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Discrimination of sediment provenance using rare earth elements in the Ulleung Basin, East/Japan Sea

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ABSTRACT

In order to discriminate the origins of Ulleung Basin (East/Japan Sea) sediments using rare earth elements (REEs), sediments from 15 box cores and one piston core collected in the shelf, slope, and basin were analyzed for major elements (Al, Fe, Ca, and Mn) and REEs. The major sedimentary components in this basin were presumed to be detrital materials from land, even in the basin sediments, based on Al and organic contents (carbon and opal). Post-depositional recycling processes involving Fe and Mn were identified in the basin sediments. Thus, the Ce anomaly and the fractionation factors of light REEs (LREEs) and middle REEs (MREEs) relative to heavy REEs (HREEs) could not be used as provenance indicators in the deep basin sediments (>2000 m of water depth) based on a feasibility check using their covariation with Fe and Mn. For the shelf, slope, and basin B (sites near islands; water depths of 1200–1800 m) regions, the Eu anomaly, $LREE_N/HREE_N$, and $MREE_N/HREE_N$ could be successfully used to discriminate possible provenances, including Nakdong River sediments (NRS), Chinese River sediments (CRS), Ulleungdo volcanic rocks (UVR), and Dokdo volcanic rocks (DVR).

From the provenance indicators, slope as well as the shelf sediments (called the Korea Strait shelf mud; KSSM) in the Ulleung Basin can be regarded as mixtures of NRS and CRS with decreasing portions of NRS in the KSSM with distance from the Nakdong River. Basin B sediments were mixtures of UVR or DVR and CRS. These findings can be explained if sediments discharged from the Nakdong River were transported and deposited (KSSM) northward within the strong coastal front in normal periods and if sediment flumes from summer floods flowed out across the coastal front, were carried with the Tsushima Warm Current, and then deposited in the slope area. This study indicated that CRS were very important detrital sediments and that REE compositions can be successfully used as a provenance indicator in even hemipelagic sediments close to land.

1. Introduction

The East/Japan Sea, a marginal sea of the Pacific Ocean, is a semi-enclosed basin with various marine environmental features such as characteristic circulation patterns including northward surface currents and southward thermohaline deep currents (Zheng and Klemas, 1982; Gamo et al., 1986; Chang et al., 2004; Min and Warner, 2005), various morphological features ranging from continental shelf to deep abyssal basin (Chough et al., 2000; Lee et al., 2004), and regions near the mainland that are the ultimate sites of deposition of land-derived materials of both natural and anthropogenic origins (Park, 1985; Park et al., 1995; Park et al., 1999; Chough et al., 2000; Bahk et al., 2004). Because few rivers discharge directly into this sea and the input pathways of land-derived materials are related to incoming current systems or atmospheric deposition, investigation of the provenance of sediments can be valuable for environmental management as well as for an oceanographic understanding of this sea.

The elemental composition of sediments has been used for the determination of sediment provenance (Bertine, 1974; Cho et al., 1999; Yang et al., 2003; Cha et al., 2007). Rare earth elements (REEs) have been used as reliable tracers because of their extremely low mobility during earth surface processes (Munksgaard et al., 2003; Chavagnac et al., 2005; Song and Choi, 2009; Xu et al., 2009b; Dou et al., 2010). It is widely accepted that the REE composition of sediments in the marine environment is often controlled by source rocks and the weathering environment, which enables the use of REEs as provenance tracers. Because characteristic features of REEs, including Ce and Eu anomalies and fractionation of light rare earth elements (LREEs) or middle rare earth elements (MREEs) relative to heavy rare earth elements (HREEs), represent compositional differences between sediment provenances, sediment origin can be successfully discriminated if the signals from source-related materials can be identified and distinguished. The similarity and/or the mixing relationships among sources can also be established among sediment samples.

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However, REE compositions can also be affected by post-depositional diagenetic processes including changes in redox conditions and the formation of authigenic minerals, such as carbonates, phosphates, and Fe oxides (Piper, 1974; De Baar et al., 1988; Murray et al., 1991; Hannigan and Sholkovitz, 2001; Haley et al., 2004; Song and Choi, 2009), which restrict their usage as provenance tracers in deep sea sediments. Thus, before a determination of sediment provenance is made, it is necessary to confirm that the REE features characterizing the sediments being considered were not influenced by post-depositional diagenetic processes.

Thick sequences of fine-grained sediments exist extensively from the shelf to the abyssal plain in the Ulleung Basin in the southwestern East/Japan Sea. The sediments consist mostly of detrital particles with lesser amounts of biogenic silica, organic carbon, authigenic oxy-hydroxides, and volcanic particles (Machida, 1999; Bahk et al., 2005; Cha et al., 2007; Khim et al., 2008). In the shelf area, fine-grained sediments are distributed in a narrow band pattern close to the southeastern Korean peninsula called Korea Strait shelf mud (KSSM). The extensive shelf area offshore of the coastal fine-grained mud belt is covered with sandy deposits with abundant relict calcareous shells.

Numerous studies have examined the sedimentological, geophysical, geological, and geochemical characteristics of the Ulleung Basin sediments (Kato et al., 1983; Oba et al., 1991; Piper and Isaacs, 1996; Crusius et al., 1999; Bahk et al., 2004; Cha et al., 2007). These studies revealed environmental changes at the geologic timescale, the evolution of the basin, and the biogeochemical processes of the slope and basin area; however, examination of provenance was very limited (Bahk et al., 2000; Bahk et al., 2004; Cha et al., 2007). Two different hypotheses for the origin of the near-shelf mud belt (KSSM) have been suggested: the first is that sediments discharged from the Nakdong River of Korea are solely responsible for the formation of the KSSM (Park et al., 1999); the second invokes mixed contributions from the Nakdong River and the Changjiang River (Lim et al., 2007; Jung et al., 2012). Because fine-grained sediments also cover the slope and basin areas, as well as the KSSM, it is reasonable to suggest that additional input sources, other than the Nakdong River, must contribute to this basin.

The goal of this study was to use REEs to discriminate the sources of Ulleung Basin sediments. To achieve this goal, the feasibility of using REEs as a provenance tracer of the sediments was first checked using the elemental composition of the sediments and by comparing the REE signals of possible source-related materials. We next discriminated the sources of each area, including the shelf, slope, and basin plain.

2. Geological and hydrological setting

The East/Japan Sea is a semi-enclosed marginal sea that is connected with the South Sea of Korea and the East China Sea at its southern part and with the Okhotsk Sea and the Pacific at its northern part through four shallow, narrow straits having water depths of less than 130 m. The Tsushima Warm Current (TWC), which is a branch of the Kuroshio Current, flows into the East/Japan Sea through the Korea Strait. This surface current flows northeastward and then out of the East/Japan Sea through the Tsugaru, Soya, and Tartar straits (Min and Warner, 2005; Mooers et al., 2005). Before entering the East/Japan Sea, the TWC forms a strong oceanic front called the South Korean Coastal Front (SKCF) with the South Korean Coastal Current (SKCC), which flows eastward along the coastline (Fig. 1; Zheng and Klemas, 1982; Park, 1985; Wells, 1988; Park et al., 1995; Park et al., 1999). After entering the East/Japan Sea through the Korea Strait, the TWC divides into two branches along the Japanese and Korean coasts, respectively. From the northern East/Japan Sea, a cold water surface current, called the North Korean Cold Current (NKCC), flows southward along the eastern coast of Korea and borders the TWC along a sub-polar front across the East/Japan Sea at 37–38°N, thus aiding TWC outflow along the sub-polar front through the Tsugaru, Soya, and Tartar straits (Mooers et al., 2005).

Elemental compositions and sedimentation rates of the surface sediments in the Ulleung Basin generally vary with physiographic setting. The continental shelf is characterized by shallow water depths (less than 200 m), high sedimentation rates, and high carbonate contents (Cha et al., 2007). The Nakdong River, located at the southeastern tip of the Korean Peninsula, annually discharges about 10×10^6 t of sediment. Most of sediments from the Nakdong River are deposited near the river mouth and then transported along the southeastern coast of Korea to form the KSSM mud belt on the shelf (Park, 1985; Park et al., 1995; Park et al., 1999). The KSSM can be divided into the proximal mud deposits (PMD) and the distal mud deposits (DMD) based on the acoustic and physical characteristics of sediments (Park et al., 1999; Kim et al., 2001; Lee et al., 2005).

The continental slope is relatively narrow and steep at the western margin and wide and gentle at the southern margin. It consists mainly of mud and is characterized by a variety of mass movement deposits (Lee et al., 1996). The sedimentation rates on the continental slope are relatively lower than those of the shelf area and decrease with water depth (Cha et al., 2007). Below a water depth of 2000 m, the basin plain, which has the lowest sedimentation rates, is covered with very fine-grained sediments (Cha et al., 2007). The sediments of the basin

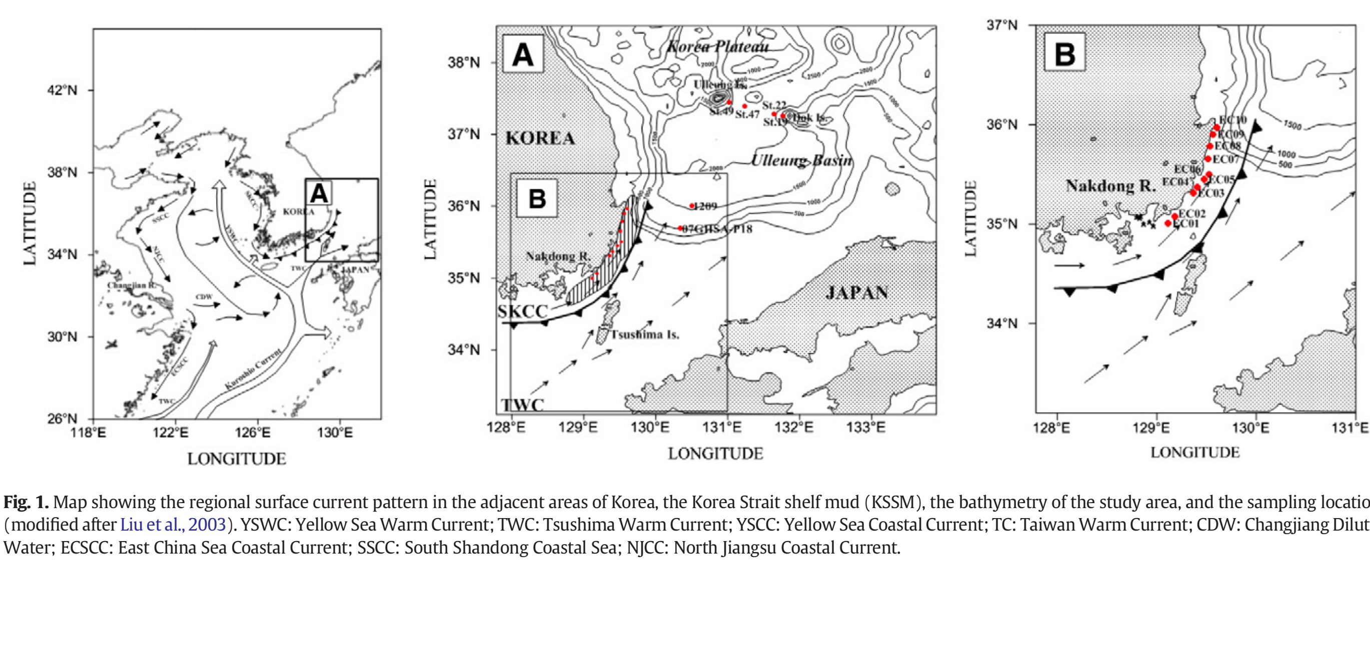

Fig. 1. Map showing the regional surface current pattern in the adjacent areas of Korea, the Korea Strait shelf mud (KSSM), the bathymetry of the study area, and the sampling locations (modified after Liu et al., 2003). YSWC: Yellow Sea Warm Current; TWC: Tsushima Warm Current; YSCC: Yellow Sea Coastal Current; TC: Taiwan Warm Current; CDW: Changjiang Diluted Water; ECSCC: East China Sea Coastal Current; SSCC: South Shandong Coastal Sea; NJCC: North Jiangsu Coastal Current.