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Tectonically active sediment dispersal system in SW Taiwan margin with emphasis on the Gaoping (Kaoping) Submarine Canyon

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ABSTRACT

The sediment dispersal system in southwestern Taiwan margin consists of two main parts: the subaerial drainage basin and the offshore receiving marine basin. In plan view, this sediment dispersal system can be further divided into five geomorphic units: (1) the Gaoping (formerly spelled Kaoping) River drainage basin, (2) the Gaoping (Kaoping) Shelf, (3) the Gaoping (Kaoping) Slope, (4) the Gaoping (Kaoping) Submarine Canyon and (5) the Manila Trench in the northernmost South China Sea. The Gaoping River drainage basin is a small (3250 km^2), tectonically active and overfilled foreland basin, receiving sediments derived from the uprising Central Range of Taiwan with a maximum elevation of 3952 m. The Gaoping Submarine Canyon begins at the mouth of the Gaoping River, crosses the narrow Gaoping Shelf (~10 km) and the Gaoping Slope, and finally merges into the northern termination of the Manila Trench over a distance of ~260 km. The SW Taiwan margin dispersal system is characterized by a direct river-canyon connection with a narrow shelf and frequent episodic sediment discharge events in the canyon head.

In a regional source to sink scheme, the Gaoping River drainage basin is the primary source area, the Gaoping Shelf being the sediment bypass zone and the Gaoping Slope being the temporary sink and the Manila Trench being the ultimate sink of the sediment from the Taiwan orogen. It is inferred from seismic data that the outer shelf and upper slope region can be considered as a line source for mass wasting deposits delivered to the lower Gaoping Slope where small depressions between diapiric ridges are partially filled with sediment or are empty.

At present, recurrent hyperpycnal flows during the flood seasons are temporarily depositing sediments mainly derived from the Gaoping River in the head of the Gaoping Submarine Canyon. On the decadal and century timescales, sediments temporarily stored in the upper reach are removed over longer timescales probably by downslope-eroding sediment flows within the canyon. Presently, the Gaoping Submarine Canyon serves as the major conduit for transporting terrestrial sediment from the Taiwan orogen to the marine sink of the Manila Trench. Seismic data indicate that the Gaoping Submarine Canyon has been eroding the Gaoping Slope intensely by presumed hyperpycnal flows and transporting sediments from the canyon head to the middle and lower reaches of the canyon. The middle reach is a sediment bypass zone whereas the lower reach serves as either a temporary sediment sink or a sediment conduit, depending on relative prevalence to deposition or erosion during canyon evolution. Contrast differences in channel gradient and travel length between the Gaoping and Amazon sediment dispersal systems suggest that the Gaoping (Kaoping) River-Canyon system is an active sediment dispersal system for transporting terrestrial materials to the deep sea. The fate of the Gaoping River sediment is the northern Manila Trench.

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1. Introduction

Source-to-Sink studies focus on examination of variations in sediment discharge passing through morphodynamic units of sediment dispersal systems, revealing relevant climate, tectonics and sea-level changes and linkage between terrestrial source and marine sink, and towards a better understanding of the global change record (MARGINS, 2004). Active convergent continental margins are focused study areas because much terrestrial sediments were transported in and deposited in adjacent marine closed basins, such as the type localities of the Fly River and adjacent Gulf of Papua and the Waipaoa River System on the east coast of the North Island, New Zealand.

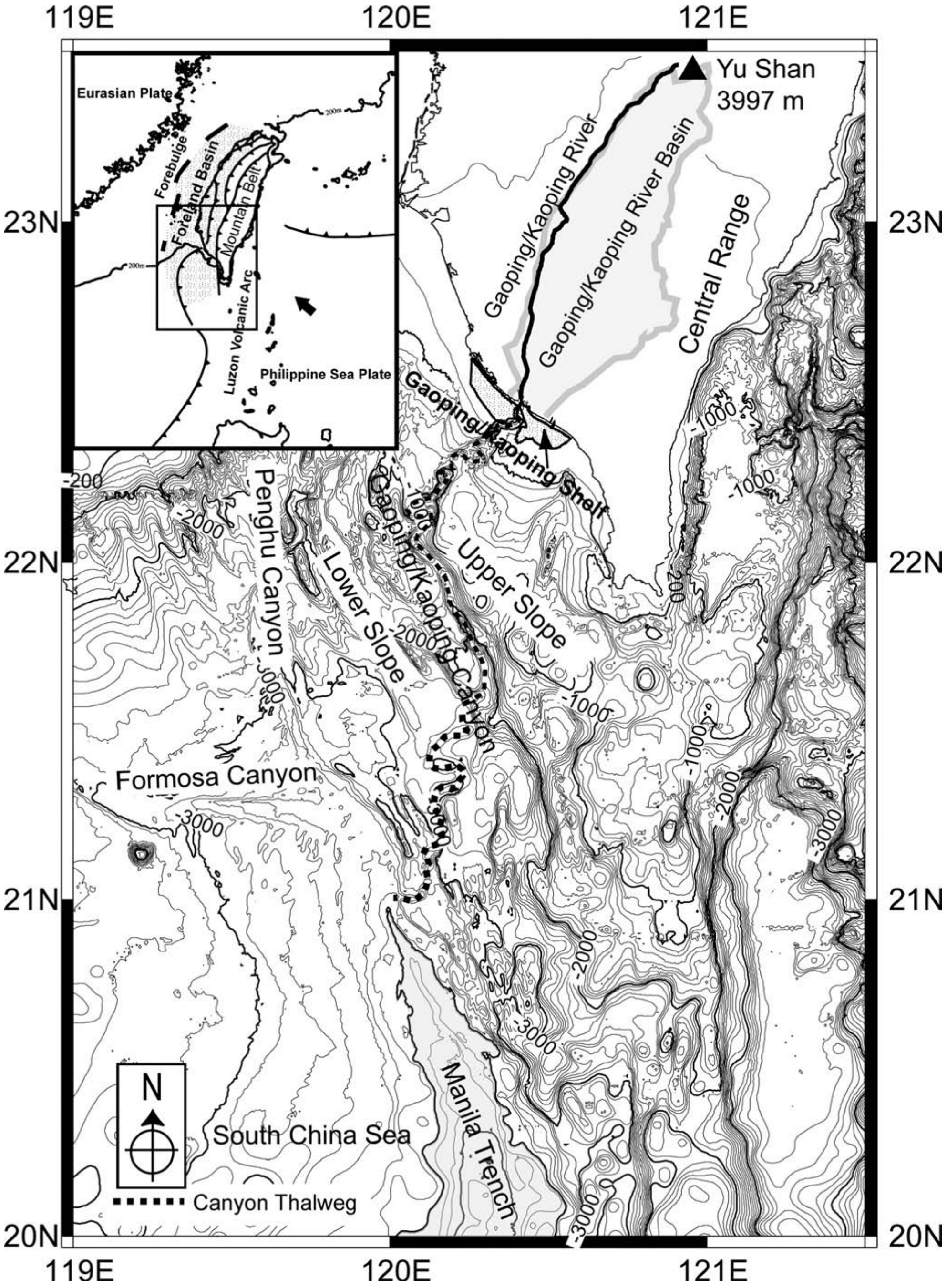

Fig. 1. The sediment dispersal system in SW Taiwan margin consists of five geomorphic units: (1) the Gaoping (Kaoping) River drainage basin, (2) the Gaoping (Kaoping) Shelf, (3) the Gaoping (Kaoping) Slope, (4) the Gaoping (Kaoping) Submarine Canyon and (5) the Manila Trench in the northernmost South China Sea. The inset at upper left corner shows the geological setting of Taiwan characterized by a foreland basin west of the Taiwan mountain belt. The sediment dispersal system in SW Taiwan margin operates in a young developing foreland basin.

The fold-and-thrust mountain belt of Taiwan in an arc-continent collision setting that has been frequently cited as one of the few modern examples of an ongoing tectonically active region (Lallemand and Tsien, 1997; Byrne and Liu, 2002). Taiwan is characterized by high erosion rates (3–6 mm yr^{-1}) resulting from heavy rainfall especially during the frequent typhoons (Dadson et al., 2003; Galewsky et al., 2006). In addition, the rivers in Taiwan are small mountainous rivers, supplying large amount of sediments to the adjacent coastal sea commonly during flood events (Milliman and Syvitski, 1992). Therefore, the climatic and tectonic conditions of Taiwan are favorable for large amount of sediments to be delivered to generate hyperpycnal flows in the coastal seas.

Lately, the link between terrestrial sediment source from the rising Taiwan orogen and the adjacent coastal sea sink has received much attention. For example, Dadson et al. (2005) pointed out that small mountainous rivers draining the tectonically active island of Taiwan commonly discharge suspended sediments to the coastal seas at hyperpycnal concentrations, typically during typhoon-related floods. Concerning the fate of hyperpycnal sediment discharge from rivers in southwestern Taiwan, Milliman and Kao (2005) postulated that the Gaoping (formerly spelled Kaoping) and Penghu Submarine Canyons serve as sediment conduits for transporting parts of sediments derived from southwestern Taiwan to the adjacent South China Sea. Galewsky et al. (2006) discussed the tropical cyclone triggering of sediment discharge in Taiwan and concluded that orographic effects localized heavy rainfall over the southwestern slopes of the Central Range triggering high sediment discharge on the Gaoping (Kaoping) River.

Similar to the Fly River/Gulf of Papua System, a modern developing foreland basin, the SW Taiwan margin is a developing foreland basin and receives considerable terrestrial sediment derived from the uprising Central Range in the southern Taiwan (Covey, 1984; Yu, 2004; Chiang et al., 2004). However, the river-canyon connection setting is different from that of Fly River/Gulf of Papua system. The sediment dispersal system in the southwestern Taiwan foreland basin spans various source to sink environments, characterized by a very narrow shelf with a river-canyon connection, and allows for comparison to those of the Fly River/Gulf of Papua System as well as sediment dispersal systems in passive margins.

1.1. Geological setting

The island of Taiwan was formed by oblique collision between the Luzon Arc and the passive Chinese margin beginning about 5 Ma ago (Suppe, 1981; Lallemand and Tsien, 1997; Byrne and Liu, 2002). Topographic and tectonic loading of the Taiwan Orogen flexed down the foreland platform of the Chinese margin to form a foreland basin from Late Pliocene to the present (Fig. 1; Covey, 1984; Yu and Chou, 2001). Pleistocene–Quaternary sediments with thickness up to 5000 m derived from the Taiwan Orogen have been deposited in the foreland basin west of mountain belts of Taiwan (Covey, 1984). Therefore, the processes of sediment dispersal in the nearby foreland basin can be examined at different temporal and spatial scales.

The foreland basin in southwestern Taiwan margin comprises three distinct geomorphic units: the subaerial Gaoping (Kaoping) River (KPR) basin, the shallow marine Gaoping (Kaoping) Shelf and the deep-water Gaoping (Kaoping) Slope (Fig. 1). The KPR drainage basin is located at west of the southern Taiwan orogen and covers a watershed area of about 3250 km^2 (Fig. 2A). The basin is filled by Pliocene–Quaternary sediment more than 3000 m thick (Chiang et al., 2004). The uppermost strata of the coastal plain are Recent alluvial deposits consisting mainly of sand and mud (Ho, 1988). Seaward of the coastal plain is the relatively narrow Gaoping Shelf. The broad Gaoping Slope is located immediately downslope of the Gaoping Shelf, ranging in water depth from about 80 m along the shelf edge to 3400 m at its toe in the northern South China Sea abyssal plain. The Gaoping (Kaoping) Submarine Canyon (KPSC) is about 260 km long extending from the river mouth, across the shelf-slope region and merging into the Manila Trench in the northern South China Sea.

1.2. Sediment dispersal system in SW Taiwan

The sediment dispersal system in SW Taiwan margin comprises five geomorphic units: (1) the KPR drainage basin, (2) the Gaoping Shelf, (3) the Gaoping Slope, (4) the KPSC, and (5) the Manila Trench in the northernmost South China Sea (Fig. 1). The following sections describe briefly essentials of each geomorphic unit.

1.2.1. Gaoping (Kaoping) River drainage basin

The KPR drainage basin is a small (3250 km^2), but the second largest drainage basin in Taiwan, receiving sediment derived from the Central Range of Taiwan with a maximum elevation of 3952 m at of the summit of Yu Shan (Jade Mountain, Fig. 2A). The main trunk of the KPR flows parallel to the strike of the Taiwan orogen in a nearly N–S direction. The KPR is the second largest river in Taiwan with a length of ~170 km, originates from the Yu Shan summit located in the central-south Central Range. It is a small mountainous river characterized by very high sediment yield (11,000 t km^{-1} yr^{-1}), frequently generating hyperpycnal flows at the river mouth during seasonal floods. The drainage system consists of at least six distributary rivers of which the Nanzinshian River to the north and Laonong River to the northeast are the major ones (Fig. 2A).

1.2.2. Gaoping (Kaoping) Shelf

The Gaoping (Kaoping) Shelf is a narrow (<10 km) and is the seaward continuation of the coastal plain of southwestern Taiwan (Yu and Chiang, 1997). Terrestrial sediments mainly transported by KPR flowing on the coastal plains were emptied into the coastal ocean and redistributed on the sea floor, prograding seaward to form the relatively narrow Gaoping Shelf along the mountainous coast. This young (less than 400,000 years) shelf is still growing and prograding seaward, mainly controlled by uplift rate of the Taiwan orogen and accompanying foreland basin sedimentation. Considering its morphology and tectonic setting, Yu and Chiang (1997) named the Gaoping Shelf as an island shelf, distinguishing it from the passive margin shelf.

1.2.3. Gaoping (Kaoping) Slope

The Gaoping (Kaoping) Slope continues from the Gaoping Shelf edge southwestward to the northern South China Sea

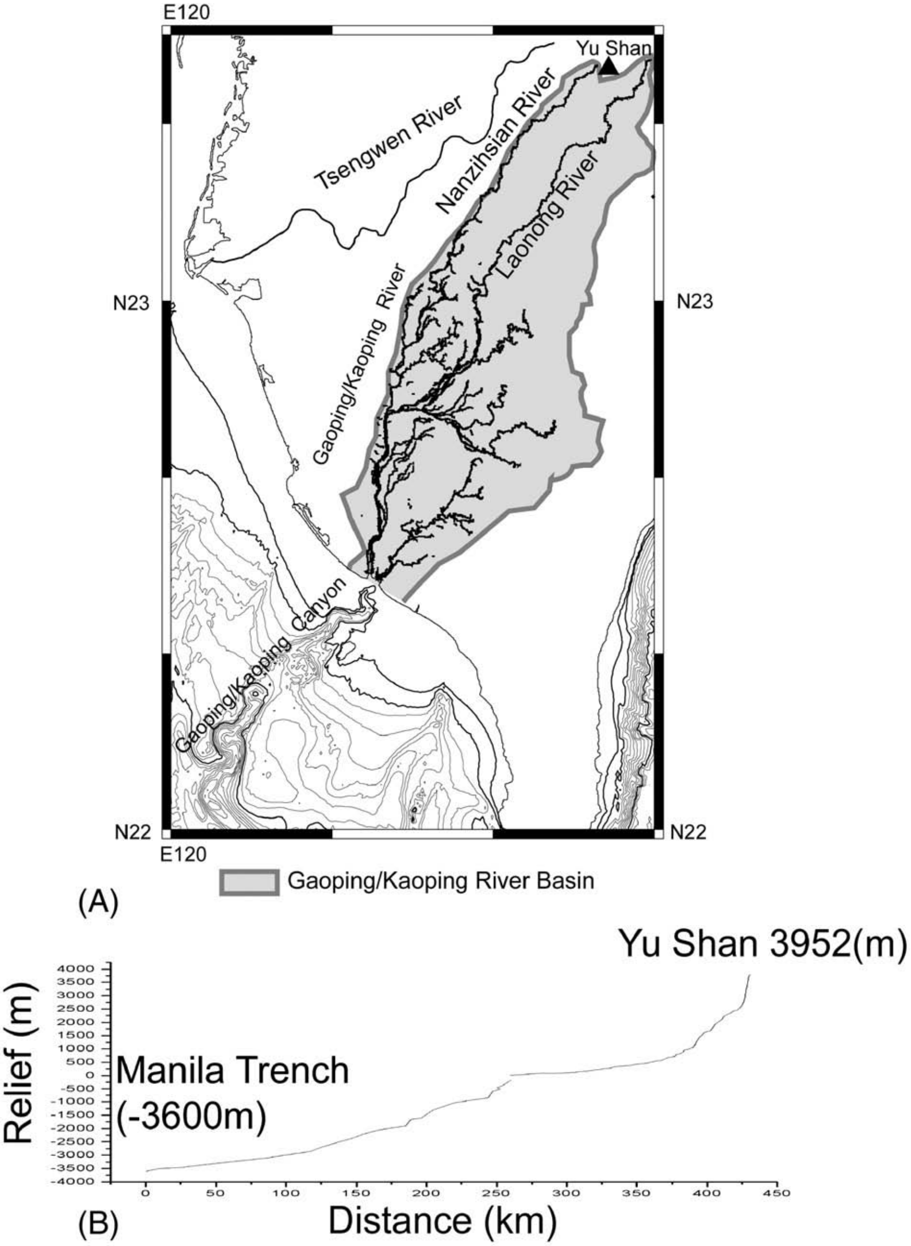

Fig. 2. The KPR drainage basin is a small (3250 km^2), but the second largest drainage basin in Taiwan, receiving sediments derived from the Central Range of Taiwan with a maximum elevation of 3952 m at the summit of Yu Shan (Jade Mountain). The KPR, the second largest river in Taiwan with a length of ~170 km, originates from the Yu Shan summit located in the central-south Central Range. (A). The KPRSC system depth profile (B).

and ends at the Manila Trench and its northern continuation of the Penghu Submarine Canyon (Fig. 1) The bathymetry of this slope is complex as it dissected by several named submarine canyons and unnamed gullies. This slope is further divided into an upper slope and a lower slope by isobaths between 1000 and 1200 m in water depth. This boundary between these two slopes is marked by one or more scarps with more than 1000 m relief, producing a steep upper slope and a gentle sloping surface of the lower slope. For detailed descriptions of morphology of the Gaoping Slope refer to Yu and Song (2000). Structurally, the Gaoping Slope is dominated west-vergent folds and thrust faults and is also associated with active mud diapirism (Liu et al., 1997; Chiang et al., 2004). In a longer time scale back to Late Pliocene the Gaoping Slope is considered the main sink of sediments derived from the southwestern Taiwan orogen as an immature under-filled foreland basin (Covey, 1984; Yu, 2004). Pliocene–Pleistocene sediment more than 5000 m thick beneath the coastal plain in southwestern Taiwan extended seaward to the Gaoping Slope (Wu, 1993). Fuh (1997) showed that Pleistocene (NN19) sediment in the coastal plain extend seaward into the Gaoping shelf-slope region. During the last 7000 years of sea-level high stand, large amount of sediments from the Gaoping drainage basin might have easily crossed the narrow Gaoping Shelf and were deposited on the Gaoping slope and continue infilling the deep marine foreland basin. The majority of terrestrial sediment derived from the southwestern Taiwan orogen and the KPR drainage basin accumulated largely in six sub-basins, ranging from 10 to 40 km in length and 10 to 20 km wide, in the upper Gaoping Slope (Yu and Huang, 2006).

1.2.4. Gaoping (Kaoping) Submarine Canyon (KPSC)

The KPSC extends from the mouth of the KPR, crosses the Gaoping Shelf and the broad Gaoping Slope, and finally merges into the northern Manila Trench near the location at 120° E, 21° N over a distance of ~260 km (Chiang and Yu, 2006). This canyon consists of three distinct segments along its course: an upper reach, a middle reach and a lower reach. The upper reach ranging in water depth from 126 to 1750 m flows seaward meandering toward the southwest on the upper slope area and characterized by great relief. The middle reach with canyon floors from 1750 to 2800 in water depth runs almost straight southeastward along an elongate escarpment and makes a sharp turn to the southwest, connecting to the lower reach ranging in water depth from 2800 to 3600 m and flowing sinuously down-slope to the northern Manila Trench (Fig. 1). The course and morphology of the KPSC are strongly controlled by mud diapiric intrusions (Chiang and Yu, 2006) in the upper reach and thrust faulting in the middle and lower segments which produce two prominent sharp bends of the canyon course. Note that the KPSC has down-cut the broad Gaoping Slope before merged into the Manila Trench.

1.2.5. Manila Trench

The Manila Trench is a deep-sea bathymetric trough associated with the subduction zone west of the Luzon Arc (Ludwig et al., 1967). The northern termination of the Manila Trench occurs around 120° 10′ E and 21° N where it loses its characteristic deep-water trench in terms of depth and width (Yu, 2000). North of the 3600 m isobath, axial parts of the Manila Trench gradually become narrower and shallower and branched into two smaller troughs which merge into the Penghu Submarine Canyon and the Formosa Submarine Canyon, respectively (Fig. 1).

1.3. Scope and purpose

The special issue of the fate of terrestrial substances on the Gaoping Shelf and in the KPSC off southwestern Taiwan has integrated multidisciplinary research results mainly from the study site of a river–sea system off southwestern Taiwan, consists of the Gaoping River, Shelf and Submarine Canyon. The study site of the Gaoping (Kaoping) River-Submarine Canyon (KPRSC) system begins at the river mouth and extends to the canyon head segment within a distance of about 50 km. Strictly speaking, the study site is a small focused local river–sea system within a much larger regional sediment dispersal system mainly consisting of the KPR drainage basin and the South China Sea basin. Therefore, the primary goal of this paper is to present a regional source to sink scheme in southwestern Taiwan that serves as the regional sediment dispersal system for reference. This new proposed regional sediment dispersal scheme shows that sediments are derived from mountain top at a maximum height of 3952 m of the Yushan summit, and delivered to the deep-sea Manila Trench floor at a water depth of about 3600 m within a distance of ~430 km via a small mountainous river (KPR) and a river-connected large submarine canyon (KPSC).

The KPSC with its head about 1 km seaward of the KPR is the immediate sink for fluvial discharge (Liu et al., 2002). However, the middle and lower segments of the KPSC have not been studied in context of source to sink. In order to accomplish a complete characterization of a source to sink system along the KPSC one needs relevant information of the middle and lower segments of the canyon. Hence, the second objective of this paper is to present newly collected seismic data, revealing erosion, deposition and transportation in the middle and lower segments of the canyon and increasing the spatial and temporal scales of understanding for the KPSC as an important role in the sediment dispersal system. This paper presented a conceptual sediment dispersal system in southwest Taiwan and had no intention to fully discuss each geomorphic unit within it. Rather, the middle and lower reaches of the KPSC are focused research areas of this paper because of available new seismic data.

2. Methods and data

This paper applies the schemes of source to sink system and sediment dispersal system defined by MARGINS (2004) to study the sediment dispersal system in SW Taiwan margin. Sediment, resulting from erosion in landscapes, passes through linked geomorphic environments and ultimately accumulate on adjacent flood plain, continental shelf or marine basin floor.

Multiple channel seismic reflection profiles were collected in the middle and lower segments of the KPSC using the R/V Ocean Researcher I, National Taiwan University (Fig. 3). These data supplement the river-canyon connection investigation in the upper reach and provide an examination of the entire KPSC, showing its role as a major conduit of terrestrial source sediments to the marine sediment sink. An air-gun array with a volume of 1380 in^3 is the seismic energy source. Seismic signals are recorded on a 300-m long, 4-channel streamer with a DFS-V floating gain digital system. Seismic reflection data were processed using SIOSEIS system and PROMAX software at the university laboratory. Recorded seismic data were processed as follows: spectral analysis, automatic gain control, band-pass filter, velocity analysis, stack, frequency-wavenumber analysis, and migration.

3. Results and interpretations

3.1. Gaoping Canyon, sediment conduit

This paper discusses new data from seismic sections across the middle and lower segments of the KPSC and the northern Manila Trench. A series of four seismic sections parallel each other across the middle segment of the KPSC and show that canyon floors are devoid of sediments but that the nearby elongate depressions on the Gaoping Slope are

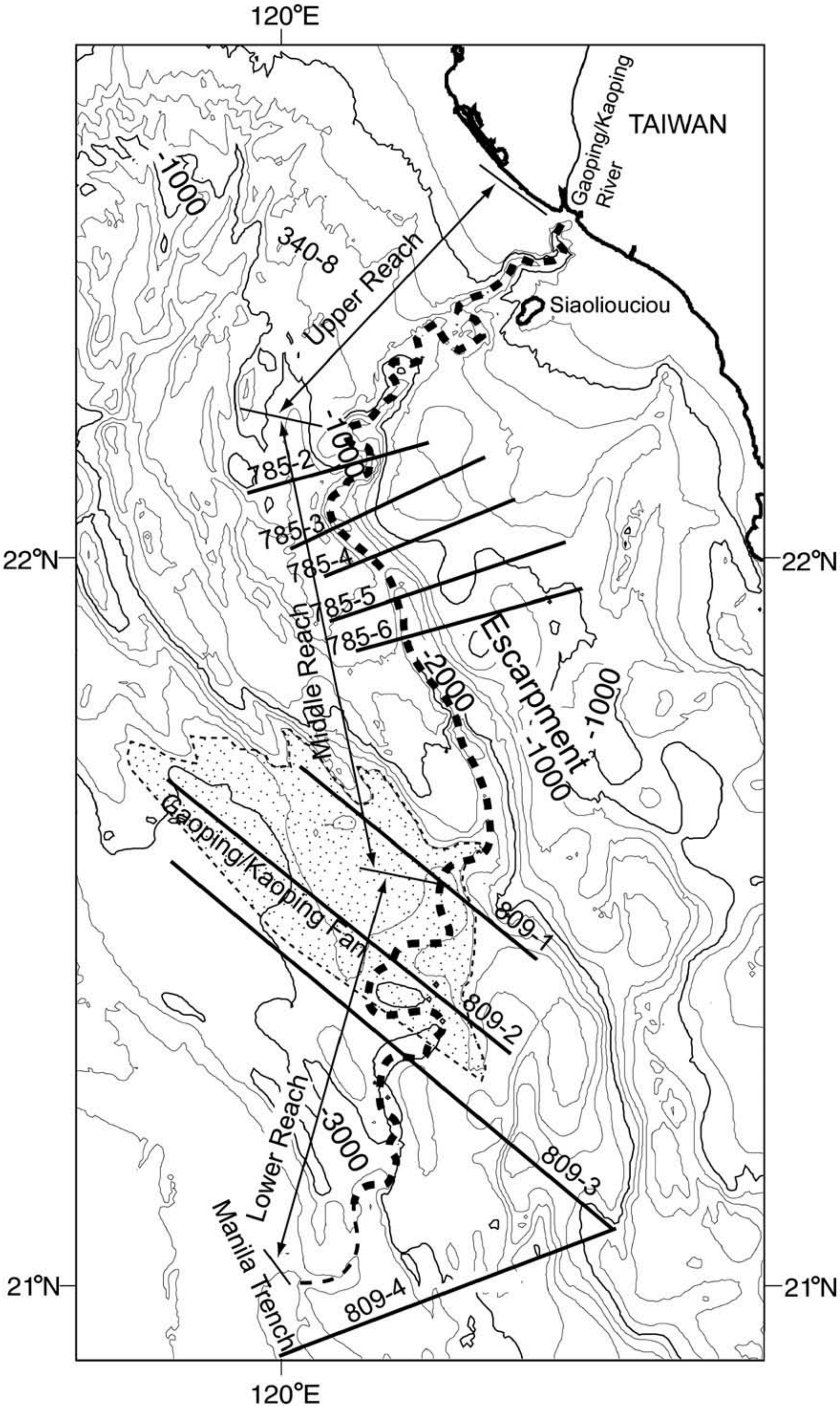

Fig. 3. Nine multi-channel seismic profiles across the middle and lower segments of the KPSC were collected with one additional seismic profile across the northern Manila Trench and nearby lower Gaoping Slope. Seismic characteristics are used to determine sedimentary processes in term of sediment dispersal. A small submarine fan can be recognized in the lower reach of the KPSC.

partially filled by sediments, strongly suggesting erosion of canyon floor and sediment bypass in the middle segment and sediments being transported down-canyon to the lower segment. Seismic section 785-2 shows that this canyon segment is V-shaped with a steeper wall to the southwest and a gentler wall to the northeast (Fig. 4). The northeastern wall is highly irregular that could be the result of slumping or sliding on the canyon wall. Some failed sediment may be transported to the canyon axis where sediments are temporarily deposited as evidenced by the presence of flat

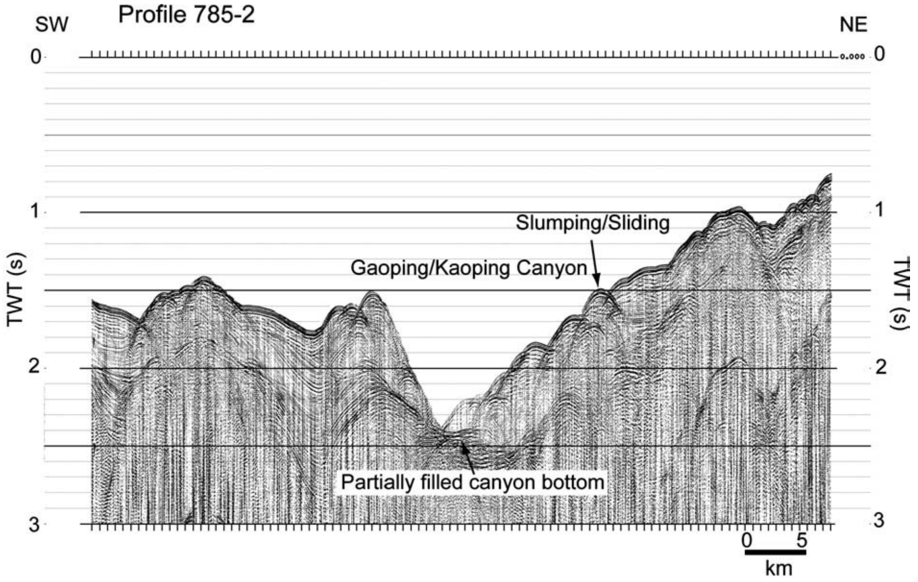

Fig. 4. Seismic profile 785-2 crossing middle reach of the KPSC shows that the presence of a typical V-shaped cross section, indicating erosion in the canyon floor. The northeast wall surface is highly irregular that could be resulted from slumping or sliding on the canyon wall. Some failed sediments may be transported to the canyon axis where sediments are temporarily deposited.

reflectors on the canyon bottom. Farther down-canyon, seismic section 785-3 (Fig. 5) indicates that the canyon has a V-shaped cross section, typical erosional canyon morphology, with both steep but smooth walls, strongly suggesting erosion being the major sedimentary process. However, southwest of the canyon wall the depression on the Gaoping Slope is partially filled by sediments as evidenced by onlap seismic facies. Farther down-canyon, seismic sections 785-4 and 785-5 (Fig. 6) show similar seismic characteristics to those of section 785-3. V-shaped canyon morphology strongly suggests erosion in the canyon floor. It is noted that the depression northeast of the canyon on the Gaoping Slope is partially filled, implying sediments transported down-slope on the Gaoping Slope from the upper slope region were trapped in the depression before reaching the KPSC. Therefore, the middle segment of the KPSC is considered to be a sediment bypass zone at present.

In the lower segment of the canyon, three seismic sections trending NW–SE across the canyon course show features of deposition and erosion. Seismic profile 809-1 shows that the cross-sectional morphology of the canyon is represented by an asymmetrical broad low-relief trough with a steeper wall to the southeast (Fig. 7A). The steep canyon wall is the flank of an uprising mud diapiric ridge. There is no distinct V-shaped canyon thalweg, implying weak incision. Instead, the canyon floor is irregular probably resulting from multiple alternating

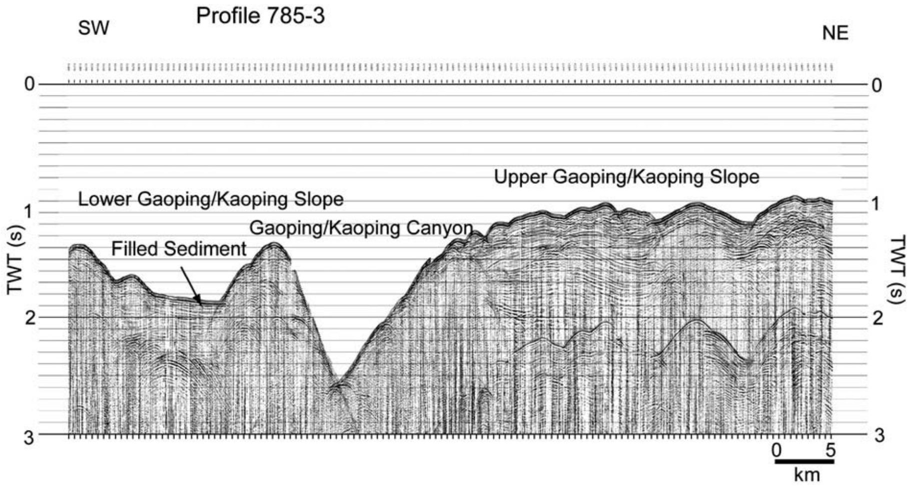

Fig. 5. Seismic profile 785-3, farther down-canyon, shows that the canyon has a symmetrical V-shaped cross section, typical erosion canyon morphology, with both steep but smooth walls, strongly suggesting erosion being the major sedimentary process. Note that southwest of the canyon wall the depression on the Gaoping Slope is partially filled by sediments, indicating sediments removed away in the canyon but sediments accumulated in the nearby structural low, a temporary sediment sink.

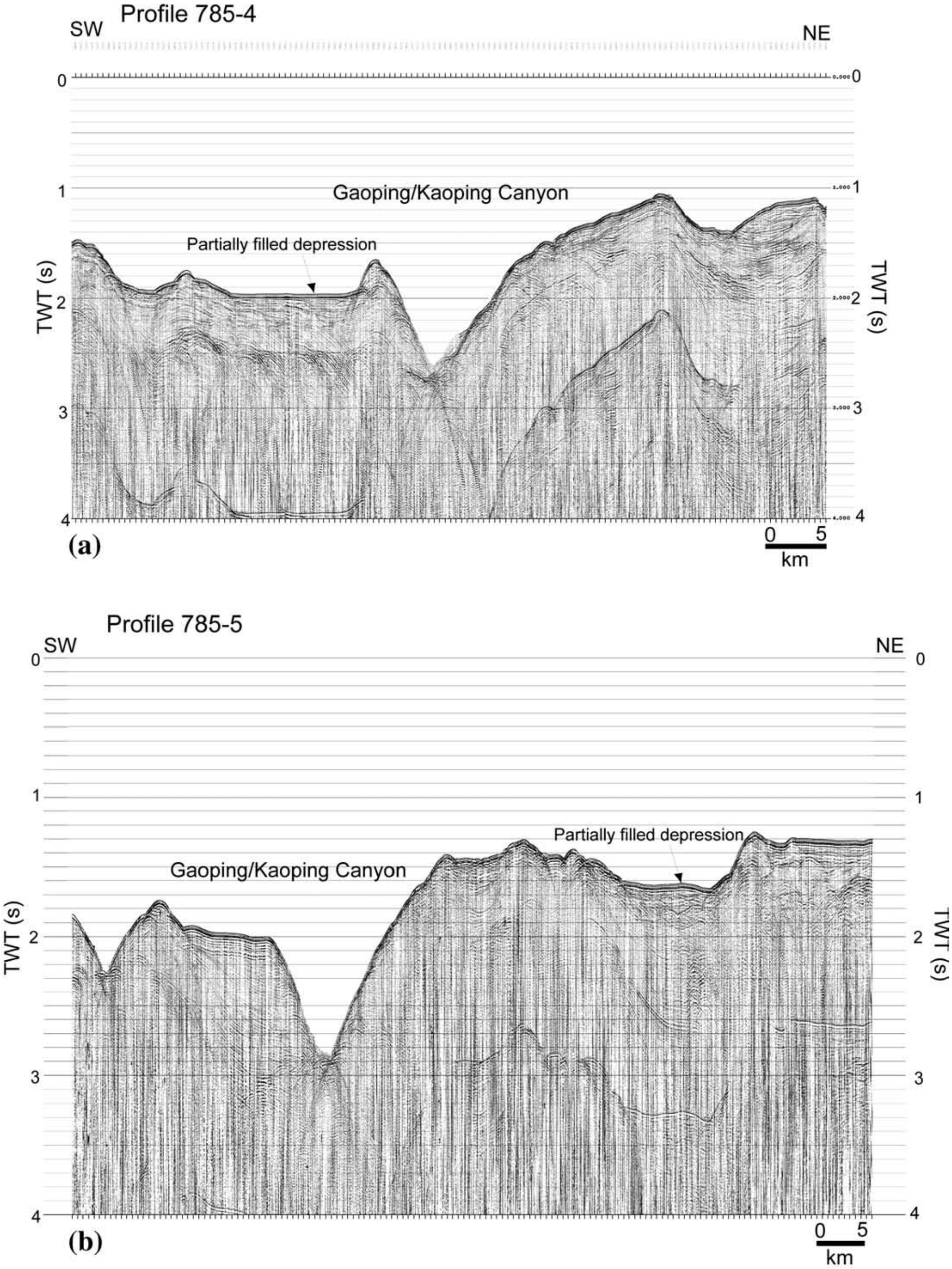

Fig. 6. Farther down-canyon, seismic sections 785-4 and 785-5 show similar seismic characteristics to those of section 785-3. Sharp V-shaped canyon morphology strongly suggests erosion in the canyon floor. Noted that the depression on the lower slope northeast of the canyon is partially filled, implying sediments from the upper slope region transported down-slope to the Gaoping Slope trapped in the depression before reaching the KPSC.

episodes of deposition and erosion. Canyon floor sediments could be derived from failure of canyon walls and from the up-canyon deposits. These sediments are deposited temporarily at the canyon bottom and toes of canyon walls. Subsequently, some sediment is removed by down-slope sediment flows and transported down-canyon, resulting in an irregular canyon bottom. Immediately northwest of the canyon edge there are parallel reflections which may represent some combination of deposition of overbank sediment from the canyon and hemipelagic sediments over

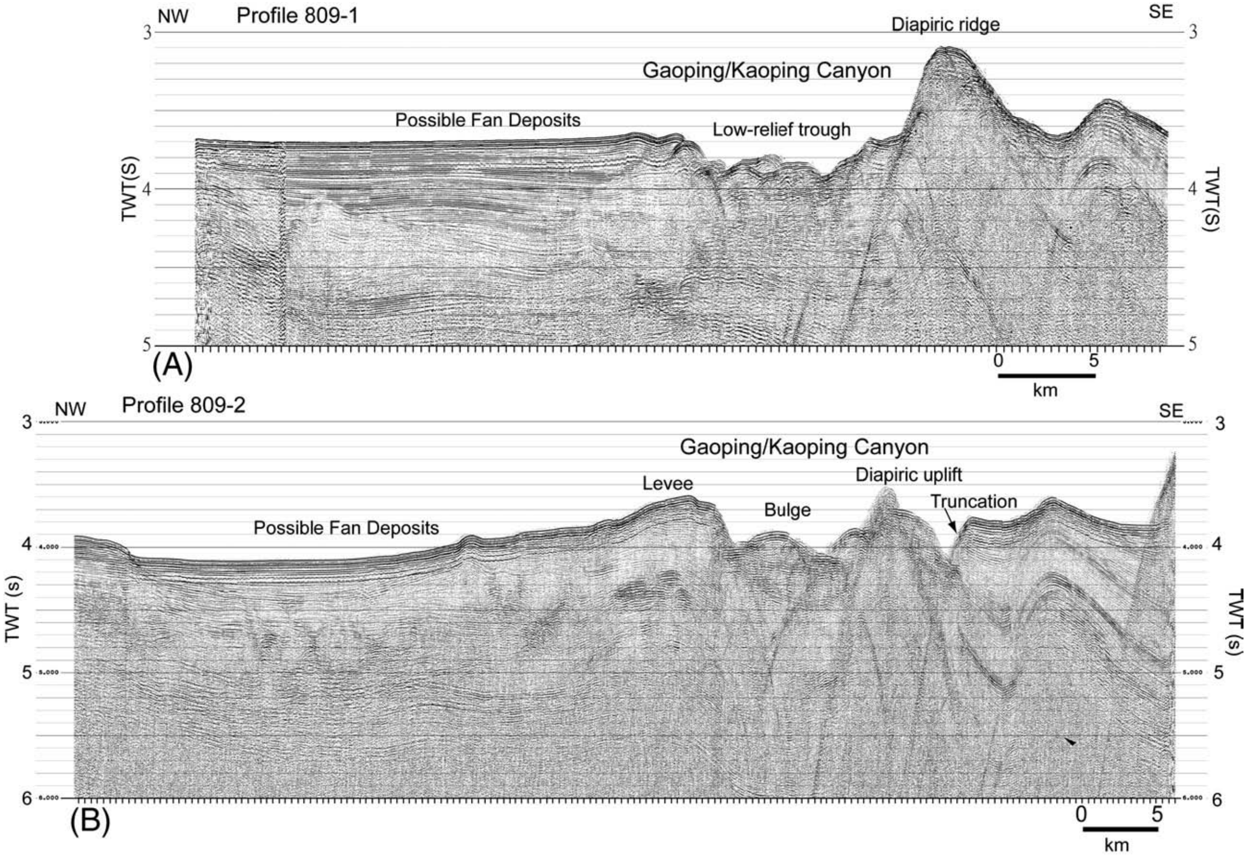

Fig. 7. Crossing the lower segment of the canyon, seismic profile 809-1shows that cross-sectional morphology of the canyon is represented by an asymmetrical broad low-relief trough with steeper wall to the southeast. The steep canyon wall is the flank of an uprising mud diapiric ridge. The canyon floor is irregular probably resulting from alternating episodes of deposition and erosion. (A) Farther down-canyon, seismic profile 809-2 shows similar seismic facies to that of the profile 809-1. Note that the middle part of the canyon floor is a small bulge that may be an expression of mild uplift of mud diapirism, suggesting sedimentary processes in the canyon being mixed by structural disturbance. Truncation of parallel reflectors against a sharp steep sloping surface is observed southeast of the small bulge in the center of canyon floor, suggesting relatively intense down-cutting. The sea floor northwest of canyon wall and beyond are characterized by tilted parallel reflections that could be interpreted as overbank levees. Seismic characteristics shown on profile 809-2 indicate complex features of overbank deposition, intense local canyon floor erosion and structural disturbance. (B).

the lower Gaoping Slope. Farther down-canyon, seismic profile 809-2 (Fig. 7B) shows similar seismic facies to that of the profile 809-1. However, there are some differences between them. The middle part of the canyon floor contains a small bulge that may be an expression due to mild uplift of mud diapirism, suggesting sedimentary processes in the canyon being mixed by structural disturbance. The sea floor northwest of canyon wall and beyond are characterized by tilted parallel reflections that could be interpreted as overbank levees. It is noted that truncated reflectors against a sharp steep slope is observed southeast of the small bulge in the center of canyon floor, suggesting relatively intense down-cutting of canyon floor sediments. Hence, seismic characteristics shown on profile 809-2 indicate complex features of overbank deposition, intense local canyon floor erosion and structural disturbance. Farther down-canyon, seismic profile 809-3 shows a small canyon with an asymmetrical V-shaped cross section with steeper wall to the southeast (Fig. 8). The steep canyon wall is the flank of an uprising mud diapiric ridge. There is no sediment accumulation in the canyon floor, suggestive of erosional processes. Parallel reflections beneath the sea floor northwest of the canyon are interpreted as a result of hemipelagic deposition in the lower Gaoping Slope. Noted that the depression between two uprising mud diapiric ridges southeast of the canyon is partially filled, implying sediments transported down-slope to the Gaoping Slope trapped in the depression before reaching the Gaoping Submarine Canyon. Therefore, seismic profiles 809-1, 809-2 and 809-3 indicate that the lower segment of the KPSC serves as either a temporary sediment sink or a sediment conduit, depending on relative prevalence to deposition or erosion during canyon evolution.

3.2. Manila Trench, the ultimate sediment sink

Seismic profile 809-4 trends NE–SW across the axis of the northern Manila Trench along the toe of the Gaoping Slope and shows that the northern Manila Trench is a small shallow depression not a typical deep-sea trench (Fig. 9). From the viewpoint of source to sink, sediments derived from the Gaoping Shelf and upper Gaoping Slope must infill up depressions (intraslope basins) on the lower Gaoping Slope

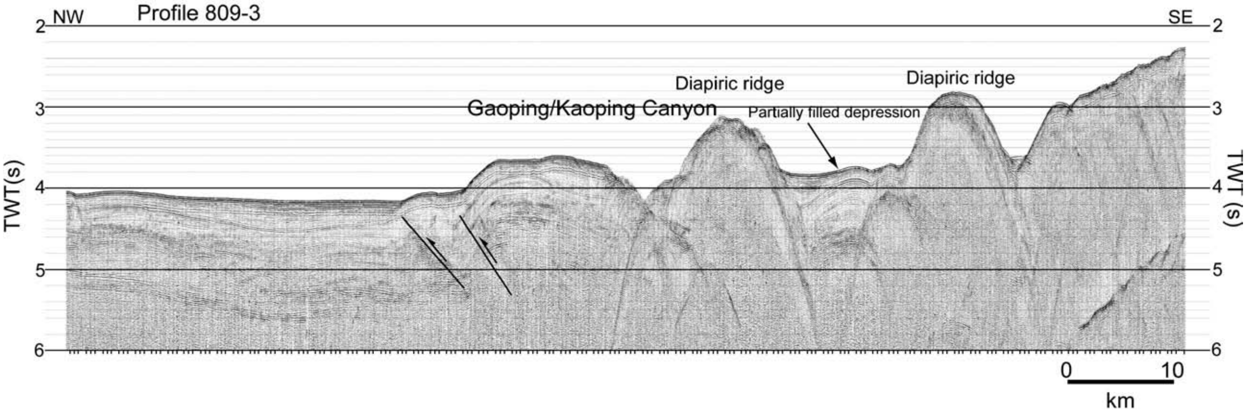

Fig. 8. Seismic profile 809-3 farther down-canyon, shows a small trough with an asymmetrical V-shaped cross section with steeper wall to the southeast. There is no sediment accumulation in the canyon floor, suggesting erosion or sediments being removed. Parallel reflections beneath the sea floor northwest of the canyon are interpreted as a result of hemipelagic deposition in the lower slope. Noted that the depression between two uprising mud diapiric ridges northeast of the canyon is partially filled, implying sediments from the upper slope region transported down-slope to the lower Gaoping Slope and trapped in depressions before reaching the KPSC.

northeast of the Manila Trench and then excess sediments can overspill the infilled depressions and then reach to the Manila Trench. Apparently, sediments filling the northern Manila Trench mainly come from the canyons of the Penghu, Formosa and Gaoping together (Fig. 1). The relative sediment contribution of each canyon to the Manila Trench has not been determined yet. We suggest that sediments derived from KPR drainage basin can only be delivered to the Manila Trench via the KPSC. Sediments from localized failures of upper Gaoping Slope are most likely transported by down-slope mass wasting to the lower Gaoping Slope where sediments are trapped in intraslope depressions. Probably no excess sediments can be

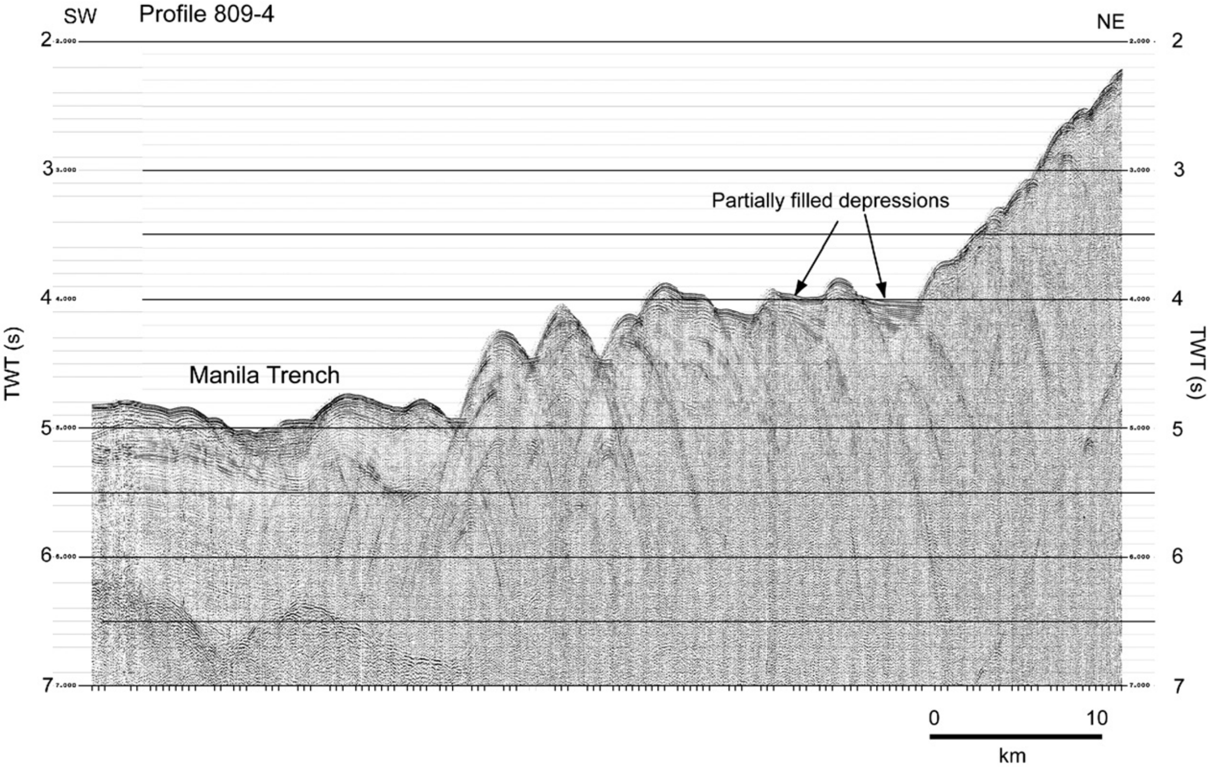

Fig. 9. Seismic profile 809-4 across the axis of the northern Manila Trench shows that the trench is represented by a small shallow depression, partially filled with sediments. Note that some depressions (small intraslope basins) on the lower Gaoping Slope northeast of the Manila Trench are partially filled with sediment. Other depressions at the slope toe are empty. Sediments derived from the Gaoping Shelf and upper Gaoping Slope must infill depressions on the lower slope and then excess sediments can overspill the filled depressions and then reach to the Manila Trench.

transported over the toe of the Gaoping Slope to the Manila Trench.

We suggest that relatively high sediment load was temporarily stored in the upper part of the canyon (e.g., including terraces and sediment bulge). The high sediment load has bypassed the middle part of the canyon (as evidenced by empty canyon morphology) and then relatively low sediment load was deposited in the lower reach of the KPSC (as evidenced by partial sediment infilling and submarine fan). Hence, the Manila Trench is the ultimate sink for KPR sediments.

4. Discussions

4.1. Comparison to sediment dispersal systems in passive margins

In general, sedimentary dispersal systems in passive margins are characterized by a relatively large subaerial drainage basin, a low-gradient river, a river-mouth delta, a wide shelf, a continental slope, submarine channels and canyons and a large submarine fan on the basin floor (Fig. 10). In contrast, the sediment dispersal system in SW Taiwan in the collision margin is characterized by an actively developing foreland basin with connected geomorphic units of small subaerial drainage, a small mountainous river, a narrow shelf, a broad continental slope, submarine canyons and a deep-sea trench (Fig. 10). Major differences between these two systems are apparent. For example, river-mouth delta and submarine fan are not present in the sediment dispersal system in SW Taiwan. The contrast between width of shelf (wide versus narrow) and the disconnection or connection between river and submarine canyons are other fundamental difference between these two systems. One to one comparisons between each geomorphic unit or connected geomorphic units are beyond the scope of this study. Our emphasis is mainly focused on the KPSC.

Submarine canyons on passive margins incise wide shelves and erode sea beds of the continental slopes transversely with a relatively straight canyon course such as the Amazon Submarine Canyon (Damuth et al., 1988). The canyon mouth serves as a point source, feeding sediment downslope and forming deep-sea fans. Slope canyons occur either as shelf-indenting canyons or slope-confined canyons. Sediments transported by longshore drift and shelf currents are brought to the heads of the shelf-indenting canyons where sediments can be delivered down-canyon by downslope sediment flows (Pratson et al., 1994), eroding canyon floor and serving as a sediment conduit. Slope-confined canyons are characterized by their heads being below the shelf edge. Downslope-eroding sediment flows triggered by localized failure of upper slope around the canyon heads actively eroded canyon floors and transport sediments down-canyon (Pratson et al., 1994; Pratson and Coakley, 1996). In other words, sediment input to the canyons is not directly from river mouth. The disconnection of canyon heads to the river mouth suggests that river sediments would not produce hyperpycnal flows during flood seasons in head segment of submarine canyons in passive margins.

By contrast, the KPSC is directly connected to the KPR characteristic of a small mountainous river with relatively high tendency to generate hyperpycnal flows during flood

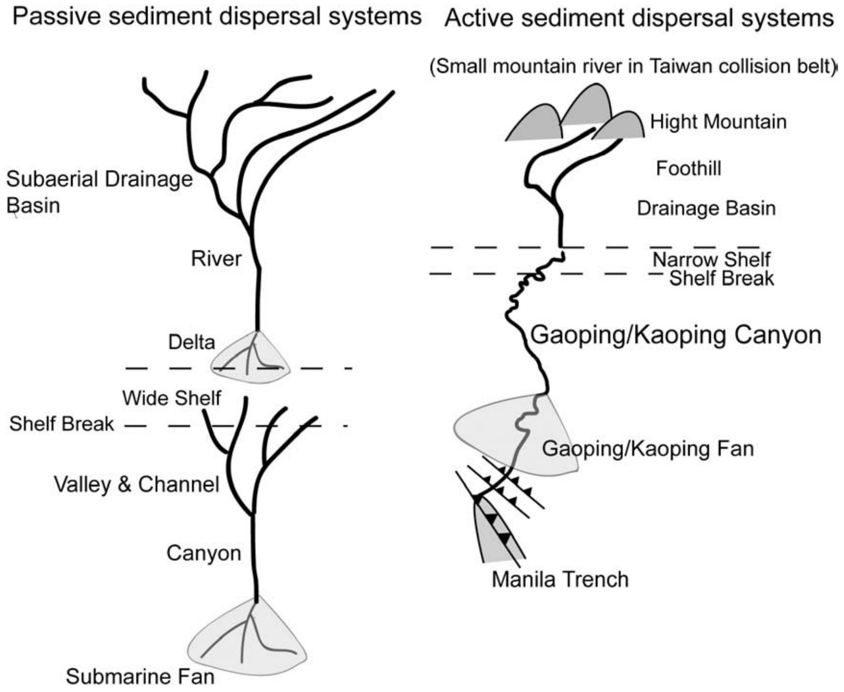

Fig. 10. Sedimentary dispersal systems in passive margins are characterized by a relatively large subaerial drainage basin, a low-gradient river, a river-mouth delta, a wide shelf, a continental slope, submarine channels and canyons and a large submarine fan in the basin floor (left panel). After Lisitzin (1991). The sediment dispersal system in SW Taiwan in the collision margin is characterized by an actively developing foreland basin with relatively small subaerial drainage, a small mountainous river, a narrow shelf, a broad continental slope, submarine canyons and a deep-sea trench (right panel).

seasons. Apparently, presumed hyperpycnal flows are the most likely transport mechanism for sediment dispersal in the KPRSC system especially during flood seasons.

4.2. Fate of the Gaoping River sediments

With little quantitative measurements of sediment discharge in the Gaoping Shelf and KPSC we can only speculate the fate of the KPR sediments, following the diagrammatic scenario showing sediment discharges passing through the morphodynamic segments of sediment dispersal systems (Fig. 11). The KPR discharges directly into the KPSC, about 90% sediment load feeding the KPSC and the rest of 10% sediment discharge distributing on the Gaoping Shelf. The narrow Gaoping Shelf is considered a sediment bypass zone rather than a terrestrial sediment sink because of its shelf width of <10 km, allowing more than 80% of the sediment easily to cross narrow shelves and be delivered to the deep-water slope and basin floor. For example, the Sepik (Papua of New Guinea) and Eel (northern California) shelves at collision margins both have shelf width <10 km and showed 90% of off-shelf accumulation and 80% of off-shelf accumulation, respectively (Walsh and Nittrouer, 2003).

At present, the Gaoping Slope receives sediments mainly from localized failures of the shelf-upper slope that is transported by downslope mass wasting processes via numerous gullies, channels and canyons, except the KPSC (Figs. 1, 7 and 8). In contrast, the KPSC has been eroding the Gaoping Shelf and Gaoping Slope intensely by hyperpycnal flows and transporting sediments from the canyon head to the lower reach of the canyon and finally filling the Manila Trench with sediments from the KPR. Therefore, the fate of the KPR sediments is the Manila Trench, the ultimate sediment sink.

Fig. 11 implies that by the time sediment load reached the Manila Trench and the load became relatively low in our conceptual model. Observation of the presence of a small submarine fan associated with the lower reach of the KPSC

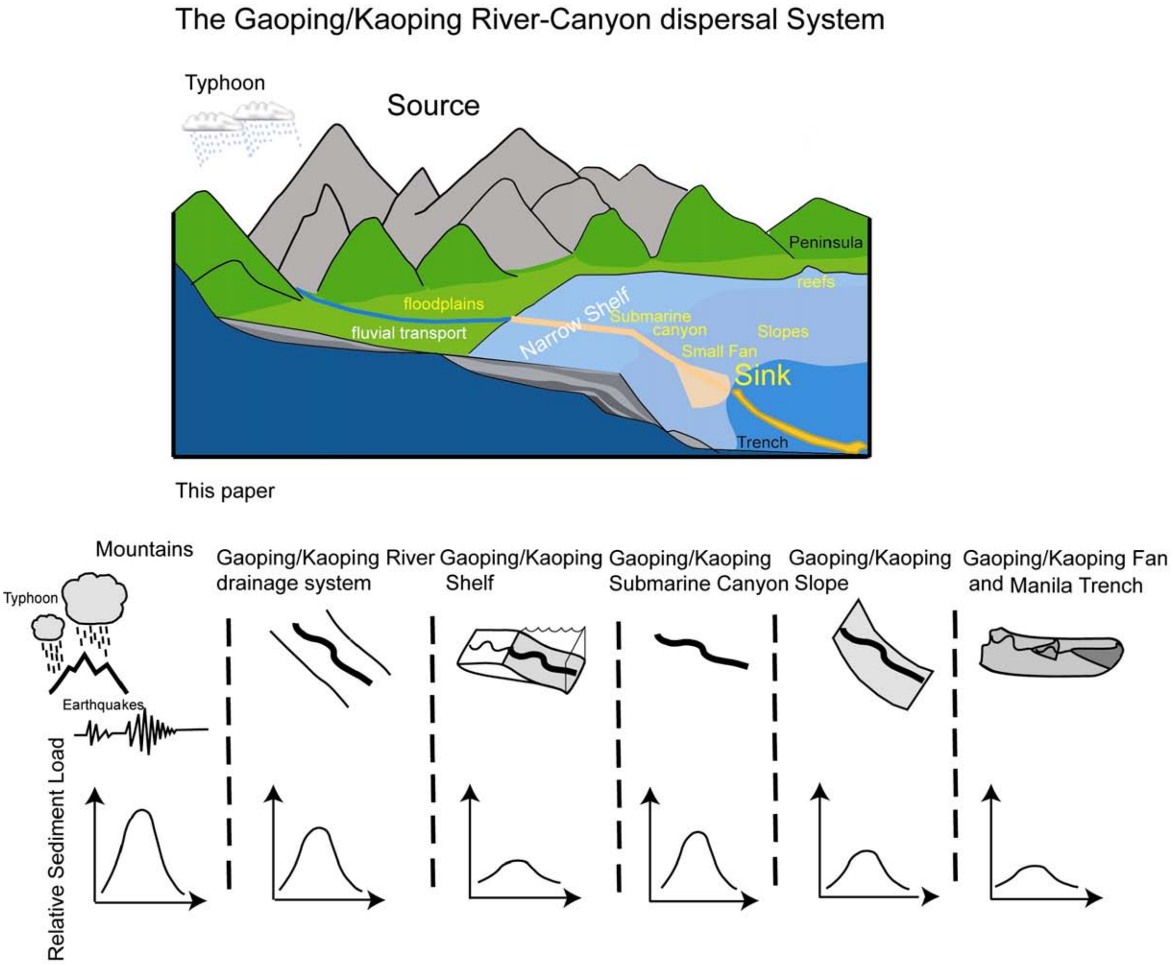

Fig. 11. The sediment dispersal system in SW Taiwan margin is characterized by a river-canyon connection in an active collision margin with climatic conditions of typhoons and localized heavy rainfalls (upper panel). This system shows that sediment discharges pass from the mountain top through various geomorphic units to deep-sea trench, the ultimate sediment sink. Note that large sediment input in the uplands that progressively decreases downstream and sediment discharges bypass the narrow Gaoping Shelf and mainly transported via the KPSC and finally reach the Manila Trench with small amount of sediment load (lower panel). After MARGINS (2004).

(Fig. 3) may shed light on explanations of this implication. This submarine fan is suggestive of a temporal sink for sediments mainly derived from the middle reach and partly derived from the upper Gaoping Slope. The possible presence of the submarine fan in the lower reach of the KPSC was mentioned by Chiang and Yu (2006, their figures 2, 4 and 10). The nature of this proposed submarine fan was not explicitly discussed by Chiang and Yu (2006).

We suggest that sediment is derived from the mouth of the middle reach and allows for sediment flow expansion down-slope to form a mall fan in the lower reach (Fig. 3). The submarine fan continued to develop until the lower reach sharply changed its course from southwest to the east where sediment overspilling from the canyon stopped. Seismic profiles 809-1 and 809-2 show possible submarine fan deposits due to overspill canyon sediment. This small submarine fan is considered here as a canyon feeder fan.

Fig. 11 also shows a small fan at the head of the trench in our conceptual model. Elongate submarine fans are commonly associated with basin floor-trench in active margin settings where are characterized by narrow shelf and sediment bypassing on the upper slope (Ito, 1998; Chakraborty and Pal, 2001). This is not the case here. At present, the submarine fan in the lower reach does not extend down to the Manila Trench to form a smaller fan because down-slope sediment transport is prevented from structural disturbance of thrust faults and mud diapirism (Figs. 9 and 10).

The Gaoping River and Canyon depth profile (Fig. 2B) implies that the possible sediment dispersal passage begins at the Yu Shan about 3952 m in height and ends at the northern Manila Trench of 3600 m in water depth for a distance of about 430 km. The most distinct characteristic is the short distance from the source areas to the sediment sink when it is compared to that of sediment dispersal systems in passive margins. For example, the Amazon River and Canyon system show that sediments derived from the Andes mountain ranges are transported via the Amazon Submarine Canyon to the abyssal plain for a distance more than 7500 km long (Pirmez and Imran, 2003). The distance from source to sink of the KPRSC system is much shorter than the length of Amazon system by about twenty times. In addition, the gradient of KPRSC system of about 15 m km^{-1} is steeper than that of 0.8 m km^{-1} of the Amazon River-Canyon system by about two orders of magnitude. Contrast differences in channel gradient and travel length between the Gaoping and Amazon systems suggest that the KPRSC system is an active sediment dispersal system for transporting terrestrial materials to the deep-sea trench.

5. Conclusions

In a regional source to sink scheme, the KPR drainage basin is considered the primary source area, the Gaoping Shelf being the sediment bypass zone and the Gaoping Slope being the temporary sink and the Manila Trench being the ultimate sink of the sediment from the Taiwan orogen. Seismic data imply that the outer shelf and upper slope region can be considered as a line source for mass wasting deposits delivered to the lower Gaoping Slope where small depressions between diapiric ridges are sometimes partially filled with sediment or empty.

At present, recurrent hyperpycnal flows during the flood seasons are temporarily depositing sediments mainly derived from the KPR in the head of the KPSC. On the decadal and century timescales, sediments temporarily stored in the upper reach are removed over longer timescales probably by downslope-eroding sediment flows within the canyon. At the present time, the KPSC serves as the major conduit for transporting terrestrial sediment from the Taiwan orogen to the marine sink of the Manila Trench in the northern South China Sea.

Seismic data indicate that the KPSC has been eroding the Gaoping Slope intensively by presumed hyperpycnal flows and transporting sediments from the canyon head to the middle and lower reaches of the canyon. The middle reach is a sediment bypass zone whereas the lower reach serves as either a temporary sediment sink or a sediment conduit, depending on relative prevalence to deposition or erosion during canyon evolution.

Contrasting differences in channel gradient and travel length between the Gaoping and Amazon systems suggest that the KPRSC system is an active sediment dispersal system for transporting terrestrial materials to the deep-sea trench. The fate of the KPR sediment is the northern Manila Trench.

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References

Byrne, T.B., Liu, C.S., 2002. Preface: introduction to the geology and geophysics of Taiwan. In: Byrne, T., Liu, C.S. (Eds.), Geology and Geophysics of an Arc-Continent Collision, Taiwan. Geol. Soc. Amer. Spec. Paper, vol. 358, pp. v–vii.

Chakraborty, P.P., Pal, T., 2001. Anatomy of a forearc submarine fan: upper Eocene-Oligocene Andaman Flysch Group, Andaman Islands, India. Gondwana Res. 4, 477–486.

Chiang, C.S., Yu, H.S., 2006. Morphotectonics and incision of the Kaoping submarine canyon, SW Taiwan orogenic wedge. Geomorphology 80, 199–213.

Chiang, C.S., Yu, H.S., Chou, Y.W., 2004. Characteristics of wedge-top depozone of the southern Taiwan foreland basin system. Basin Res. 16, 65–78.

Covey, M., 1984. Lithofacies analysis and basin reconstruction, Plio-Pleistocene western Taiwan foredeep. Petrol. Geol. Taiwan 20, 53–83.

Dadson, S.J., Hovius, N., Chen, H.G., Dade, W.B., Hsieh, M.L., Willet, S.D., Hu, J.C., 2003. Links between erosion, runoff variability and seismicity in the Taiwan orogen. Nature 426, 648–651.

Dadson, S., Hovius, N., Pegg, S., Dade, W.B., Horng, M.J., Chen, H., 2005. Hyperpycnal river flows from an active mountain belt. J. Geophys. Res. 110, 1–13 (F04016).

Damuth, J.E., Flood, R.D., Kowsmann, R.O., Belderson, R.H., Gorini, M.A., 1988. Anatomy and growth pattern of Amazon Deep-Sea Fan as revealed by long-range side-scan sonar (GLORIA) and high-resolution seismic studies. AAPG Bull. 72, 885–911.

Fuh, S.C., 1997. Structural evolution of the oblique arc-continent collision onland and offshore southern Taiwan. National Taiwan University, Ph.D. thesis, 166 pp.

Galewsky, J., Stark, C.P., Dadson, S., Wu, C.C., Sobel, A.H., Horng, M.J., 2006. Tropical cyclone triggering of sediment discharge in Taiwan. J. Geophys. Res. 111, 1–16 (F03014).

Ho, C.S., 1988. An Introduction to the Geology of Taiwan: Explanatory Text of the Geological Map of Taiwan, 2nd edition. Ministry of Economic Affairs, Taipei. 192 pp.

Ito, M., 1998. Submarine fan sequences of the lower Kazusa Group, a Plio-Pleistocene forearc basin fill in the Boso peninsula, Japan. Sediment Geol. 122, 69–93.

Lallemand, S.E., Tsien, H.H., 1997. An introduction of active collision in Taiwan. Tectonophysics 274, 1–3.

Lisitzin, A., 1991. Characteristics of global-sediment formation in regions of high- and superhigh-accumulation rates. In: Osborne, R.H. (Ed.), From Shoreline to Abyss: Contributions in Marine Geology in Honor of Francis Parker Shepard. SEPM Spec. Publication, vol. 46, pp. 79–97.

Liu, C.S., Huang, I.L., Teng, L.S., 1997. Structural features off southwestern Taiwan. Mar. Geol. 137, 305–319.

Liu, J.T., Liu, K.J., Huang, J.C., 2002. The effect of a submarine canyon on the river sediment dispersal and inner shelf sediment movement in southern Taiwan. Mar. Geol. 181, 357–386.

Ludwig, W.J., Hayes, D.E., Ewing, J.I., 1967. The Manila Trench and West Luzon Trough—I. Bathymetry and sediment distribution. Deep Sea Res. 14, 533–544.

MARGINS Science Plans, 2004. http://margins.wustl.edu/Publications/SciencePlans/MARGINSSciencePlans.html.

Milliman, J.D., Kao, S.J., 2005. Hyperpycnal discharge of fluvial sediment to the ocean: impact of Super-Typhoon Herb [1996] on Taiwanese rivers. J. Geol. 113, 503–516.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. J. Geol. 100, 525–544.

Pirmez, C., Imran, J., 2003. Reconstruction of turbidity currents in Amazon Channel. Mar. Pet. Geol. 20, 823–849.

Pratson, L.F., Coakley, B.J., 1996. A model for the headward erosion of submarine canyons induced by downslope-eroding sediment flows. Geol. Soc. Amer. Bull. 108, 225–234.

Pratson, L.F., Ryan, W.B.F., Mountain, G.S., Twichell, D.C., 1994. Submarine canyon initiation by downslope-eroding sediment flows: evidence in late Cenozoic strata of the New Jersey continental slope. Geol. Soc. Amer. Bull. 106, 395–412.

Suppe, J., 1981. Mechanics of mountain building and metamorphism in Taiwan. Geol. Soc. China Mem. 4, 67–89.

Walsh, J.P., Nittrouer, C.A., 2003. Contrasting styles of off-shelf sediment accumulation in New Guinea. Mar. Geol. 196, 105–125.

Wu, L.C., 1993. Sedimentary basin successions of the upper Neogene and Quaternary Series in Chishan area, southern Taiwan and its tectonic evolution. National Taiwan University, Ph.D. thesis, 212 pp.

Yu, H.S., 2000. Closure of Manila Trench north of Latitude 21 N in transition of passive-convergent margin south of Taiwan. Acta Oceanogr. Taiwanica 38, 115–127.

Yu, H.S., 2004. An underfilled foreland basin in the northern South China Sea off southwest Taiwan: incipient collision and foreland sedimentation. In: Clift, et al. (Ed.), Continent-Ocean Interactions within East Asian Marginal Seas. Geophysical Monograph Series, vol. 149, pp. 159–173.

Yu, H.S., Chiang, C.S., 1997. Kaoping Shelf: morphology and tectonic significance. J. Asian Earth Sci. 15, 9–18.

Yu, H.S., Chou, Y.W., 2001. Characteristics and development of the flexural forebulge and basal unconformity of Western Taiwan Foreland Basin. Tectonophysics 333, 277–291.

Yu, H.S., Huang, Z.Y., 2006. Intraslope basin, seismic facies and sedimentary processes in the Kaoping Slope, offshore southwestern Taiwan. Terr. Atmos. Ocean. Sci. 17, 659–667.

Yu, H.S., Song, G.S., 2000. Submarine physiographic features in Taiwan region and their geological significance. J. Geol. Soc. China 43, 267–286.