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Ecological shifts due to anthropogenic activities in the coastal seas of the Seto Inland Sea, Japan, since the 20th century

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ABSTRACT

Multiproxy analyses were conducted using sediment cores in a low-polluted coastal site (Hiuchi-nada) in the Seto Inland Sea (SIS), Japan. Heavy metal and organic pollution peaked in the 1960s and the bottom environments have ameliorated since the 1980s due to several environmental regulations. First ecological shifts in meiobenthic ostracodes and diatoms occurred in the 1960s due to the initiation of eutrophication. Then, a second ecological shift occurred in the 1980s due to the amelioration of the water and the bottom quality. A compilation of similar analytical results in the coastal seas of the SIS reveals three types of ecological and environmental history since the 20th century. The environmental improvement since the 1980s affects the ecosystems, in particular, in a low-polluted bay. However, ecological compositions are different from those prior to the 1960s, suggesting that the ecosystem was not recovered but changed into the next stage in the SIS.

1. Introduction

Because estuaries, enclosed bays, and coastal seas primarily face human occupied areas, anthropogenic activities directly influence the organisms living there (e.g., Jackson et al., 2001; Lotze et al., 2006). Ecological deterioration such as diversity declines, decreases in total abundance, and faunal or floral changes induced by anthropogenic pollution have intensified in marine systems worldwide since the 19th and 20th centuries (see Yasuhara et al., 2012, 2017 for a review). Yasuhara et al. (2012) compiled downcore microfossil records from 150 studies and reinterpreted them from an ecological degradation perspective. These records indicate that ecological degradation in marine systems began significantly earlier in Europe and North America (~1800s) compared to Asia (post-1900) due to the earlier industrialization in European and North American countries, that ecological degradation accelerated globally in the late 20th century due to post-World War II economic growth, and that recovery from the degraded state in late 20th century following various restoration efforts and environmental regulations has only occurred in limited localities.

The Seto Inland Sea (SIS) is the largest inland sea in Japan and one of the world's prominent inland seas (Fig. 1). It is surrounded by the three main Japanese islands: Honshu, Shikoku, and Kyushu, and contains approximately 700 small islands (Fig. 1). The SIS had beautiful scenery with good water quality and high biodiversity; therefore, in 1934, it became the first designated national park in Japan. However, severe deterioration in the water and bottom qualities occurred, particularly in seas facing highly populated cities, and intensive industrialization in the coastal plains progressed from 1955 to 1973 due to the Japanese post-war economic miracle (JPWEM) (e.g., Takeoka, 2002; Imai et al., 2006). Reclamation along the natural coasts for the development of industries, eutrophication, hypoxia in water, red tides, and organic and heavy metal pollution in bottom sediments progressed widely in the SIS during this period. Accordingly, since 1979, the Japanese Government has regulated several effluents such as the chemical oxygen demand (COD), total phosphorus (TP), and total nitrogen (TN) in the water. The water quality in the SIS improved, and the concentrations of dissolved inorganic nitrogen (DIN) and PO_4-P decreased rapidly in the late 1970s to early 1980s and continued to be stable thereafter (Tarutani, 2007). However, this decrease has caused damage such as the discoloration of cultured seaweed, or *nori*, since the 2000s (e.g., Matsuoka et al., 2005; Hori et al., 2008; Tada et al., 2010). In addition, the amount of fish catches in the SIS continues to decline, suggesting that the fishery productivity there is deteriorating (Tanda et al., 2014).

Therefore, the SIS is the best location to evaluate the degree of anthropogenic impacts on ecosystems in time and space. The SIS has ten

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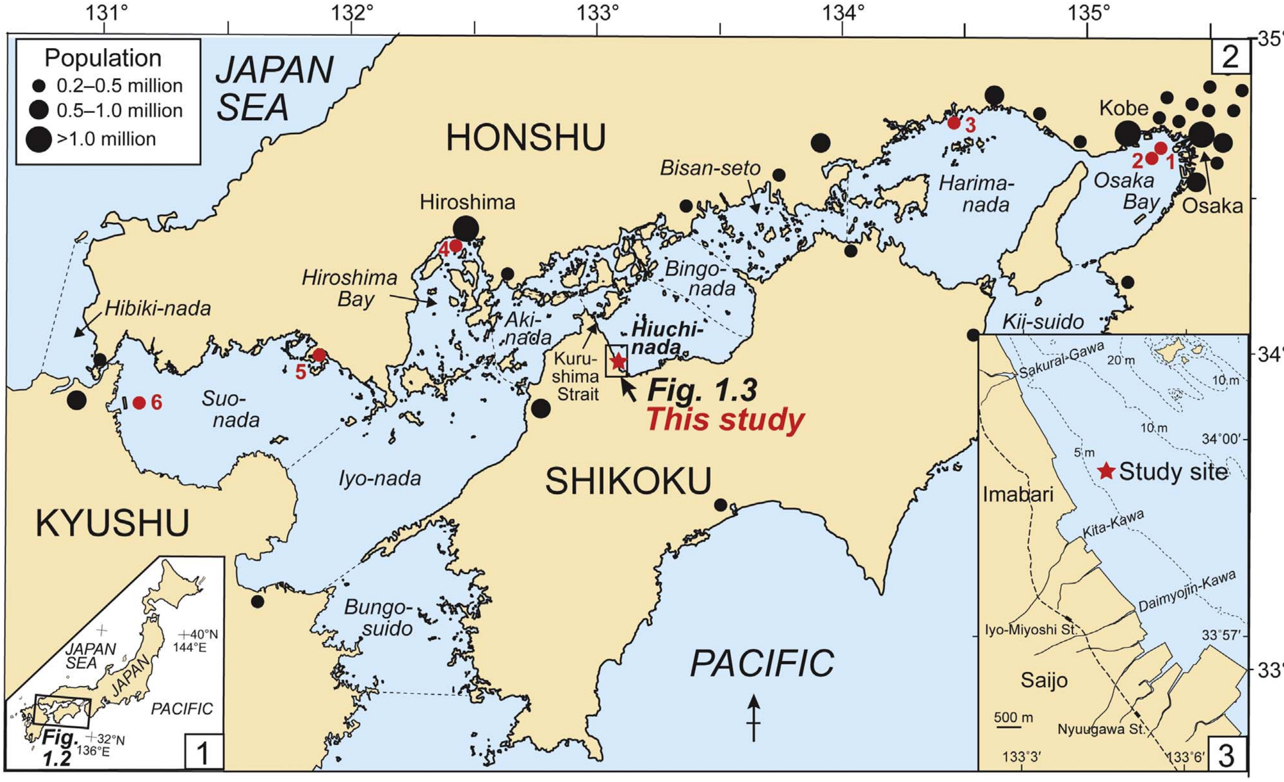

Fig. 1. Maps showing the Seto Inland Sea and the study area (Hiuchi-nada). Red stars in Panels 2 and 3 show the present study site. Red circles with numerals show core sites by the previous studies: 1.inner part of Osaka Bay, OBY (water depth: 14 m, Yasuhara and Yamazaki, 2005; Yasuhara et al., 2007), 2. inner part of Osaka Bay, OB3 (water depth: 17.8 m, Tsujimoto et al., 2006, 2008; Yasuhara et al., 2007), 3. northern part of Harima-nada, Ha-72 (water depth: 13.6 m, AECSIS, 2008, Komai et al., 2015) and HNB (water depth: 13.6 m, Yoshioka et al., 2012), 4. inner part of Hiroshima Bay, H99-0 (water depth: 16 m, Yasuhara et al., 2003), 5. Kasado Bay in northeastern Suo-nada, Ks1 (water depth: 8.2 m, Irizuki et al., 2015), 6. western Suo-nada, Su-121 (water depth: 15.6 m, AECSIS, 2009, Komai et al., 2015). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

basins called “nada” or “wan” (bay) and two channels called “suido” or “seto” (Fig. 1). A great number of organism and water and bottom quality monitoring studies in the SIS have been conducted (e.g., see Takeoka, 2002 for a review). Recently, micropaleontological studies have been used to reconstruct the paleoenvironments in the SIS. In these studies, microfossils such as Foraminifera (amoeboid “protist” with tests of calcium carbonate or agglutinated sediment particles), Ostracoda (meiobenthic Crustacea with bivalves of calcium carbonate), and Diatom (unicellular algae with siliceous frustules), the latter two of which are main targets of the present study, are examined because their tests, valves, and frustules can be preserved a long time and sufficient individual numbers to conduct quantitative analyses are easily obtained from a small quantity of samples such as those in cored sediments (e.g., Cronin and Vann, 2003; Yasuhara et al., 2003, 2007, 2017; Ruiz et al., 2004, 2005; Frenzel and Boomer, 2005; Hirose et al., 2008; Katsuki et al., 2009; Yoshioka et al., 2012; Irizuki et al., 2011, 2015; Hong et al., 2017). Several ostracode species to indicate anthropogenic pollution have been clarified (e.g., Rosenfeld and Ortal, 1982; Mezquita et al., 1999: Yasuhara et al., 2003; Irizuki et al., 2011, 2015). Thus, previous studies showed that ostracodes and diatoms could be used as a model to reconstruct/represent more general ecosystem history beyond particular taxonomic groups.

In strongly polluted enclosed muddy areas in the SIS, Osaka Bay, Harima-nada, and Hiroshima Bay (Fig. 1), which face larger cities (populations > 0.5 million) with intensive industrial areas, many researchers have discussed human-induced environmental and ecological deterioration based on microfossil data from short sediment cores (e.g., Yasuhara et al., 2003, 2007; Yasuhara and Yamazaki, 2005; The Association for the Environmental Conservation of the Seto Inland Sea (AECSIS), 2006, 2008; Tsujimoto et al., 2006, 2008; Hirose et al., 2008; Yoshioka et al., 2012; Komai et al., 2015). Whereas, moderately to low-polluted enclosed muddy areas in the SIS, such as Suo-nada and Hiuchi-nada (Fig. 1) face cities with < 0.2 million inhabitants. AECSIS (2009), Irizuki et al. (2011, 2015), and Komai et al. (2015) have investigated the relationships between meiobenthos (Ostracoda and/or Foraminifera) and several environmental factors in Suo-nada since the 19th and 20th centuries. Therefore, the first aim of the present study is to reconstruct temporal profiles of Diatom, Ostracoda, and environmental factors based on multiproxies (the grain size, X-ray fluorescence (XRF), total organic carbon, total nitrogen, and total sulfur (CNS) elemental analyses) in another moderately to low-polluted muddy bay, Hiuchi-nada, where few detailed micropaleontological studies have been conducted. Then, we compare these study results to those of previous similar studies in the SIS. Finally, ecological shifts represented by meiobenthic ostracodes and diatoms relative to human-induced environmental changes are evaluated in the SIS in time and space.

2. Materials and methods

2.1. Study area and sampling

Hiuchi-nada is situated in the central part of the SIS and is ~60 km in length from east to west and ~40 km in length from north to south (Fig. 1). It has an area of 1619 km^2 and an average water depth of 24 m. It is connected to Bingo-nada to the north. Strong tidal currents enter through the Kurushima Strait. Eutrophication and organic pollution started in ~1965, and the disappearance of seaweed beds, the formation of oxygen-depleted water, and red tides have occurred since the end of the 1960s, particularly in the eastern part of Hiuchi-nada (e.g., Fisheries Agency Seto Inland Sea Fisheries Coordination Office, 1972; Imabayashi, 1983; Ochi and Takeoka, 1986; Ochi, 1992; Tsujino, 2008). Horseshoe crabs (*Tachypleus tridentatus* (Leach)) live in the