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Evidence of sea ice-driven terrigenous detritus accumulation and deep ventilation changes in the southern Okhotsk Sea during the last 180 ka

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ABSTRACT

Sediment core OS03-1 retrieved from the Akademia Nauk Rise in Southern Okhotsk Sea was analyzed for the contents of rare earth elements (REEs) and combined with carbon isotope ($\delta^{13}C$) time series of benthic foraminifera to infer changes in terrigenous accumulation and bottom water ventilation on glacial–interglacial timescales in the study area. The age model of OS03-1 was constructed by a combination of foraminifer $\delta^{18}O$ stratigraphy and ^{14}C AMS dating, revealing that the 380 cm long core provides a window on climate change in the southern Okhotsk Sea since ~180 ka. A grain size-controlled-REE content shows strong glacial–interglacial changes. The Cerium and Europium anomalies vary from 0.89 to 1.32 and from 1.14 to 1.37, respectively. The $(La/Yb)_N$ values range between 0.55 to 0.92. Both results suggest a significant contribution of volcanic debris in the core sediments. In addition, the relationships between Sm vs. Nd suggest main contribution origin from the Amur River and sea ice during warm intervals and from the sea ice during cold intervals, indicating that the sea ice played an important role in transporting terrigenous materials to the study site in the southern Okhotsk Sea. During the last 180 ka, the mass accumulation rates (MAR) of $\sum$REEs are relatively higher during glacials and lower during interglacials with a peak accumulation during the early deglacial period. We infer that an intensified Mongolia High is responsible for the first-order accumulation pattern of $\sum$REEs in the southern Okhotsk Sea by mediating the dynamic changes in sea ice extent. Furthermore, six $\delta^{13}C$ minima are associated with intensified Asian monsoon (AM) precipitation and maximum MARs of $\sum$REEs, indicating that the dominance of barrier layer effects by high fresh water input through sea ice melting. The maximum MAR of $\sum$REEs during the Marine Isotope Stage (MIS) 5c coincides with the minimum of benthic foraminiferal $\delta^{13}C$, indicating a major interruption of ventilation in the bottom water in the Okhotsk Sea. The major low ventilation event in the deep water of the Okhotsk Sea appears to be dampened by a cooling condition and a major blooming of surface productivity preceded the event.

1. Introduction

Understanding the sources, transportation pathways, and fluxes of terrigenous detritus in marine sediments is crucial to quantitatively assessing and explaining the stratigraphy of sedimentary records under changing climatic and oceanic conditions (MARGINSOffice, 2003). While the transportation of terrigenous detritus from the land to the ocean in the mid and low latitudes of the western Pacific marginal seas is carried out mainly by rivers and eolian processes (Chavagnac et al., 2008; Milliman and Meade, 1983), sea ice plays a dominant role in the high latitudes (Asahara et al., 2012; Nuernberg and Ralf, 2004; Polyak et al., 2009; Spielhagen et al., 2004). Thus changes in the transportation of terrigenous detritus are sensitive to the glacial–interglacial climate change on regional to global scales.

The Okhotsk Sea is one of the western Pacific marginal seas adjacent to the Eurasian continent in the high-latitude Northern Hemisphere. The Okhotsk Sea is covered by pronounced seasonal sea ice (Harada et al., 2006; Nuernberg and Ralf, 2004), and it

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receives terrigenous detritus from various sources such as rivers, eolian dust, sea ice, and ash from volcanic eruptions. Sediments that have accumulated in the Okhotsk Sea are high quality archives for past climate change, reflecting weathering intensity in the source regions, sea ice coverage, and changes in sea level and land-sea interactions (Nuernberg and Ralf, 2004). Previous studies have focused on the changes in accumulation patterns of terrigenous materials in the Okhotsk Sea by investigating magnetic susceptibility (Chou et al., 2011; Gorbarenko et al., 2002b, 2010, 2012), ice-rafted detritus (Sakamoto et al., 2005, 2006), mineralogy and major elements (Liu et al., 2006; Nuernberg and Ralf, 2004), light and heavy minerals (Nuernberg et al., 2011), and terrigenous biomarkers (Seki et al., 2003, 2004, 2012,; Ternois et al., 2001). Although some these studies have been conducted to deal with the origin of terrigenous detritus in the Okhotsk Sea sediments based on mineralogy and geochemistry as well as the content of ice-rafted debris (Liu et al., 2006; Nuernberg et al., 2011; Nuernberg and Ralf, 2004), little information has been obtained from the rare earth elements (REEs) in the sediments of the Okhotsk Sea (Sakhno et al., 2010).

The REEs are a group of elements with unique geochemical characteristics due to their chemical properties characterized by 4f electronic configurations (Henderson, 1984). All REEs in a trivalent state behave as a coherent group of elements during geochemical processes, whereas Cerium (Ce) and Europium (Eu) often change their oxidation states into tetra- and di-valent states under varying redox conditions. These unique chemical properties of Ce and Eu compared to their neighboring REEs provide us with opportunities to use Ce and Eu anomalies as sensitive geochemical proxies for paleoclimatic and paleoceanographic reconstructions in marine sediments (Dou et al., 2010), ice cores (Gabrielli et al., 2010), stalagmites (Zhou et al., 2008), lake sediments (Tanaka et al., 2007) and loess deposits (Liu et al., 1993).

In this study, we report the results of REEs analysis (elements La to Lu) based on the sediment core OS03-1 retrieved from the slope of the Akademia Nauk Rise in the southern Okhotsk Sea. Our aim is to reconstruct the changes in terrigenous detritus accumulation and its response to regional and global climatic processes such as the expansion/contraction of sea ice, changes of sea surface temperature (SST) pattern, and intensification/weakening of the Mongolian High.

2. Study area

The Okhotsk Sea is the second largest marginal sea in the Northwestern Pacific with an area of 1.59×10^6 km^2 (Wang, 1999); it is bounded by the Siberian mainland to the west, the Pacific to the east, and the Kamchatka-Sakhalin Island Arc to the north and south (Fig. 1). The connection between the Okhotsk and Japan Seas is restricted to two narrow and shallow straits, the Soya Strait and the Tartar Strait, with sill depths of 55 m and 15 m, respectively. Through the Bussol Strait (2300 m), the Kruzenshterna Strait (1800 m), and other shallower straits located near the Kuril Islands, the Okhotsk Sea is connected to the Northwestern Pacific (Fig. 1). In the northwest, the Sea has broad continental shelves, often wider than 400 km (Lapko and Radchenko, 2000). The ocean circulation in the Okhotsk Sea is very complex, characterized by a large cyclonic gyre consisting of the northward West Kamchatka current and the southward East Sakhalin current (Fig. 1). Moreover, the hydrological and sedimentary processes in the Sea are strongly influenced by Amur River runoffs along with the cold shelf water mass and Soya warm current, determining the transportation paths and patterns of terrigenous material. Off the eastern of the Sea, the Kuroshio transports warm, saline waters to the subarctic Pacific after deflects from the Pacific coast of Japan at 140°E and 35°N as the Kuroshio Extension (Qiu, 2001). The Oyashio, which flows southwestward along Kuril Island, mainly originates from the Okhotsk Sea Mode Water with relatively low temperature and salinity (Qiu, 2001; Talley, 1991).

The Okhotsk Sea is characterized by pronounced seasonal sea ice coverage (Fig. 1). The sea ice is not only an important factor in regulating the Earth's climate change through albedo, but also acts as a main carrier of terrigenous detritus from the continents to the ocean basins. Modern observations show that the sea ice coverage in the Okhotsk Sea changes interannually (Watanabe et al., 2004), expanding and contracting over the past 100 ka (Sakamoto et al., 2005; Shiga and Koizumi, 2000), which is attributed to changes in atmospheric circulation over the high latitudes of the Northern Hemisphere (Katsuki et al., 2010; Nuernberg and Ralf, 2004; Sakamoto et al., 2006; Seki et al., 2004). Moreover, the Amur River runoff also has a significant impacts on the formation of sea ice in the Okhotsk Sea (Ogi and Tachibana, 2006), and transports terrigenous detritus to the Sea. There are also numerous active volcanoes around the Sakhalin and Kuril Islands and the Kamchatka Peninsula, delivering a substantial source of volcanic detritus to the Sea.

3. Materials and methods

The core OS03-1 is a gravity core with a length of ~380 cm. OS03-1 was collected from the slope of the Akademia Nauk Rise in the southern Okhotsk Sea (49.498°N, 150.01°E; Fig. 1) at a water depth of 960 m, well above the regional carbonate compensation depth (~1800 m) (Barash et al., 2008), by the exploration ship "*Xuelong*" during the First China's Arctic Scientific Expedition in 1999. The sediment is dominated by gray-green silt and clayey silt and the entire core contains visible gravels. Three visible layers of volcanic ash with different thicknesses and colors can be observed (Fig. 2). Most sediment layers contain abundant benthic and planktonic foraminifera shells.

The age model of OS03-1 was constructed by using multiple methods (Fig. 2). We measured the oxygen isotope (δ^{18}O) values of the benthic foraminiferal samples at a 4 cm interval from the core and we identified successfully thirteen oxygen isotopic age control points (Fig. 2b). Moreover, our age model based on benthic foraminiferal δ^{18}O curve matches very well with the δ^{18}O curves of benthic foraminifera from the nearby cores LV28-42-4 (Nuernberg and Ralf, 2004) and GGC-27 (Brunelle et al., 2010) and thus is highly consistent with published age models in the Okhotsk Sea and. Based on these regional comparisons, our OS03-1 age model reveals that the sedimentation rate at this site has been very low (<5 cm/ka) over the past 180 ka. Based on this age model, we obtain the mass accumulation rate (MAR) of the sediments by multiplying the linear sedimentation rate (LSR) with the dry bulk density (DBD) (MAR = LSR $\times$ DBD). In addition, we were also able to determine the ages of three volcanic ash layers from the top to the bottom of our core as follows: 43.1 ka (92 cm), 100.1 ka (200 cm) and 156 ka (322 cm), which provide future possibilities for tephrostratigraphic correlations in the southern Okhotsk Sea.

AMS ^{14}C dating of planktonic foraminiferal shells provides age constraint for the top part of the core; the age of the bottom part (>40 ka) of the core was constructed by wiggle matching the OS03-1 δ^{18}O curve of benthic foraminifera (*Uvigerina* spp.) with the SPECMAP (Martinson et al., 1987) (Fig. 2). We picked up single species of planktonic foraminifera *Neogloboquadrina pachyderma* with size >150 μm from three depth intervals (16–18 cm, 68–70 cm, and 246–248 cm) for AMS ^{14}C dating. The dating was done at the Leibniz Radioactive Dating and Isotope Research Laboratory in Germany. We applied a standard method to calibrate the AMS