Modern transport and deposition of settling particles in the northern South China Sea: Sediment trap evidence adjacent to Xisha Trough

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A B S T R A C T

Studies on modern sediment transport and deposition, especially studies analyzing settling particles collected with sediment traps, have rarely been carried out in the northern South China Sea. Using sediment trap time series data from Site XS1 (17° 24.5′ N, 110° 55.0′ E, water depth 1690 m) adjacent to the Xisha Trough, variations in sediment source through time have been reconstructed. These observations include total particle flux (TPF) and current data, grain size distributions, and clay mineral compositions obtained from two sediment traps deployed in 500 m and 1500 m water depth, respectively. Time series records at Site XS1 changed seasonally for both sampled layers. TPF in the lower layer (426 mg/m²/d) was several times that of the upper layer (113 mg/m²/d) and is affected by lateral transport. However, mean grain size (Mz) of the upper layer is greater than that of the lower layer (29 vs 10 μm) due to contributions from biogenic materials. There are no clear seasonal changes in clay mineral assemblage in either the upper or lower layers. The annual percentages of four main clay minerals were 82%–83% illite, 7%–9% kaolinite, 6%–8% chlorite and 1%–3% smectite. Taiwan was the dominant sediment source (42%–74%), while sediment contributions from the Red River and Annamite Chain account for 23%–53% and 0%–15%, respectively. Sediment supply from Taiwan could be explained by deep water current flow, while coastal currents may aid sediment transport from the Red River and small mountainous rivers of central Vietnam.

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1. Introduction

Sediment mineralogical and geochemistry have been used to constrain sources and transport routes in the South China Sea (e.g. Shao et al., 2001; Liu et al., 2011, 2013; Wei et al., 2012). Earlier work indicated that illite and chlorite in the modern northern South China Sea (SCS) were mainly derived from Taiwan, while kaolinite and smectite originated from the Pearl River and Luzon arc system, respectively (Wan et al., 2007; Liu et al., 2010a, 2010b). However, Shao et al. (2009) suggested that sediments deposited southeast of the Dongsha Islands (Fig. 1) were predominantly derived from Taiwan with additional flux from South China. Liu et al. (2012, 2014a) argue that sediments discharged from east of Pearl River delta cannot be ignored as potential sediment sources to the northern SCS. To make the situation more complex it is now clear that the rivers have changed their compositions through time in response to climatic forcing and more recently because of anthropogenic disruption. For example, Hu et al. (2013) have shown that prior to ~3 ka the Pearl River was also an important source of smectite, as well as Luzon.

Sediment is also supplied to the deep basin by rivers draining the east coast of Vietnam. Sediment supply from central Vietnam has typically been ignored in previous provenance analysis, despite the fact that a large amount of material is being discharged into the central part of Vietnam shelf from the Annamite Ranges, as shown by higher sedimentation rate there compared the southern and northern parts of the Vietnamese shelf away from the Red and Mekong River deltas (Schimanski, 2002; Schimanski and Stattegger, 2005). If we are to use the deep-sea sediment record to reconstruct ancient environmental conditions then current transport must be constrained. In this paper we address the present transport and deposition processes from sea surface to the seafloor.

Time-series sediment traps that directly collect settling particles in the water column are effective tools for understanding the modern sedimentation processes (Yamasaki and Oda, 2003; Buesseler et al., 2007), and analyses of sediment trap material will improve our ability to ground truth monsoon proxies...
Fig. 1. Sediment traps XS1 (pink star), M1, M2 and SCS-C (gray stars) in the northern SCS, (a) surface current in winter (green arrowed lines, from Fang et al., 2012; Liu et al., 2014b), Kuroshio Current intrusion in winter (blue lines, Qiu et al., 2011), and sea surface temperature during January (grey dashed lines with numbers, unit °C, Huang et al., 2011), (b) surface current in summer (red arrowed lines, from Fang et al., 2012; Liu et al., 2014b), summer upwelling along the Vietnamese coast is added according to surface chlorophyll distribution (pink dotted area, Yu et al., 2008) and sea surface temperature (SST) during July (black dashed lines with numbers, unit °C, Huang et al., 2011). Large arrows with numbers represent annual sediment loading of surrounding major sources (unit: Mt/a, from Milliman and Farnsworth, 2011). Black (from Sarnthein et al., 2013) and brown solid lines (from Zheng and Yan, 2012) represent the assumed deep water current, and black dashed arrow is the assumed intermediate-water current circulation pathways in the middle SCS (from Wang et al., 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
(Chen et al., 1998; Wang et al., 2005). Since the late 1990s, the properties, distribution, behavior and flux of particulates in the northern SCS have been studied with water column filtrations and deployments of time-series sediment traps, which are parts of the SCS Integrated Biogeochemical Experiment and the Southeast Asian Time-series Study programs (Chung et al., 2004). Previously, studies of the modern oceanography in the northern SCS have focused on organic sediment fractions, especially planktonic foraminiferal records (including isotopes and assemblage) (e.g. Lin et al., 2004, 2011; Lin and Hsieh, 2007; Huang et al., 2008; Hung and Gong, 2010). Although planktonic foraminifers are useful paleo-climate proxies the seasonal and inter-annual variance of chemical and mineral compositions in settling particles are also important for understanding sediment transport and the influences of marine currents (Ramiaswamy et al., 1991, 1997; Unger et al., 2003).

The Xisha Trough is an important channel for Red River sediments entering the deep water basin of the SCS, and is influenced both by deep water current flow and summer monsoon-related upwelling offshore southeast Vietnam to the south. However, little work on modern sedimentation has been carried out in this area, especially the tracing of sediment sources and transport pathways through analysis of trap sediment samples. In this study, we examine variations of sediment flux, grain size and clay minerals in the water column adjacent to the Xisha Trough through analysis of the suspended particle materials collected by sediment trap over a period of almost three years (2009–2012). We then estimate the relative contribution from different sediment sources based on clay mineral assemblages. Finally, we explore the power of current transport adjacent to Xisha Trough combined with current data measured in-situ.

2. Background

2.1. Correlated currents

As the largest semi-enclosed marginal sea in the west of tropical western Pacific, the SCS is bounded by the landmass of South China and the Indochina Peninsula to the north and west, and by the Philippine Island chain (including Luzon), Borneo and Sumatra to the east and south. There are various water masses at different water depths in the SCS (Fig. 1). In the East Asia region, differential heating between the NW Pacific and the Asian landmass leads to a seasonal reversal of monsoon winds and resultant seasonal surface circulation patterns over the SCS. In winter (November to March), the northeast monsoon prevails due to high atmospheric pressure over central Asia, leading to a cyclonic surface circulation in the deep-sea basin (Fang et al., 2012). During that period, Western Pacific surface water intrudes into the SCS through the Luzon Strait and then moves southwestward along the continental slope (Shaw and Chao, 1994; Qiu et al., 2011). However in summer (June to September), the southwest monsoon prevails and a low-pressure system occurs over Asia. At that time, the alongshore component of the winds causes upwelling of nutrient-rich, and high-salinity water offshore SE Vietnam, and the circulation in the northern SCS turns to be anticyclonic under the effect of the southwestern wind (Chung and Wu, 2005). The Kuroshio Current intrudes into the northern SCS and transports the top 300–500-m water westward along the northern continental slope of the SCS (Shaw and Chao, 1994; Liu et al., 2011). Deeper Western Pacific water enters the SCS at depths between 1500 and 1900 m, after which it sinks to the bottom of deep sea basin, while its upper water mass eventually flows out of the basin at intermediate depths of 500 and 1000 m (Gong et al., 1992). Below ~1500 m, there is a persistent baroclinic pressure gradient driving flow (named the deep water current, DWC) from the Pacific into the SCS through the Luzon Strait. Recently the “Deflection Current” which is located at depths > 1500 m was reported to flow northeastward in the northern SCS (Wang et al., 2013). After entering the SCS through the Luzon Strait, the DWC first turns northwestward and then turns southwestward along the continental margins offshore southeast China and Vietnam (Qu et al., 2006; Zheng and Yan, 2012; Sarthein et al., 2013).

In the SCS, temperature, salinity and nutrients in seawater change seasonally and annually because of variations of wind direction and intensity (Li and Zhan, 1989; Chen et al., 2007). The modern sea surface temperature (SST) ranges from 28 to 29°C and shows a small north–south gradient in the northern SCS in summer, when average salinity is relatively low as a result of the inflow of fresh water into the coastal region. The water is strongly stratified, with a poor supply of nutrients reflecting decreasing organic production (Gong et al., 1992; Liu et al., 2002). By contrast, average surface temperature ranges from 20 to 26°C and shows a north–south gradient in winter, when the sea surface salinity (SSS) is relatively stable (Wyrkti, 1961).

2.2. Sediment supply of surrounding potential sources

The terrigenous input derived from large rivers is larger than that from aeolian particles transported from mainland China or volcanic ashes from the Philippine and Indonesian islands (Wiesner et al., 1996; Chung et al., 2004). At Ocean Drilling Program (ODP) Site 1146 (Fig. 1), only ~10% of the total clay and around 10% of the terrigenous fractions were related to eolian supply (Boulay et al., 2007; Wan et al., 2007). Study of the inner shelf of the East China Sea also revealed that the Yangtze River (loading of 470 Mt/a, Milliman and Farnsworth, 2011) does not supply significant sediment to the SCS through the Taiwan Strait (Xu et al., 2009). At the same time, most of the Mekong River sediments (loading of 150 Mt/yr) were deposited along the shore after southwestward transporting away from the river mouth (Liu et al., 2009; Xue et al., 2010).

Pearl River sediment discharge (~80 Mt/yr) is mostly transported southwestward, but these sediments are largely deposited on the inner shelf (Liu et al., 2011, 2014b; Ge et al., 2014). Meanwhile, low sediment flux (~1 Mt/a) from Hainan is consistent with low mass accumulation rates (MAR) on the neighboring shelf (Wang, 1999). Sediments from Luzon sediments (~11 Mt/a) are generally deposited to the northwest of Luzon and are not significantly transported onto the northern shelf by the branch of the Kuroshio Current (Liu et al., 2011).

In contrast, southwestern Taiwan supplies large amounts of sediments (~70 Mt/a) into the northeastern SCS (Liu et al., 2008b) via small mountainous rivers (e.g. Kaoping River). Likewise, small mountain rivers from the Annamite Chain in central Vietnam annually supply 40–100 Mt of sediments into the SCS, and about half of their loading sediments were deposited on the central part of the Vietnamese shelf (Schimanski, 2002; Schimanski and Stattegger, 2005). Furthermore, the Red River annually supplies 110 Mt of sediments into the Gulf of Tonkin, but most of these have been sequestered close to the delta coast during the Holocene (Tanabe et al., 2003, 2006; Hori et al., 2004).

3. Materials and methods

3.1. Sediment trap moorings

Two sediment traps (SMD-26S) were deployed at 500 m and 1500 m water depths at XS1 (17 24.5’S, 110 55.0’E, water depth 1690 m) (Fig. 1) from June 2009 to June 2012, with a collecting area of 0.5 m² and a sample duration of 14–16 days (two samples per month). In some cases samples were not available because of
very low recovery. The sampling cups were filled with in situ filtered seawater (0.45 mm filter) collected from trap locations to which 3.3 g/L HgCl₂ was added before deployment to prevent decomposition of organic material. Samples in polyethylene bottles (250 mL) were kept at 4 °C and transported to the laboratory of the South China Sea Institute of Oceanology (SCSIO), Chinese Academy of Sciences (CAS). A total of 134 trap samples were collected with two sediment traps during three years. Among them, 71 and 63 samples from the lower and upper traps, respectively, were collected for related measurements.

Each trap sample was split into four quarters after removing by hand all recognizable zooplankton ‘swimmers’. Two splits of each

Fig. 2. Temporal changes of major components in the upper and lower layers at XS1, downwards are total particle flux (TPF) of bulk samples, mean grain size (Mz), four clay minerals (smectite, illite, kaolinite and chlorite). Mz of the upper layer is given for bulk samples, while that of the lower layer is given for terrigenous component.
sample were used for grain size and clay mineral measurements, respectively. The total particle flux (TPF) was determined by weighing the dry weight of the materials on an analytical balance. Given the sampling area of the trap and the exposure time, we calculate flux (mg/m²/d).

Current velocity and direction were measured in-situ using current meters (Seaguard RCM DW) attached to a mooring string, which measured the current every 30 min. Because of excessive consumption under low temperatures the current meter only worked for the first 2–3 months for the lower layer. In order to explain monthly and seasonal variations in sediment transport and deposition, we calculate the average current velocity and direction for each month.

3.2. Grain size analyses

Because there were not enough particles to measure terrigenous grain size in the upper layer, we just measured grain size from the lower layer. Lower layer sediments were pretreated with excess H₂O₂ (10%), HCl (10%) and Na₂CO₃ (2 N) successively, and then centrifuged three times to isolate the terrigenous component. Grain-size distribution measurements were carried out with a Malvern Mastersizer2000 at SCsio, CAS, which accounts for grains in the 0.02–2000 μm range. The measurement repeatability of the instrument is 0.5%, and the reproducibility is better than 2%.

3.3. Clay mineral analyses

Clay minerals (<2 μm) were separated according to Stoke’s settling velocity principle after removing organic matter and carbonate with 10% H₂O₂ and 0.5 N HCl, respectively (Wan et al., 2007). Clay mineralogy determinations were performed by standard X-ray diffraction (XRD) on a D8 ADVANCE diffractometer with CuKα radiation (40 kV, 25 mA) in the Key Laboratory of Marine Geology and Environment, Institute of Oceanology, CAS. Identification of clay minerals was made mainly using the position of the (0 0 1) series of basal reflections on the XRD diagram of ethylene glycol salvation. Mixed-layers mainly of smectite-illite were included in “smectite” and mixed-layers mainly of chlorite-illite with very minor abundance were not calculated following the procedure of Liu et al. (2010a). Relative percentages of the four main clay mineral groups were estimated by weighting integrated peak areas of characteristic basal reflections (smectite-17 Å, illite-10 Å, and kaolinite/chlorite-7 Å) in the glycolated state using the Topas 2P software with the empirical factors from Biscaye (1965). Relative proportions of kaolinite and chlorite were determined using the ratio of the 3.57 Å/3.54 Å peak areas. According to Biscaye (1965), the accuracy of this method is ±5–10% for the above four clay minerals. Moreover, clay mineral data of the modern Luzon, Taiwan, Red and Pearl River sediments were recalculated from Liu et al. (2007a, 2007b, 2008a, 2010a).

4. Results

4.1. Total particle flux

TPF at Trap Site XS1 ranged from 7 to 281 mg/m²/d (averaging 111 mg/m²/d) at 500 m water depth, which was consistent with previous observations in the northern and central SCS that indicated that TPF was only about 100 mg/m²/d or less for shallow sediment traps (Wiesner et al., 1996; Lahajnar et al., 2007). However at 1500 m water depth, TPF increased rapidly from 68 to 1527 mg/m²/d (averaging 418 mg/m²/d), which was about four times that in the upper layer (Fig. 2). Higher TPF at greater depths has been noted elsewhere in the SCS (Chung et al., 2004). At Site M1 (21°32′N, 119°28′E, water depth 2948 m,Fig. 1), average TPF increased from 284 mg/m²/d at 248 m depth to 486 mg/m²/d at 948 m water depth. Similarly at Site M2 (19°01′N, 117°32′E, water depth 3740 m) mean TPF increased from about 200 mg/m²/d at 1240 m depth to 260 mg/m²/d at 3240 m depth. However at Trap SCS-C (14°35′–37′N, 115°07′–09′E, water depth ~4300 m) from the central deep water basin, TPF in the shallow trap was almost the same as in the deep trap (Chen et al., 2007), which might be explained by sediment transport by current because the former sites (XS1, M1, M2) were located on/around a major current route so that terrigenous components could be transported into the deep water at these sites while the latter site (SCS-C) is located far from the current (Fig. 1). Resuspension and lateral transport from the continental shelf or slope might be the dominant factor accounting for higher TPF in the deeper traps compared to the shallow ones (e.g. Chung et al., 2004; Lahajnar et al., 2007; Szczucinski et al., 2009).

Great monthly variations were observed in TPF for both the upper and lower layers at Site XS1 (Fig. 3). For the 500 m layer, TPF during the wintertime (averaging 138 mg/m²/d) was higher than those during the other seasons (averaging 92 mg/m²/d). Similarly in the lower 1500 m trap, TPF during the wintertime (averaging 555 mg/m²/d) was much higher than during the other seasons (averaging 334 mg/m²/d). These confirmed the hypothesis that most sediment on the continental shelves was transported during the winter (e.g. Yang et al., 1992; Sun et al., 2000; Dong et al., 2011). TPF for both the 500 and 1500 m layers at Site XS1 increased rapidly during the study Period (Fig. 4). TPF of the lower layer increased from 220 mg/m²/d during 2009–2010 and reached 689 mg/m²/d during 2011–2012. Similarly, average TPF of the 500 m layer increased from 72 mg/m²/d during 2009–2010 to 155 mg/m²/d during 2011–2012. Although current velocity decreased gradually for the 500 m layer, current direction changed at the same time so that more particles could be transported from the northeast, probably affected by the DWC and/or Kuroshio Current (Fig. 1).

4.2. Grain size

Mean grain size (Mz) of the 1500 m layer particles varies from 6 μm to 19 μm with an average of 9.7 μm, and a single peak at 4–11 μm on grain size frequency distribution curves (Fig. 5). These sizes are similar with to those of surface sediment samples, with one significant peak of 400–600 μm for the latter. We interpret this peak as probably connected with turbidite current transport within the Qiongdongnan Basin (He et al., 2013; Su et al., 2014).

Compared with the relatively stable grain size of the lower layer (8–10 μm), annual the Mz values of upper layer sediment fluctuated from 18 μm to 44 μm (Fig. 4), which correlated with calcareous and siliceous biogenic production (e.g. Chen and Tan, 1997; Lin and Hsieh, 2007; Zhang et al., 2010). In this paper we only discuss the terrigenous origin of suspended particles, we do not consider further these biogenic components.

4.3. Clay minerals

At Site XS1, the clay mineral assemblage of the settling particles is 83% illite, 7% kaolinite, 8% chloride and 1% smectite for the upper (500 m) layer, and 82% illite, 9% kaolinite, 6% chloride and 3% smectite for the lower (1500 m) layer. There are both seasonal and inter-annual changes in clay mineral assemblage for both upper and lower layers at XS1 (Figs. 2–4), but these changes are not well defined, probably because of intense mixing (e.g. Yu et al., 2006; Xie et al., 2013) as revealed by trends in total particle flux and grain size. Illite percentage in particles from both the upper and lower layers fluctuated from 76% to 91% with an average of 83%. Great differences similarly occurred between the two layers in terms of the kaolinite and chlorite percentages. Kaolinite and chlorite percentages varied from 3% to 15% (averaging 7%) and from 2% to 18% (averaging 8%), respectively in the upper 500-m-layer; while
Fig. 3. Monthly (seasonal) variance of TPF, Mz, smectite, illite, kaolinite and chlorite in the upper and lower layer samples at the sediment trap site, together with current velocity and flow direction measured in-situ. Mz of the upper layer is given for bulk samples, while that of the lower layer is given for terrigenous component.
kaolinite and chlorite changed from 5% to 17% (averaging 9%) and from 3% to 11% (averaging 6%), respectively in the lower 1500-m-layer.

5. Discussion

5.1. Sediment contribution estimation based on clay minerals

Among the major potential sources surrounding the northern SCS shown in Fig. 1, sediments from both Taiwan and Red River were characterized as having high illite percentage (averaging 71% and 62%, respectively; Liu et al., 2007b, 2008a), while sediments from both Luzon and the Annamite Chain were characterized by high smectite percentage (averaging 74% and 20%, respectively; Liu et al., 2008a; Schimanski, 2002). Moreover, sediments from both Hainan island and the Pearl River are presently characterized by high kaolinite percentage (averaging 68% and 37%, respectively, from S.M. Wan, personal communication, 2014 and Liu et al., 2007b).

Fig. 6 shows clay mineral variations for the upper and lower layers as well as potential sources. The clay mineral assemblage of both the upper and lower layers lies within the range of the Red River and Taiwan sediments, suggesting their influence. High smectite percentage might also be explained by flux from the Annamite Chain. Here we discuss possible sediment contributions from the Red River, Taiwan and the Annamite Range using the minimum error method of Liu et al. (2012, 2013). We recalculated the average clay mineral percentages of the above three sources using the method of Biscaye (1965), which resulted in an average composition of 3% smectite, 19% kaolinite and
Fig. 5. Grains size distribution of the lower particles (2010D9T collected between October 16 and October 31, 2009 and 2011D9T collected between January 16 and January 31, 2011 as examples, respectively) at XS1 and adjacent surface sediment sample (D21-7, 17°41.9’N, 110°0.3’E, water depth 1740 m as example) from the northern SCS. Grain size data of the upper layer are not shown here because different materials (one was bulk samples and the others were terrigenous components) were measured for grain size.

Fig. 6. Ternary diagram showing variation in clay mineral composition of the settling particles from the upper and lower layers at the sediment trap site from the northern SCS. Clay mineral compositions in sediments from Luzon, Taiwan, Pearl River, and Red Rivers are recalculated from Liu et al. (2007a, 2007b, 2008a, 2010a), those of Annamite chain sediments are sourced from Schimanski (2002), and those of Hainan Sediments (S.M. Wan, personal communication, 2014).

Our results show that sediments from Taiwan and Red River could account for the sediment at the lower level of the trap site by average contributions of 63% and 37%. The lower level sediments could be produced by a mixture of 57%, 35%, and 8% from Taiwan, the Red River and the Annamite Ranges. This result is simply an average and we recognize that sediment flux from the three sources changed monthly for both the upper and lower layers (Fig. 7). Annamite sediments account for < 15% for the lower layer and less than 10% for the upper layer sediments. In contrast, Taiwan is the predominant source and contributed between 50% and 70%. The remaining sediment is presumed to be derived from the Red River.

Our results confirmed that the Red River is significant source of sediment to the study area. However, we clearly show that Taiwan provides the bulk of the sediments to the Xisha Trough, just as it does to sediment drifts around the Dongsha Islands. At ODP Sites 1144, 1146 and 1148 on the northern margin of the SCS, sediment drifts have principally been sourced from Taiwan since at least 3 Ma (Hu et al., 2012; Wan et al., 2010). Nd isotopic variations in recent sediments on the northern slope at the southeast of Dongsha Islands further indicated that over 80% of the rapidly accumulated sediments there came from Taiwan and possibly from coastal areas of South China, including ~20% from the Pearl River (Shao et al., 2009). In addition, we note that some of the sediment is sourced from the Annamite Range to the study area, especially to the lower 1500-m-layer. This hypothesis is consistent with studies that indicated that sediments on the central part of Vietnam shelf were mainly delivered from small mountainous rivers draining the Annamite Chain (Schimanski, 2002; Schimanski and Stattegger, 2005).

5.2. Force driving sediment transport

How can sediment be transported over 1000 km from Taiwan? The Deep Water Current (DWC) is one possible mechanism. Hydrographic data analysis revealed that southward flow of the DWC along the eastern slope of Taiwan entered the SCS through the Luzon Strait (Qu et al., 2006; Lan et al., 2013). Current data measured in-situ at Site XS1 further suggested that a stable deep water current with an average velocity of 5–6 cm/s flows southward towards 170–180° at the trap site through much of the year (Fig. 3).

The DWC are known to transport sediments over long distances and form drift deposits with high sedimentation rates in several ocean basins (Robinson and McCave, 1994; Rhein et al., 1995). In the northern SCS, a strong DWC flows southwestward along the continental slope under the influence of the Coriolis Effect (Shao et al., 2007). This in turn has controlled deposition of Taiwanese sediments on the Chinese continental slope (Ludmann et al., 2005; Wan et al., 2010). Clay mineral data from surface sediments from deep SCS indicate that this current might reach as far west as 112° E and south to 13°N along the 2000 m isobaths and thus transport Taiwan sediments southwestward into the central SCS (Liu et al., 2013). Our estimates show that the contribution from Taiwan to the lower 1500-m-layer reached a peak (62%) in winter, and decreased to a minimum (48%) in summer (Fig. 7). This is consistent with current observation and model analysis in the northern SCS that indicate that the DWC is at a maximum in winter (Xie et al., 2013).

The contribution of Red River sediment to the upper layer trap via coastal currents reached a peak in the winter (38%), but decreased to 30–34% in summer and autumn. Sediment contribution from the Red River correlates well with current velocity measured in-situ (Fig. 7). When current velocity accelerated, more Taiwanese sediment was transported into the study area, but more sediment from the Red River was deposited when the current decelerated. Oceanographic models similarly revealed that the Kuroshio Current (KC) intrudes the western SCS during the autumn following a period of summer surface offshore transport (Xue et al., 2004). Results from time-series sediment trap (M1 and M2) in the northern SCS documented that downward TPF was at a maximum during the northeast monsoon (Lahajnar et al., 2007).

It should be noted that TPF to the lower layer was several times more than those to the upper layer (Figs. 2–4). This suggests that lateral transport is possibly a dominant pattern of sediment transport (e.g. Hung et al., 1999; Honda et al., 2000). In our analysis we have neglected changes in clay mineral assemblage caused by sediment transport and the differential flocculation of different clay minerals (Gibbs, 1977; Addai-Mensah, 2007). Our sediment budget is also only based on clay mineral assemblages, which represent only 10–20% of the sediments. In fact the coarse-grained fraction (>2 μm) dominates in the traps (80–90%) but their origin is harder to determine, except that we presume they are transported less far from their sources.
6. Conclusions

Sedimentary records of particles from both upper (500 m) and lower (1500 m) layers of sediment trap Site XS1 located adjacent to Xisha Trough changed seasonally and inter-annually. The TPF to the lower layer (on average 426 mg/m²/d) is nearly four times that of the upper layer (on average 113 mg/m²/d), reflecting the influence of lateral sediment transport. Grain size for the upper
layer sediment (29 μm in average) is about three times that of the lower layer (10 μm in average) because of the contribution of siliceous and calcareous components from shallow waters.

Compared with the great difference in particle flux rate and grain size, the clay mineral assemblage in the two layers changes less on both monthly and seasonal scales. The annual average clay mineral assemblage is 83% illite, 7% kaolinite, 8% chlorite and 1% smectite for the upper layer, and 82% illite, 9% kaolinite, 6% chlorite and 3% smectite for the lower layer. We used the minimum error method of Liu et al. (2012, 2013), to estimate sediment contribution from the Red River, Taiwan and the Annamite Chain of Central Vietnam. Taiwan is the dominant source (57% for the lower layer and 65% for the upper layer), while the Red River supplied 35% and 33% for the lower and upper layers, respectively. The DWC of the northern SCS may be responsible for transporting Taiwanese sediments to the study site. Low intensity during the summer is consistent with minimum sediment flux from Taiwan to the lower trap. However in the upper layer, estimated sediment contributions from the Red River matched well with current velocity measured in-situ, indicating that sediments from the Red River were supplied under the effect of coastal currents driven by summer monsoon winds.

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