34-90, V34-98 (circle) and a generalized scheme of the surface water circulation in the OS; ESC—East Sakhalin Current, NOC—North Okhotsk Current, WKC—West Kamchatka Current, CKC—Compensation Kamchatka Current, SC—Soya Current.

seasonal variability, subsurface cold water appears (Moroshkin, 1966; Kitani, 1973) or the Sea of Okhotsk dichothermal layer (SODL) (Yang and Honjo, 1996), with a negative temperature and low salinity (33.0–33.2‰) which is formed during the winter period and preserved during summer and can be seen throughout the entire OS.

The Sea of Okhotsk intermediate water (SOIW) is suggested to be formed by an isopycnal mixing of the dense and cold Shelf Derived water (SDW), originating during winter sea ice formation and brine rejection, with the inflow of North Pacific water. SOIW is characterized by a low positive temperature of 1–2°C, a lowered salinity of 33.4–34.3‰ and high oxygen content of 2.5–6.5 ml/l (Kitani, 1973; Freeland et al., 1998). Wong et al. (1998) distinguished the SOIW as between an upper SOIW above a potential density of 27.0 at the depth of 500–600 m, being directly modified by SDW, and the lower SOIW below 500–600 m down to 1000 m. The oxygenated SOIW spreads across the OS, leaves the Sea at the rate of 2.7 Sv and ventilates the intermediate depth waters of the North Pacific (Talley, 1991; Wong et al., 1998).

The mesothermal maximum layer at around 1000 m with a rather high and stable temperature (1.7–2.5 °C), minimal oxygen content (0.5–0.8 ml/l) and rather high salinity (34.4–34.5‰) originates from the warm Pacific deep water (PDW) (Moroshkin, 1966; Kitani, 1973). Below the mesothermal layer the OS is bathed by old and cold deep Pacific water inflowing into the Sea through the deep Bussol' and Kruzenshtern Straits.

As the OS is located between the Siberian High and the Aleutian Low, northerly winds and some of the lowest temperatures in winter form the pronounced winter sea ice coverage (Alfutis and Martin, 1987). The significant freshwater input, especially from the Amur River, contributes to the strong stratification of the WSW and causes the formation of the SODL during the summer (Freeland et al., 1998).

2. Materials and methods

The core LV27-2-4 (54°30′N., 144°45′E; core length 738 cm; water depth 1305 m), was recovered during Cruise 27 of the R/V

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