Morphology and Canyon Forming Processes of Upper Reach of the Penghu Submarine Canyon off Southwestern Taiwan

Ching-Yao Chuang[1] and Ho-Shing Yu[1,*]

ABSTRACT

The main course of the Penghu Submarine Canyon is located along the intersection of bottoms of the Kaoping Slope and the South China Sea Slope in a nearly north-south direction. The Penghu Canyon can be considered a single head canyon with three major tributary canyons joining into the main course to form the fan-shaped upper reach of the canyon. The upper reach begins near the shelf edge of the Taiwan Strait Shelf and extends about 150 km southwards to a water depth about 2200 m at the lower slope where no tributary canyons are present. The upper reach of the Penghu Canyon shows high relief, steep walls and V-shaped cross sections, showing typical canyon morphology.

Characteristics of seismic profiles suggest that the formation of the upper reach of the Penghu Canyon is mainly attributed to foreland basin sedimentation and accompanying incision of the syn-depositional orogenic sediments of the basin. Orogenic sediments derived from Taiwan progressively onlap westward and bury the Chinese passive margin and deposit in the bottom of the foreland basin. The main course of the Penghu Canyon has resulted mainly from excavating the orogneic sediments along the axis, tilting southward, of the deep foreland basin.

Slumping and sliding and downward excavation into the sea floors by downslope sediment flows are the major forming processes in the canyon head and upper canyon part. Diapiric intrusion becomes important in the formation of the lower parts of the upper reach of the Penghu Canyon.

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

1. INTRODUCTION

1.1 Tectonic Setting

The island of Taiwan is located at the junction between the Ryukyu and the Luzon Arcs in

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the northwestern Pacific (Fig. 1). About five millions years ago, the oblique collision between the Chinese margin and the Luzon Arc formed the Taiwan Island (Suppe 1981; Ho 1988) and an accompanying foreland basin west of the Taiwan orogen (Covey 1984). The region in
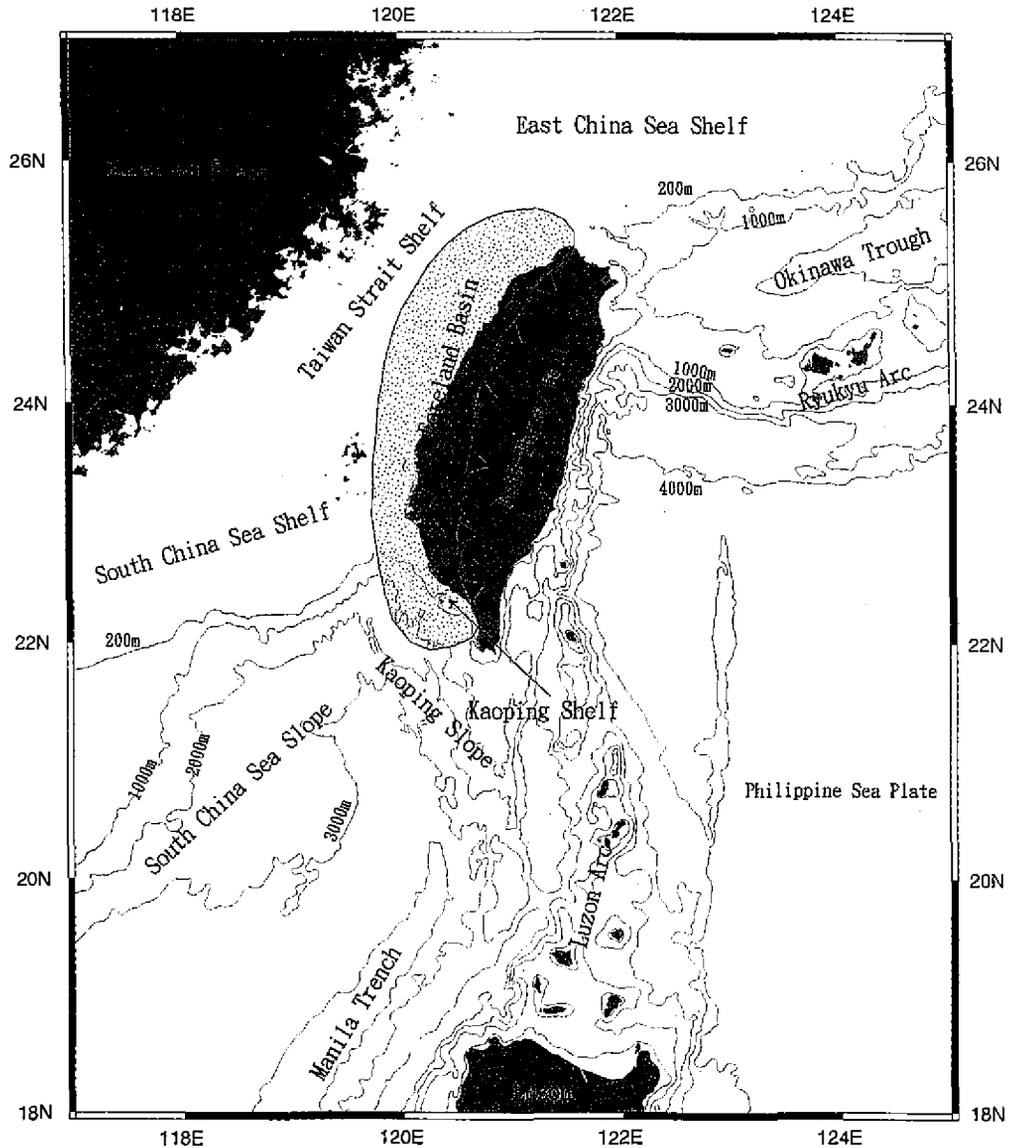
Fig. 1. Map showing tectonic setting of Taiwan and its surroundings. Taiwan is located at the junction of the Luzon and Ryukyu Arcs in the northwest Pacific. The island of Taiwan is represented by the nearly N-S trend fold-thrust belt and a west flanking foreland basin. Note that the foreland basin off Southwest Taiwan is juxtaposed by the Chinese passive margin.

southwestern Taiwan, including offshore areas, is an immature foreland basin receiving orogenic sediments from the rising Taiwan orogen (Covey 1984; Yu 1993; Brusset et al. 1999). The seaward progradation of sediments from the coastal plain of southwest Taiwan has formed the Kaoping Shelf with a regional trend in a northwest to southeast direction. The regional trend of the southwest Taiwan margin is mainly in response to the southward propagation of arc-continent collision in the Taiwan region (Yu and Chiang 1997). Pliocene-Quaternary sediments underlying the Kaoping Shelf and Kaoping Slope are deformed into a series west-vergent folds and thrusts (Liu et al. 1997), representing an active margin.

West of the Kaoping Slope, rock sequences underlying the Chinese margin, including the South China Sea Slope (Yu and Song 2000), are mainly Cenozoic clastic sediments with a thickness more than 5,000 meters (Sun 1982, 1985). A widespread regional unconformity from the Middle Oligocene separates the Tertiary strata into Paleogene and Neogene sequences (Sun 1982). The Neogene sequences have resulted from regional thermal subsidence and deposition of shallow marine sediments with relatively mild normal faulting, showing a typical passive margin.

1.2 Physiography

The sea floor off southwestern Taiwan is occupied by the narrow Kaoping Shelf and the relatively broad Kaoping Slope which extends to a depth of about 3,000 m at the northern limit of the abyssal plain of the South China Sea (Fig. 2). West of the Kaoping Slope lies the South China Sea Slope which extends from the shelf edge of the South China Sea Shelf to the northern abyssal plain of the South China Sea, and merges eastward into the Kaoping Slope. The sea floor between Southwest Taiwan and South China is characterized by two broad, deep water (3000 m) submarine slopes that are marked by convex bending of bathymetric contours. The isobaths on the Kaoping Slope mainly trend northwest to southeast. In contrast, the bathymetric contours on the South China Sea Slope trend in NE-SW and are aligned to the regional structural trend of the southeastern Chinese margin. The physiographic boundary separating these two deep submarine slopes is coincident with the main course of the Penghu Submarine Canyon (Fig. 2).

Submarine canyons and gullies are the most prominent undersea features on the southwestern Taiwan margin and mainly occur on the upper slope. Some canyons are named after nearby towns, for example, the prominent Kaoping Canyon crossing the Kaoping Shelf and the Kaoping Slope (Fig. 2). Similarly, the upper part of the South Chian Sea Slope is transversely dissected by unnamed submarine gullies and canyons, producing an irregular sea floor topography (Fig. 2). It is noticed that the courses of these canyons on both submarine slopes are more or less normal to shorelines, respectively, and can be classified as slope canyons (Shepard 1981). They represent short range linear down-hill mass transport to erode, transport and deposit mass on the continental slopes and upper slopes, in particular.

1.3 Previous Studies and Purpose

The Penghu Submarine Canyon was named by Lee (1992) after the Penghu Islands which lie about 100 km north of the Penghu Canyon in the Taiwan Strait. This canyon was consid-
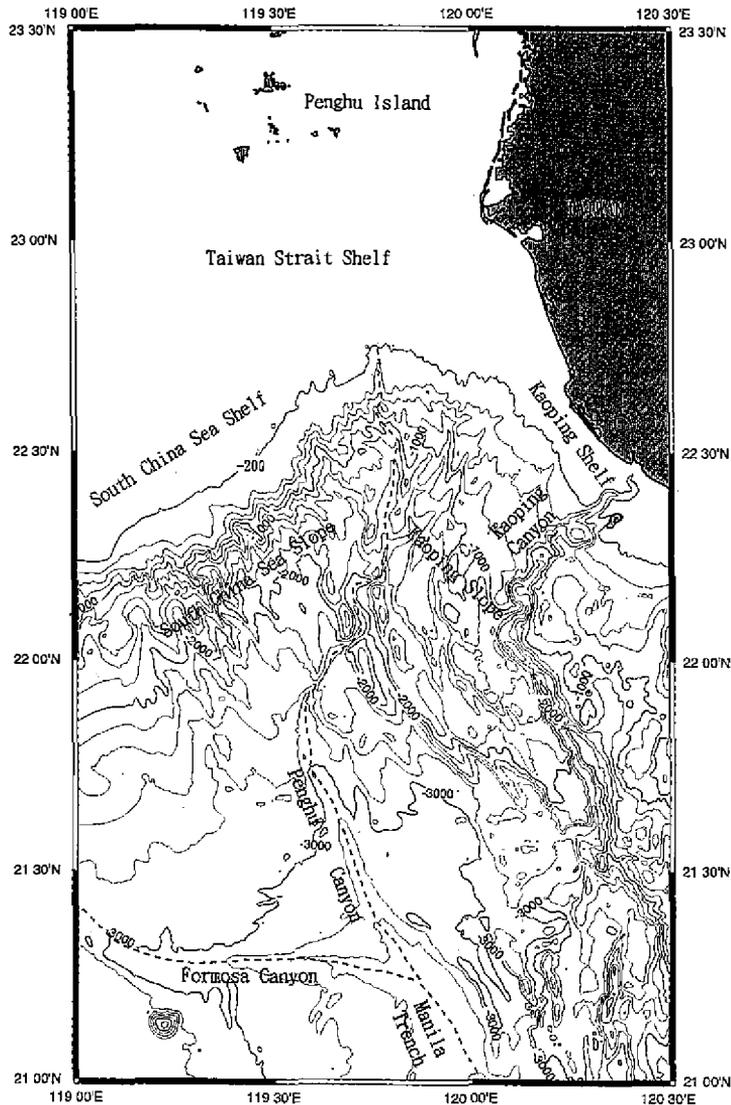
Fig. 2. The offshore region between Southwest Taiwan and South China con-
sists mainly of two broad and deep (greater than 3000 m) slopes marked
by outward bowing bathymetric contours. The isobaths of Kaoping Slope
mainly trend northwest to southeast but the South China Sea Slope trends
in a NE-SW direction. The physiographic boundary marked by dotted
line separating these two deep marine slopes is coincident with the Penghu
Canyon. Note that the Penghu Canyon, joined by the Formosa Canyon
on the South China Sea Slope, merges gradually into the Manila Trench
in the south. It is noted that numerous submarine gullies and canyons
occur on these two slopes.

ered a multi-headed canyon initiating on the upper slope near the shelfbreak. Three distinct canyon heads coalesce in forming a single canyon and extend downslope to a water depth of about 1400 m where the canyon ends (Yu and Lee 1993). Yu and Huang (1998) determined a major tributary Shoushan Canyon on the Kaoping Slope that extends southwestward to a water depth of 1700 m where it joins the main course of the Penghu Canyon. Chen (2001) considered the Penghu Canyon to be a multi-head canyon, consisting of three parts: the upper, middle and lower reaches with seven tributary canyons. Due to different approaches of interpreting the courses of the Penghu Canyon, the location of the canyon head and the courses of tributary canyons remain controversial. The purpose of this paper is to map the upper reach of the Penghu Canyon in greater detail, to determine its head location and the relationships between the canyon course and tributary canyons. We examine the cross-sectional morphology and plan view of the upper reach of this canyon and describe its morphological characteristics. Sedimentary processes forming the Penghu Canyon can be inferred from the seismic reflection profiles.

1.4 Data

A marine survey of the upper slopes south of the Taiwan Strait Shelf was carried out to map the upper reach of the Penghu Canyon and its adjacent tributary canyons. Bathymetric profiles and four-channel reflection seismic sections in the study area were acquired during the cruise aboard R/V Ocean Researcher I during June, 2000 (Fig. 3). The bathymetric profiles were collected by using a Simrad EK 500 Sonar. Newly acquired bathymetric data were integrated into the bathymetric databank at the Center for Ocean Research, National Taiwan University. Bathymetric data (one data point every 100 m) were then gridded and contoured using the GMT system (Wessel and Smith 1991) to generate a bathymetric chart covering the offshore areas southwest of Taiwan (Fig. 2). Nine seismic reflection profiles trending E-W across the upper reach of the Penghu Canyon were acquired. The total length of these seismic profiles is about 500 km. An air-gun array was deployed as seismic energy. The DFS-V floating gain digital system was the recording device for the reflection seismic signals. Seismic reflection data were processed using the SIOSEIS system at the Institute of Oceanography, National Taiwan University.

2. MORPHOLOGY

2.1 Plan View

Examining the newly generated bathymetric chart (Fig. 3) and bathymetric transects (Fig. 4) across the upper reach of Penghu Canyon, we determined the main course of the Penghu Canyon. It is located along the intersection of bottoms of the Kaoping Slope and the South China Sea Slope in a nearly north-south direction. It begins at the upper slopes immediately below the shelf edge of the Taiwan Strait Shelf and ends at the northernmost part of the Manila Trench, stretching for a distance of about 200 km (Fig. 2). Three major tributary canyons join into the main course of the Penghu Canyon to form the upper reach characterized by a fan-
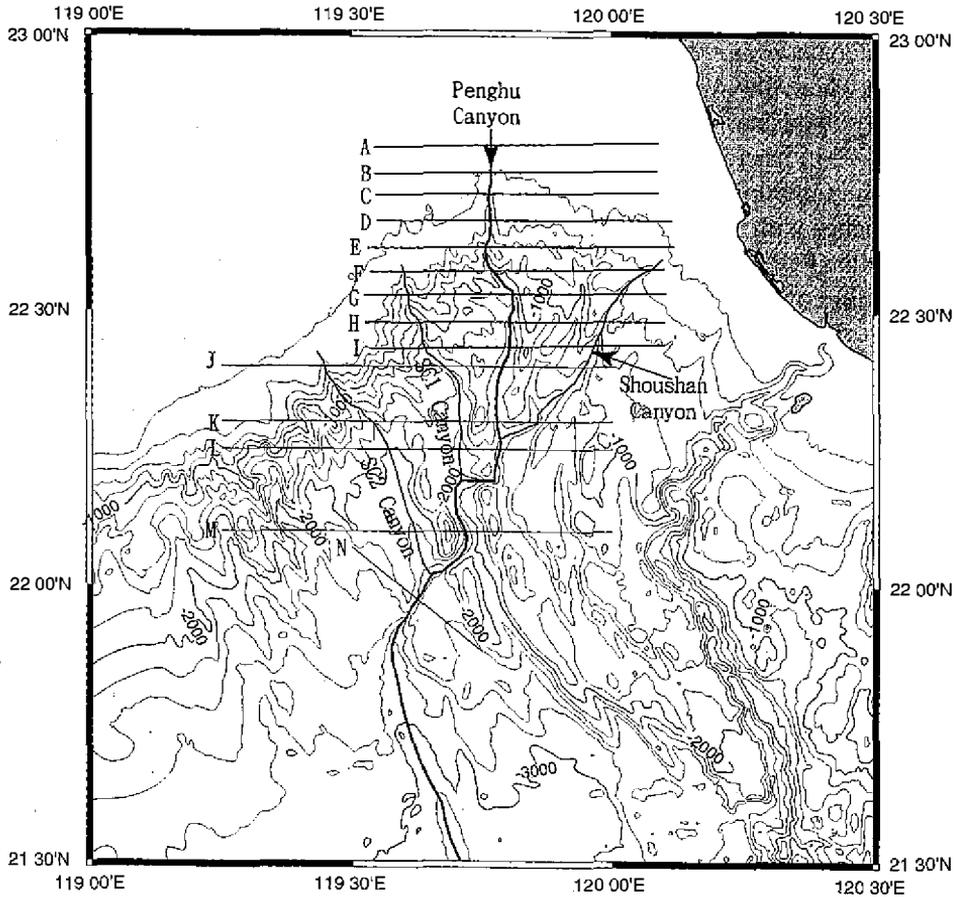
Fig. 3. Nine E-W trending bathymetric transects and seismic profiles, labeled as
A through I, across the upper reach of the Penghu Canyon were collected
on cruise of ORI 584 in 2000. Additional five synthetic bathymeric
transects, labeled as J through N, made from bathymetric data bank com-
piled by the Center for Ocean Research, National Taiwan University in
order to reveal the morphology of lower parts of the upper reach of the
canyon. The refined bathymetric chart shows that the Penghu Canyon is
located along the intersection of bottoms of the Kaoping Slope and South
China Sea Slope following in a near N-S direction. Three major tributary
canyons join into the main course of the Penghu Canyon to form the
upper reach characterized by a fan-shaped network.

shaped network. The upper reach of the Penghu Canyon extends about 150 km southwards to
a water depth about 2200 m at the lower slope where no tributary canyons merge into the main
course of this canyon. The lower reach of the Penghu Canyon stretches curve-linearly for a
distance of about 50 km to merge into the Manila Trench. We consider that the Penghu Can-
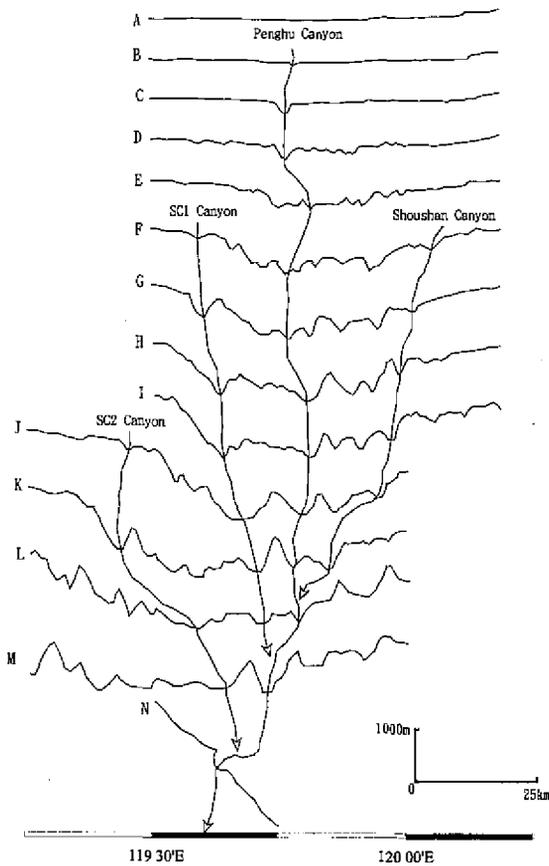
Fig. 4. Cross-sectional morphology of the Penghu Canyon revealed by fourteen bathymetric transects. Locations of these fourteen bathymetric profiles are shown in Fig. 3. The Penghu Canyon is a sea valley with V-shaped cross sections, high and steep walls (7 to 9 degrees), joined by three major tributary canyons.

yon is a single head canyon joined by tributary canyons instead of a multi-head canyon (Yu and Lee 1993; Yu and Huang 1998).

The head of the Penghu Canyon begins as a V-shaped small notch at the intersection of 200-meter bathymetric contours in the region southwest of Taiwan and southeast of China Mainland (Figs. 3 and 4). The canyon head continues to extend southwards along the bases of the Kaoping Slope and the South China Sea Slope, the deepest parts of sea floor of these two facing submarine slopes. This canyon course extends down slope to a water depth of about 1800 m where the Shoushan Canyon on the Kaoping Slope merges into the Penghu Canyon from the east. An unnamed tributary canyon to the north merges into the Shoushan Canyon. The joint place is around 1600 m in water depth. Extending southward from the intersection of the Penghu and Shoushan Canyons to a water depth of about 2100 m, the main course of the Penghu Canyon is joined by the SC1 tributary canyon from the west on the South China Sea Slope. The Penghu Canyon continues its course southward to a water depth of about 2200 m and is merged by the SC2 tributary canyon on the South China Sea Slope, ending the upper reach of the Penghu Canyon. The upper reach of the Penghu Canyon displays a characteristic fan-shaped drainage pattern, showing a cross-sectional span opened up by tributary canyons about 80 km wide.

2.2 Cross-sectional Morphology

Cross-sectional morphology of the upper reach of the Penghu Canyon is presented in Fig. 4. Profile A, located on the Taiwan Strait Shelf at water depths shallower than 200 m, shows relatively flat sea floor without noticeable depressions. Farther south lies the Profile B. A relatively small V-shaped trough appears near the middle of Profile B where lie the intersection of 200 m bathymetric contours in the region southwest of Taiwan and southeast of China Mainland (Fig. 4). This trough has a width of about 1.4 km and the relief between bottom and edges of about 54 meters and steep walls of slope ranging from 3 to 8 degrees. Farther south lies Profile C that crosses over the upper slopes of the Kaoping Slope and the South China Sea Slope. A V-shaped trough, as shown on Profile C, appears at the intersection of these two facing slopes. This trough is about 2.5 km wide and 423 m deep, with a relief of about 200 meters and steep walls of slope angles about 9 degrees. These two V-shaped troughs are aligned along bottoms of the slopes shown on Profiles B and C, respectively, and can be traced southward to the main course of the Penghu Canyon. Therefore, they are considered to be parts of the head of Penghu Canyon. The upper slope immediately below the shelf edge is the common place for inception of canyon incision by sediment failure (Twichell and Roberts 1982; Farre et al. 1983; Pratson and Coakley 1996). Then, the head of Penghu Canyon is suggested to be located at the intersection of the uppermost parts of the Kaoping Slope and the South China Sea Slope, as a small trough with a bottom depth around 246m, as shown on Profile B.

Farther down-canyon, Profiles D, E and F show that axes of V-shaped depressions can be traced in a north-south direction along the intersection of bottoms the Kaoping Slope and the South China Sea Slope. This segment of the Penghu Canyon increases its width to about 4.3 km and maintains steep walls (7 to 9 degrees). The relief between canyon bottom and edges is about 190 m. A few smaller troughs east of the main course of the Penghu Canyon appear on the Kaoping Slope. They are tributary gullies and canyons. Farther south, Profiles G, H and I show that the canyon course increases its width to about 5.7 km and maintains similar slopes of canyon walls (6 to 10 degrees). The canyon bottom is about 1460 m deep. The relief increases to about 515 meters. East of the main course of the Penghu Canyon lie three distinct troughs that include two unnamed tributary canyons and the Shoushan Canyon from west to east, respectively. West of the main canyon course, the SC 1 tributary canyon on the South China Sea Slope is typically V-shaped. It is noted that this segment of the Penghu Canyon is separated by a topographic high from tributary canyons on the eastern side. This part of the Penghu Canyon west of the topographic high shows an asymmetrical V-shaped form with the east walls steeper than the west walls.

Profiles J and K, farther down-canyon, show that the Penghu Canyon is about 1650 m deep and increases its width to about 8 km, and has an asymmetrical V-shaped form. East of the Penghu Canyon distinct troughs can be clearly identified as tributary canyons and the Shoushan Canyon, respectively. West of the Penghu Canyon lies the SC1 tributary canyon. A relatively prominent topographic high separates these two canyons. SC2 tributary canyon on the South China Sea Slope between water depths from 400 to 1400 m can be recognized on the west parts of the bathymetric profiles. Farther south, Profile L shows that the SC2 and SC1

tributary canyons occupy the deepest parts of the sea floor, with a topographic high in between. East of the SC1 tributary canyon, the Penghu Canyon appears as a relatively small V-shaped trough about 3 km wide, 1830 m deep, with a relief of about 250 m between canyon bottom and canyon wall.

Profile M, farther down-canyon, shows that the main course of the Penghu Canyon occurs as a prominent V-shaped trough, with typical canyon morphology in cross section. It is about 9.2 km wide and about 2227 m deep, and is separated from the SC2 tributary canyon to the west by a noticeable topographic high. Here the relief between canyon bottom and edges of about 910 m is the greatest along the canyon course. Below the confluence of main course of the Penghu Canyon and the SC2 tributary canyon, the main course of Penghu Canyon narrows to a width of 3.3 km and a relief of about 315 m as shown on Profile N.

Profiles B through N show that the upper reach of the Penghu Canyon and tributary canyons in cross section are represented by V-shaped troughs with steep walls. The slope angles of the canyon walls ranging from 3 to 12 degrees and 7 to 9 degrees are common ones. The floor of the main course increases its depth from 246 m at the head to a depth of 2500 m where is the joint point of the main course of the SC 2 tributary canyon. It stretches for a length of about 150 km and has an averaged width of 4.5 km.

In summary, plan view and cross-sectional form of the upper reach of the Penghu Canyon show a submarine valley with a V-shaped cross section, high and steep walls, winding course and numerous tributaries. It is a typical submarine canyon (Shepard and Dill 1966).

3. CANYON FORMING PROCESSES

Nine seismic reflection profiles trending E-W across the upper reach of the Penghu Canyon are examined to infer the tectonic influences on the canyon formation and to determine the sedimentary processes forming the canyon (Figs. 5 through 9). Locations of these seismic profiles are shown in Fig. 3.

3.1 Tectonic Influences

Seismic lines A through I across both the Southwest Taiwan and South China Sea margins show juxtaposition of sedimentary sequences of quite different seismic characteristics, indicating differences in structures and stratigraphy of the South China passive margin to the west and the Southwest Taiwan active margin to the east, respectively. Seismic Line A (Fig. 5) shows that seismic characteristics can be distinguishable between these two margins. Sedimentary sequences between sea floor and 400 ms time interval of the Southwest Taiwan margin are displayed by discontinuous, low-amplitude and sub-parallel reflectors. Below 300 ms, strata of the Southwest Taiwan margin are represented by discontinuous and hummocky chaotic reflectors. In contrast, the South China margin shows characteristic continuous, parallel and divergent reflectors tilting eastwards. In response to the southward propagation of arc-continent collision along the strike of the Taiwan orogen contraction occurs between these two margins, some strata of the Southwest Taiwan margin are mildly deformed into anticlines, while those of the South China margin are deformed into thrust faults (Fig. 5). Alternatively,

PROFILE A

WEST   EAST
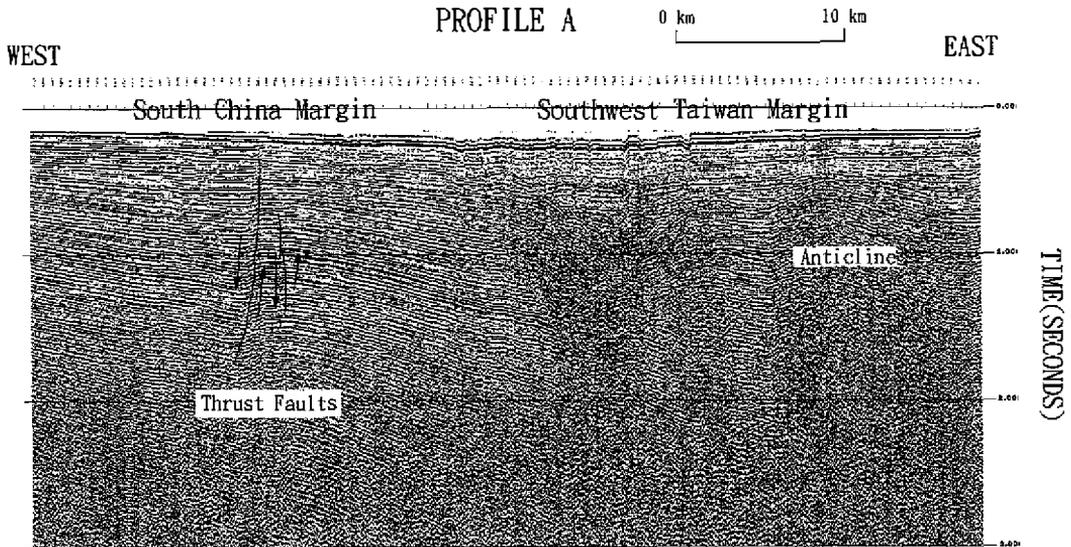
Fig. 5. Seismic profile A indicates that the South China margin is characterized
by continuous, parallel and divergent reflection patterns, whereas the
Southwest Taiwan margin has chaotic and hummocky characteristics.
Thrust faults are possibly present in the South China margin and anti-
clines appear in the Southwest Taiwan margin, indicating contraction
due to arc-continent collision between the Luzon Arc and the Chinese
continental margin. The dashed line is the tentative boundary separating
these two margins. Location of seismic profile A is referred to Fig. 3.

the displacements across the faults could be due to normal faulting or strike-slip movements.
Under tension, the sedimentary sequences characterized by reflections of divergent and dip-
ping eastwards tend to develop down-to-basin normal faults with fault planes dipping east.
Hence, the west-dipping fault planes shown on Line A are not likely produced by normal
faults. The strike-slip movement across the faults cannot be determined positively without
other cross lines. Therefore, the possible thrust faults shown on Line A are debatable. Oro-
genic sediments from Southwest Taiwan are advancing westwards and overriding the outer
shelf and slope of the South China passive margin as a result of loading of the Taiwan orogen
over the outer South China passive margin (Chou 1999). The contact between the frontal strata
of the Southwest Taiwan margin and the adjacent buried South China margin is probably a
basal decollement, tilting upward and westwards (Fig. 5). Both seismic Lines B and C (Fig. 6)
have seismic characteristics similar to that of Line A, except for the presence of V-shaped
troughs on the sea floor (Fig. 6). The southernmost part of the Taiwan Strait Shelf, crossed
over by Lines A through C, is a portion of the mature foreland basin of western Taiwan (Yu
and Chou 2001). Pleistocene-Quaternary sediments derived from the Taiwan orogen are trans-
ported westwards and deposited far to the middle of the Taiwan Strait. Shallow marine sedi-
ments fill the Taiwan Strait Shelf close to the sea level, burying older Pliocene-Pleistocene
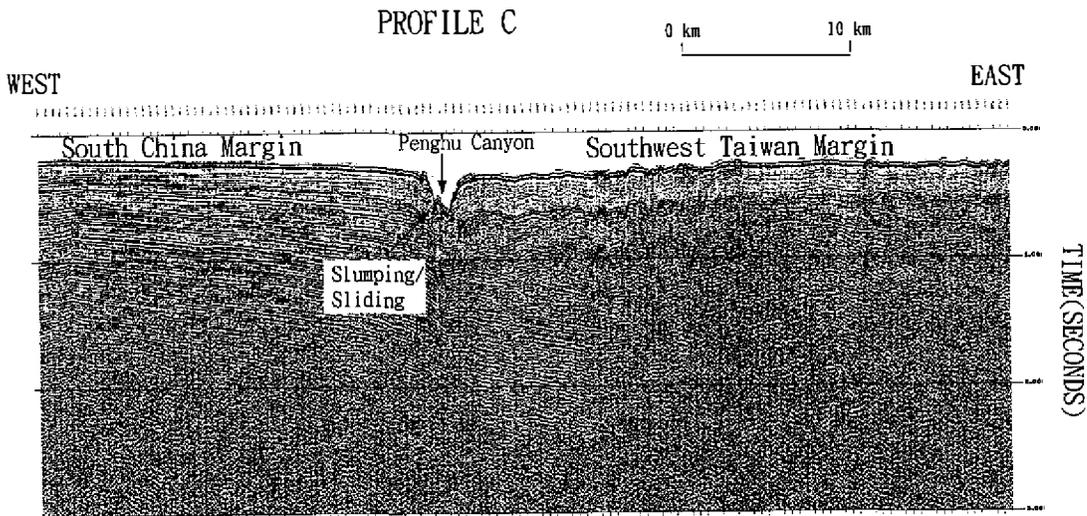
PROFILE C

Fig. 6. Seismic profile C shows a V-shaped trough, the Penghu Canyon, located at the boundary between the South China and Southwest Taiwan margins. Significant down-cuttings into the seafloor occur at the head part of the Penghu Canyon. The west wall of the canyon shows a stepped and curved surface probably resulted from slumping or sliding which can widen the canyon through its development. Location of seismic profile C is referred to Fig. 3.

deep-water sediments of the basin in the early under-filled stage (Yu and Chou 2001).Seismic Lines D through G transverse deep submarine sloping regions and show two distinct patterns of seismic facies. To the west the South China Sea margin is characterized by continuous, parallel and divergent reflection, titling eastward. On the Taiwan side, the seismic facies is characterized by chaotic and distorted reflections that are representative of orogenic sediments derived from Taiwan transported, mainly by downslope mass movement and accumulated rapidly, as shown on Line E (Fig. 7). We infer that orogenic sediments derived from Taiwan began to fill the deepest parts of the trough between the Kaoping Slope and the South China Sea Slope. Continuous filling of sediment accompanied by westward movement of the Taiwan orogen lead sediments at the toe of the Kaoping Slope progressively onlap the passive margin. The younger deep-water sedimentary facies of the active margin overlying the older passive margin strata indicates that the western Taiwan foreland basin is in the under-filled stage. It is noted that sea floors of the Kaoping Slope and the lower part of South China Sea Slope are dissected by numerous submarine gullies and canyons, producing very irregular sea floor topography.

Farther down-canyon, seismic Lines H (Fig. 8) and I (Fig. 9) show that the lowest parts of the Kaoping Slope and South China Sea Slope are represented by chaotic and distorted seismic reflections, indicating that the sediments were mainly transported by down-slope mass movement and accumulated rapidly. Clearly, orogenic sediments fill deep marine basin proxi-

PROFILE E   0 km   10 km

WEST   EAST
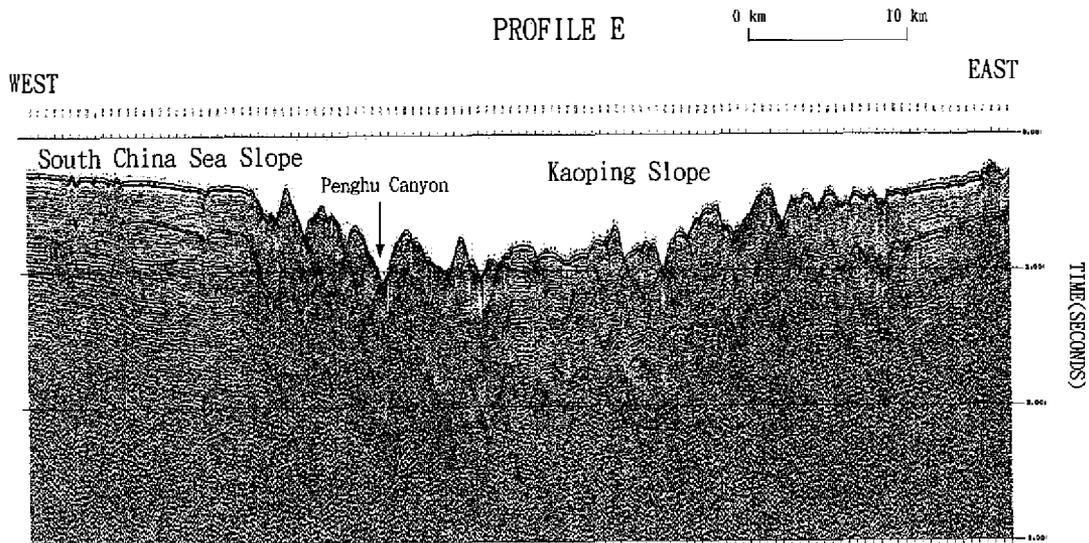
Fig. 7. Seismic profile E shows many V-shaped troughs appearing on both sub-
marine slopes, indicating continued down-cutting of the Penghu Canyon
and tributary canyons. Location of seismic profile E is referred to Fig. 3.

mal to the Taiwan orogen, indicating an early stage of development of the foreland basin in
southern Taiwan (Sinclair 1997; Chou 1999). It is noted that the frontal sediments are de-
formed into anticlines and diapiric structures (Fig. 9).

Seismic characteristics observed from these seismic lines indicate that the upper reach of
the Penghu Canyon is in a transition from an immature basin underlying by the Kaoping Slope
and the South China Sea Slope to a mature foreland basin (Taiwan Strait Shelf). Sediments
mainly derived from Taiwan fill the deep marine trough between the Southwest Taiwan and
the South China Sea Margins from northeast to southwest. Sediments fill up the northern part
of the trough firstly. Subsequent filling of the trough by orogenic sediments causes a regional
gradient of the basin tilting southward. Deposition of the orogenic sediments progressively
on-lapping westward and burying the South China passive margin results in the bottoms of the
Kaoping Slope and the South China Sea Slope consisting mainly of orogenic sediments de-
rived from Taiwan. The main course of the Penghu Canyon has developed along the axis of
deep marine basin in a nearly north-south direction, following the regional trend tilting south-
wards and paralleling the development of the foreland basin west of Taiwan.

3.2 Sedimentary Processes

Seismic Line A (Fig. 5), across the Taiwan Strait Shelf and immediately north of the
canyon head, shows no prominent V-shaped troughs and indicates no significant downward
incisions. The presence of V-shaped troughs, as shown on Lines B and C (Fig. 6), suggests that
significant down-cutting takes place at the upper slopes immediately below shelf edge and
results in the initiation of the Penghu Canyon. Over-steeping of the upper slope near shelf edge

PROFILE H

WEST

EAST
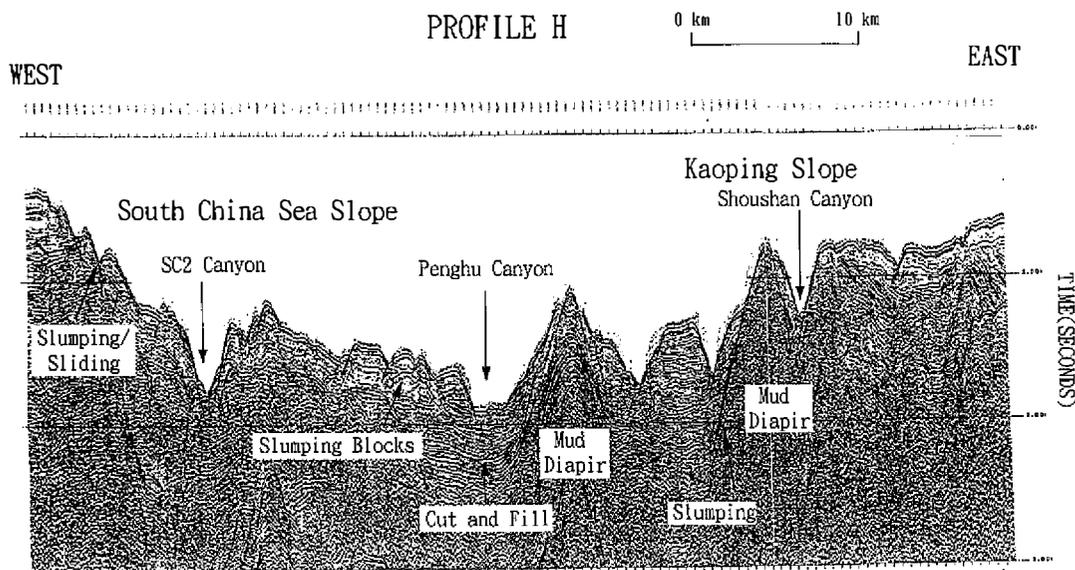
Fig. 8. Seismic profile H indicates that the diapiric intrusion, slumping and down-ward erosion are the dominant canyon forming processes in the lower parts of the upper reach of the Penghu Canyon. A cut and fill feature can be recognized at the bottom of the Penghu Canyon with a flat floor. Location of seismic profile H is referred to Fig. 3.

results in sediment failure which is a common process in the initiation and development of submarine canyons (Twichell and Roberts 1982; Farre et al. 1983; May et al. 1983). The upper slope segment between Lines B and C has a slope gradient of 2.26 degrees and is steeper than that at the down-canyon segment. The head of Penghu Canyon, occurring at the steeper upper slope immediately below the shelf edge of the Taiwan Strait Shelf, is reasonably expected. The west wall of the Penghu Canyon, shown on Line C, shows stepped and curved surfaces that can have resulted from slumping or sliding. Slumping and sliding are volumetrically most important as erosive agents for canyon formation (May et al. 1983). The canyon head shown on Line C also shows slumping on canyon walls and sediment spillover that can widen the canyon. This part of canyon is deepened by excavation of canyon floor by down-canyon sediment flows.

Farther down-canyon the main course of the Penghu Canyon becomes wider (4.3 km) and deeper (1420 m). We infer from previous work of Shepard (1981) that continued failures of over-steeping walls due to slumping or sliding combined with axial down-cutting would widen and deepen the course of the Penghu Canyon. It is noted that the seismic facies west and east of the Penghu Canyon is characterized by chaotic reflection pattern as shown on profile E (Fig. 7). As previously mentioned, orogenic sediments from Taiwan have characteristic chaotic seismic facies. This means that sedimentary materials removed by erosion along the canyon axis are mainly derived from Taiwan. Extensive downward incisions appear on the sea floors

PROFILE I

WEST   EAST
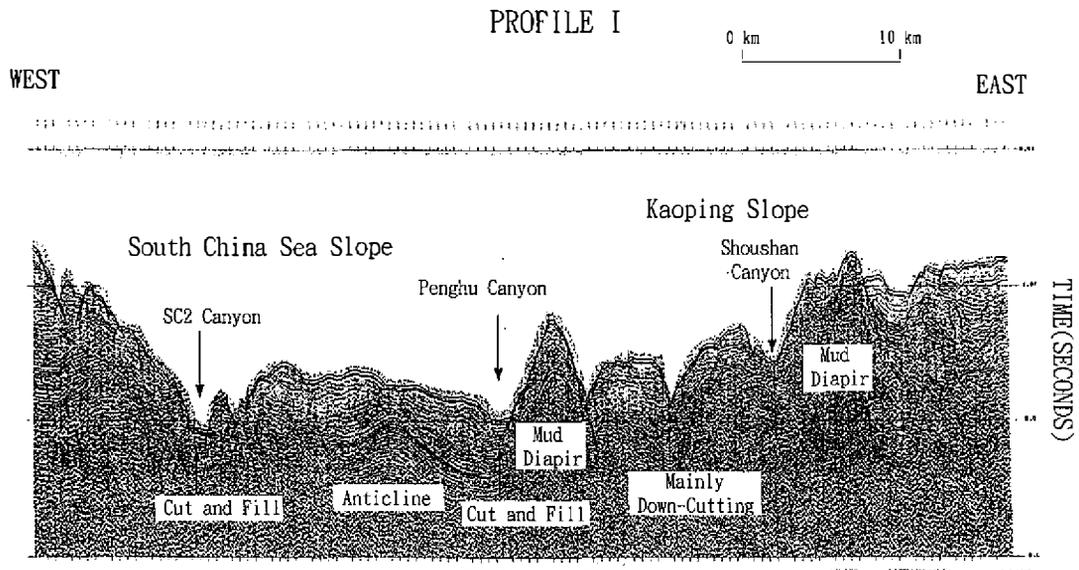
Fig. 9. Seismic profile I indicates that the mud diapiric intrusions penetrate up-
ward and rise above the sea floor to form a relatively great bathymetric
relief of 910 m that is the height difference between the canyon bottom
and east wall edge of the Penghu Canyon. Cut and fill features are found
at the bottom of the Penghu Canyon and SC2 tributary canyon, indicat-
ing alternations of erosion and deposition. Location of seismic profile I
is referred to Fig. 3.

of both Kaoping and South China Sea slopes, producing many V-shaped troughs, such as the
Shoushan Canyon to the east and SC1 tributary canyon to the west, respectively (Fig. 7).

Seismic evidence shows that diapiric intrusion and downward erosion are the dominant
canyon forming processes for the deeper canyon courses, as shown on Lines H (Fig. 8) and I
(Fig. 9), respectively. The mud diapiric intrusions penetrate upward and through the overlying
slope sediments and rise above the sea floor to form a relatively great bathymetric relief and to
form two canyon segments flanking the bathymetric ridge. To the west of the ridge, the Penghu
Canyon displays an asymmetrical V-shaped trough, representing the intersection of western
flank of the ridge and the east-dipping slope sediment. Slumping and sliding are prevalent on
the slopes. It is noted that a relatively large mass could have resulted from slumping and being
accumulated at the base of the South China Sea Slope (Fig. 8). A cut and fill feature can be
recognized at the bottom of the Penghu Canyon with a flat floor (Figs. 8 and 9). The flat layer
overlying the canyon axis suggests that sediments transported from eroded canyon walls nearby
or from upcanyon are deposited and partially had filled up the bottom of the canyon, resulting
in a flat surface. Cut and fill features are commonly found in modern and ancient canyons. For
example, Yu and Chiang (1996) found cut and fill features in the nearby modern Kaohsiung
Canyon. Alternations of cut and fill events were found in the Wilmington Canyon in Miocene

Penghu Canyon Axis Gradient

Penghu Canyon Axis Relief
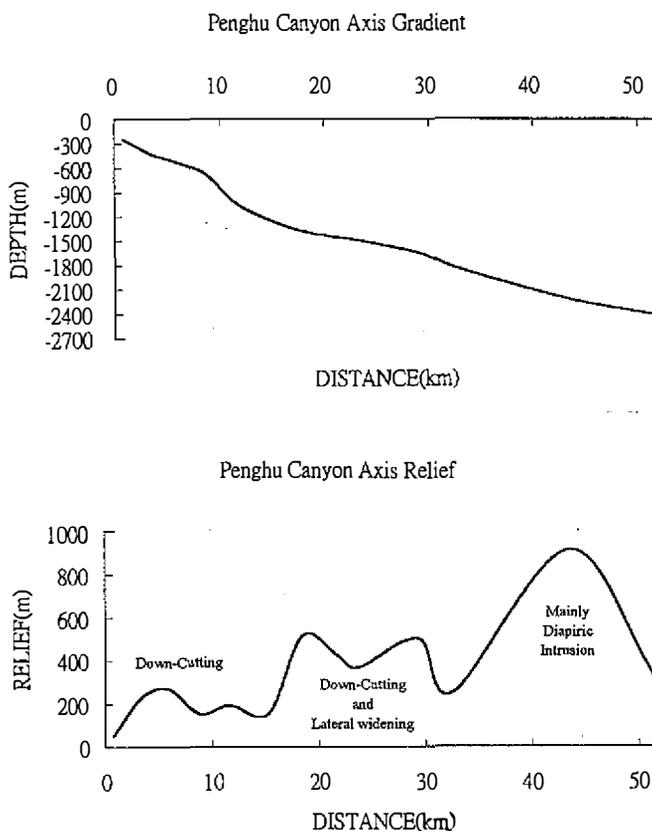
Fig. 10. Axial profile of the Penghu Canyon shows two noticeable knick points in the longitudinal profile, implying down-cutting of canyon floor not in equilibrium with erosion processes (top of the figure). Canyon relief plotted along the canyon course suggests that the up-canyon segment with incision depth around 200 m is mainly due to downward excavation. The middle parts of the upper reach of the canyon with incision depth around 500 m are mainly due to lateral widening and down-cutting whereas the down-canyon segments with a maximum relief of 910 m are mainly due to diapiric intrusion (top of the figure).

(McGregor 1981). The insignificant amount of cut and fill features in the Penghu Canyon suggests that effect of erosion is greater than that of deposition at the present time. To the east of the bathymetric ridge is a tributary canyon. Further east lies the Shoushan Canyon which was formed by the same processes as that of the Penghu Canyon.

The bottom of the canyon shows a continuous gentle inclination and the gradients of the upcanyon segment (average 1.84 degrees) greater than that (average 1 degree) of the downcanyon course. This means that downslope sediment flows are the major eroding process cutting canyon floor along the regional gradient. Lithology or structural deformation of the

slope sediments seem to have little effect on the axis gradient of the Penghu Canyon. Changes of relief between canyon bottom and canyon edges along the canyon course are expected to be in accordance with the canyon axial slope. As a matter of fact, relief along the canyon course shows considerable variations, although it increases progressively from the head to lower parts of the canyon (Fig. 10). The variations of canyon relief and the longitudinal profile suggest that canyon forming processes other than downslope sediment flows can be significant.

The canyon head, with an incision depth of 54 m, increases to a maximum relief of 909 m at the lower parts of the course, and then abruptly decreases to 315 m farther down (Fig.10). Seismic evidence together with canyon relief along the course indicates that down-cutting dominates at the canyon head, lateral widening by slumping of canyon walls is prevalent at the upcanyon segment, and diapiric intrusion becomes an important agent for shaping the canyon forms at the lower slope section of the canyon. The maximum relief of 909 m indicates the greatest extrusion of the mud diapir from the adjacent sea floor (Fig. 10).

4. SUMMARY AND CONCLUSIONS

Penghu Canyon can be considered a single head canyon with tributary canyons from the Kaoping Slope to the east and the South China Sea Slope from the west joining into the main course to form the upper reach of the canyon. Penghu Canyon and its tributary canyons show high relief, steep walls and a V-shaped cross section, with typical canyon morphology.

Slumping and sliding and downward excavation into the sea floors by downslope sediment flows are the major forming processes in the canyon head and upper canyon part. Diapiric intrusion plays an important role in shaping the canyon form in the deeper and lower parts of the Penghu Canyon. Bathymetric ridges arise from sea floor due to diapiric intrusion and the resulting steep flanks of the ridges become the canyon walls.

Orogenic sediments derived from Taiwan orogen progressively onlap westward and bury the Chinese passive margin and deposit in the bottom of the foreland basin. The main course of the Penghu Canyon has resulted mainly from down-slope sediment flows excavating the orogenic sediments along the axis of deep marine basin in a nearly north-south direction.

In summary, sediment failure of the upper slope initiates the canyon head and determines the canyon course along the bottom of two opposing slopes and focus downslope sediment flows excavating canyon floor during the development of the Penghu Canyon. Downslope erosion continued to deepen and widen the gullies on the upper slopes into tributary canyons that in turn flowed downslope and coalesced to form the upper reach of the Penghu Canyon characterized by a fan-shaped network.

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