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Assessment of the impacts of trace metals on benthic foraminifera in surface sediments from the northwestern Taiwan Strait

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ABSTRACT

The distribution patterns of foraminiferal assemblages in relation to trace metals, sediment grain size, and calcium carbonate were studied in 232 surface sediments collected from the northwestern Taiwan Strait. Multivariate analyses of biotic and abiotic data revealed a separation of near-shore, coastal, and deep-water zones. The modified degree of contamination suggested that the overall contamination was very low to low. Trace metals were enriched in the near-shore and outside bays. Their distribution was likely determined by sediment transport pathways and hydrodynamic conditions. High metal concentrations co-occurred with a low density and diversity of foraminiferal assemblages. Pb, Ba, organic carbon, Ga, Zn, Cu, and Co had a positive correlation with near-shore assemblage, whereas Cr and Ni positively related to the deep-water assemblages. Some calcareous foraminifera were favored by $CaCO_3$, Sr, and sand. This study highlights species' responses that are specific to environmental variables.

1. Introduction

The pioneering works of Person (1960) and Watkins (1961) stimulated research on the use of benthic foraminifera as biological indicators of polluted marine environments. In a review of benthic foraminiferal responses to estuarine pollution, Alve (1995) summarized the main pollution sources that influence foraminiferal fauna, including organic matter, heavy metals (or trace metals), chemicals, oil, and power plants. Over the last several decades, numerous field surveys have placed particular emphasis on the relationship between faunal distribution patterns and pollutant concentrations. For instance, pollution exerts strong adverse effects on foraminiferal ecology (see reviews by Armynot du Châtelet and Debenay (2010), Frontalini and Coccioni (2011), and Pati and Patra (2012)). An extremely low foraminiferal density and species diversity has been observed in highly polluted environments (e.g., Schafer (1973), Yanko et al. (1998), Samir (2000), Elberling et al. (2003), Bergamin et al. (2005, 2009), Ferraro et al. (2006), Debenay and Fernandez (2009)). A large decrease in the number of species has been shown to result from increased trace metal pollution effects based on historical records in a sediment core (Alve et al., 2009). Laboratory experiments have illustrated that pollution (e.g., heavy metals, oil spills) are likely responsible for the test abnormalities of certain benthic species (Morvan et al., 2004; Le Cadre and Debenay, 2006). The percentage of deformed tests from polluted environments increases dramatically and exceeds the threshold (i.e., 1%) of total abnormal tests under non-stressed conditions (Alve, 1991; Yanko et al., 1994; Samir, 2000; Frontalini and Coccioni, 2008; Frontalini et al., 2009), despite the fact that test deformities are connected to both elevated anthropogenic pollution and changes in the natural environment (see Sen Gupta (1999) and Coccioni et al. (2009)).

Foraminiferal communities can also be modified under stressed conditions provoked by pollution. The degree of pollution tolerance or intolerance varies from species to species. Most species are sensitive and non-tolerant to pollution; only a few species called opportunistic species can adapt to polluted environments. Pollution acts as a filter for benthic foraminiferal fauna, within which pollution-sensitive species are diminished and pollution-tolerant (opportunistic) species bloom. For example, Frontalini and Coccioni (2008) suggested that increasing trace element concentrations increase the relative abundance of opportunistic species. However, our understanding of the foraminiferal strategies toward pollution toxicity is still very incomplete. Further laboratory culture studies need to be conducted to

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decipher the specific response of foraminifera to specific pollutants (Nigam et al., 2006).

Trace metals increase public awareness of environmental problems because these elements are preserved in sediments for long periods of time, and their high concentrations are toxic to a variety of living organisms. Trace metals are derived from natural and anthropogenic sources (Ridgway et al., 2003). However, natural sources play minor roles in metal accumulation compared to anthropogenic inputs (Oursel et al., 2013). In most cases, trace metals of anthropogenic origin are released from urban and industrial areas adjacent to rivers and estuaries.

Coastal and estuarine areas are important due to their close relationship with human activities. These locations, the ultimate destination of terrestrial runoff, have become increasingly contaminated by trace metals in recent decades. The toxic effects of metals preserved in sediments seriously threaten coastal ecosystems. Accordingly, determining the concentration and distribution of trace metals deposited on the seabed is important.

The aims of this study were to: (1) identify foraminiferal assemblages based on a self-organizing map (SOM) classification and their spatial distribution patterns; (2) present and map the spatial variation in trace metals and organic carbon and interpret the delivery of the metals in a sediment transport regime; and (3) determine the benthic foraminiferal response to spatial changes in trace metals.

2. Study area

The Taiwan Strait is located between Taiwan and mainland China. This strait connects two large marginal seas in China: the East China Sea and the South China Sea. Sediments in the Taiwan Strait are mainly delivered from western Taiwan and southeast China by rivers that flow into the strait. Sediment properties (e.g., mineralogical analysis, magnetic properties, and radionuclides) have been used as traces to the sources, pathways and accumulation rates of sediments in the Taiwan Strait, establishing sediment source-to-sink dispersal systems that are closely related to hydrodynamics in this strait (Xu et al., 2009; Horng and Huh, 2011; Huh et al., 2011). The Taiwan Strait is primarily influenced by two different hydrodynamic systems: the China Coast Current (CCC) and Taiwan Warm Current (TWC) (Fig. 1). The CCC dominates the western side of the Taiwan Strait, whereas the TWC, a current branch that separates from the Kuroshio, dominates the middle and northern part of the strait. During winter months, NE monsoons weaken the TWC; meanwhile, the CCC is strengthened (Fig. 1a). During summer months, the SW monsoon prevails and promotes the TWC, whereas the CCC is nearly nonexistent (Fig. 1c).

The study area was situated on the northwestern side of the Taiwan Strait (Fig. 2a). Fuzhou Harbor, Fuqing Bay, Xinghua Bay, Meizhou Bay, and the partial inner shelf constituted the study area (Fig. 2b). Semidiurnal tides predominate the partly enclosed bays of Fuqing, Xinghua, and Meizhou (tidal coefficient <0.5) (Chen et al., 1994). The rise and fall of tides produce a reciprocating flow. Tidal flats build up along the shoreline, and underwater shoals form within the inner bays. A continental shelf plain is located outside of the bays.

3. Materials and methods

3.1. Sediment sampling

Surface sediment samples were collected at 232 sites during the summer and autumn of 2012, and water depth ranges from 1 m to 75 m. Sampling locations were determined with a differential global positioning system (DGPS). Sediments were collected from a boat using a Petersen grab sampler. To avoid disturbing lighter bottom materials, we set the hinged jaws and lower to the bottom slowly. Water depth was measured using the boat's sonar. Only the top ~5 cm of sediment was retained for laboratory analyses. The bathymetry of the study area and the location of the selected sites are displayed in Fig. 2b.

3.2. Foraminiferal analysis

Although the literature suggests both positive and negative aspects of the application of total (living plus dead) assemblages on environmental assessment (Romano et al., 2009), we investigated the total assemblage to reduce the effects of seasonal variability and spatial heterogeneity (Scott and Medioli, 1980; Debenay et al., 2001; Morvan et al., 2006; Albani et al., 2010; Donnici et al., 2012; Celia Magno et al., 2012). All samples were dried at 50 °C and weighed. The samples were then gently washed through a 63-μm sieve with tap water to remove clay and silt. Generally 150–250 benthic foraminiferal specimens were counted per sample, and the minimum number of specimens was 100 for samples with very low species number. The count was standardized as a relative abundance (percentage). Special care was taken to count specimens that were well presented. The benthic foraminifera were taxonomically identified largely following Zheng (1979, 1980), Wang et al. (1988) and Zheng and Fu (2001).

Foraminiferal parameters were determined based on the species census. Foraminiferal density (FD) is defined as the total number of individuals per gram of dried sediment. Species richness is referred to as the number of species per sample. The Shannon–Weaver index $H(S)$ (Shannon, 1948) and Fisher α index (Fisher et al., 1943) were calculated using the PRIMER (Plymouth Routines In Multivariate Ecological Research) v5 software (Clarke and Gorley, 2001).

3.3. Trace metals, organic carbon, and calcium carbonate analyses

For trace metal analyses, a fraction of each sample (0.4–4 g) was dried and reduced to a fine powder. Chromium and Zr were measured via inductively coupled plasma-optical emission spectrometry (ICP-OES) (PE optima 4300DV, PerkinElmer, Waltham, Massachusetts, USA). Inductively coupled plasma-mass spectrometry (ICP-MS) (Thermo X2 series, Thermo Fisher Scientific, Waltham, Massachusetts, USA) was used to determine the concentrations of Ba, Co, Cu, Ni, Ga, Pb, Sc, Sr, V, and Zn. A variety of sediment quality standards were used as controls. The detection limits for the trace metals were Ba: 0.02 mg kg^{-1}, Cr: 0.02 mg kg^{-1}, Co: 0.02 mg kg^{-1}, Cu: 0.02 mg kg^{-1}, Ni: 0.08 mg kg^{-1}, Ga: 0.01 mg kg^{-1}, Pb: 0.05 mg kg^{-1}, Sc: 0.12 mg kg^{-1}, Sr: 0.02 mg kg^{-1}, V: 0.01 mg kg^{-1}, Zn: 0.09 mg kg^{-1}, and Zr: 0.28 mg kg^{-1}.

The organic carbon content was determined by titration with ferrous ammonium sulfate after dissolution in a potassium dichromate sulfuric acid solution (Nelson and Sommers, 1974). Calcium carbonate content was measured by the ethylene diamine tetraacetic acid (EDTA) complexometric titration method. Approximately 0.3 g of dried sample was dissolved in dilute acetic acid, and calcium fluoride was filtered out. Calcium was then titrated at pH 12.0 after adding triethanolamine solution.

3.4. Modified degree of contamination

Modified degree of contamination (mC$_d$, Hakanson, 1980) was used to determine sediment qualification in comparison with the criteria (Abrahim and Parker, 2008) given in Table 1.

$$\mathrm{mC_d} = \frac{\sum_{i=1}^{n} C_f^i}{n}$$