

Tidal and flood signatures of settling particles in the Gaoping submarine canyon (SW Taiwan) revealed from radionuclide and flow measurements

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ABSTRACT

Sediment transport and sedimentation processes in the Gaoping submarine canyon were studied using sediment trap and current meter moorings deployed at a location during the winter (January–March) and the summer (July–September) months in 2008. At the end of each deployment, sediment cores were also collected from the canyon floor at the mooring site. Samples from sediment traps and sediment cores were analyzed for ²¹⁰Pb and ²³⁴Th by gamma spectrometry. In conjunction with particle size and flow measurements, the datasets suggest that sediment transport in the canyon is tidally-modulated in the drier winter season and flood (river)-dominated in the wetter summer season. From the magnitude and temporal variation of sediment flux in the canyon with respect to the burial flux and sediment budget on the open shelf and slope region, we reaffirm that, on annual or longer timescales, the Gaoping submarine canyon is an effective conduit transporting sediments from the Gaoping River's drainage basin (the source) to the deep South China Sea (the ultimate sink).

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1. Introduction

Submarine canyons, especially those located at collision margins with narrow shelves, are effective pathways for the transport of sediments from ocean margins to deep ocean basins (e.g., Shepard, 1981; Milliman and Meade, 1983; Milliman, 1995; Woolfe et al., 1998; Walsh and Nittrouer, 2003). This and other related issues have been explored for numerous submarine canyons around the world, such as the Eel Canyon off northern California (Puig et al., 2004; Mullenbach and Nittrouer, 2000, 2006; Lamb et al., 2008), the Monterey Canyon off central California (Xu et al., 2002), the Sepik Canyon off north Papua New Guinea (Kineke et al., 2000), the “Swath of No Ground” on the Bengal Shelf (Michels et al., 2003; Kottke et al., 2003) and the Cap de Creus Canyon in the northwestern Mediterranean (Palanques et al., 2008). The Gaoping submarine canyon (GPSC) off southwestern Taiwan is similar to these canyons in many ways. Not only is the GPSC a prominent geomorphic feature, it is also a major conduit transporting fluvial sediments directly from the mountainous Taiwan to the abyss in the South China Sea (Liu et al., 2002, 2006; Yu et al., 2008; Huh et al., 2009).

As with the Sepik Canyon, which extends into the Sepik River's mouth (Kineke et al., 2000), the GPSC (see Fig. 1) is nearly connected

to the Gaoping River (GPR). The GPR stems from the Jade Mountain (3952 m; the highest mountain in Taiwan), meanders 171 km (the second longest river in Taiwan) toward the southwest and drains the Gaoping catchment (3257 km²; the largest drainage basin in Taiwan). The climate in the GPR's basin is tropical to sub-tropical and is influenced by the annual monsoon cycle and typhoons. Mean annual rainfall in the basin is 3046 mm, which sustains an annual river discharge of $8.5 \times 10^9 \text{ m}^3$ (WRA, 1997). More than 70% of the basin's annual rainfall and river discharge occurs from May to September, and is closely linked with the occurrence of typhoons. Highly erodible sedimentary and metamorphic rocks in the drainage basin, coupled with a steep landscape, humid climate, frequent typhoons and earthquakes, provide favorable conditions for physical and chemical weathering/erosion in the basin (Li, 1976; You et al., 1988; Chung et al., 2009).

Sediment load of the Gaoping River is reported to range from 36 MT/yr (WRA, 1997; Milliman and Kao, 2005) to 49 MT/yr (Dadson et al., 2003), leading to a sediment yield of $1.1\text{--}1.5 \times 10^4 \text{ ton km}^{-2} \text{ yr}^{-1}$, which is about an order of magnitude higher than similar but much larger rivers such as the Eel River in Northern California ($1.7 \times 10^3 \text{ ton km}^{-2} \text{ yr}^{-1}$; highest in the conterminous United States; Brown and Ritter, 1971) and the Sepik River in New Guinea ($1.1\text{--}1.3 \times 10^3 \text{ ton km}^{-2} \text{ yr}^{-1}$; Chappell, 1993; Syvitski and Morehead, 1999; Walsh and Nittrouer, 2003). The much smaller spatial scale but higher sediment yield and flux render the GPR and GPSC's source-to-sink

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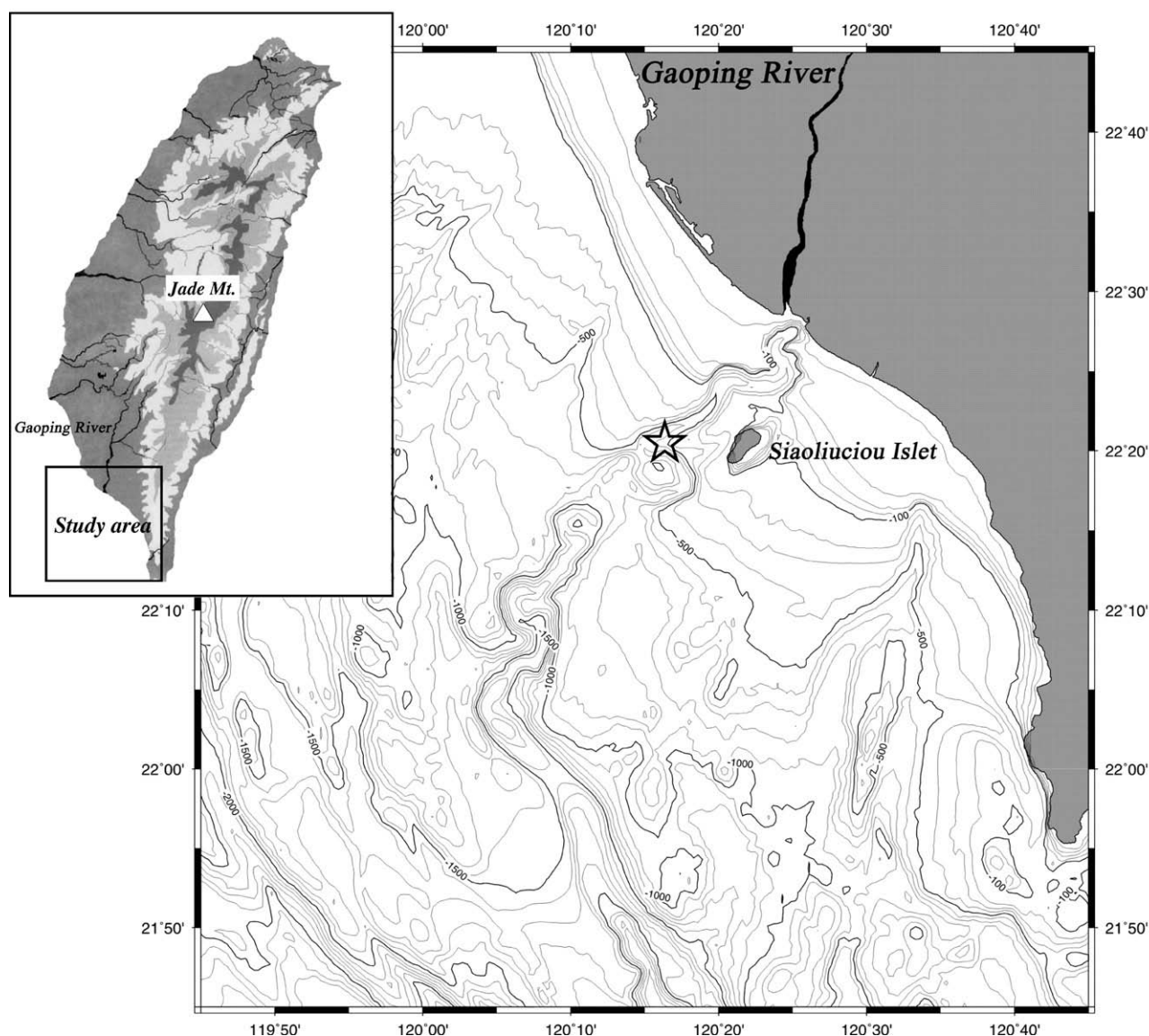


Fig. 1. Map showing location of the T6KP and T7 KP moorings (indicated by the star), the Gaoping River and its headwater in the Jade Mt. (the triangle) and the bathymetry off southwestern Taiwan.

dispersal system an ideal one for studying sedimentation and transport processes from a small mountainous river located at an active margin with a submarine canyon near its mouth traversing a narrow shelf, a condition more common during low stands of sea level in the Pleistocene (Milliman, 1995; Woolfe et al., 1998; Syvitski and Morehead, 1999).

Based on radionuclide profiling of an extensive collection of box cores off SW Taiwan around the GPSC, Huh et al. (2009) showed that sediment deposited in the open shelf and slope region only accounted for less than 20% of GPR's sediment load. The calculated budget, coupled with the presence of short-lived ^7Be and non-steady state distribution and low levels of ^{210}Pb in sediments along the GPSC, suggests rapid transport of sediment from the GPR's watershed via the GPSC to the deeper part of South China Sea via gravity-driven flows.

The speed of down-canyon sediment transport could be very high. For instance, turbidity flows generated by the 2006 Pingtung earthquake off SW Taiwan resulted in a sequential breakage along the GPSC of 11 submarine cables crossing the lower reaches of the canyon. From the timing of cable break and traveling distance along the canyon, it is calculated that turbidity current velocities varied from 20 to 3.7 m s^{-1} (correlated positively with bathymetric slope), and it took merely 8.47 h

for the involved turbidity current to advance 230 km from the continental slope to the Manila Trench (Hsu et al., 2008). Thus, unlike the open shelf and slope, the GPSC is a very dynamic environment in which sediment transport, sedimentation and mass sediment movements take place at much higher and variable rates.

As a component of the FATES program (Liu et al., 2009a,b), we apply natural radionuclides as time and process tracers to study sedimentation and particle dynamics. The purpose of this work is to develop a better understanding of the processes responsible for sediment transport and mass movements in the GPSC. This was done by deploying sediment traps and making ancillary observations and measurements so that processes of different timescales (from event to seasonal) and their controlling factors, such as tides and turbidity currents, can be quantitatively investigated.

2. Data collection

2.1. Sediment trap and current meter moorings

A sediment trap mooring was first deployed from January 10 to March 20, 2008 (a dry season) at 650 m water depth in GPSC (Fig. 1).

The mooring is at a key location (22°21.239'N, 120°16.419'E) where the canyon floor widens drastically and changes from V-shaped to U-shaped, with intra-canyon meandering in its lower reaches. Also, chirp sonar records indicate canyon-wall slumping in this segment of the canyon, known to be favorable for triggering gravity flows (Chiang, Cheng-Shing, personal communication). This mooring, identified as T6KP, is the 6th sediment trap deployment in the GPSC in the course of the FATES program. It contains a USGS-type sediment trap (Rendigs et al., 2009) placed at 597 m depth, or 53 m above the canyon floor, and a Nortek current meter ~5 m above the sediment trap.

The mooring site was reoccupied July 7–September 11, 2008 (a wet season). On this mooring, identified as T7KP, were one USGS-type sediment trap at 608 m depth (42 m above the bottom), a current meter placed 12 m above the trap, at 596 m water depth, and a PPS3/3 sediment trap (Hung and Chung, 1998) at 267 m depth near the canyon rim. The upper trap was set to collect samples at a 5-day interval for the 12 collection cups.

During the recovery cruises of the moorings, sediment cores were also taken from canyon floor near the mooring site.

2.2. Sampling and analytical methods

To avoid potential overflow problem of the PPS3/3 sediment trap during wet seasons when river floods and typhoons produce extremely high concentration of suspended particles in GPSC (Liu et al., 2006), USGS-type sediment traps were used near the canyon floor in both T6KP and T7KP moorings. The sediment collector is a fiberglass cone of ~1 m in height and 25 cm in diameter on the top opening. Below the cone is a PVC tube with a plastic core liner inside. An intervalometer dispenses Teflon discs (the size of casino chips) at a fixed time-interval to the collected sediment in the plastic core liner as time markers. To prevent bioturbation of the collected sample inside the liner supersaturated solution of seawater and sodium azide is slowly introduced to top of the liner via a 'dripping' device. The length of the plastic core liner used in this study is 1.5 m for dry-season and 2 m for wet-season deployment.

At the recovery of the T6KP trap, 82 cm of the 1.5-m core liner was filled with fluffy sediment. Due to natural compaction, however, the length of the sediment shortened to 70 cm prior to extrusion and sampling in the laboratory. The extrusion was done using a hydraulic jack pushing the trap material up through the core liner at 1-cm intervals. At the end of extrusion, the total samples added up to 62 cm.

The 2-m core liner of the USGS-type trap on the T7KP mooring was completely filled during the wet season deployment. In addition, the funnel collector was also loaded with sediment up to the position of the intervalometer that was hung in the middle of the funnel (Fig. 2). In order to sample the trap material for the construction of radionuclide and other profiles upon which a sediment chronology can be established, subcores were inserted to collect samples from the trap funnel. Unfortunately, due to geometry of the trap design, it was not possible to reach the bottom of the trap funnel, thus resulting in a gap in the profiles. The trap material in the liner and the subcores were sectioned at 1-cm intervals and put into plastic jars for drying and subsequent analyses.

From sectioned sediment trap and core samples, small aliquots were taken for particle size analysis (Liu and Lin, 2004) and the remainder were freeze-dried. Based on weight loss after freeze-drying, water contents (hence, sediment porosity) of the wet samples were determined. The trapped material from the PPS3/3 trap was processed in the same way as described in Liu and Lin (2004) and Lin et al. (2005).

2.3. Analysis of radionuclides by γ -spectrometry

This is the first time in the FATES program that sediment trap samples were analyzed for radionuclides nondestructively by γ -spectrometry prior to other chemical analyses. Using a 120% efficiency

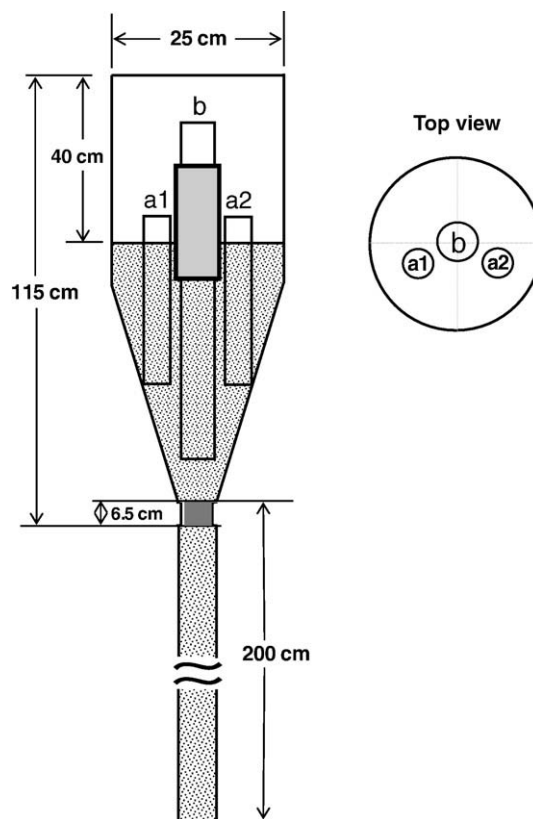


Fig. 2. A sketch (not drawn to scale) of the USGS trap recovered from the T7KP mooring showing the configuration of the intervalometer (the shaded area), the upper funnel, and the lower core liner. Sediment was filled up to the upper funnel and partially buried the intervalometer. Three subcores (a1, a2 and b) were inserted to collect sediment in the funnel. The intervalometer was removed prior to the insertion of subcore b. The lowermost part of the funnel and the "neck" connecting the funnel and the core liner was not sampled (see text for details).

(relative to 3×3 NaI) HPGe detector (ORTEC GMX-120230), the samples were analyzed for ^{210}Pb , ^{234}Th and ^{214}Pb based on photon peaks centered at 46.52 keV, 63.29 keV and 351.99 keV, respectively. Counting efficiencies of the detector for various photon energies were calibrated using IAEA standards 133A and 327 for sample weight at 100 g as a reference, coupled with an in-house secondary standard for various masses from 20 g to 250 g to calibrate the effect of sample mass on γ -ray attenuation. Taking 20-g samples for example, absolute efficiencies are 16.2% for ^{210}Pb , 28.3% for ^{234}Th , and 7.5% for ^{214}Pb .

^{214}Pb was used as an index of supported ^{210}Pb whose activity concentration was subtracted from that of the measured, total ^{210}Pb to derive excess ^{210}Pb ($^{210}\text{Pb}_{\text{ex}}$). To determine the levels of supported ^{234}Th , the samples were re-counted 5 months later following the decay of excess ^{234}Th ($^{234}\text{Th}_{\text{ex}}$). The $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$ data reported here were decay-corrected to the date of trap recovery for the USGS trap or to the mid-point of each sampling interval for the PPS3/3 trap-collected samples. All radionuclide data reported here are calculated on salt-free dry weight basis. Error bars plotted on the figures represent $\pm 1\sigma$ from the mean based on counting statistics.

3. Results and discussion

3.1. Records of sedimentation and water flow at the depths of trap deployments

3.1.1. The T6KP mooring deployed in a tide-dominated period

Fig. 3 shows a pronounced cyclic pattern with the activity concentrations of both $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$ oscillating in phase with wt.% of water content and $<63\text{-}\mu\text{m}$ -size particles. Such correlation

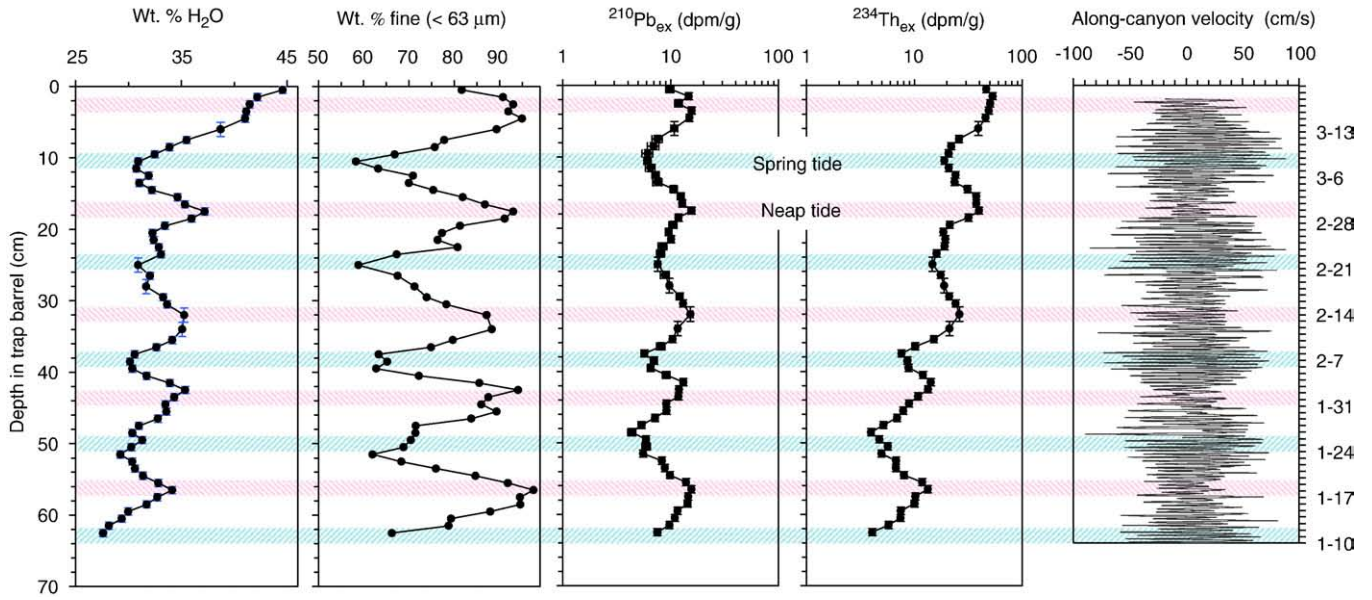


Fig. 3. Profiles of water content (wt.%), particle size (wt.% clay + silt), and activities (dpm/g) of $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$ in the trap barrel from the T6KP mooring. Also shown is the time series of along-canyon velocity recorded about 5 m above the trap. The velocity is positive up-canyon toward the canyon head and negative down-canyon.

reflects the fact that fine particles associated with higher sediment porosity and water contents are more effective than sand-sized particles in scavenging particle-reactive chemical species from seawater.

Also shown in Fig. 3 are the time series of along-canyon velocity recorded at 5 m above the trap. The current meter measurements indicate that, during the dry-season deployment, the topography-steered flow along the canyon was dominated by tidal motions at semidiurnal frequencies (Lee et al., 2009a,b; Wang et al., 2008). Superimposed on the semidiurnal oscillation is a low-frequency oscillation at a periodicity of approximately two weeks, as manifested by changes in the amplitude of along-canyon velocity (Liu et al., in review). Note that the timing of maximum and minimum amplitudes in along-canyon velocity corresponds to that of spring tide and neap tide, respectively. The temperature data (not shown here) also exhibit strong semidiurnal fluctuations, with flood tide bringing in deeper and colder offshore water up the canyon and ebb tide carrying shallower and warmer inshore water down the canyon (Liu et al., 2006; Wang et al., 2008). In general, daily mean temperature is lower during neap tides than in spring tides. During spring tides, wider tidal range leads to greater semidiurnal oscillation in along-canyon velocity, thus providing a more energetic condition for the suspension and dispersal of coarser grained particles (with lower $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$) from the canyon wall and/or the open shelf and slope regions (Liu et al. in review). Conversely, finer particles prevail in the less energetic conditions during neap tides.

Profiles of $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$ in the trap barrel show that $^{210}\text{Pb}_{\text{ex}}$ fluctuated around 10 dpm/g ($1\sigma = 3$ dpm/g) without any trend, while $^{234}\text{Th}_{\text{ex}}$ decreased with depth by a factor of more than 7. This difference reflects that, during the deployment period of 70 days, the decay of ^{210}Pb ($T_{1/2} = 22.3$ years) is negligible while that of ^{234}Th ($T_{1/2} = 24.1$ days), over almost three half-lives, is substantial. By normalizing the activity concentration of $^{234}\text{Th}_{\text{ex}}$ against that of $^{210}\text{Pb}_{\text{ex}}$, the particle size effect is largely cancelled out, resulting in an exponential decrease with depth of the $^{234}\text{Th}_{\text{ex}}/^{210}\text{Pb}_{\text{ex}}$ activity ratio (Fig. 4) that can be simply explained by radioactive decay of both nuclides following trapping of the sediment particles in the barrel; i.e.,

$$\frac{^{234}\text{Th}_{\text{ex}}}{^{210}\text{Pb}_{\text{ex}}} = \frac{(^{234}\text{Th}_{\text{ex}}^0)e^{-\frac{\lambda_1 Z}{S}}}{(^{210}\text{Pb}_{\text{ex}}^0)e^{-\frac{\lambda_2 Z}{S}}} = \frac{^{234}\text{Th}_{\text{ex}}^0}{^{210}\text{Pb}_{\text{ex}}^0} e^{\frac{\lambda_2 - \lambda_1 Z}{S}}.$$

Where $^{234}\text{Th}_{\text{ex}}$ and $^{210}\text{Pb}_{\text{ex}}$ represent activities of excess ^{234}Th and ^{210}Pb , respectively, S is sedimentation rate, Z is depth in the trap barrel, λ_1 and λ_2 are the decay constants of ^{234}Th and ^{210}Pb , respectively, and the superscript zero refers to nuclide activity at depth zero. From the slope of the depth profile, which is $(\lambda_2 - \lambda_1)/S$, linear sediment accumulation rate in the trap barrel (S) can be calculated. The regression line shown in Fig. 4 suggests that, during the trap deployment period, the flux of sediment to the trap was fairly steady with a mean linear accumulation rate of 0.887 cm/d in the trap barrel, in excellent agreement with that expected from the length (62 cm) of the sectioned sediment material in the trap barrel and the deployment time (70 days). The data suggest that, in this particular

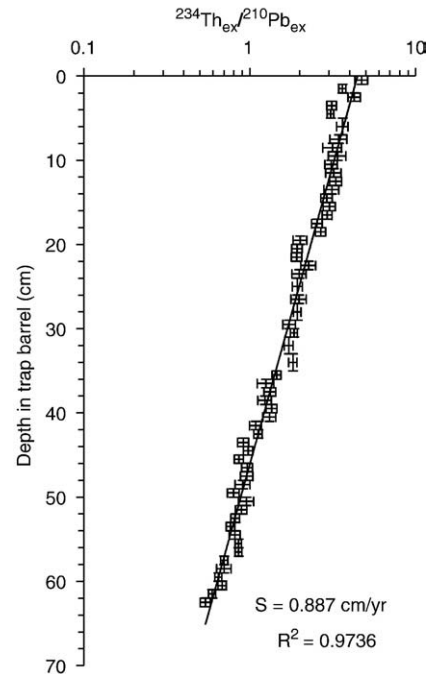


Fig. 4. Profile of the $^{234}\text{Th}_{\text{ex}}/^{210}\text{Pb}_{\text{ex}}$ activity ratio in the trap barrel from the T6KP mooring.

Table 1A summary of mass flux and nuclide activities^a measured by sediment traps and cores from the study site.

	T6KP 1/10/2008–3/20/2008			T7KP 7/8/2008–9/11/2008		
	Mass flux (g m ⁻² d ⁻¹)	²¹⁰ Pb _{ex} (dpm g ⁻¹)	²³⁴ Th _{ex} (dpm g ⁻¹)	Mass flux (g m ⁻² d ⁻¹)	²¹⁰ Pb _{ex} (dpm g ⁻¹)	²³⁴ Th _{ex} (dpm g ⁻¹)
267 m (upper trap)	–	–	–	72	12.6	103
597–608 m (lower trap)	110	9.9	44.5	7 200	1.0	3.5
650 m (bottom core)	595	7.4	18	n.d. (high)	1.8	4

^a Nuclide activities (dpm/g; 60 dpm = 1 Bq) are decay-corrected mean activities in the trapped sediment material or at the top of sediment cores.

setting and time period, ²³⁴Th_{ex} is an ideal, built-in time element for tracing the migration and deposition of particles.

Dividing the measured accumulation rate in the trap barrel by 87.46, the ratio of the trap's collection area at the top (2002 cm²) to the cross-sectional area of the core liner at the bottom (22.89 cm²), we get the actual daily mean sedimentation rate, 0.0101 cm/d. If corrected for sediment porosity, a mean mass accumulation rate of 114 g m⁻² d⁻¹ is obtained. These (and other) data are summarized in Table 1 for further discussion later.

3.1.2. The lower trap in the T7KP mooring deployed in a flood-dominated period

During wet season deployment from July 7 to September 11, 2008, two typhoons, Kalmaegi (July 17–18) and Fung Wong (July 26–29), made land fall on Taiwan resulting in floods and extremely high sediment fluxes in the GPSC. Consequently the core liner was overfilled. Due to different diameters of the collection cone (varies with height) and core liner (constant), the thickness of each sampling interval was normalized relative to the trap's collection area at the funnel opening; this was done by dividing the sampling layer's thickness by a factor which is the ratio between the trap's collection area and the cross-sectional area at the sampling interval's position in the trap assembly. In so doing, we can obtain “areal normalized depth” against which our measured data can be meaningfully plotted for the following discussion. The gap between the core liner and the subcores in the cone (Fig. 2) was bridged by interpolation.

Shown in Fig. 5 are profiles of water content, particle size, ²¹⁰Pb_{ex}, ²³⁴Th_{ex} and the ²³⁴Th_{ex}/²¹⁰Pb_{ex} activity ratio versus normalized depth for the T7KP lower trap. To constrain chronology, six arrows are indicated on

the ²³⁴Th_{ex}/²¹⁰Pb_{ex} profile; the bottommost and topmost ones correspond to the dates of trap deployment and recovery (July 7 and September 11), respectively, while the other four arrows mark the time when the first three timer discs settled in the trap (July 8, 13 and 18) and the time when the intervalometer was buried and malfunctioned (August 2). From the decrease with depth of ²³⁴Th_{ex} and ²³⁴Th_{ex}/²¹⁰Pb_{ex} in the upper part of the profiles, we calculated a linear sedimentation rate of ~0.25 cm/d, suggesting that sediment accumulated in the trap reached the bottom of the timing device, thus shutting it off on August 2, 2008, ~40 days prior to trap recovery. This is consistent with the finding below the timer of the 4th and the 5th timer discs which were released on July 23 and July 28, respectively. However, due to physical disturbance caused by the insertion and retrieval of subcores in the trap funnel, exact location of these two timer discs cannot be determined with certainty.

Progressive vectors (PV) derived from the current meters on both moorings are plotted in Fig. 6. During the dry season the PV on T6KP shows the normal pattern of water movements near the canyon floor which include short-term tidal oscillations at semidiurnal frequencies superimposed on a net landward movement (Fig. 6a). The beginning of the wet season (T7KP) deployment, from July 7 to 17, was similarly tide-dominated (Fig. 6b). Based on the finding of two timer chips back-to-back near the bottom of the trap liner (Fig. 5), we calculated the lowest sediment flux (~0.08 cm/d or ~0.1 g cm⁻² d⁻¹) corresponding to the highest ²³⁴Th_{ex} and ²¹⁰Pb_{ex} activities prior to July 13. After Typhoon Kalmaegi hit Taiwan on July 17, however, sediment transport became dominated by down-canyon movements of warmer water associated with likely the flood of the GPR in the ensuing days. In this period, sediment flux was exceedingly high, resulting in a substantial drawdown (due to dilution) of ²¹⁰Pb_{ex} and

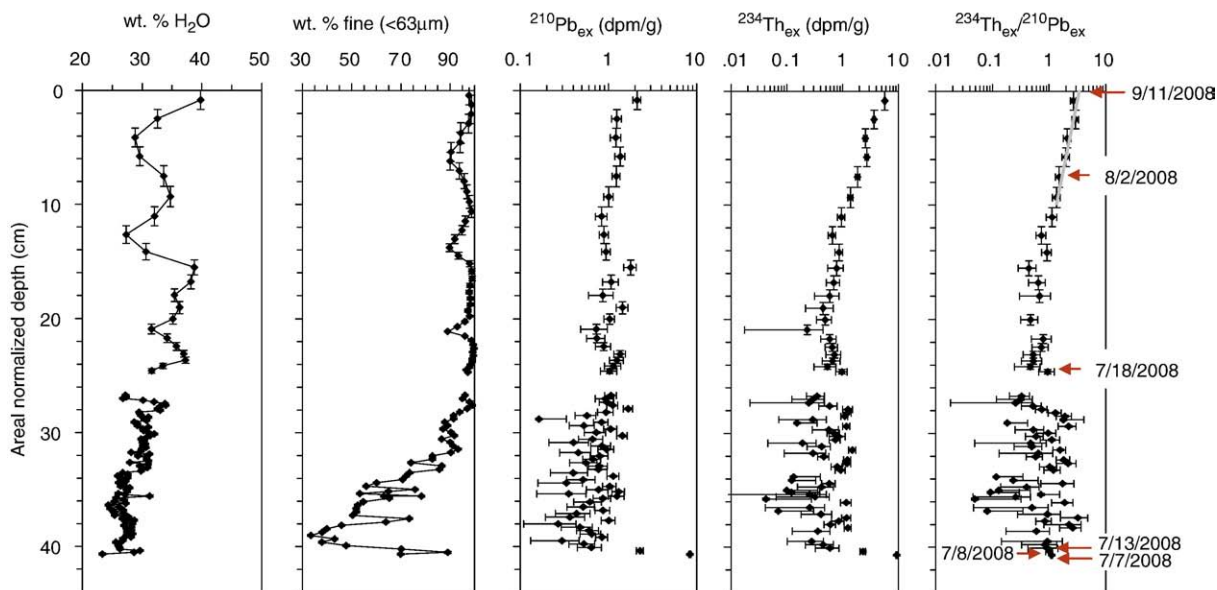


Fig. 5. Profiles of water content (wt.%), particle size (wt.% clay + silt), ²¹⁰Pb_{ex} and ²³⁴Th_{ex} activity (dpm/g), and the ²³⁴Th_{ex}/²¹⁰Pb_{ex} activity ratio versus areal normalized depth for the T7KP lower trap. Dates shown at the right are derived from a timing device and constrained by profiles of ²³⁴Th_{ex} and ²³⁴Th_{ex}/²¹⁰Pb_{ex} (see Section 3.1.2 for details).

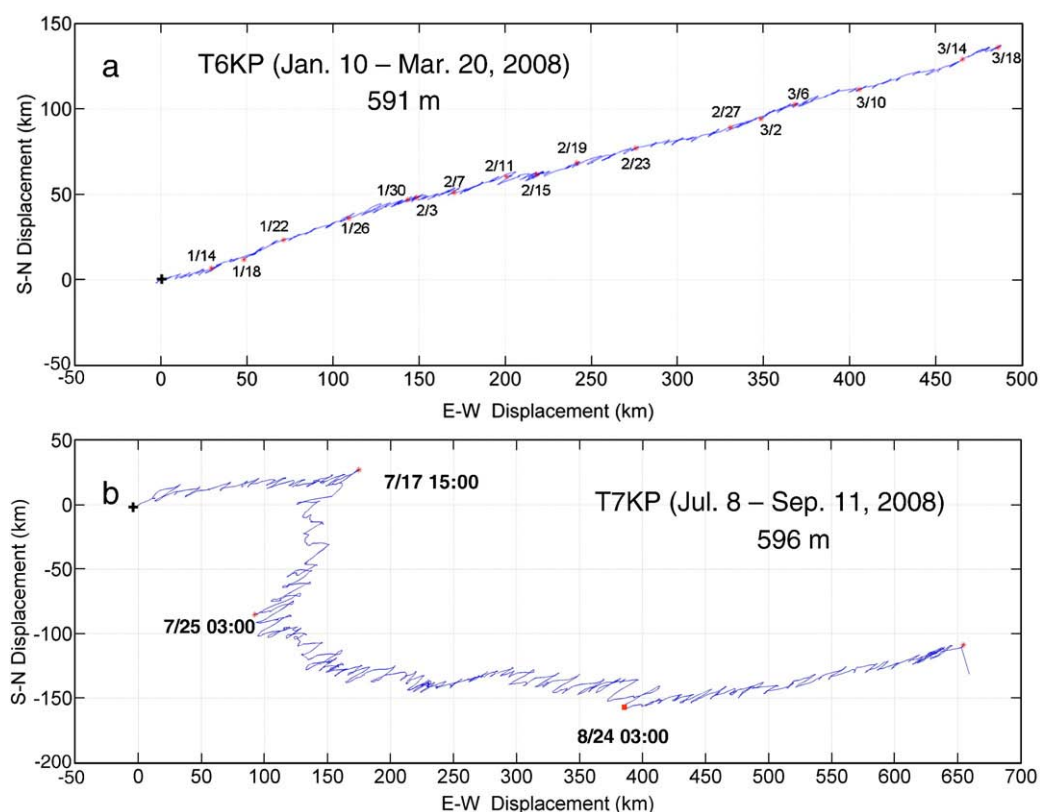


Fig. 6. Progressive vector derived from current meters deployed near the T6KP (a) and T7KP (b) lower traps. The three dates/time marked on (b) separate four periods: an initially tide-dominated period, a flood-dominated period following Typhoon Kalmaegi, a transition period from flood-dominated to tide-dominated, and a tide-dominated period at the end.

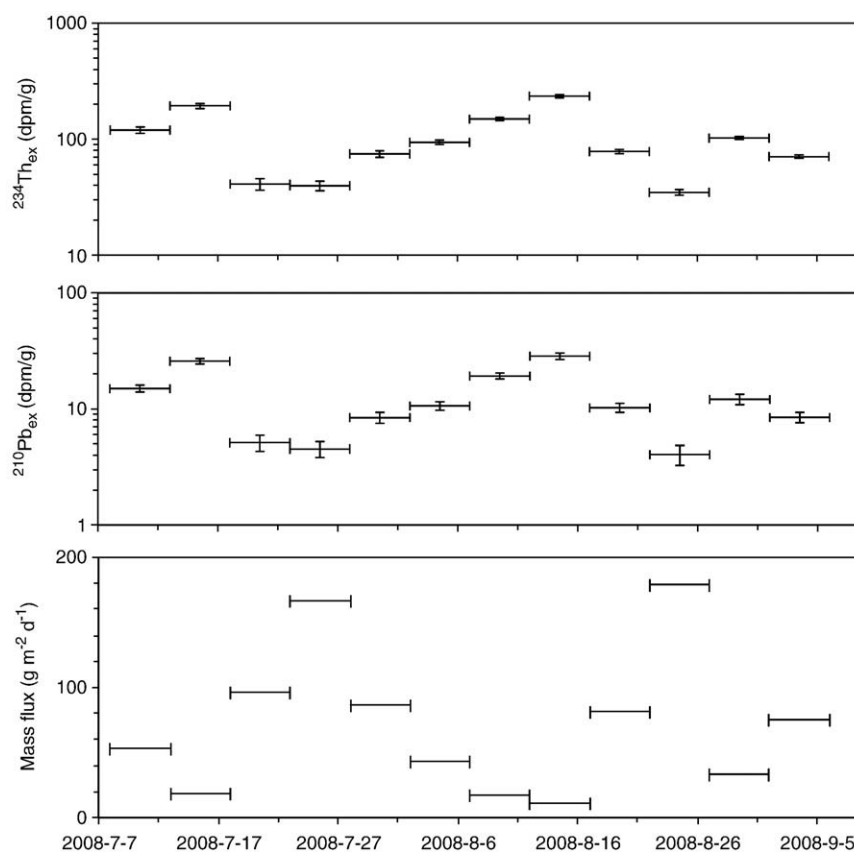


Fig. 7. Time series of $^{234}\text{Th}_{\text{ex}}$ and $^{210}\text{Pb}_{\text{ex}}$ activities and mass flux measured by the T7KP upper trap at 267 m.

$^{234}\text{Th}_{\text{ex}}$ activities in the trapped material. In the second half of wet season deployment, the system gradually switched from flood-dominated mode back to tide-dominated mode, as revealed in the turning of the PV and more regular profiles of $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$ with increased activities similar to those observed in the T6KP mooring.

From the T7KP mooring and the time controls discussed above, the mean sedimentation rates were calculated to be 0.62 cm/d (or $7200 \text{ g m}^{-2} \text{ d}^{-1}$) during the entire (66-day) period and 1.9 cm/d (or $21000 \text{ g m}^{-2} \text{ d}^{-1}$) during the typhoon-affected period from July 17 to August 2, 2008. These fluxes are ~60 to 190 times that (0.0101 cm/d , or $110 \text{ g m}^{-2} \text{ d}^{-1}$) in the tide-dominated dry season estimated from the T6KP mooring. It is important to note that, fine ($<63 \mu\text{m}$) particles caught in the T7KP trap after July 18, 2008 were significantly higher (90–95% in wt.%) than those near the bottom of the T7KP trap (70–90%). However, the measured activities of both $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$ at the top of the T7KP trap were considerably lower than those at its bottom. If corrected for decay, the contrast is even greater for the short-lived ^{234}Th — one order of magnitude higher at the bottom before the Kalmaegi-induced flood. This can only be explained by either shorter residence time or higher SPM concentration in the water column for fine particles caught in the upper part of the T7KP trap. They could have deposited somewhere as an ephemeral flood layer before being resuspended and transported to the trap site later. Alternatively, fluvial particles may remain suspended from one to several months in their pathways before settling down, as suggested by ^7Be data (Huh et al., 2009) and by earlier studies of Liu et al. (2002, 2006) which showed that a benthic nepheloid layer (BNL), often more

than 100 m above bottom, is present all year around along the thalweg of the upper GPSC.

3.1.3. Divergent transport in the water column of GPSC

Fig. 7 shows the measured time series of $^{234}\text{Th}_{\text{ex}}$ and $^{210}\text{Pb}_{\text{ex}}$ activities and mass flux from the upper trap (267 m water depth) near the canyon rim. The mean mass flux ($72 \text{ g m}^{-2} \text{ d}^{-1}$) is two orders of magnitude lower, while the decay-corrected activities of both $^{234}\text{Th}_{\text{ex}}$ and $^{210}\text{Pb}_{\text{ex}}$ are more than one order of magnitude higher than their respective values measured from the lower trap (Fig. 5). The activities of both nuclides, $^{234}\text{Th}_{\text{ex}}$ and $^{210}\text{Pb}_{\text{ex}}$, correlate negatively with the mass flux, suggesting that the production and availability of these nuclides for scavenging are limited with respect to the supply of sediment particles, thus causing a dilution of nuclides adsorbed on sediment particles.

Besides the vast difference in mass flux between the upper and lower traps, their temporal trends are also substantially different (Figs. 5 and 7). The vertical structure of the flow field (Fig. 8) measured by a long range ADCP deployed concurrently near the T7KP mooring in the canyon reveals that the mean flows, hence the sediment transport, near the canyon rim (267 m) were decoupled from the canyon floor (608 m). This appears to indicate the existence of a dispersal mechanism that contains a buoyant plume supplying sediments to the open shelf and slope and a gravity-driven flow transporting sediments down the canyon. Such a divergent transport was also observed in the Monterey Canyon (Xu et al., 2002) and the Sepik River's sediment dispersal (Kineke et al., 2000), and it may be a

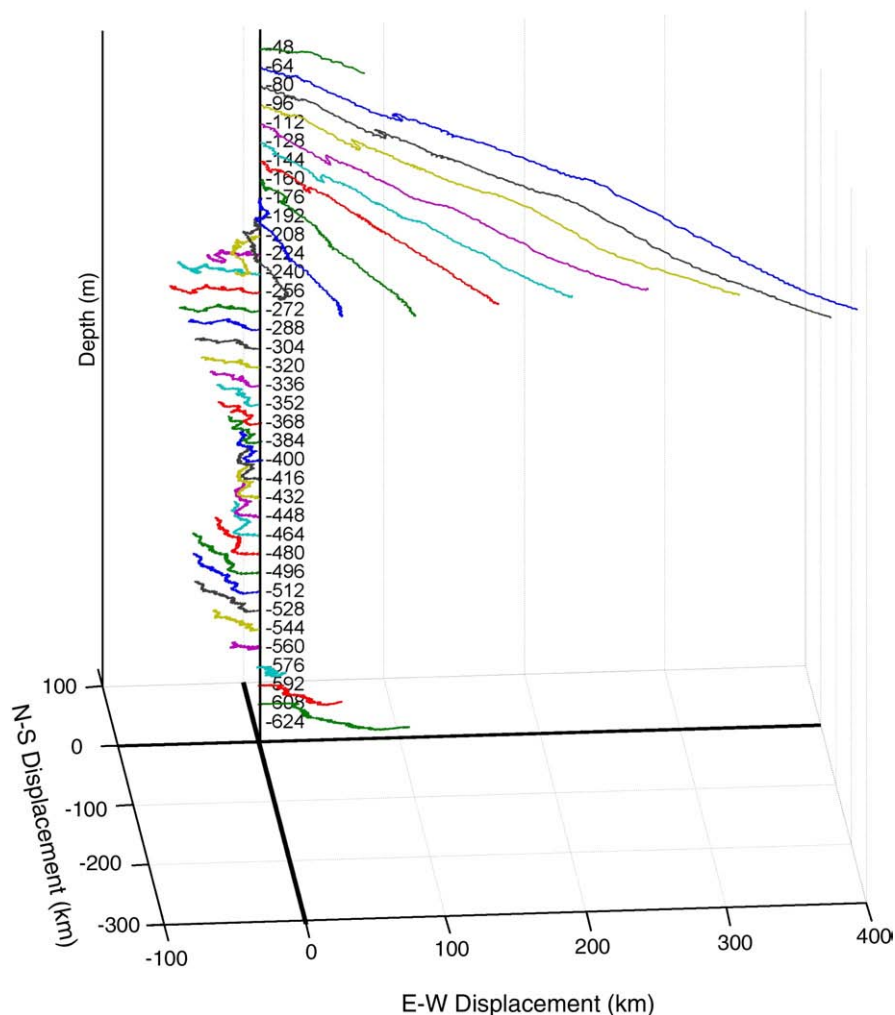


Fig. 8. Progressive vector at different water depths at the trap site derived from LADCP deployed during July 8–September 11, 2008.

common phenomenon during periods of sea-level low stands, and for collision-margin rivers during high river floods.

3.2. Comparison of trap-measured fluxes with in-situ production of excess ^{234}Th and ^{210}Pb – implications for scavenging of particle-reactive chemical species in the water column of GPSC

^{234}Th and ^{210}Pb are constantly produced in the water column from radioactive decay of ^{238}U and ^{226}Ra , respectively. Atmospheric fallout is an additional source for ^{210}Pb . Both ^{234}Th and ^{210}Pb are removed from seawater by adsorption onto particles followed by settling of particles, causing their deficiency (relative to their respective progenitors) in the water column and surplus in settling particles. Fluxes of excess ^{234}Th and ^{210}Pb measured by sediment traps reflect the scavenging of these two nuclides directly and that of other particle-reactive chemical species indirectly.

Using the equation of Ku et al. (1977), the activity concentration of ^{238}U in the mooring site (with a salinity of $\sim 34\text{‰}$) is about 2.4 dpm/l, which yields an integrated ^{234}Th production of $\sim 4.1 \text{ dpm cm}^{-2} \text{ d}^{-1}$ over a water column of 600 m (i.e., about the depth of the lower trap in the T6KP and T7 KP moorings). Based on the data summarized in Table 1, trap-measured mean fluxes of excess ^{234}Th during the T6KP and T7KP moorings were $0.49 \text{ dpm cm}^{-2} \text{ d}^{-1}$ and $2.52 \text{ dpm cm}^{-2} \text{ d}^{-1}$, respectively, which account for $\sim 12\%$ to $\sim 61\%$ of the ^{234}Th production in the overlying water column. It's quite conceivable that high suspended load associated with typhoon floods would deplete dissolved ^{234}Th in seawater and this may very well be the cause for the lower ^{234}Th activity at the top (after flood) compared with that at the bottom (before flood) of the T7KP trap, as discussed earlier (in Section 3.1.2).

The same calculations can be done for excess ^{210}Pb . Given a mean ^{226}Ra activity concentration of 0.1–0.2 dpm/l (Chen, Weifang, personal communication) in the 600 m water column above the trap, ^{210}Pb production in the water column is $\sim 0.2\text{--}0.4 \text{ dpm cm}^{-2} \text{ yr}^{-1}$. From the correlation between soil inventory of fallout nuclides and mean annual rainfall in Taiwan (Huh and Su, 2004), atmospheric ^{210}Pb flux off SW Taiwan (given an annual rainfall in the range 2000–4000 mm) is estimated to be $\sim 1\text{--}2 \text{ dpm cm}^{-2} \text{ yr}^{-1}$. Thus, in-situ production of ^{210}Pb

is within $2.4 \text{ dpm cm}^{-2} \text{ yr}^{-1}$, or $\sim 0.007 \text{ dpm cm}^{-2} \text{ d}^{-1}$, which is very trivial compared with the fluxes of excess ^{210}Pb measured from the T6KP and T7KP moorings ($0.11 \text{ dpm cm}^{-2} \text{ d}^{-1}$ and $0.72 \text{ dpm cm}^{-2} \text{ d}^{-1}$, respectively). This is clearly due to extra ^{210}Pb delivered from GPR's drainage basin and, even more importantly, boundary scavenging of ^{210}Pb associated with the intrusion of Kuroshio water. As with the passage of the Kuroshio main stream over the southern Okinawa Trough, a branch of Kuroshio water from the Luzon Strait flows over the sea off SW Taiwan and up the Penghu Channel toward the northern Taiwan Strait (Jan and Chao, 2003; Jan et al., 2006; Liang et al., 2003). The advection of ^{210}Pb -laden water from the open ocean through an ocean margin area with large sediment supply would inevitably result in enhanced particle scavenging and thus unusually high ^{210}Pb removal (Lee et al., 2004; Huh et al., 2006).

3.3. Observations from sediment cores collected under the lower traps: implications for sediment transport in the canyon

Gamma spectrometric analysis was also performed on core samples taken from the canyon floor near the mooring site during the recovery cruises. Fig. 9 shows the data obtained from a multi-core collected near the trap site (at $22^\circ 21.407'\text{N}$, $120^\circ 16.430'\text{E}$, water depth: 661 m) at the end of the T6KP deployment. Compared with trap-collected sediments, the sediments from the canyon floor have similar porosity and $^{210}\text{Pb}_{\text{ex}}$ activity, but substantially lower $^{234}\text{Th}_{\text{ex}}$ activities at the sediment–water interface. This downcore decrease of $^{234}\text{Th}_{\text{ex}}$ (or $^{234}\text{Th}_{\text{ex}}/^{210}\text{Pb}_{\text{ex}}$) indicates a fairly steady sedimentation rate of 0.057 cm/d (or $600 \text{ g cm}^{-2} \text{ d}^{-1}$) in the past ~ 6 months (i.e., prior to March 20, 2008), which is 4–5 times higher than deposition rate measured at the trap (T6KP) 53 m above the canyon floor. This implies the presence of a BNL, commonly observed not only in the GSC (Liu et al., 2002) but in other canyons (e.g., Xu et al., 2002), that supplies more sediment to the floor than to the sediment trap due to vertical gradient of sediment concentration.

In contrast, the bottom core collected at the end of the wet season deployment (at $22^\circ 21.212'\text{N}$, $120^\circ 16.455'\text{E}$, water depth: 634 m) showed a very different result (Fig. 10). The activities of $^{210}\text{Pb}_{\text{ex}}$ and $^{234}\text{Th}_{\text{ex}}$ are much lower than observed in the dry-season core, and

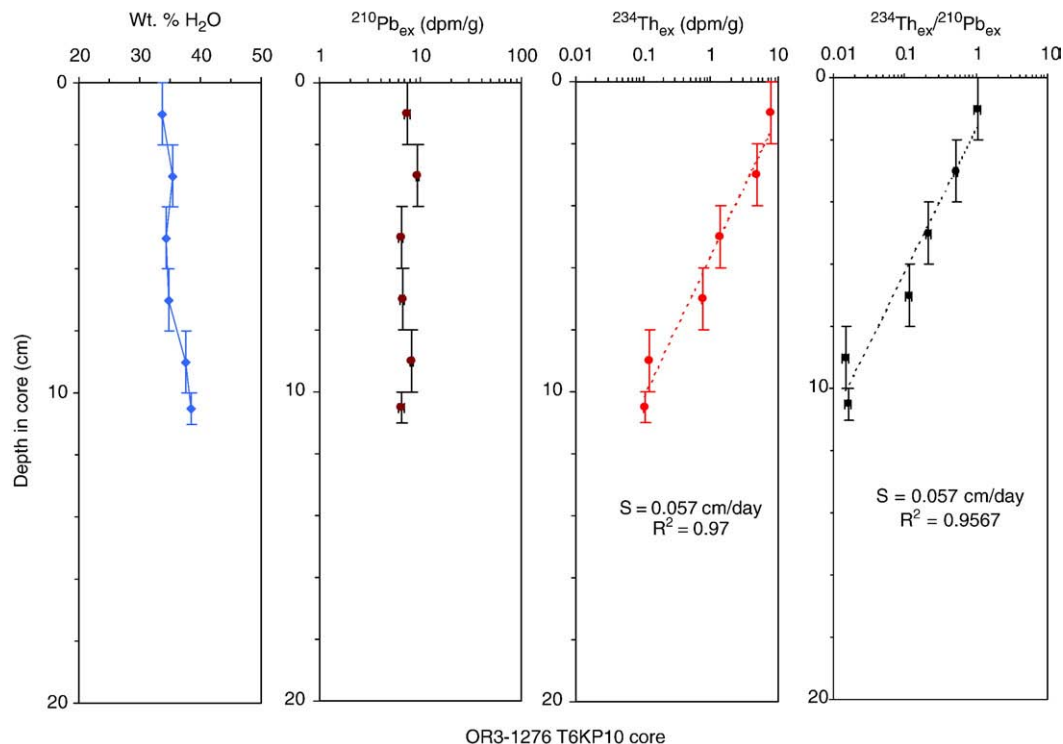


Fig. 9. Profiles of water content, $^{210}\text{Pb}_{\text{ex}}$, $^{234}\text{Th}_{\text{ex}}$ and the $^{234}\text{Th}_{\text{ex}}/^{210}\text{Pb}_{\text{ex}}$ activity ratio in a sediment core collected below the T6KP mooring.

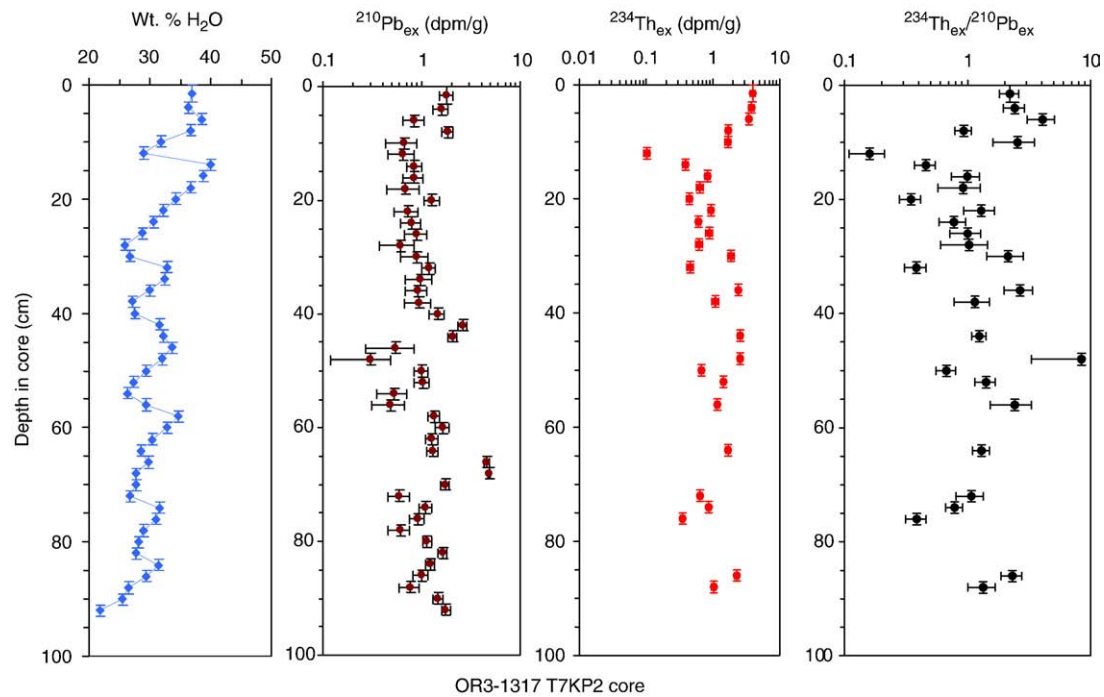


Fig. 10. Profiles of water content, $^{210}\text{Pb}_{\text{ex}}$, $^{234}\text{Th}_{\text{ex}}$ and the $^{234}\text{Th}_{\text{ex}}/^{210}\text{Pb}_{\text{ex}}$ activity ratio in a sediment core collected below the T7KP mooring.

there is no clear trend of variation with depth. This similarity to the trapped material 42 m above the bottom coupled with deep penetration of low but detectable $^{234}\text{Th}_{\text{ex}}$ in the core, clearly suggests rapid deposition of flood-derived sediments.

Both the trap-measured and core-derived sedimentation rates discussed above are seemingly inconsistent with the observation of Huh et al. (2009) which, based on the distribution of ^{210}Pb -derived sedimentation rates and the calculated budget of sediment off southwestern Taiwan, suggested that the GPSC was an effective conduit rather than a sink of sediment in this sediment dispersal system. The time-scale difference between sediment trap and sediment core data is likely an explanation for this paradox. The sediment trap data reported here represent a time series of slightly over 2 months at an approximately daily resolution. Previous studies (Liu et al., 2002, 2004, 2006) showed evidence for a net landward particle transport by tidal currents inside the canyon on daily to monthly timescales. In contrast, sedimentation records from the seafloor represent net results over a much longer period of time, although they may still be ephemeral in a dynamic setting like the GPSC. Based on the presence of ^7Be , a short-lived tracer for flood deposits, in surficial sediments following episodic events, and the non-steady-state and low levels of ^{210}Pb along the GPSC thalweg, Huh et al. (2009) suggested a rapid transport of sediments from the GPR's mountainous watershed via the canyon to the deep South China Sea. Conceivably, sediments deposited in a more regular fashion under less energetic conditions during the dry season can be easily disturbed and replaced by gravity-driven flows during flood or typhoon seasons. The V-shaped cross section in the upper reaches of the GPSC suggests that, over time, erosion tends to counterbalance deposition in the canyon (Yu et al., 2008). In other words, although the canyon may serve as a temporary sink for sediments within a season, in long term it functions more like a conduit for the transport of terrigenous sediments to deep ocean basins.

4. Conclusions

Sediment trap and bottom sediment core samples were collected from the GPSC in two contrasting (dry versus wet) seasons in 2008 and analyzed for two particle-reactive radionuclides, ^{210}Pb and ^{234}Th . The

data were interpreted in conjunction with current meter and ADCP observations with a view to develop a quantitative understanding of the sedimentation and sediment transport processes in the most dynamic setting of a sediment source-to-sink dispersal system off SW Taiwan. An overview of the measured quantities discussed above and recapitulated in Table 1 leads us to the following conclusions:

- (1) Sediment flux at ~ 600 m water depth (thalweg depth 650 m) in the GPSC varied between $114 \text{ g m}^{-2} \text{ d}^{-1}$ in the dry, tide-dominated season and $7200 \text{ g m}^{-2} \text{ d}^{-1}$ in the wet, flood-dominated season in 2008. Even in the dry season, the measured flux was one order of magnitude higher than mean sedimentation rate observed in the open shelf and slope regions around the canyon (Huh et al., 2009).
- (2) In the flood-dominated season, sediment flux measured by the upper trap (at 267 m water depth) near the canyon rims was two orders of magnitude lower than that measured by the lower trap inside the canyon. Vertical structure of the flow field revealed divergent transport of sediment at the two depth levels.
- (3) The inverse correlation between sediment flux and activities of both ^{210}Pb and ^{234}Th in trap samples suggests a very rapid down-canyon transport (hence short residence time in seawater) of sediment particles associated with typhoon and river floods.
- (4) Based on the depth profile of $^{234}\text{Th}_{\text{ex}}$ (as well as $^{234}\text{Th}_{\text{ex}}/^{210}\text{Pb}_{\text{ex}}$) in a sediment core collected near the T6KP (dry season) mooring, sedimentation rate at the bottom during the past ~ 6 months was ~ 5 times that measured by the sediment trap 50 m above, suggesting the existence of a bottom nepheloid layer in the tide-dominated season. During the flood-dominated season (i.e., the T7KP deployment), sedimentation rate at the bottom cannot be determined with certainty. However, the presence of excess ^{234}Th deep in the sediment core taken near the wet season mooring indicates an even higher sediment flux, probably driven by gravity. When coupled with longer-term sediment budget elucidated from Huh et al. (2009), these data suggest that far more sediments are exported via the canyon than deposited either in the canyon or on the open shelf and slope region.

- (5) T7KP data reveal a type of typhoon-related disturbance that is not easily detected without the combination of measurements of sinking particles and deposited sediment.

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