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# Anthropogenic effects on sediment quality offshore southwestern Taiwan: Assessing the sediment core geochemical record

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ABSTRACT

Slag material was dumped in two sites off southwestern Taiwan by the China Steel Corporation during 1984–1995. By geochemically analyzing four sediment cores, we investigated the impact of slag on the sediment chemistry. Elemental profiles from the dumping sites show a strong depletion in detrital elements and enrichment in alkaline and redox-sensitive elements, especially for the top ~20 cm of sediments. The relative enrichment factor ($EF_{rel}$) exhibits wider range for Ca (0.73–13.33), Fe (0.88–3.03), Mg (0.94–9.58) and Mn (1.22–33.30) due to contamination of sediments by slag. Sediment weathering indicators also show a distinct change with lower values in sediments influenced by dumping due to Ca and Sr addition. Higher $EF_{rel}$ for As, Cd and Pb in the top sections of the cores indicate an additional modern/industrial input of these elements since ~1950. Our study suggests that slag dumping may have a localized effect on biogeochemical processes by inducing the diagenetic remobilization of certain elements.

## 1. Introduction

The geochemical composition of estuarine and coastal marine sediments is largely governed by the physicochemical characteristics (pH, $E_h$, $O_2$, etc.) of the depositional environment and associated natural biogeochemical processes such as diagenesis, adsorption/desorption on/from organic matter and precipitation–dissolution of Fe–Mn oxyhydroxides (e.g. Berner, 1980). Nevertheless, since the 1950s, elemental concentrations in sediments deposited near major cities and harbor areas have been significantly influenced by various contaminants/wastes produced through modern human and industrial activities. Determination of anthropogenic impact from those of natural processes on sedimentary composition is essential for environmental monitoring studies because sediments are very sensitive and reliable recorders of both natural and anthropogenic source contributions at accurately detectable levels (Förstner and Wittmann, 1981; Szefer, 2002). The spatial and temporal geochemical records of sediments are thus deemed to be vital to evaluate recent contamination levels and pollution histories within estuarine, coastal and shelf regions world-wide (Szefer et al., 1995; Zwolsman et al., 1996; Nolting et al., 1999; Selvaraj et al., 2004).

Coastal and offshore regions of southwestern Taiwan (Fig. 1) annually receive ~35 million tons ($Mt\,yr^{-1}$) of chemically weathered sediments from the high mountains of Taiwan and the upper crust of the Yangtze Craton (UC-YC, China), mainly through river input and substantially by aeolian pathways. With nearly 36,000 $km^2$ of land and a population over ~23 million, Taiwan generated ~1.6 Mt of domestic and industrial wastes in the year 2000, primarily from factories, farming activities, hospitals and other major business organizations, which increased the heavy metals and organics loads in natural environments (Tsai and Chou, 2004). The steel industries, in particular, play an important role in the island's economic development and are equally responsible for producing an appreciable quantity of solid waste, i.e., ~420 $kg\,ton^{-1}$ of steel production (Topkaya et al., 2004). The China Steel Corporation, the largest producer of steel in Taiwan, used the offshore region of southwestern Taiwan as their solid waste disposal site from 1984 to 1995 (Fig. 1). During this time period, ~2 Mt of slag were dumped in the old dumping site (Fig. 1) located approximately 14 km from Kaohsiung Harbor (Chou et al., 2002). Since 1988, in the establishment of the island's strict Environmental Pollution Prevention regulations, dumping activities were shifted to a new site (documentation data are not available for this site), located ~14 km from the old one (Fig. 1). Marine waste disposals induce

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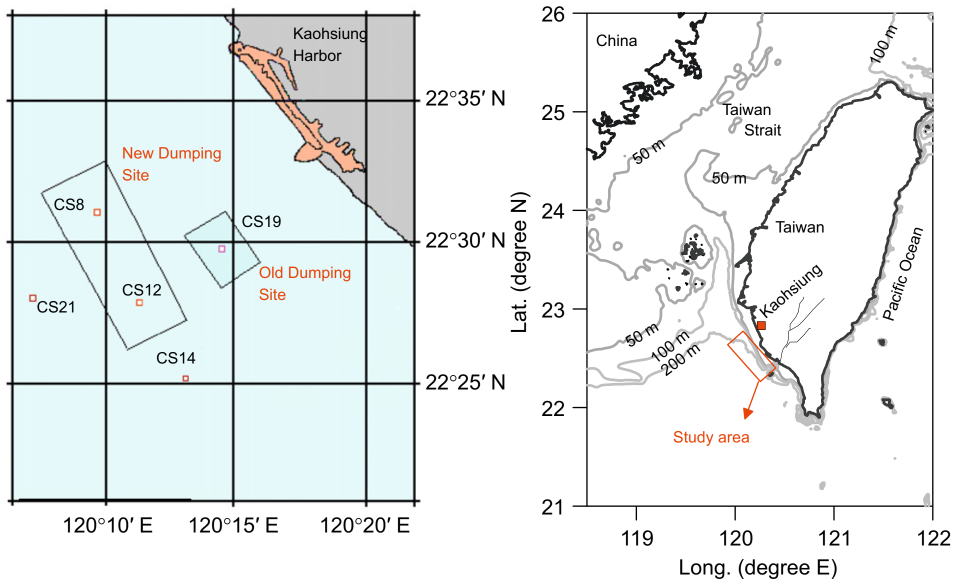

**Fig. 1.** Map showing the study area off southwestern Taiwan. The locations of core samples used in this study, including the old and new dumping sites, are also shown as an enlargement. Core CS8 is not included in this study because of its short length (9 cm).

water column turbidity changes, seabed smothering effects and sediment contamination, which all in turn affect the habitat characteristics, food chain integrity and ultimately fishery resources (e.g. Johnson and Frid, 1995). Most importantly, the bed sediment is disturbed and brought from anoxic to oxic conditions by dumping of higher density materials such as steel slag. Such a disturbance can alter the sediment characteristics by affecting the ongoing biogeochemical processes; as a result, sediment can act either as a sink or a pollutant source for the overlying water column (Standring et al., 2002).

In order to investigate the impact of slag material on the sediment chemistry, extensive seabed monitoring surveys at a high spatial resolution were conducted in and around slag dumping sites as well as in the region near Kaohsiung Harbor during 1995. This work was done based on the assumption that the dumped material is characterized by a higher density than the surrounding sediment dominated by mud (silt+clay) and helped us to follow the sediment layers in the topmost tens of cm of the sediment column for selecting suitable core sampling locations. During the program, 12 short gravity sediment cores were raised from the seabed in the former region. Here, we present the results of a detailed geochemical evaluation of four sediment cores, CS12, CS14, CS19 and CS21. Among them, core CS19 was dated by the $^{210}$Pb method to infer the recent history of contamination with respect to pre-industrialization in Taiwan, i.e., before 1950. The analyzed dataset was used to investigate (a) the anthropogenic contribution from the provenance contribution; (b) the contaminant inventory compared to the regional background; (c) the geochemical processes responsible for the mobility of elements and/or dispersion of contaminants; and (d) the geochemical factors responsible for the interrelationships among chemical parameters studied through a statistical approach.

## 2. Materials and methods

### 2.1. Study area and sampling

The study area off of southwestern Taiwan occupies 70 km$^2$ east of Kaohsiung Harbor at water depths of ca. 100–400 m (Fig. 1). During 1995, on the basis of high resolution sediment acoustic profiling, 12 stations were sampled from the region with the help of a 2-m single-tube gravity corer available onboard the R/V *Ocean Researcher 3* (Cruise No. 274). The collected cores were capped, sealed airtight and frozen before they were brought back to the shore laboratory for further investigation. Four of the cores (CS12, CS14, CS19 and CS21; see Fig. 1 for sampled locations) were selected site-specifically for detailed grain size and geochemical analyses of major and trace elements. All cores were sliced at 1–2 cm intervals down to 10 cm depth and 2, 5 and 10 cm intervals were applied for the remaining length of the cores. Details of the investigated cores, including the number of sub-samples in each core, are given in Table 1.

### 2.2. Grain size and elemental analyses

Prior to the detailed laboratory work, all 77 sub-samples were freeze-dried for 24-h to achieve a constant weight and homogenized (removal of particles $>2$ mm). Grain size analysis was carried out on a part of each homogenized sample using a Coulter LS-100 laser particle size analyzer after removal of carbonate with 1 N HCl and organic matter using 30% $H_2O_2$. Another portion of each sediment sample was finely ground to ~200-mesh in an agate mortar and pestle for elemental (C and N) and geochemical analyses. For elemental analysis, the sub-samples of bulk sediments ($<2$ mm) were oven-dried at 60 °C, homogenized and finely powdered by using an agate mortar. Total carbon (TC) and nitrogen (TN) were determined by using a LECO CHN-932 elemental analyzer. The instrument was calibrated with reference standards, BCSS-1 and NIST-2704, and triplicate analyses of standards as well as samples yielded a precision better than 5%. Inorganic carbon (IC) was measured after liberating $CO_2$ with 1 N HCl and measuring its concentration with a UIC Coulometer. The analytical accuracy and precision were better than 5%. The IC was converted to calcium carbonate by multiplying its value by 8.333. Organic carbon (OC) was calculated as the difference between TC and IC.

### 2.3. Geochemical analysis of sediments

The total concentrations of 22 major and trace elements (Al, As, Ca, Cd, Cl, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, Rb, S, Si, Sr, Ti,