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Geochemical constraints on the sources of beach sand, southern Sendai Bay, northeast Japan

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ABSTRACT

Unraveling the precise sources of sand and their quantitative contributions to a beach is beneficial for effective coastal management. To demonstrate a method for provenance analysis serving that practical purpose, we conducted a case study of the southern coast of Sendai Bay, a storm-wave dominated coast facing the NW Pacific Ocean. To eliminate the effect of hydraulic sorting, which changes sediment composition independently of the sediment source, we analyzed only medium-sand-sized light minerals (density $< 2.65\ g\ cm^{-3}$), which consisted mainly of quartz and feldspars. Concentrations of Al, Na, K, Ca, Mg, Fe, Rb, Sr, Ba, and Pb in the fraction were measured. In addition to that, the Sr isotope ratio, $^{87}Sr/^{86}Sr$, was considered to compensate for the weakened compositional contrast due to the limited mineralogy. We first compared the chemical compositions, which were transformed to centered log-ratio in order to get rid of the constant-sum constraints, and Sr isotope ratio between beach samples and possible sources. Second, we estimated the contributions of the presumed sources by comparing the chemical and isotopic composition of beach sand samples with an ideal composition calculated by assuming simple mixing of source sediments. Finally, under the assumption that the contributions derived by analyzing medium-sand-sized light minerals are also applicable to bulk beach sand, we calculated the total amount contributed by the sources to the beach in the past few decades as the sum of the products of the contributions of each source and the change of the sediment volume at each site along the coast. Our measurements of 19 samples of beach sand and 12 of riverbed sediment showed that the main sources of beach sand were the Abukuma River, which enters the ocean near the center of the study area, and coastal cliffs composed of Mio-Pliocene sedimentary rocks at the southern end of the beach. Contributions from other rivers were negligible. The contribution of the Abukuma River gradually increased northward from about 10% at a point 20 km south of the river's mouth to more than 80% at a point 20 km north of the mouth. We inferred that this alongshore change was due to the dominant northward direction of longshore currents and the locations of the two main sources. Thus, sediments from both sources migrate preferentially northward, transported by the longshore currents, and the amount of sediment derived from the Abukuma River, relative to the amount from the coastal cliffs, increases northward. We assumed that the sources of the medium-sand-sized light-minerals are the same as those of the bulk sediments and estimated the annual contribution of the Abukuma River and the coastal cliffs to the whole beach system to be $3.8 \times 10^4\ m^3$ and $4.1 \times 10^4\ m^3$, respectively. The annual contribution of the river to the beach sediment is about 34% of its estimated annual sediment discharge. The rest of the discharged sediment is presumably retained on the seafloor.

1. Introduction

A coastal sandy beach is a dynamic system because sediment accretion or erosion occurs continuously. Accordingly, sandy beach systems are likely to be influenced by various human activities such as coastal engineering, extractive industry, and agricultural and recreational activities (Woodroffe, 2002; Cooper, 2007). Most such activities generate coastal erosion, but aggressive efforts to counteract erosion, such as by constructing seawalls, often have undesired consequences. To manage a coastal area efficiently, accurate estimation of sediment sources and transport pathways, and the relative contribution of each source to the beach, is essential.

A provenance analysis of beach sand can provide a strong basis for such estimation. Beach sand provenance has been estimated by using various sediment properties as source indicators, including sediment texture and roundness (e.g., Pyökäri, 1997), mineral and chemical

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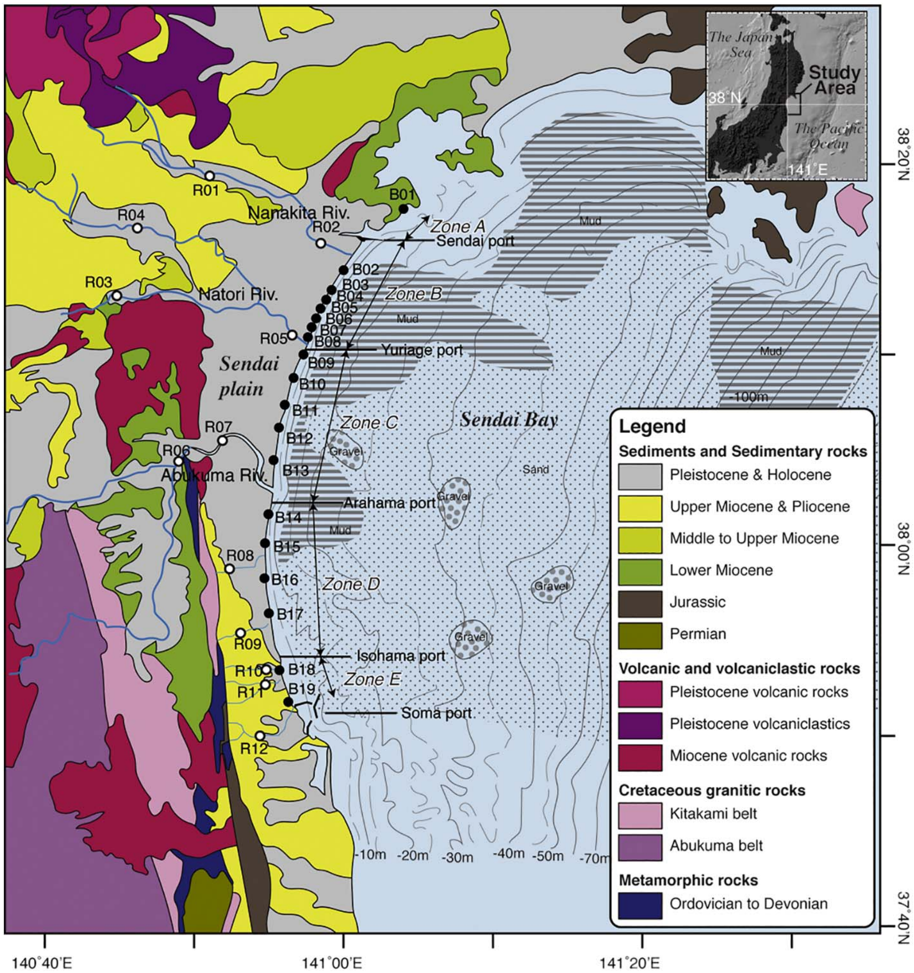

Fig. 1. Locations of sampling sites, study area geology, and bathymetry and bottom sediment distribution in Sendai Bay (after Geological Survey of Japan, AIST, 2015; Saito, 1989).

composition (e.g., Carranza-Edwards et al., 1998), heavy mineral composition (e.g., Clemens and Komar, 1988), and the isotopic ages of zircon grains (e.g., Sircombe, 1999). However, few studies have been oriented toward coastal management applications. In particular, the results of most provenance studies have been insufficiently quantitative or representative to be useful for coastal management application.

Beach sand is composed primarily of mineral grains of various sizes and densities. Hydraulic processes during transport and at the time of deposition strongly affect the relative abundances of minerals with different hydraulic behaviors (Morton and Hallworth, 1999; Garcia et al., 2004). In particular, denser grains are concentrated in finer grained fractions because detrital minerals with the same settling velocity are deposited together (Garzanti et al., 2008). Therefore, bulk mineralogy and chemistry of beach sand are inadequate as a source indicator because they reflect sedimentary processes in addition to source information. Although such bias can be excluded by targeting the grains of specific minerals such as zircon that are resistant to weathering and convey useful source information (e.g., Sircombe, 1999; Veevers et al., 2005), such favorable minerals are commonly only a minor constituent of sediments. Moreover, the high density of such grains decreases their representativeness with respect to the mobile component of beach sand. In contrast, light minerals, mainly quartz and feldspar, are dominant constituents and, owing to their low density, are also highly representative of the mobile component of beach sand. However, their ubiquitous nature can obscure differences between sources.

The Sr isotopic ratio is widely used in provenance studies of fine sediments such as silt and clay (e.g., Asahara et al., 1995; Revel et al., 1996; Saitoh et al., 2011, 2015); it has been applied less often in provenance studies of sand-sized sediments (e.g., Rosenbauer et al., 2013). The Sr isotopic ratio is the ratio of ^{87}Sr, which is the product of beta decay of ^{87}Rb (half-life, 4.88×10^{10} years) to stable ^{86}Sr. Rb and Sr are common minor constituents of many mineral species because they readily substitute for K and Ca, respectively. Old or Rb-rich rocks and minerals have high ^{87}Sr/^{86}Sr, whereas young or Rb-poor ones have low ^{87}Sr/^{86}Sr. This ratio can thus reveal significant differences between sources that are similar in mineral and chemical composition. For example, ^{87}Sr/^{86}Sr is usually higher in K-feldspar from older granites than in K-feldspar from younger granites.

In this study, we conducted a quantitative provenance analysis of beach sand along the southern coast of Sendai Bay, northeast Japan. Bias due to hydraulic sorting was eliminated by using only samples of light minerals in a certain grain-size fraction. We also developed an effective method for applying Sr isotopic analysis to sand-sized sediments. One obstacle to applying the Sr isotope ratio to provenance analysis of sand-sized sediments is their mineralogical heterogeneity. The source signal tends to be obscured by the mineralogical variety because ^{87}Sr/^{86}Sr depends not only on the source of the sample but also on its mineral composition. By using only light minerals for our analysis, we suppressed this mineralogical noise from the Sr isotope ratio as well as hydraulic bias from the sample.

The southern coast of Sendai Bay is a typical, temperate, storm-wave-dominated coast facing the Pacific Ocean. Because other studies have already investigated sediment distribution, transport, and budgets along this coast, the area is particularly suitable for a study of beach sand provenance. Coastal erosion is a long-standing problem in Sendai