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Okhotsk Sea ice coverage and Kamchatka glaciation over the last 350 ka — Evidence from ice-rafted debris and planktonic $\delta^{18}O$

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ABSTRACT

High-resolution records of ice-rafted debris (IRD) and oxygen isotope records spanning an E–W-trending transect across the Okhotsk Sea unravel the marine and terrestrial cryogenic history of NE-Siberia over the last 350 kyr. IRD, predominantly dispersed basin-wide by sea-ice, shows lowest fluxes during interglacial periods implying a reduced and seasonal sea-ice coverage. Highest IRD accumulation rates are observed during glacial and deglacial periods with a more extended, but highly dynamic ice cover. Although being rather synchronous, IRD fluxes are on average higher in the western Okhotsk Sea than in the eastern part, pointing to a persistent but mobile, particle-supplying sea-ice cover even during full glacial conditions, presumably less dense in the eastern parts. MIS 6 is exceptional in this respect: Asynchronous fluxes of IRD, which vary spatially, reflect rapid paleoclimatic and paleo-glaciomarine changes. IRD accumulation rates were by factor 2–3 higher during MIS 6 as compared to the last glacial maximum, and the IRD depositional center shifted from the western Okhotsk Sea (early MIS 6) toward Kamchatka (late MIS 6), synchronous to a distinct change in the IRD mineral composition. Both, the characteristic composition of late MIS 6 IRD originating from the Sredinny Mountain Range of Kamchatka and their significantly enhanced accumulation rates refer to intensified iceberg dispersal across the eastern part of the Okhotsk Sea at ~138 ka, ~135 ka, ~129 ka, and ~128 ka BP. This scenario affords the presence of extended mountain glaciers protruding down to sea level on the western side of Kamchatka. Anomalously light planktonic stable oxygen isotopes during MIS 6.3, Termination II and MIS 5.5–5.4 suggest significant freshwater supply related to the westward drainage of Kamchatka glaciers. The intensified Kamchatka glaciation observed during late MIS 6 was repeated during MIS 3. Iceberg discharges into the eastern Okhotsk Sea are observed at ~60 ka, ~51 ka, ~42 ka, ~38 ka, ~36 ka, and ~31 ka, and may partly correspond to N-Atlantic Heinrich Events.

1. Introduction

The late Quaternary climatic conditions and glaciomarine changes in the Okhotsk Sea (Fig. 1) are still a matter of debate. Deduced from terrestrial and shallow marine morphological studies, Grosswald (1998) and Grosswald and Hughes (1998) suggested large ice-sheets covering the entire Okhotsk Sea during the late Pleistocene glacial cycles, a theory which was finally refuted. Other studies proposed rather spatially limited ice sheets (Bigg et al., 2008), temporal mountain glaciations on the surrounding hinterland, and predominating sea-ice coverage during the Last Glacial Maximum (LGM) and mid Pleistocene (e.g Frenzel et al., 1992; Zech et al., 1996, 1997; Bäumler and Zech, 2000; Shiga and Koizumi, 2000; Brigham-Grette et al., 2003; Okazaki et al., 2003; Nürnberg and Tiedemann, 2004; Okazaki et al., 2005; Sakamoto et al., 2005).

Drifting sea-ice represents a proven geological agent to dislocate ice-rafted debris (IRD) consisting of terrigenous components of varying grain sizes from shore sources to deep-sea sinks in north polar seas (e.g. Kempema et al., 1989; Reimnitz et al., 1993a; Nürnberg et al., 1994; Dethleff et al., 2000; Eicken et al., 2000; Hebbeln, 2000; Darby, 2003; Dethleff, 2005; Dethleff and Kuhlmann, 2010). Paleo sea-ice expansion in the Okhotsk Sea is commonly reconstructed from coarse lithic terrestrial particles >63 µm, hereafter referred to as sea-ice supplied IRD ($IRD_{sea-ice}$) (e.g. Gorbarenko et al., 2002; Sakamoto et al., 2003, 2005). Based on a 1.1 million year record from the central Okhotsk Sea, Nürnberg and Tiedemann (2004) proposed that terrigenous material of continental origin dominates the glacial sedimentation in the Okhotsk Sea, with sea ice rafting from

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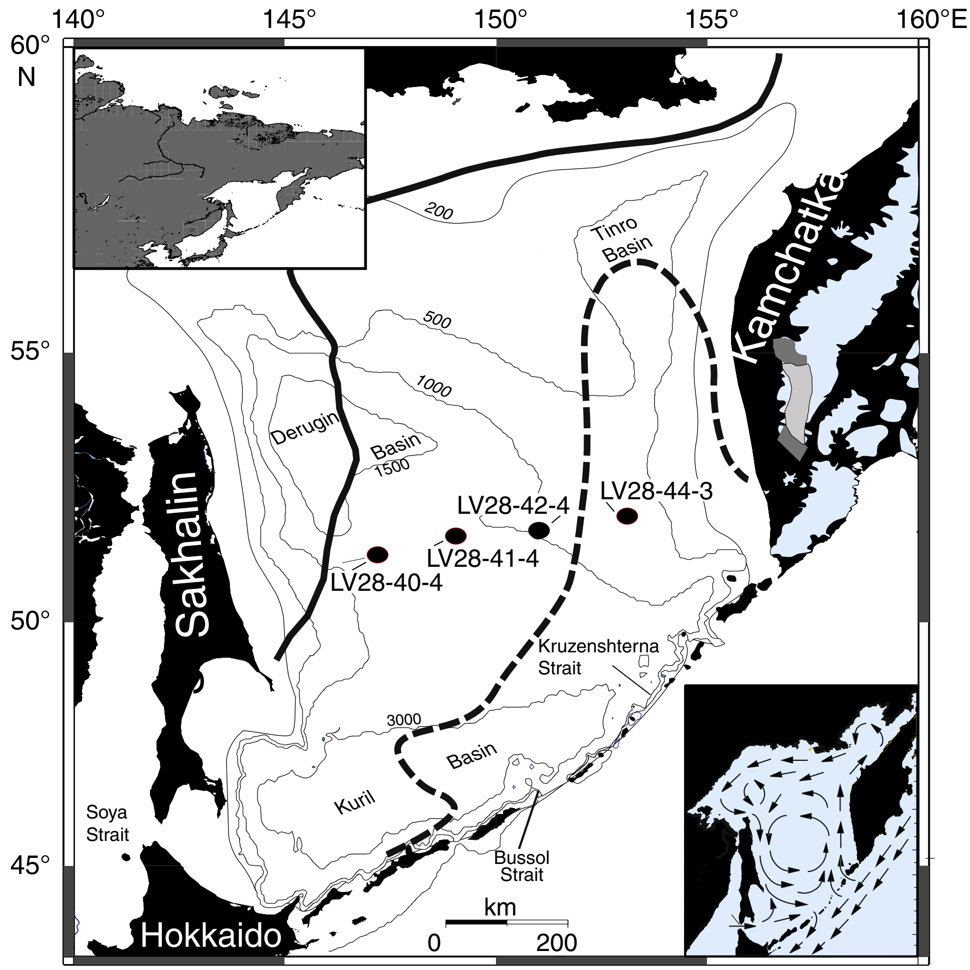

Fig. 1. Bathymetric chart of the Okhotsk Sea (NW Pacific), showing locations of sediment cores studied here (bathymetry in meters). Modern January sea-ice extent (solid bold line) and the maximum sea-ice coverage during March (dashed bold line) according to NASA Nimbus 7 and Parkinson et al. (1987) are indicated. On Kamchatka peninsula, the metasedimentary and metavolcanic rocks (dark-gray areas) and felsic paragneisses (light-gray area) of the Sredinny Mountain Range (after Bindemann et al., 2002) represent potential terrestrial source areas for $IRD_{iceberg}$. Light blue area indicates the maximal Quaternary glaciation according to Zamoruyev (2004). Inlet in lower right corner shows modern cyclonic oceanic surface circulation pattern, inlet in upper left corner provides larger view of eastern Asia.

coastal sources appearing to be the most likely and effective transport agent. This notion is supported by later studies, which deduced partly heavy and perennial ice conditions during full glacial times from the terrigenous and biogenous particle content in deep Okhotsk Sea sediments (e.g., Liu et al., 2006; Wang and Wang, 2008). In contrast to the Okhotsk Sea, studies on North Pacific sediment records identified formerly glaciated terrestrial regions as source areas of IRD, and defined the advance of icebergs as the major IRD supplying agent to the remote NW-Pacific (e.g., von Huene et al., 1973; Rea, 1994; Hewitt et al., 1997; St. John and Krissek, 1999). Iceberg-related IRD is hereafter referred to as $IRD_{iceberg}$.

The intention of our study is to decipher the marine and terrestrial cryogenic development of the central Okhotsk Sea area including parts of the Kamchatka Peninsula over the past 350 ka (MIS 1–10). Supported by planktonic oxygen isotope records, we systematically study IRD-distribution patterns across the Okhotsk Sea to assess the role of sea-ice and iceberg transport for the supply of terrigenous material to the Okhotsk Sea.

2. Okhotsk Sea environmental settings

Bordered by the Asian continent and Sakhalin Island to the northwest and north, and the Kurile-Kamchatka-Island Arc to the east and southeast, the Okhotsk Sea is the second largest marginal sea of the Pacific (Fig. 1). The straits between the Kurile Islands connect the Okhotsk Sea to the Pacific Ocean. Tatarsky and Soya straits link the Okhotsk Sea to the Japan Sea in the west and southwest. The broad, shallow northern and northeastern Okhotsk Sea shelves slope toward the extended Deryugin and Kurile Basins in the south, and toward the shallower and smaller Tinro Basin west off Kamchatka.

The present-day surface circulation is characterized by a large cyclonic gyre fed by the inflow of relatively warm and saline Pacific water masses through Kruzenshterna Strait (Fig. 1). This Pacific intrusion contributes to the northward directed West Kamchatka Current, which additionally mixes with partly re-circulating water masses from the East Sakhalin Current and with water from the broad northern shelf areas (e.g., Leonov, 1960; Moroshkin, 1966; Alfutis and Martin, 1987). Further gyre-feeding saline surface waters intrude from the Sea of Japan through Soya Strait. The Okhotsk surface waters are characterized by salinities between 32 and 34, while lower salt contents of 20 to 25 are restricted to areas influenced by the Amur River discharge around the northern tip of Sakhalin Island (Watanabe and Wakatsuchi, 1998; Gladyshev et al., 2003). During winter, intense sea-ice formation on the western, northern and eastern Okhotsk Sea shelves cause the generation of dense water (Martin et al., 1998; Gladyshev et al., 2003; Shcherbina et al., 2003), which is suggested to