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Typhoon- and earthquake-enhanced concentration and inventory of dissolved and particulate trace metals along two submarine canyons off southwestern Taiwan

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ABSTRACT

The influence of typhoon and earthquake events on the distributions of dissolved and particulate trace metals (Al, Fe, Mn, Cd, Cu, Pb, Zn) is evaluated along the Gaoping Canyon and Fangliao Canyon in a tectonically active margin off southwestern Taiwan. The Fangliao Canyon was mightily struck by a large Pingtung Earthquake (M_L 7.0) in winter when terrestrial inputs were insignificant. This large earthquake clearly enhanced the concentration and inventory of total suspended matter (TSM), dissolved and particulate metals by 2–5 fold in Fangliao Canyon and nearby Gaoping Canyon, as compared to those in normal winter conditions. The Gaoping Canyon is typically inundated with massive amounts of terrestrial materials during summer typhoons from the mountainous Gaoping River. Strong contrast of particle and metal distributions can be found between summer and winter and between typhoon and regular summer periods in the Gaoping Canyon, which was apparently caused by various strengths of river inputs followed by sediment resuspension and lateral advection at intermediate and near-bottom depths along the canyon. The water-column and canyon-wide inventories of TSM, dissolved and particulate metals increased up to 2-fold higher during the post-typhoon period than during the rainy period in summer in the Gaoping Canyon. After extreme events, most metals tend to increase their release into the dissolved phase through the increase of TSM concentration. In addition to huge river inputs during typhoon, both typhoon and earthquake induce energetic sea conditions that cause sediment resuspension and enhance the concentration and inventory of particles and metals in submarine canyons.

1. Introduction

The island of Taiwan, which is located on the boundary of Eurasian and Philippine plates, is subjected to earthquakes of varying strengths each year. The island is also subjected to three or four typhoons on average during summer (CWB, 2012). The synergistic effects of typhoons and earthquakes result in Taiwan having one of the highest denudation rates in the world (Li, 1976; Dadson et al., 2003). Although previous studies have described the impacts of typhoons and earthquakes on the increased water and sediment transport from Taiwan's rivers (Dadson et al., 2003, 2004; Galewsky et al., 2006; Milliman and Kao, 2006; Goldsmith et al., 2008; Kao and Milliman, 2008), the fate of terrestrial materials in the ocean derived from such extreme events is not fully understood. Liu et al. (2006) determined that Typhoon Nakri, which passed over Taiwan on July 9–10, 2002, had a profound influence on the sediment flux and down-canyon particle transport from the Gaoping (Kaoping) river-canyon system. Goldsmith et al. (2008) identified exceptionally high concentrations of suspended sediment and particulate organic carbon (POC) from Taiwan's Choshui River, which generated a hyperpycnal plume upon reaching the ocean during Typhoon Mindulle in 2004. Liu et al. (2008) noted that the small Taiwanese rivers that are subjected to episodic events are likely responsible for the resulting sediment distribution pattern in the Taiwan Strait. Nevertheless, very few studies have linked earthquakes to the distribution and transport of terrestrial materials in coastal seas adjacent to Taiwan.

Submarine canyons are important conduits for off-shelf transport of terrestrial sediment (Gardner, 1989; Nittrouer and Wright, 1994; Liu et al., 2006; Ogston et al., 2008; Martin et al., 2011). High-energy events such as storms, earthquakes, and internal waves and tides, typically result in increased particle flux and water turbidity below surface water and form an intermediate nepheloid layer and/or a benthic nepheloid layer in many canyons (Hickey et al., 1986; Xu et al., 2002; Puig et al., 2004; Ogston et al., 2008; Martin et al., 2011). The distance between the canyon head and

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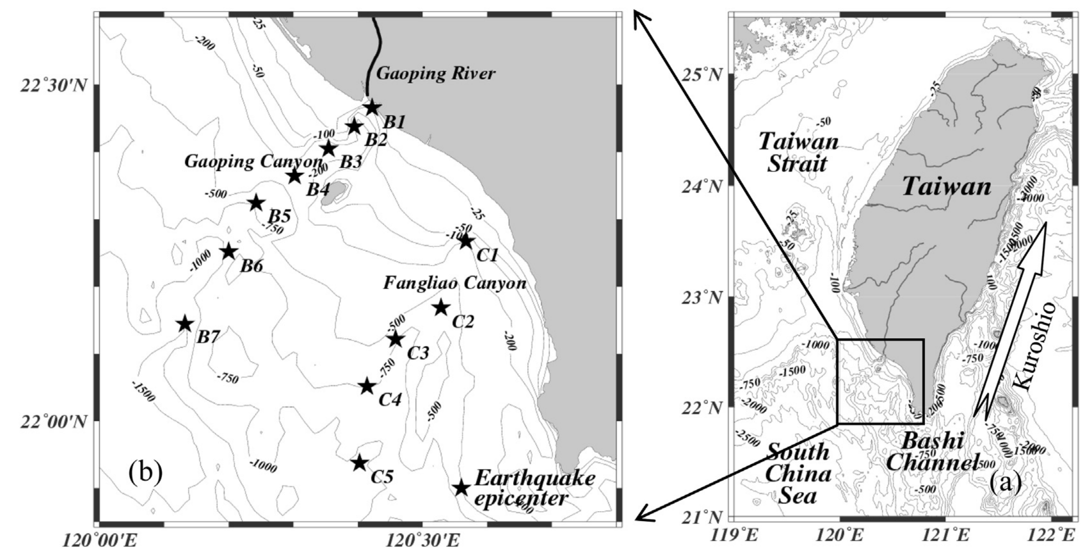

Fig. 1. The study area (a) and sampling locations (b) in the Gaoping Canyon and Fangliao Canyon off southwestern Taiwan.

the sediment source may also determine the dynamics of terrestrial sediment over a canyon. Consequently, the sediment gravity flow was reported to typically have a dominant role in episodic transport of sediment to the deep sea in the canyon penetrating closely to the river mouth (Xu et al., 2002, 2010; Puig et al., 2004).

Trace metals in rivers are derived from either terrestrial weathering or human activities in land, and may serve as terrestrial source indicators when trace metals are transported into oceans (Windom et al., 1989; Zwolsman et al., 1996; Hung and Hsu, 2004). Notably, trace metals are generally carried by suspended particulate matter through the river-sea boundary (GESAMP, 1987). As the Gaoping River, the largest river in southern Taiwan, flows through densely populated areas and industrial districts around the lower watershed, massive amounts of natural and anthropogenic trace metals empty into the ocean during extreme events (Lai, 2003; Hung and Hsu, 2004). Previous studies have demonstrated that over 90% of most trace metals were carried in particulate form by the Gaoping River during the high flow (summer) season (Hung and Hsu, 2004). The river also discharged more than 70% of its annual water (8.5×10^9 m^3 yr^{-1}) and sediment (3.6×10^8 ton yr^{-1}) during summer (Hung et al., 2009, 2012). The Gaping Canyon (GaC) is unique, extending from the Gaoping River mouth into the South China Sea (SCS) to meet the Manila Trench, such that the GaC may act as a trap and conduit for mud exchange between the Gaoping River and offshore (Liu et al., 2006). The study of most metals in Gaoping coastal sediments also indicates different patterns of metal distributions between canyon and canyon-excluded shelf (Hung and Hsu, 2004). Very few studies have focused on the Fangliao Canyon (FaC) likely because of the lack of direct river inputs. However, the terrestrial sediment can be fed into the FaC via the longshore current. Hale et al. (2012) may be the significant one addressing typhoon-induced sedimentation in the FaC. Notably, the epicenter of the Pingtung Earthquake (M_L 7.0), a large earthquake that hit on 26 December 2006, was near the FaC. The earthquake caused the rapid movement of sediment and severely damaging submarine cables in the area (Hsu et al., 2008), but its impact on metal re-distribution has not yet been explored before in this or other regimes. The aim of this study is to understand and identify the effects of extreme events, such as typhoons and earthquakes, on distributions of trace metals in the GaC and FaC within the active continental margin.

2. Materials and methods

2.1. Study area and hydrographic data acquisition

This study was carried out in six cruises onboard *Ocean Researcher III* to collect seawater samples during spring (March/2005), summer (August/2004), late autumn to early winter (November/2005 and November/2007) and winter (January/2006) as well as 4 days after typhoon in summer (August/2005) and 1 week after earthquake in winter (January/2007) along the GaC and FaC transects. The impact of earthquake in winter with little river discharge can be distinguished from the impact of typhoon in summer with huge river discharge. Fig. 1 shows the study area and sampling locations. Seawater samples were taken with clean 10-L Niskin bottles mounted on a CTD/Rosette (General Oceanic, USA). The CTD and transmissometer recorded water temperature, salinity, depth and light transmission, which can be used as a proxy for suspended matter.

The hydrological condition varied with the interplay of three types of water masses including the effluent from Gaoping River, South China Sea and Kuroshio waters in the GaC, but the condition was less affected by river effluent in the FaC (Liu et al., 2009). The Barotropic and baroclinic tidal forcings were both important in addition to a strong presence of internal tides (Liu et al., 2009). The gross primary production was higher in summer than in winter in both canyons, and also much higher in GaC than in FaC in summer (Hung et al., in press). Distribution of dissolved oxygen showed oxygenic condition in all water columns, with high in surface and low in bottom (Ho, 2008). Surface sediment was largely composed of mud (50–99%, clay: 5–17%) in the GaC (Hung et al., 2009) and of silt (40–70%), clay (15–30%) and sand (1–10%) in the FaC (Hale et al., 2012). Sedimentation rates ranged from 0.094 to 0.215 cm yr^{-1} in the GaC (Hung et al., 2012), but no reliable data can be found in the FaC. Diagenesis of organic matter in sediments contributed notable dissolved organic carbon (DOC) to the bottom water of GaC (Hung et al., 2012). Sediment resuspension and deposition occurred frequently in both canyons, particularly during the typhoon periods (Liu et al., 2009; Hale et al., 2012).

2.2. Seawater and particulate matter sampling

The method for recovery of particulate matter from seawater has been described previously (Hung et al., 1999, 2007). Briefly,