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The Penghu Submarine Canyon off Southwestern Taiwan: Morphology and Origin

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ABSTRACT

The main course of the Penghu Submarine Canyon extends along the intersection of the Kaoping Slope and the South China Sea Slope in a nearly north-south direction. It is about 180 km long from its head below the shelfbreak of the Taiwan Strait Shelf to its mouth merging into the Manila Trench. This canyon consists of two distinct parts: an upper reach and a lower reach.

Three major tributary canyons join into the main course to form a fan-shaped upper reach of the canyon. It mainly occupies the upper slopes extensively cut by tributary canyons and gullies and has a maximum width of about 80 km opened up by tributary canyons. The upper reach shows high relief, steep walls and V-shaped cross sections, showing typical canyon morphology. The lower reach is characterized by a single course without tributary canyons. It shows broad trough in cross section and relatively small relief between edges and bottom of the canyon without characteristic canyon morphology.

The floors of the Penghu Canyon show a gentle continuous inclination with an average slope angle of about one degree. A knick point about 2500 m deep separates the canyon into the upper reach with a steep slope angle of 1.42 degrees and the lower reach with a gentle slope angle of 0.5 degree. Canyon relief along its course changes from its head to the mouth considerably and ranges from about 54 to 845 m.

Downward excavation by downslope sediment flows and slumping and sliding on the canyon walls are the major forming processes in the canyon head and upper part of the canyon. Diapiric intrusions are mainly responsible for the high relief of the lower parts of upper reach of the canyon. The lower reach of the canyon is mainly formed by low-intensity downward erosion and mild structural uplift by thrust faults.

(Key words: Submarine Canyon, Penghu, Taiwan, Morphology, Origin)

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1. INTRODUCTION

1.1 Canyon Setting

Submarine canyons and gullies occur on the sea floor off the southwestern Taiwan coast and form the most prominent undersea features (Fig. 1). Most of these canyons develop on the submarine slopes with their heads normal to the shoreline along the southwestern Taiwan margin, except for the Penghu Submarine Canyon. For example, the notable Kaoping Canyon is normal to the shoreline of southwestern Taiwan and indents into the narrow shelf (Fig. 1).

The offshore areas of southwestern Taiwan are characterized by a very narrow Kaoping Shelf, around 10 km wide, and a relatively broad Kaoping Slope to a water depth of around 3200 m in the northernmost South China Sea (Fig. 1). The South China Sea Slope is located west of the Kaoping Slope and extends shoreward to the South China Sea Shelf on the Chinese margin (Liu et al. 1998, Yu and Song 2000). The bathymetric contours of the Kaoping Shelf and Kaoping Slope are mainly oriented in a northwest-southeast direction. But, the isobaths of the South China Sea Slope mainly trend northeast following the regional structural trend of the Chinese margin. The sea floors off southwest Taiwan and southeast China converge obliquely northward and form a triangle which opens and deepens to the south. The main course of the Penghu Canyon trending nearly in a north-south direction forms the physiographic boundary between these two submarine slopes (Fig. 1).

1.2 Previous Studies

The Penghu Canyon was postulated a relict Late Pleistocene sea valley continuing southwards from the Penghu Channel, crossing the shelf and ending on the Kaoping Slope (Boggs et al. 1979, Liu et al. 1998). Yu and Lee (1993) suggested that the Penghu Canyon is a multi-head slope canyon resulting mainly from down-slope erosion on the upper part of the Kaoping Slope. Yu and Huang (1998) considered the Shoushan canyon on the Kaoping Slope to be a tributary canyon joining the larger Penghu Canyon and suggested the Penghu Canyon has a composite origin. The main course of the Penghu Canyon is coincident with the location of the deformation front on the Kaoping Slope and is related to structural control other than downward erosion of slope sediment. Chen (2001) suggested that the Penghu Canyon is a multi-head canyon with seven tributary canyons and can be divided into the upper, middle and lower parts along its main course. Chuang and Yu (2002) considered that the Penghu Canyon is a single head canyon consisting of two parts: an upper and a lower reach. The upper reach is fan-shaped with three major tributary canyons. However, detailed studies of morphology and canyon-forming processes of the lower reach of the Penghu Canyon have not been given by Chuang and Yu (2002) due to insufficient data.

1.3 Purpose and Data

In order to complete the mapping of the Penghu Canyon as a whole, we conducted a marine survey mainly covering the lower reach of the canyon (Fig. 2). This paper is a presentation of the results of that cruise integrated with previous studies. It presents detailed mor-

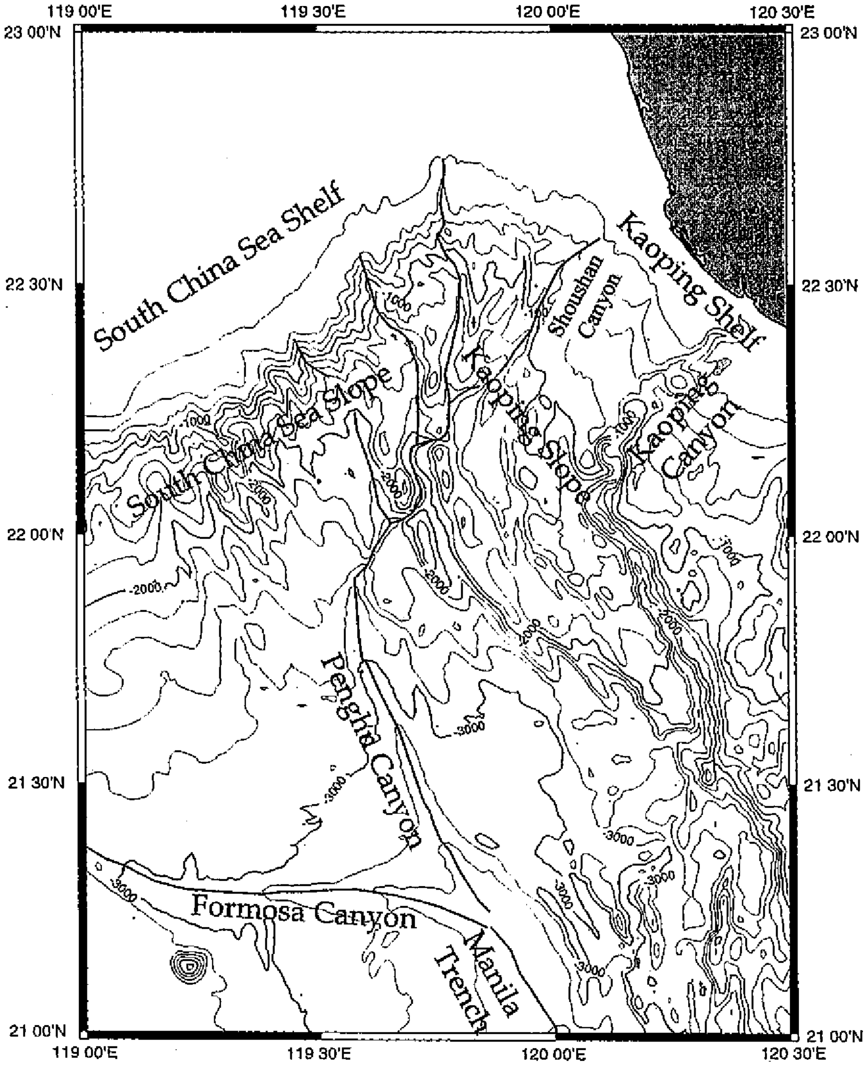

Fig. 1. The sea floor off southwestern Taiwan is mainly occupied by the Kaoping Slope with a regional trend in a NW-SE direction. West of the Kaoping Slope lies the South China Sea Slope that trends mainly northeast. The physiographic boundary of these two submarine slopes is the Penghu Canyon that begins immediately below the shelfbreak and extends southwards and gradually merges into the Manila Trench. Numerous gullies and canyons develop on the Kaoping Slope and South China Sea Slope with their main courses normal to the shorelines.

phology of the Penghu Canyon from head to mouth in plan view and cross section forms. Interpretations of seismic profiles across the canyon lower reach augmented by other bathymetric and sesimic data are used to discuss the origin of the canyon.

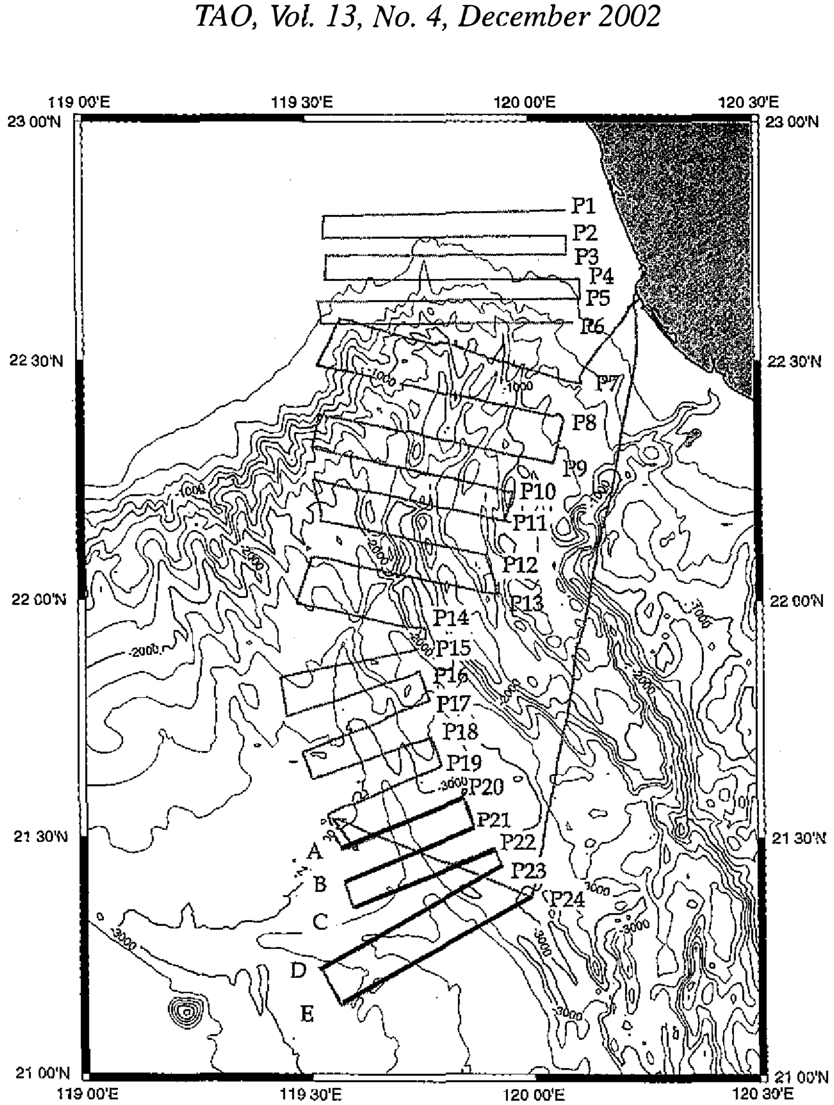

Fig. 2. Eighteen bathymetric track lines, labeled as P7 through 24, generally normal to the axis of lower reach of the Penghu Canyon were collected. Five additional seismic profiles, labeled as heavy lines from A to E, near the canyon end or mouth areas were acquired. Bathymetric profiles labeled as P1 through P6 across the head parts of the Penghu Canyon are taken from Chuang and Yu (2002). These bathymetric profiles allowed us to reveal the detailed cross-sectional morphology of the Penghu Canyon from its head to the mouth.

Bathymetric profiles and four-channel seismic reflection sections in the lower reach of the Penghu Canyon were acquired during the 613 cruise aboard R/V Ocean Researcher I in August, 2001 (Fig. 2). Track lines are designed to be normal to the direction of the main course of the Penghu Canyon. Emphases are placed on the determination of location of the canyon mouth and its continuation southwards into the Manila Trench. Five seismic profiles in the canyon-trench transition areas are collected. The seismic energy is an air-gun array. The DFS-V floating gain digital system is the recording device for the reflection seismic signal. Seismic data are processed using the SIOSEIS system at the Institute of Oceanography, National Taiwan University. Eighteen bathymetric profiles across the canyon course (Fig. 2) are collected using a Simrad EK 500 Sonar. Bathymetric data are integrated into the databank of bathymetry at the National Center for Ocean Research. Bathymetric data (one data point every 100 m) are then gridded and contoured using the GMT system (Wessel and Smith 1991) to make bathymetric charts in the offshore areas of southwestern Taiwan.

2. MORPHOLOGY

2.1 Plan View Shape

The main course of the Penghu Submarine Canyon extends along the intersection of bases of the Kaoping Slope and the South China Sea Slope in a nearly north-south direction (Fig. 1). This canyon is about 180 km long from its head below the shelfbreak of the Taiwan Strait Shelf to its mouth immediately north of the Manila Trench. The Penghu Canyon consists of two distinct parts: an upper reach and a lower reach (Fig. 3). The upper reach begins near the shelf edge of the Taiwan Strait Shelf and extends southwards about 100 km to a water depth around 2200 m where a tributary canyon on the South China Sea Slope merges into the main course from the west. It displays a fan-shaped network of sea valleys with three major tributary canyons joining into the main canyon course. It mainly occupies the upper slope extensively cut by tributary canyons and gullies and has a maximum width of about 80 km opened up by tributary canyons. Sea floors of the upper reach are highly irregular.

The lower reach is characterized by a single course without tributary canyons. It begins from the apex of the fan-shaped upper reach and extends linear-curvedly southwards for a distance of about 80 km and gradually mergers into the northern end of the Manila Trench. The drainage area of the lower reach is much smaller than that of the upper reach. The lower reach of the Penghu Canyon erodes the sea floor of lower slope into a single canyon of about 10 km wide.

2.2 Cross-sectional Forms

Twenty four bathymetric profiles nearly normal to the main course of the Penghu Canyon are presented to reveal its cross-sectional morphology (Fig. 3). Profiles 1 through 6 cross the head parts of the Penghu Canyon. The canyon head is located at the intersections of the uppermost parts of the Kaoping Slope and the South China Sea Slope and is shown as a small linear trough with width ranging from 1.4 to 4.3 km and steep walls of 3 to 9 degrees. The relief between canyon bottom and edges shown by these profiles ranges from 54 to 190 m. The head segments of the Penghu Canyon display a V-shaped cross section characteristic of submarine canyons as shown profiles 3 and 4.

Profiles 7 and 8, farther down-canyon, show that sea floor of the lower parts of the Kaoping

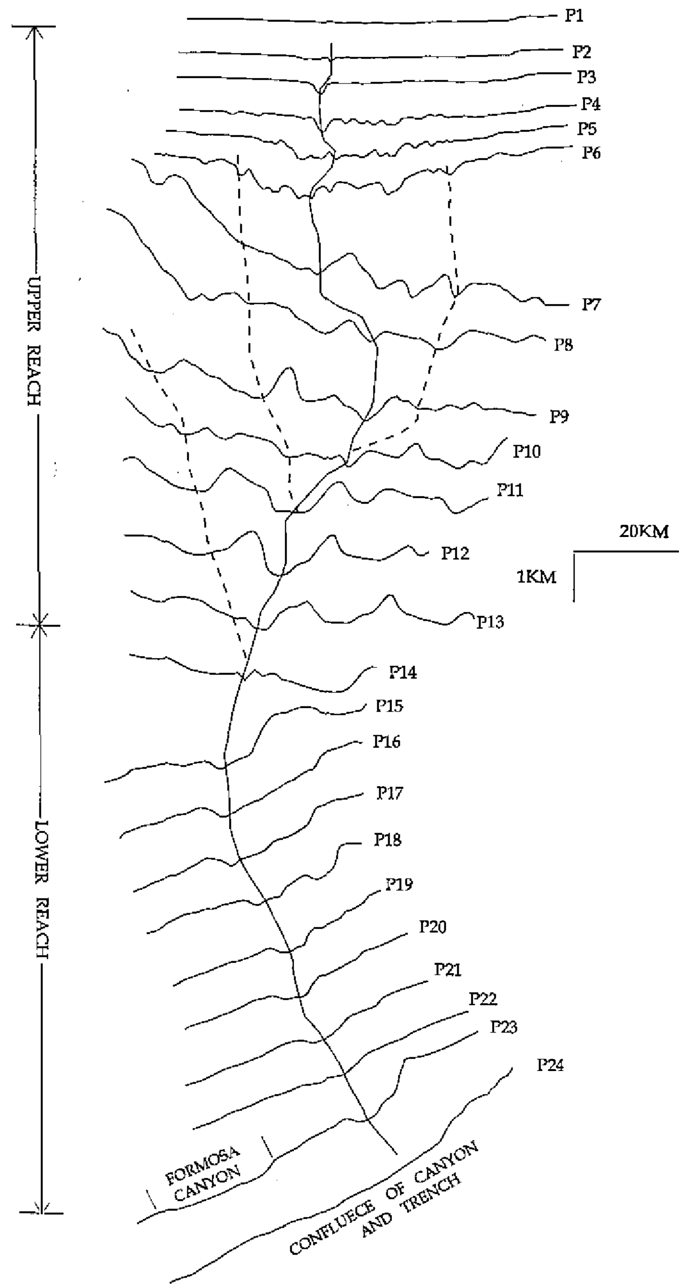

Fig. 3. Cross-sectional morphology of the Penghu Canyon. The upper reach shows typical canyon morphology: high relief, steep walls and V-shaped cross sections. The lower reach shows broad trough in cross section and relatively small relief between edges and bottom of the canyon.

and South China Sea slopes are extensively cut by gullies and canyons, resulting in irregular topography. The main course of the canyon is located at the intersection of the bases of the Kaoping and South China Sea slopes, the lowest parts of the sea floors. Profile 7 shows that three tributary canyons east of the Penghu Canyon axis are apparently noticed. The tributary canyon west of the main course is not obvious as those on the Kaoping Slope. The main course of the Penghu Canyon shows a V-shaped trough on Profile 8 with a width of about 4.5 km. The sloping angles of the canyon walls range from 6.3 to 7 degrees and the relief between canyon edges and the bottoms is increases to between 243 to 274 m. Profile 7 shows that the main course of the Penghu Canyon is separated from the tributary canyon to the east by a topographic high, resulting in an asymmetrical V-shaped trough with the east wall steeper than the west wall.

Farther down-canyon, Profiles 9 through 11 show that the main course of the canyon displays an asymmetrical V-shaped trough with the east wall steeper than the west wall. The sloping angles of east walls are around 11 degrees and those of the west walls range from 4 to 6 degrees. The former is much larger than the latter. The width of the Penghu Canyon varies considerably along this segment of the main course from 7 km (Profile 9) and 3.5 km (Profile 10) to 12.5 km (Profile 11). The relief between canyon edges and bottoms ranges widely from 160 to 620 m.

Profile 12, farther south along the main course, shows a prominent V-shaped trough with sloping angles of both walls of about 9.8 degrees. The canyon width is about 15 km and the canyon relief is about 845 m. Profile 13 crosses immediately north of the apex of the upper reach and shows an asymmetrical V-shaped trough with the east wall steeper than the west wall. The sloping angle of east wall is about 11 degrees and that of the west wall is about 2 degrees. The width of the canyon narrows down-canyon from 15 km on Profile 12 to about 10 km on Profile 13.

In general, bathymetric profiles across the upper reach show V-shaped troughs with steep walls and high relief typical of canyon morphology. The width of canyon varies from 1.4 km near the head to 15 km at the farther down-canyon segment. Canyon relief ranges widely from 54 to 845 m and the sloping angles of canyon walls vary considerably from 2 to 11 degrees.

Profile 14 crosses the lower reach of the canyon where no tributary canyons join into the main course of the canyon. The canyon appears as a relatively small trough. It is about 2 km wide and has a relief from 95 to 215 m. Sea floors west and east of the canyon are relatively flat in contrast to those in the upper reach of the canyon as shown on Profiles 7 and 8. Farther down-canyon, Profile 15 shows that the cross-sectional form of the canyon changes from a small trough into a larger asymmetrical trough of about 6.5 km wide. The canyon relief increases to about 260 m.

Farther down-canyon, Profiles 16 through 18 show that cross-sectional forms of this canyon segment maintain asymmetrical troughs with a width of about 10 km. The canyon relief ranges from 165 to 263 m. The relief is relatively small compared to that of 845 m at the upper reach on Profile 12. The Penghu Canyon displays broadly U-shaped troughs shown on Profiles 19 through 21 farther down-canyon. The width of the canyon narrows to about 7 km and has a relief ranging from 167 to 235 m. Farther down-canyon, this canyon segment becomes a relatively shallow trough with decreasing relief ranging from 85-176 m as shown on Profile 22. The width of the canyon is about 8 km and both walls have sloping angles decreasing to about 2 degrees.

Farther southwards, Profile 23 crosses the Formosa Canyon to the west and the Penghu Canyon to the east, respectively. The Penghu Canyon is represented by an asymmetrical trough with east wall steeper than the west wall. The width of the Penghu Canyon is about 10 km and the relief is about 210 m. The Formosa Canyon is shown as a relatively shallow trough without typical V shape in cross section. Profile 24 across the junction between the Formosa Canyon, the Penghu Canyon and the Manila Trench shows a relatively wide and low-relief trough on bottoms of the Kaoping Slope and South China Sea Slope at water depth of 3480 m.

The trough at water depth of about 3450 m located immediately north of the junction between the Formosa Canyon, the Penghu Canyon and the Manila Trench is suggested to be the end or mouth of the Penghu Canyon. It does not show the characteristic cross-sectional form typical of submarine canyons.

The course of the lower reach is characterized by broad troughs with varying width from 6.5 to 13.5 km but with an exceptional narrowness of 2 km near the end of the upper reach of the canyon. The canyon walls are angled from 1.2 to 7.5 degrees and are less steep than those of the upper reach of the canyon. Canyon relief ranges from 90 to 350 m.

Overall, the Penghu Canyon extends along the bottoms of the Kaoping and the South China Sea slopes for about 180 km from its head below the shelfbreak of the Taiwan Strait Shelf to its mouth immediately north of the Manila Trench in a nearly north-south direction. It consists of a fan-shaped upper reach with three main tributary canyons and a lower reach of a single course without tributaries. The upper reach shows high relief, steep walls and V-shaped cross sections, showing typical canyon morphology. The lower reach shows broad trough in cross section and relatively small relief between edges and bottom of the canyon.

3. ORIGIN

3.1 Seismic Characteristics

Seismic characters, canyon axis gradient and relief plot against canyon course were used to infer processes for the formation of upper reach of the Penghu Canyon (Chuang and Yu 2002). Here we add the newly acquired data of the lower reach of the Penghu Canyon to those of the upper reach to explore the entire canyon from its head to the mouth.

Seismic profile A shows that the Penghu canyon is represented as a broad trough located at the boundary between the South China Sea Slope to the west and the Kaoping Slope to the east (Fig. 4). Stepped and curved surfaces occur on the west wall of the canyon, indicating slumping or sliding of the lower slope strata may have resulted in widening the canyon. On the contrast, the east wall probably mainly resulted from uplifting and tilting of the Kaoping Slope sediment by westward thrusts as evidenced by parallel reflectors dipping west underlying the east wall and other disturbed reflectors east of the canyon wall.

Farther down-canyon, seismic profile B shows seismic characters similar to those of the profile A (Fig. 5). It is noted that surfaces of slumping or sliding are not apparent on the west wall of the canyon. However, truncations of parallel reflectors against the west wall can be inferred from layers of lower slope sediments terminating towards the west wall, indicating erosion of the sediment at the base of the South China Slope. A relative flat reflector occurs at the bottom of the canyon. It is a cut-and-fill feature commonly found in ancient and modern canyons. Sediments from up-canyon or supplied by nearby walls are deposited and partially filled up the canyon axis, resulting in a relatively flat surface. Erosion mainly occurs at the South China Sea Slope and forms the west wall of the canyon. But westward thrusting of the

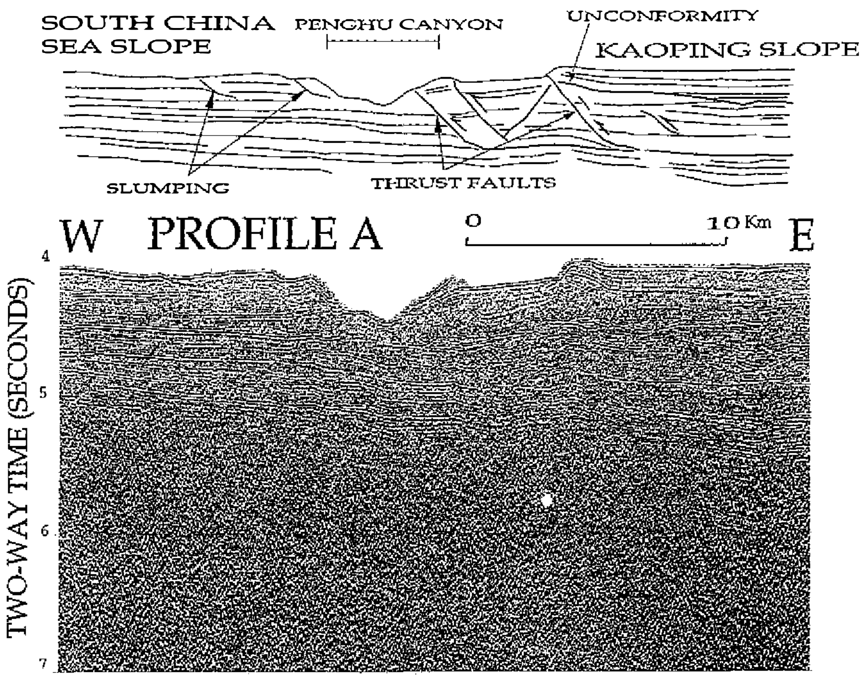

Fig. 4. Seismic profile A shows that the Penghu canyon is represented as a broad trough. Stepped and curved surfaces occur on the west wall of the canyon, indicating slumping or sliding of the lower slope strata and resulting in widening the canyon. The east wall probably mainly resulted from uplifting and tilting of the Kaoping Slope sediment by westward thrusts. Location of seismic profile A is shown in Fig. 2.

Kaoping Slope strata results in a west-dipping surface to the form the east wall of the canyon. Erosion of the east wall may be insignificant compared to that of the structural contribution.

Farther south, seismic profile C indicates that the Penghu Canyon becomes a relatively broad and shallow trough with low relief between the edges and bottom of the canyon, indicating relatively low intensity of erosion (Fig. 6). The irregular bottom of the canyon may have resulted from combined sediment-filling and structural disturbance. The westward thrusting of the Kaoping Slope sediment is likely responsible for the formation of the east wall and bottom of the canyon. The west wall of the canyon is formed by erosion of the South China Sea Slope sediment as evidenced by truncations of reflectors against the canyon wall.

Farther down-canyon, seismic profile D shows the Penghu Canyon on the east part of the profile and the Formosa Canyon on the west part of this section (Fig. 7). The Penghu Canyon is represented as a U-shaped trough with a cut-and-fill flat bottom. The east wall shows a convex upward surface that could have resulted from the rising of the ridge to the east. This ridge may represent the sea floor expression of the underlain mud diapir associated with westward thrust faults. Diapiric instrusions and westward propagation of thrust faults are common features in the formation of ridges and scarps on the sea floor of the Kaoping Slope (Chuang

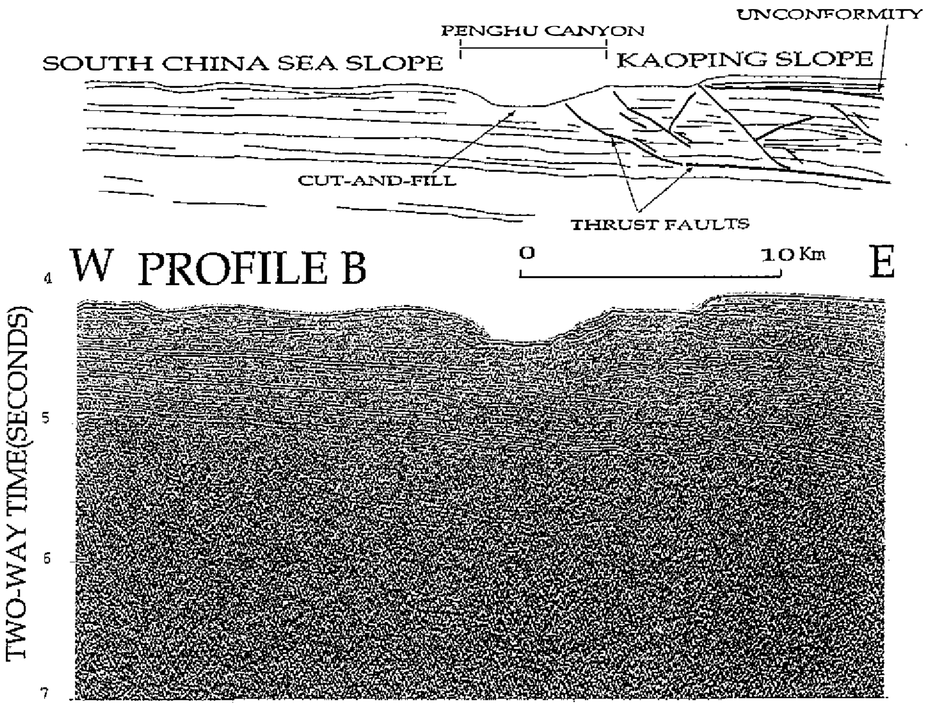

Fig. 5. Seismic profile B shows seismic characteristics similar to those of the profile A, indicating similar canyon forming processes for this segment of the canyon crossed by profiles A and B. A cut and fill feature can be recognized at the bottom of the canyon with a flat reflector. Location of seismic profile B is shown in Fig. 2.

and Yu 2002, Liu et al. 1997, Reed et al. 1992). The west wall of the canyon shows truncations of reflectors against the wall, indicating erosion has occurred. It is noted that truncations of parallel reflectors against both walls of the Formosa Canyon occurred, indicating downward cutting of the South China Sea Slope sediment.

Farther south, seismic profile E shows that the confluence of the Formosa Canyon, the Penghu Canyon and the Manila Trench is expressed in a wide and shallow trough with relatively low relief. It is located at the boundary between the South China Sea Slope to the west and the Kaoping Slope to the east (Fig. 8). The South China Sea Slope sediments are expressed in parallel and continuous reflections dipping east. Slumping or sliding occurs on the uppermost parts of the slope strata. The Kaoping Slope sediments are deformed into westward thrusts with west-dipping strata and to form the east part of the trough. Apparently, sediments supplied from the Formosa and Penghu canyons are not enough to fill up this trough and part of the sediments can be transported farther south to the deeper Manila Trench. It is noted that the intensity of downward erosion is relatively low, as evidenced by small incision depth.

In summary, seismic profiles A through D across the lower reach near the canyon end show that downward erosion and slumping or sliding mainly occur on the South China Sea

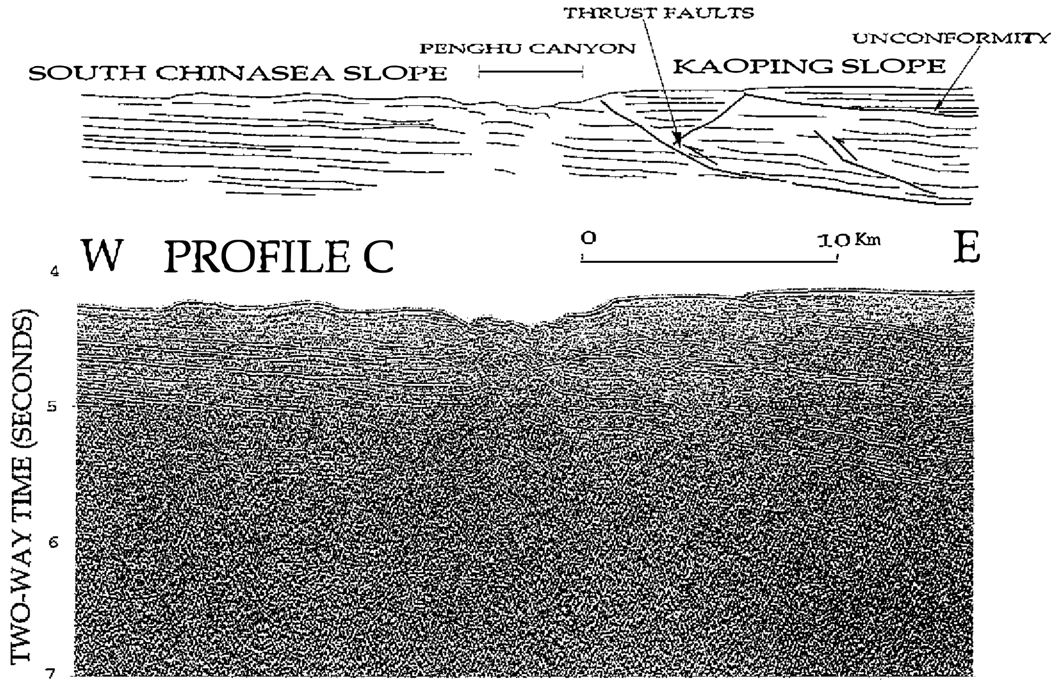

Fig. 6. Seismic profile C indicates that the Penghu Canyon becomes a relatively broad and shallow trough with low relief between the edges and bottom of the canyon, indicating relatively low intensity of erosion. Location of seismic profile C is shown in Fig. 2.

Slope to form the west wall of the Penghu Canyon. Thrust faults and associated diapiric intrusions cause the uplifting and tilting of the Kaoping Slope strata, resulting in the formation of the east wall of the canyon. Thus, downward erosion and structural uplift are the main processes forming the lower reach of the canyon.

3.2 Longitudinal Profile and Relief

The Penghu Canyon extends from its head at a water depth of 241 m to its mouth at an increasing depth of 3450 m along the main course for a distance of 180 km. In general, the floors of the Penghu Canyon show a gentle continuous inclination with an average slope angle of about 1 degree. A clear knick point occurs on the longitudinal profile of the canyon where is about 2500 m deep and about 100 km away from the canyon head. The knick point separates the canyon into the upper reach with a steep slope angle of 1.42 degrees and the lower reach with a gentle slope angle of 0.5 degree (Fig. 9). The greater slope angle of the upper reach implies greater intensity of down-slope movement of sediment flows to cut the sea floors into V-shaped canyons with high relief. The gentle gradient of the lower reach course implies less intensity for down-slope erosion of the sea floors, resulting in broad troughs with low relief. Observations of cross-sectional forms of broad troughs at the lower reach (profiles 15-23) and

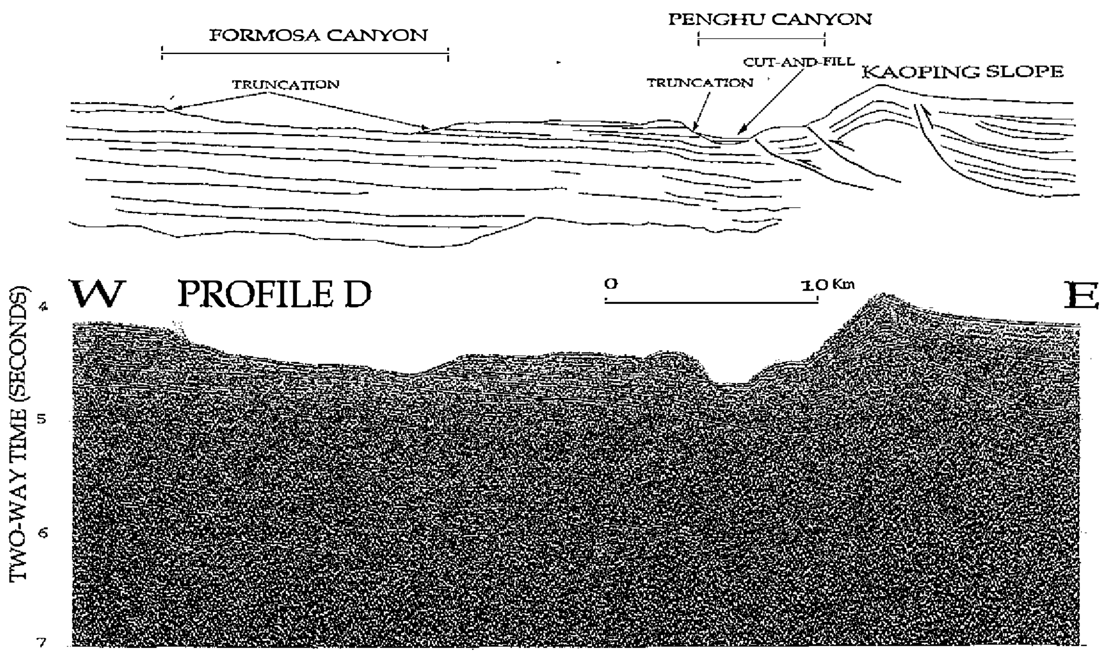

Fig. 7. Seismic profile D shows that the Penghu Canyon is expressed as a U-shaped trough with a cut-and-fill flat bottom. The east wall shows a convex upward surface that could have resulted from the rising of the ridge to the east due to underlain mud diapirs associated with westward thrust faults. The west wall of the canyon shows truncations of reflectors against the wall, indicating erosion. Location of seismic profile D is shown in Fig. 2.

V-shaped canyon at the upper reach (profiles 3-12) are in accordance with the differences in slope angles along the canyon course. This reasoning assumes that down-slope erosion is the main erosion agent without structural complication. However, the plot of canyon relief along its course shows that canyon relief changes from its head to the mouth considerably and ranges from about 54 to 845 m (Fig. 10). It is suggested that downslope sediment flows and structural controls are mainly responsible for the variations of slope angles and relief along the canyon course.

A seismic profile near the canyon head shows that parallel reflections are terminated against canyon walls, suggesting down-cutting of the slope sediments to form a small canyon with relief smaller than 200 meters (Chuang and Yu 2002, Fig. 6). Slumping and sliding on canyon walls enhance the effect of downward erosion and result in widening and deepening the canyon. A seismic profile across the lower part of the upper reach shows that diapiric intrusion is the dominating process besides the downward cutting and slumping for the formation of canyon (Chuang and Yu 2002, Fig. 9). Canyon relief caused by diapiric intrusions is greater than 800 meters in the upper reach. Seismic profiles A through D (Figs. 5 through 8)

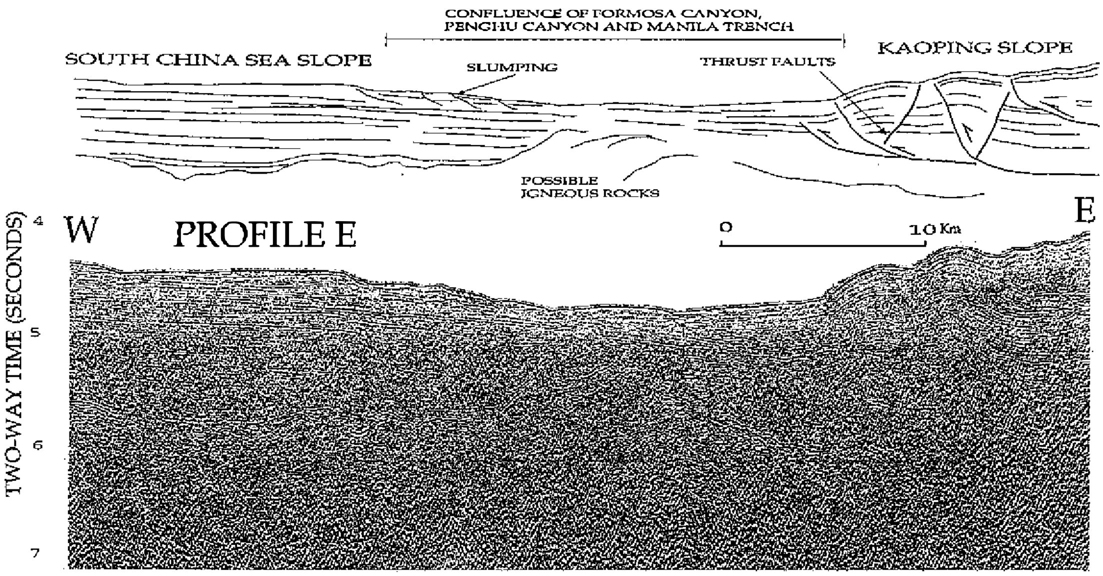

Fig. 8. Seismic profile E shows that the confluence of the Formosa Canyon, the Penghu Canyon and the Manila Trench is expressed in a wide and shallow trough with relatively low relief. Location of seismic profile E is shown in Fig. 2.

near the canyon mouth indicate that downward erosion and structural uplift are the main processes forming the lower reach of the canyon. However, magnitudes of downward erosion and structural uplift are relatively low compared to that of the upper reach of the canyon.

4. DISCUSSION

Submarine canyons are conduits for terrestrial and shallow marine sediments transported to the deep sea (Shepard 1973). The Penghu Canyon is no exception. Sediments from Taiwan orogen can be transported to the upper reach of the Penghu Canyon via tributary canyons and gullies on the upper Kaoping Slope. Apparently, less amounts of sediment from Taiwan are transported to the lower reach of the canyon through downslope mass movements because of distal to the Taiwan orogen. Sediment transportation from the Chinese margin to the Penghu Canyon is similar to that of the Taiwan margin. In turn, sediments from both the Taiwan orogen and the Chinese margin are transported southward following the regional gradient of the Penghu Canyon to the Manila Trench. The Penghu Canyon demonstrates that orogenic sediments from Taiwan and sediments from the passive Chinese margin are brought together and transported to the Manila Trench via the canyon.

Terrestrial and shallow marine sediments transported to a trench via submarine canyons are not uncommon. For example, the Markham Submarine Canyon extends eastward and merges into the New Britain Trench off northeastern Papua New Guinea (Crook 1989) and the Hualian

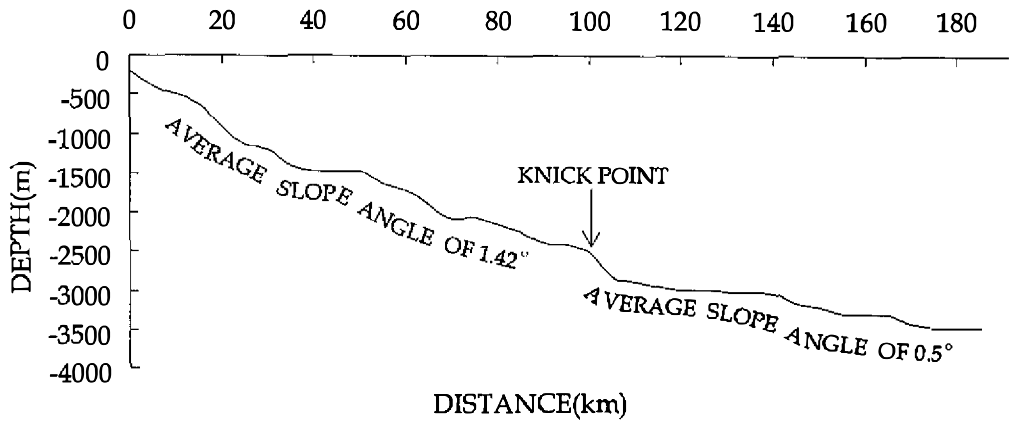

Fig. 9. The axis of the Penghu Canyon shows a gentle continuous inclination with an average slope angle of about 1 degree. A clear knick point occurs on the longitudinal profile of the canyon where it is about 2500 m deep, about 100 km away from the canyon head. The knick point separates the canyon into the upper reach with a steep slope angle of 1.42 degrees and the lower reach with a gentle slope angle of 0.5 degree.

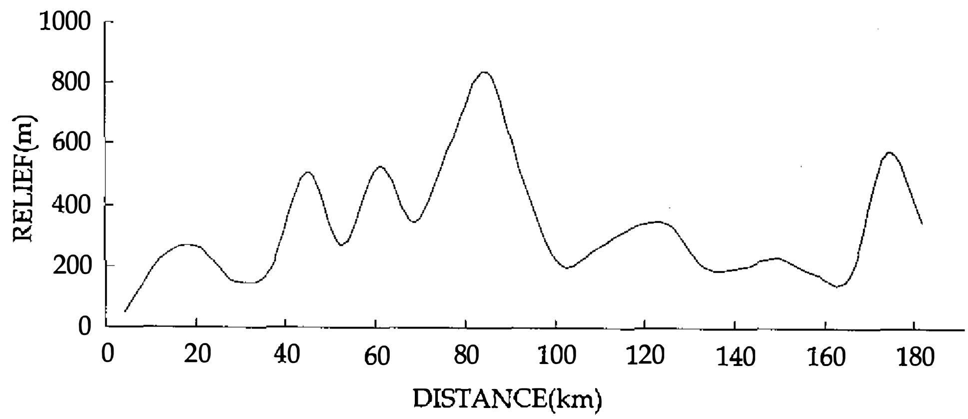

Fig. 10. The plot of canyon relief along the main course of the Penghu Canyon shows that canyon relief changes from its head to the mouth considerably and ranges from about 54 to 845 m, suggesting that downslope sediment flows and structural controls are mainly responsible for the variation of canyon relief along the canyon course.

Submarine Canyon merges into the Ryukyu Trench off eastern Taiwan (Yu and Song 1999). Sediments in the Penghu Canyon can provide clues about the sedimentary history of the orogenic sediments from southern Taiwan ending up at the Manila Trench. Analyses of cored sediment samples along the course of the Penghu Canyon may be a worthwhile study.

5. CONCLUSIONS

Newly acquired data in the lower reach of the Penghu Submarine Canyon suggest that the lower reach is characterized by a single course without tributary canyons. It shows broad trough in cross section and relatively small relief between edges and bottom of the canyon without characteristic canyon morphology. The lower reach is mainly formed by low-intensity downward erosion and mild structural uplift by thrust faults. The location and nature of the canyon mouth is determined. Thus, the variations of slope angle and relief along the entire canyon course can be made. The morphological measurements and seismic characters are integrated into previous studies of the upper reach and used to discuss the processes for the formation of the Penghu Canyon. Downward excavation by downslope sediment flows and slumping and sliding on the canyon walls are the major forming processes in the canyon head and upper canyon part. Diapiric intrusions are mainly responsible for the high relief of the lower parts of upper reach of the canyon. The lower reach of the canyon is mainly formed by low-intensity downward erosion and moderate structural uplift by thrust faults.

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