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Development of the shale diapir-controlled Fangliao Canyon on the continental slope off southwestern Taiwan

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Abstract—Fangliao Canyon is one of several major canyons on the continental slope off southwestern Taiwan. This paper evaluates the canyon morphology and its formative processes and origin using multichannel seismic reflection profiles and bathymetric data. Fangliao Canyon is a small canyon around 10 km wide and 60 km long, an order of magnitude smaller than the large canyons of the world. This canyon can be divided into two morphologically contrasting parts: the upper canyon, a relatively straight part beginning at the shelf edge and ending approximately at the 600 m isobath, and the lower canyon, consisting of two segments separated by a rising linear ridge (shale diapir) and extending downslope to about the 1000 m isobath where its mouths lack submarine fans. Seismic profiles and bathymetric data provide evidence of submarine erosion forming the upper canyon and the uplift of a shale diapir controlling the formation of the lower canyon. In the upper canyon, truncation of parallel flat-lying strata and sliding/slumping features on the canyon walls are indicative of downcutting and lateral widening of the canyon. In the lower canyon, the shale diapir uplifted the slope strata and protruded through the overlying slope sediments, producing a ridge rising from the sea floor. Here the steep flanks of the shale diapir become the walls of the steep-sided canyons. The interaction of these sedimentary and tectonic processes on the continental slope off southwestern Taiwan forms the present Fangliao Canyon.

Introduction

The continental slope off southwestern Taiwan has several canyons. From northwest to southeast, these canyons are the Penghu, Kaohsiung, Kaoping and Fangliao (Fig. 1). They have been known for more than 60 years. None of them are well understood because of insufficient data acquired by modern marine geophysical and geological techniques. For example, the sedimentary processes in these canyons are poorly known because no sediment cores from the canyons are available for sedimentologic analyses. A general geological review of these canyons was given by Yu and Liu (1994).

Fangliao Canyon (named after the coastal town; Yu and Wen, 1991) cuts the shelf edge about 20 km south of the coastline (Fig. 1). Until now, only one published paper has specifically dealt with the Fangliao Canyon (Yu and Wen, 1991). Based on limited bathymetric data and 3.5 kHz echograms across Fangliao Canyon, Yu and Wen (1991) failed to recognize branching of the lower canyon into two segments formed by a north–south trending diapiric intrusion. As a result, their conclusions on the morphology and origin of the Fangliao Canyon were only partly correct.

This paper describes the morphology of the Fangliao Canyon in detail, relates the morphology to local uplift of the shale diapir, and then discusses the origin of the canyon using newly acquired bathymetric data and multichannel seismic reflection profiles.

Geological Setting

Physiography

Taiwan, a mountainous island, is formed by the Late Cenozoic collision of the Luzon arc with the Chinese margin (Ho, 1986; Teng, 1990). Off its southwestern coast, Taiwan has a narrow (20 km) shelf which is the natural seaward prolongation of the Coastal Plain Province and the southern Central Range of the island. The shelf extends from the southern tip of the island northwestward, where it merges into the broad Taiwan Strait shelf. The shelf edge ranges from 60 to 170 m in depth. The shelf has a general northwest–southeast trend, which changes to a north–south direction parallel to the coast at the southern tip of the island (Fig. 1). The continental slope extends seaward from the shelf break to the 3000 m isobath, where it grades into the abyssal plain of the South China Sea (Fig. 1). This slope varies in gradient from 3 to 16° (Chen, 1983). The continental slope can be divided into upper and lower slopes at approximately the 1000 m isobath. Submarine canyons including the Fangliao Canyon and channels occur mainly on the upper slope (Yu and Wen, 1992). The slope also changes from the general northwest trend to a north–south trend, curving gradually along the southwestern coast of the island.

Stratigraphy

The geological framework of the region in southwestern Taiwan, including offshore areas, was established during Pliocene–Quaternary (Covey, 1984). In Pliocene the offshore area of southwestern Taiwan was a deep marine environment which became shallow marine and nearshore depositional environments as the arc–continent collision in Taiwan propagated southward in Pleistocene and Quaternary. The arc–continent collision in the Taiwan orogen resulted in the formation of a foreland basin filled with orogenic sediments up to

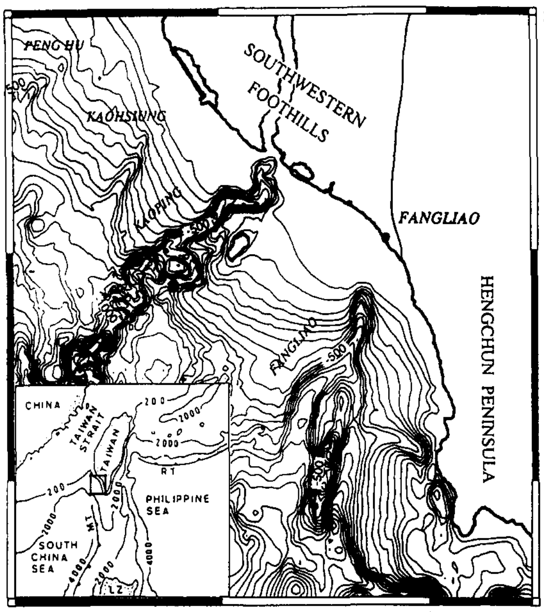


Fig. 1. Bathymetric chart showing submarine canyons on the continental slope off southwestern Taiwan. From northwest to southeast, these canyons are Penghu, Kaohsiung, Kaoping and Fangliao. The inset figure showing the geological setting of Taiwan Island. Note: MT = Manila Trench, RT = Ryukyu Trench, LZ = Luzon. The box defines the study area. Water depth in meters.

6000 m thick in the southwestern part of Taiwan (Covey, 1984; Yu, 1993). Up to 1994, there has yet to be a published paper specifically describing the stratigraphy of the continental margin off southwestern Taiwan. In spite of the limited stratigraphic information available, the stratigraphy in the study area can be inferred from the stratigraphic records of the neighbouring southwestern Foothills and the Hengchun Peninsula onland Taiwan.

According to the recent synthesis of the Late Cenozoic stratigraphy of Taiwan (Teng, 1987), the southwestern Foothills comprise mainly thick sequences of clastic sediments. The Plio–Pleistocene sequences are dominated by shales with a few thin-bedded fine-grained sandstones. The lower parts of Pliocene muds were deposited in bathyal depth around 1000 m (Teng, 1987, p. 212). The overlying Pleistocene–Holocene strata consist mainly of sandstones with minor conglomerates and shales. The Pliocene–Quaternary sequences in the southwestern Foothills represent orogenic sediments filling up the foreland basin. Similarly, the Late Plio–Pleistocene sequences of the nearby Hengchun Peninsula also represent foreland basin sedimentation. The stratigraphy in the study area inferred from onland stratigraphic data should generally have similar characteristics with some lateral facies changes. Therefore, we believe that the stratigraphy in the offshore area of southwestern Taiwan is dominated by thick Late Plio–Pleistocene shales with minor sandstones.

Structure

The offshore area of southwestern Taiwan is characterized by imbricated folds and thrusts and diapiric structures (Chang, 1993; Huang, 1993; Lundberg *et al.*, 1992; Reed *et al.*, 1992; Sun and Liu, 1993). These structural features generally covered by Quaternary sediments can be extended northward to onland Taiwan where the mountain belt shows a series of stacked folds and thrust sheets facing the west (Ho, 1982). West-vergent imbricated folds and thrusts are commonly present in the lower slope area (Reed *et al.*, 1992). In contrast, the upper slope region is dominated by shale diapirs and thrusts (Chang, 1993; Huang, 1993; Sun and Liu, 1993).

These diapiric intrusions develop NNE–SSW trending ridges, some of which pierced through overlying sediments and are exposed on the sea floor. The ridge (shale diapir) associated with the Fangliao Canyon is an example. The occurrence and development of these shale diapirs are closely related to the formation of submarine canyons and sedimentation in the offshore area of southwestern Taiwan and, hence, are briefly discussed below.

The formation of shale or mud diapirs mainly depends on the presence of thick overpressured shales or mudstones in the sedimentary sequences. In general, overburden loading due to rapid sedimentation, tectonic loading, faulting or seismic activities may induce the shale flowage upward to form diapiric structures. The fluids in sediments also play an important role in producing mud diapirs (Barber *et al.*, 1986; Brown and Westbrook, 1988).

Sun and Liu (1993) suggested a two-stage diapirism in the offshore region of southwestern Taiwan. The mud diapirs were initially formed as anticlinal structures of mudstones by tectonic force due to the arc–continent collision in the Taiwan orogen during Pliocene time. The compressive force is generally in an east–west direction. These anticlines were later developed into diapiric structures by unbalanced loading under thick channel deposits during Pleistocene time.

Diapiric structures occurring in the shelf area can be connected to those in the coastal plain of southwestern Taiwan (Pan, 1968; Hsieh, 1972). The formation of the diapirs in the coastal and shallow water (< 40 m deep) is related to movements of strike-slip or normal faults in southwestern Taiwan (Chang, 1993). In contrast, the diapirs located in the deeper water slope area between 400 and 1000 m isobaths may be formed by the activities of hydro-compounds in the mudstone sequences (Chang, 1993). Both types of diapirs were developed in Pleistocene.

The understanding of the formation of diapirs in the offshore region of southwestern Taiwan is preliminary and controversial. We think that overpressured thick mudstones were deposited in the offshore region of southwestern Taiwan during Pliocene as a result of rapid foreland basin sedimentation, following the arc–continent collision of the Taiwan orogen (Covey, 1984; Teng, 1987). The younger Plio–Pleistocene sandy sediments derived from the Taiwan mountain belt overlie the overpressured mudstones and function as the overburden. At the same time, west-vergent thrust faulting, resulting from the collision between the Luzon arc and the Chinese margin, deformed the thick Plio–Pleistocene sequences. Therefore, we speculate that the sedimentary loading and tectonic activities both contributed to the development of diapiric structures in the offshore area of southwestern Taiwan during Pleistocene. In-depth study of the mechanism for the formation of diapirs in southwest Taiwan is beyond the scope of this paper.

Morphology

Fangliao Canyon starts on the upper slope at 120° 35′E, extends downslope and ends at the base of the upper slope at approximately the 1000 m isobath. The head of the canyon begins at the shelf edge and has no apparent connection to the rivers onland. This canyon is unlike the adjacent Kaoping Canyon to the west, which is the seaward continuation of the Kaoping Hsi river (Yu *et al.*, 1991). The bathymetric chart (Fig. 1) and cross-sectional morphology (Fig. 2) indicate that the Fangliao Canyon can be divided into two morphologically contrasting parts: an upper canyon, one that is relatively straight with a well-defined course beginning at shelf edge and ending at approximately the 600 isobath, and a lower canyon, consisting of two segments separated by a rising linear ridge, a shale diapir, and extending seaward at about the 1000 m isobath, where its mouths lack submarine fans.

The upper canyon is 2–8 km wide and has a relief up to 300 m. The length of the upper canyon, between water depths 100 and 600 m, is approximately 40 km. The axial gradient displays a continuous seaward inclination (Fig. 3). The canyon walls are relatively steep with apparent slopes ranging from 3 to 6°. The upper canyon has a V-shaped cross-sectional morphology (Fig. 2) and lacks tributary valleys on either side of the canyon walls. These observations are similar to those reported by Yu and Wen (1991).

The upper canyon extends downslope southward and begins to split into two canyon segments in front of the rising shale diapir ridge (Figs 1 and 2). This narrow ridge (average 3 km wide), running north–south, is approximately 50 km long. The courses of both canyon segments are parallel to the long axis of the ridge. Chang (1993) identified this bathymetric ridge to be a mud diapiric intrusion, but did not comment on the canyon morphology.

A canyon-like trough at the east side of the ridge and a steep V-shaped trough to the west of the ridge can be seen in profile C (Fig. 2). The uplift of the ridge, which now has a relief of 389 m, has strongly influenced the canyon morphology. The separation of these two canyon segments becomes clearer as the intensity of the uplift of the ridge increases. This separation of canyon segments can be seen in profile D (Fig. 2). However, the great relief between the top of the ridge and the sea floor (profile E) draws attention to the effect of diapiric intrusion, which overprints the canyon morphology. The canyon segment west of the ridge begins to lose its canyon identity.

Longitudinal Profile and Canyon Relief

The upper canyon has an average gradient of 0.89° and deepens to a water depth of 600 m, where it splits into two segments. The axial slope along the upper canyon and west segment of the lower canyon shows a continuous seaward inclination with an average of 0.63° (Fig. 3). In contrast, the axial slope along the upper canyon and east segment of the lower canyon displays step-like sectors and shows a break of the slope at water depth of 700 m, where there is a connection between the upper canyon and the east canyon segment.

Plots of reliefs of these two canyon segments against their courses indicate that the incision depths increased gradually to about 300 m relief along the upper canyon and west segment of the lower canyon, but decrease to around 100 m at the canyon mouth (Fig. 4). In contrast, considerable variations of relief can be seen along the

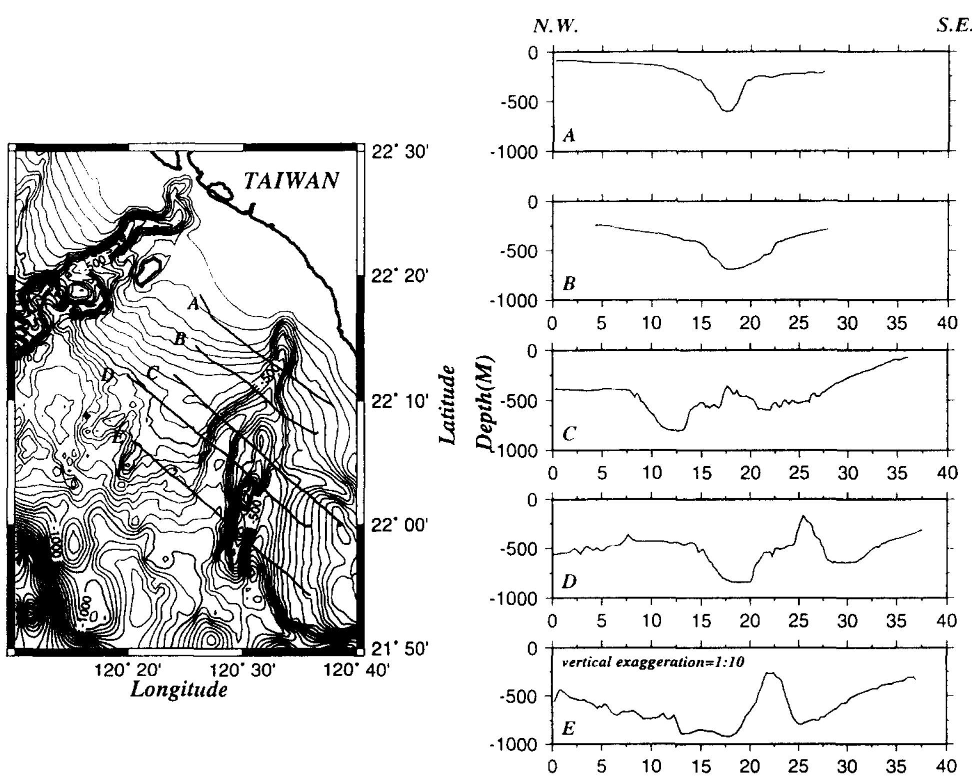


Fig. 2. The cross-sectional morphology of Fangliao Canyon shows a V-shaped trough at upper canyon and two canyon segments separated by a rising ridge at lower part of the canyon.

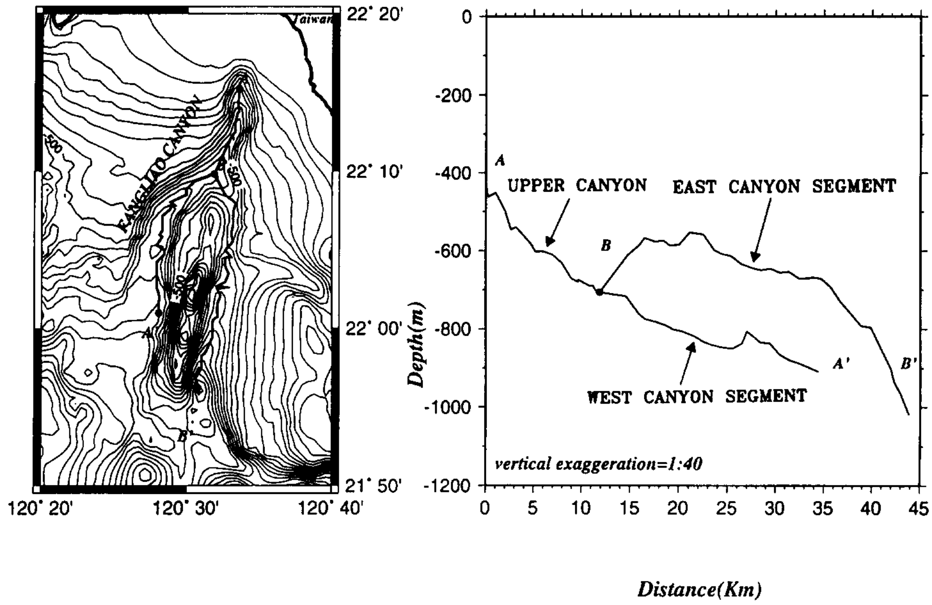


Fig. 3. Axial profiles of Fangliao Canyon. Note that the axial profile A–A′ along upper canyon and the west segment is characterized by a continuous seaward inclination, typical of a canyon profile. In contrast, the presence of a significant break in the axial profile A–B–B′ along upper canyon and the east segment suggests that the intrusion of shale diapir controls the gradient of the canyon floor.

east segment of the lower canyon (Fig. 4). The maximum reliefs of over 500 m reflect the greatest extrusion of the ridge from the adjacent sea floor.

The patterns of longitudinal profiles and variations of the relief along the canyons suggest that downcutting predominated in the upper canyon and west segment of the lower canyon, which together can be considered as one genetic whole. On the other hand, the east segment of the lower canyon was formed mainly by the uplift of the shale diapir and may not be considered as a part of the Fangliao Canyon.

In summary, bathymetric data indicate that Fangliao Canyon is morphologically distinguished from the nearby continental slope by its great wall relief, V-shaped cross-sections, sinuous courses and steep axial profiles. The dimensions of Fangliao Canyon are around 60 km long and 10 km wide, an order of magnitude smaller than the Bering Sea margin canyons (400 km long, 100 km wide), which are some of the largest in the world (Carlson and Karl, 1988).

Canyon Forming Processes

The sedimentary and tectonic processes forming Fangliao Canyon are mainly interpreted from the seismic reflection profiles. We present nine seismic sections in the study area, seven across the canyon and two down slope (Fig. 5).

Profile 1 (Fig. 6), located immediately north of the canyon head, shows parallel flat-lying reflectors in the upper part of the section, representing a thin sequence

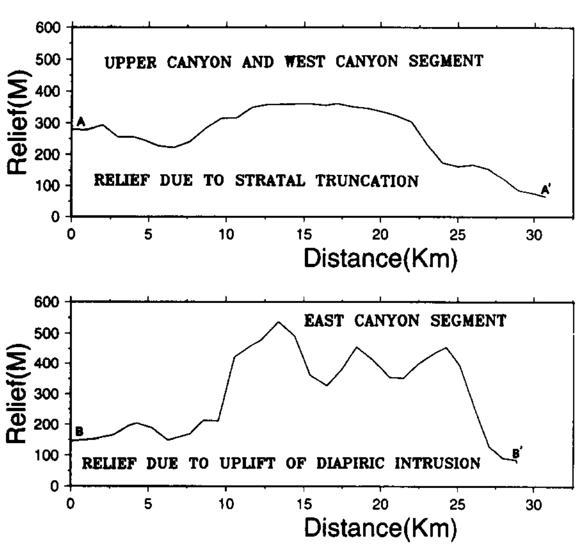


Fig. 4. Relief plotted against distance from canyon head to canyon mouth. Note the incision depths change gradually and remain around 300 m along the west canyon segment, whereas considerable variations of relief appear along the eastern segment.

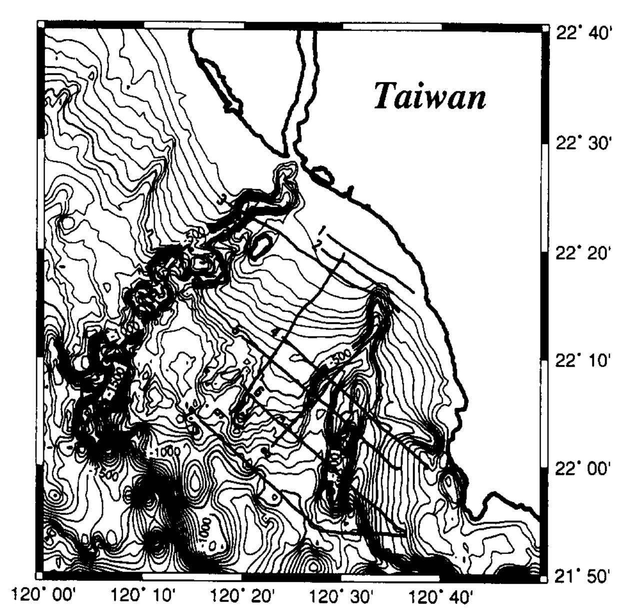
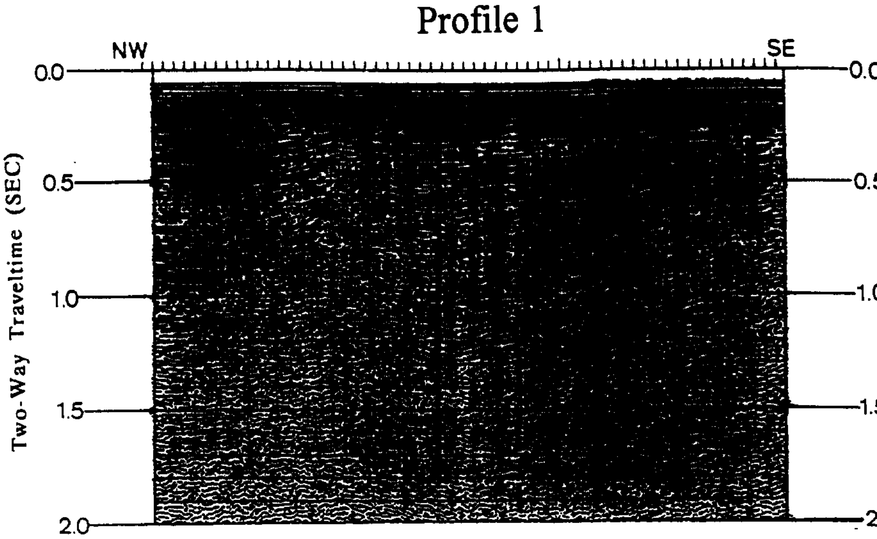


Fig. 5. Location of seismic profiles, seven across the canyon and two downdip the continental slope.



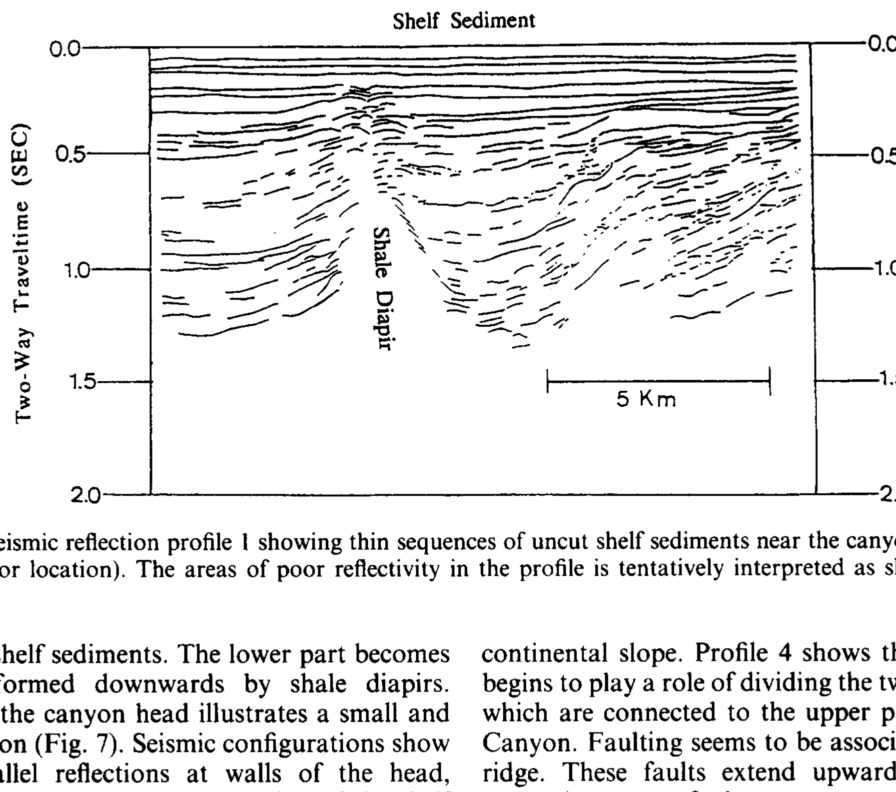


Fig. 6. Seismic reflection profile 1 showing thin sequences of uncut shelf sediments near the canyon head (see Fig. 5 for location). The areas of poor reflectivity in the profile is tentatively interpreted as shale diapir.

of undeformed shelf sediments. The lower part becomes increasingly deformed downwards by shale diapirs. Profile 2 across the canyon head illustrates a small and shallow depression (Fig. 7). Seismic configurations show terminated parallel reflections at walls of the head, suggesting erosional features. Downcutting of the shelf sediments and lateral widening of the head initiated the development of the canyon. Profile 3, farther down canyon, shows that thicker sequences of sediments are truncated, suggesting that canyon erosion continued in greater intensity (Fig. 8). It is noted that two prominent shale diapiric intrusions occur in the intercanyon area and have no influence on the formation of the canyons.

Profile 4 crosses the lower canyon and shows the two canyon axes and a low-relief ridge between them (Fig. 9). The well-defined canyon walls and floor west of the ridge were both clearly formed by erosional processes; i.e. downcutting on both walls and together with slumping/sliding on one side. In contrast, the formation of the poorly-defined canyon floor east of the ridge probably resulted from erosion by bottom currents along the bathymetric low, where there is the intersection of the uplifted ridge and the west dipping sea floor of the continental slope. Profile 4 shows that the shale diapir begins to play a role of dividing the two canyon segments which are connected to the upper part of the Fangliao Canyon. Faulting seems to be associated with the rising ridge. These faults extend upward to the sea floor, suggesting recent fault movements.

Profile 5 (Fig. 10) provides further evidence of how the rising ridge has greatly influenced on the formation of the canyon segment east of the ridge. Clearly, the steep eastern flank of the ridge becomes the canyon wall facing the opposite wall of the west-dipping sea floor of the continental slope, suggesting a diapir-controlled structural feature. The flat floor of the east canyon segment points to a erosional/depositional feature. Faults seem to be associated with the eastern part of the rising ridge. The slumping block of the canyon wall at the eastern flank could be interpreted as a rotated fault block. An erosional unconformity is discernible in the southeast part of Profile 5. It could continue across the shale ridge to northwest side and indicates differential uplift because of a higher structural position.

On the other hand, the canyon west of the ridge shows erosional truncation of the sediment layers and widening of the canyon. The west canyon segment represents the erosive section of the slope strata. The shale diapiric intrusion has little influence on the submarine excavation of this canyon segment, but it changes the canyon course.

Profile 6 (Fig. 11) shows the maximum influence of the diapiric intrusion on the formation of the lower canyon. Here the shale diapiric intrusion protruded through the overlying slope sediments and rose above the sea floor and produced a great bathymetric relief to form two canyon segments flanking the ridge. To the east of the ridge, the canyon displays an asymmetrical V-shaped morphology, representing the intersection of the eastern flank of the ridge and the west dipping sea floor of the continental slope. Seismic evidence indicates that the diapiric intrusion and the regional tilting of the continental slope are the dominant canyon forming processes. However, to the west of the ridge, the canyon segment is flanked by the west side of the ridge which has a smooth surface and shows little evidence of erosional truncation. The west wall of this canyon segment reveals marked truncation of sediment layers, suggesting downcutting of the slope strata, but with a decreasing intensity of erosion. A fault seems to be present along the western canyon margin, as indicated by different seismic characteristics and topographic relief of the canyon wall from those of the canyon floor. Erosion and faulting seemed to form the steep canyon wall. In the middle of this canyon floor is a small bulge which may be the accumulation of the sediments transported from upcanyon and nearby western walls. Alternatively, the bulge could be due to a local splitting of the wall. However, no convincing evidence can be provided by the seismic data alone.

Profile 7 crosses the mouths of these two canyon segments (Fig. 12). Seismic patterns indicate that these two canyon segments merge together into a low-relief topographic feature which is confined by the west-dipping slope sediments to the east and a small diapiric intrusion to the west. The erosive section of the slope strata cut by the canyon segments turns into a depositional area. The canyon mouth exhibits seismic and morphological characteristics that suggest channelized and overbank depositional features which are probably deposited mainly by turbidity currents in an upper fan setting (Nelson *et al.*, 1978).

Profile 8 is a down slope line extending from the upper canyon wall, crossing the canyon floor and ending at the lower canyon wall (Fig. 13). There are some slump blocks on the steep wall in the upper canyon. The canyon floor in the middle of the section is represented by a continuous reflection overlying discontinuous and noncoherent reflections, suggesting an erosional/depositional bedform. The southern part of this profile shows the canyon wall with irregular surfaces and chaotic reflection patterns, again slump features seem probable.

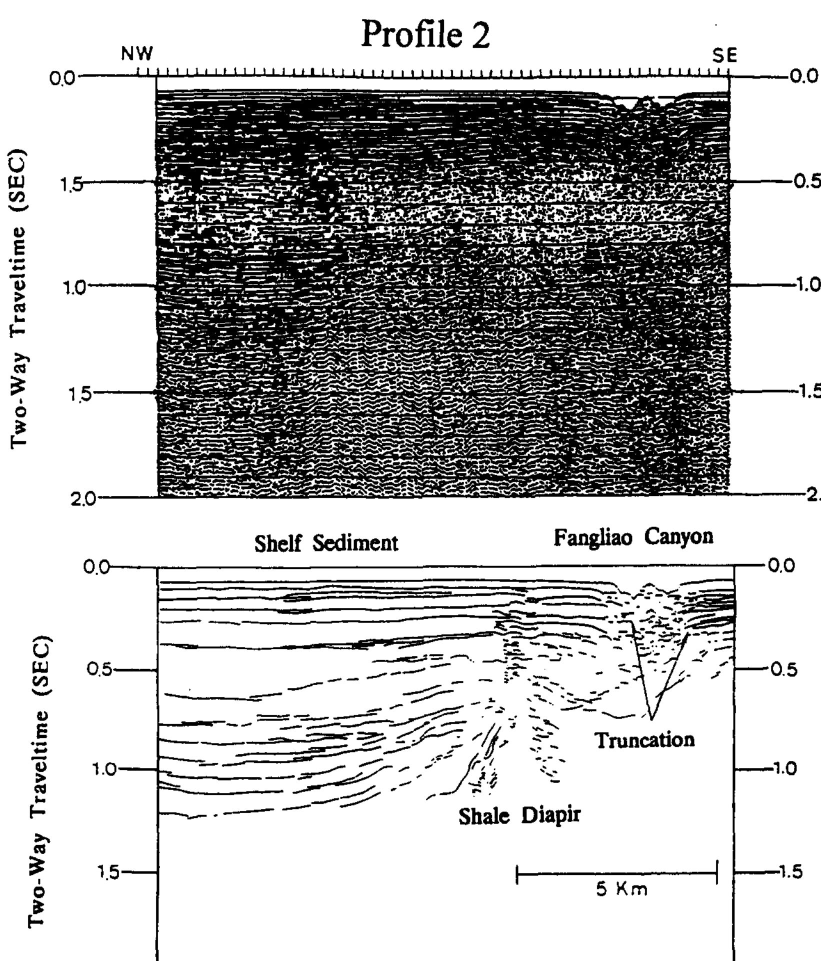


Fig. 7. Seismic reflection profile 2 across the canyon head (see Fig. 5 for location). Downcutting of the shelf sediments and lateral widening of the head initiated the development of the canyon. The areas of poor reflectivity in the profile are tentatively interpreted as shale diapir.

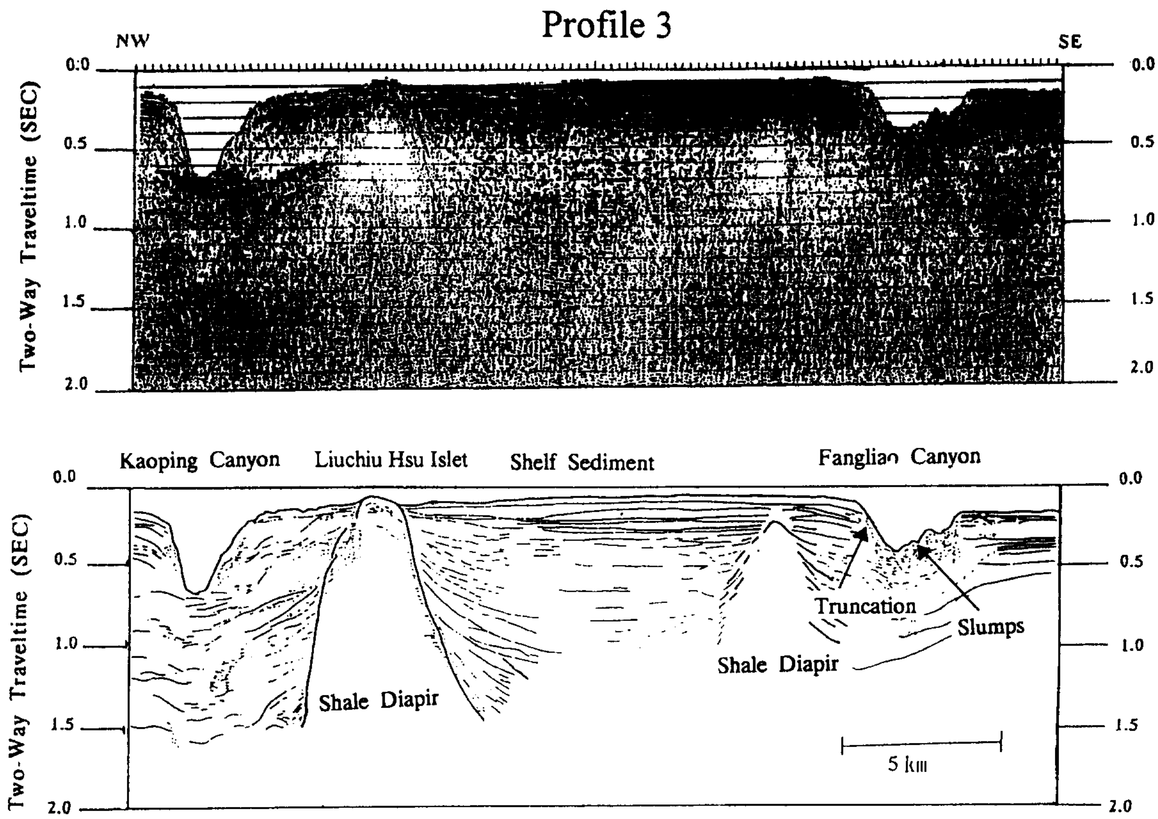


Fig. 8. Seismic reflection profile 3 across the upper canyon (see Fig. 5 for location). Canyon becomes deep and wide here. Canyon forming processes are mainly erosional, as shown by truncation of the strata, slumps and slides on both sides of the canyon wall. Note that two prominent shale diapiric intrusions occur in the intercanyon area and have no influence on formation of the canyons at this point.

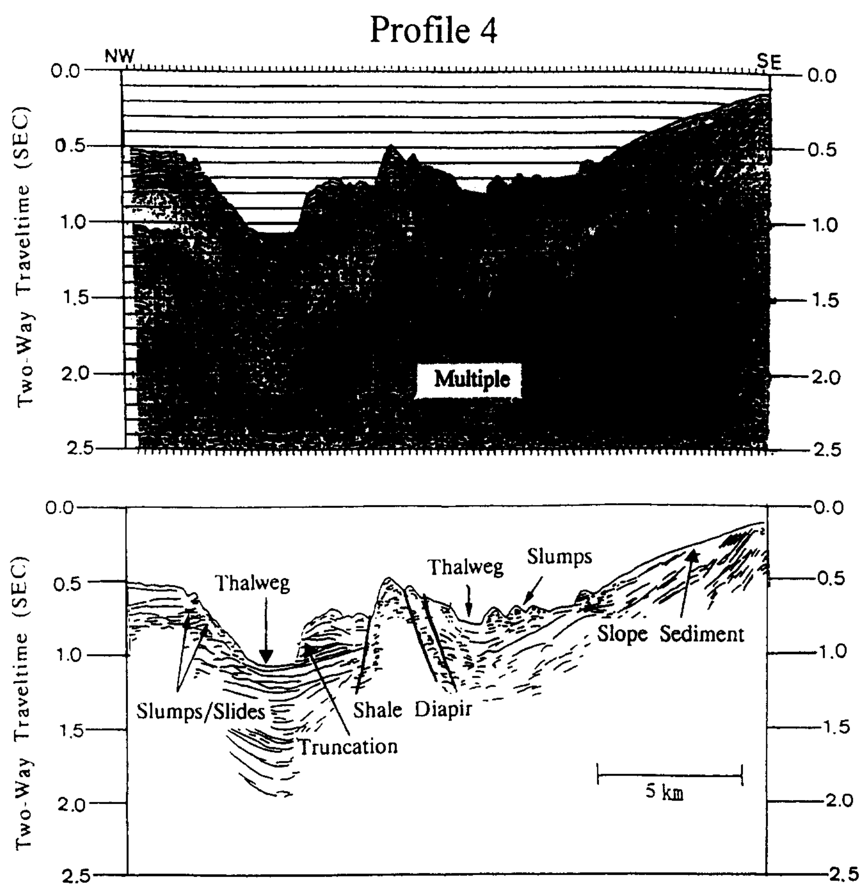


Fig. 9. Seismic reflection profile 4 across the lower canyon (see Fig. 5 for location). The shale diapir begins to play a role of dividing the continental slope strata into two canyon segments which are connected to the upper part of the Fangliao Canyon. Erosional processes of downcutting, slumping and sliding predominate in these two canyon segments.

Profile 9 west of the canyon extends from the shelf edge seaward to a depth of 750 m on the upper continental slope (Fig. 14). The northern part of Profile 9 reveals strong upper and smooth lower sea floor reflectors, dipping seaward and unconformably overlying the subparallel reflections of slope strata. Here the sea floor is an erosional surface resulting from downslope processes, as also evidenced by 3.5 kHz echograms (Yu and Lee, 1992). In contrast, the lower part of Profile 9 shows that the sea floor is a strong irregular reflector overlying discontinuous reflections. This suggests an erosional/depositional bedform formed by slumping/sliding processes. The sea floor is represented by a convex upward sloping surface which is not cut transversly by submarine canyons.

Comparison of Profiles 8 and 9 indicates that a different sea floor relief due to submarine excavation exists between the two dip sections. The downslope line along the canyon shows greater erosional relief than that of the sloping surface in the intercanyon area. Profile 9 (Fig. 14) also shows a series of rotated slump blocks on slip surfaces down the continental slope. This observation from modern canyons and slopes may be applied to interpretations of ancient canyons and continental slopes.

Origin

The understanding of the origin of submarine canyons has advanced to a composite origin with various processes operating in sequence or simultaneously (Shepard, 1981; May *et al.*, 1983). Generally, the origin of submarine canyon can be related to river incision, subaerial erosion, turbidity currents erosion, structural movements (faulting, diapirism, etc.) and biological activities.

The seismic profiles discussed provide evidence of a composite origin for the formation of the Fangliao Canyon. In the upper canyon, truncation of parallel flat-lying strata and sliding/slumping features on the canyon walls are indicative of incision deep into the shelf and slope sediments and lateral widening of the canyon. Erosional processes and faulting activities seem to have steepened the canyon walls. In the lower canyon, the shale diapir uplifted the slope sediments and protruded through the overlying strata, producing a bathymetric ridge rising from the adjacent sea floor. The steep flanks of the rising shale diapir serve as the walls of its steep-sided canyons. The interaction of sedimentary and tectonic processes operating on the continental slope forms the present Fangliao Canyon.

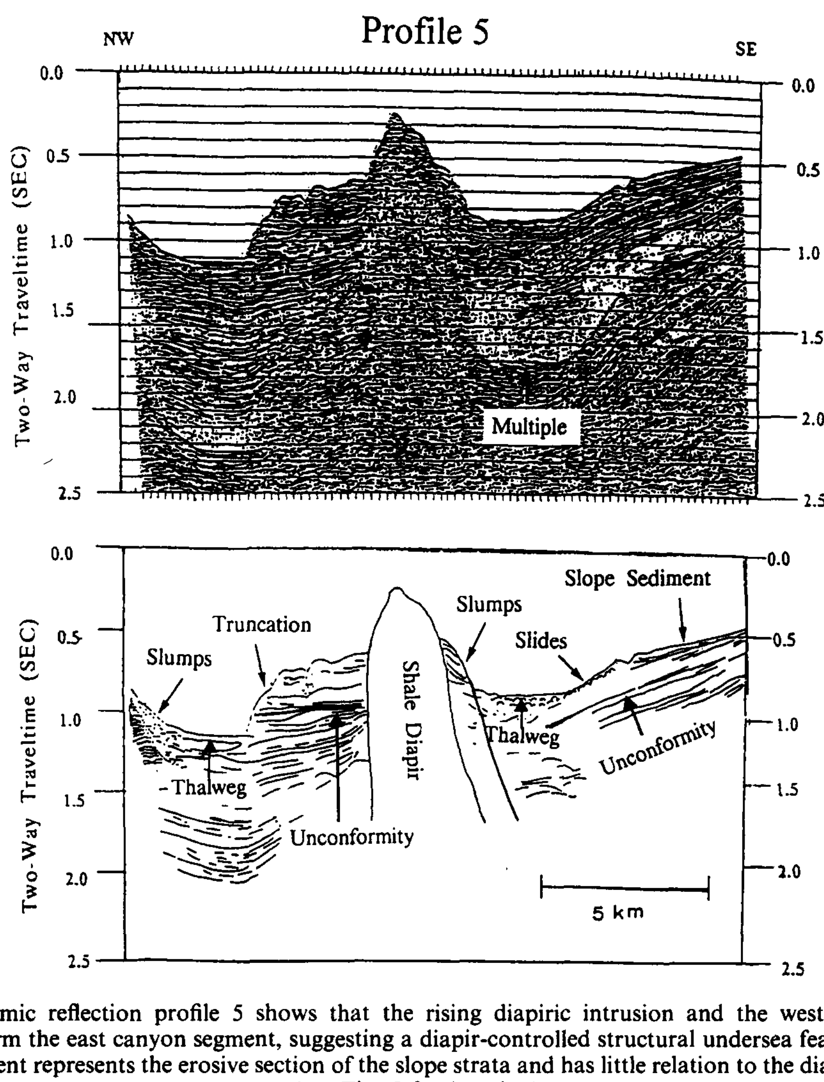


Fig. 10. Seismic reflection profile 5 shows that the rising diapiric intrusion and the west-dipping slope sediments form the east canyon segment, suggesting a diapir-controlled structural undersea feature. The west canyon segment represents the erosive section of the slope strata and has little relation to the diapiric intrusion (see Fig. 5 for location).

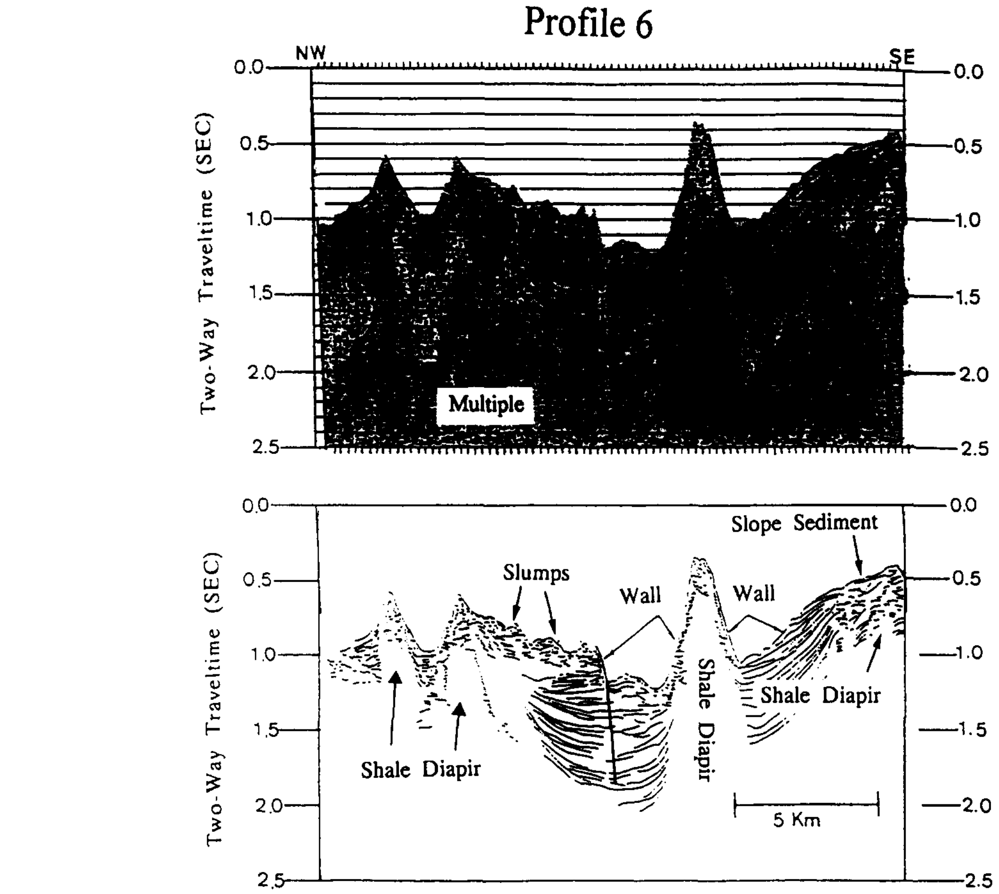


Fig. 11. Seismic reflection profile 6 showing the maximum influence on the diapiric intrusion on the formation of the lower canyon (see Fig. 5 for location). The intrusion rises above from the adjacent sea floor resulting in a steep-sided ridge. Both sides of the ridge serve as the steep walls of the canyon segments.

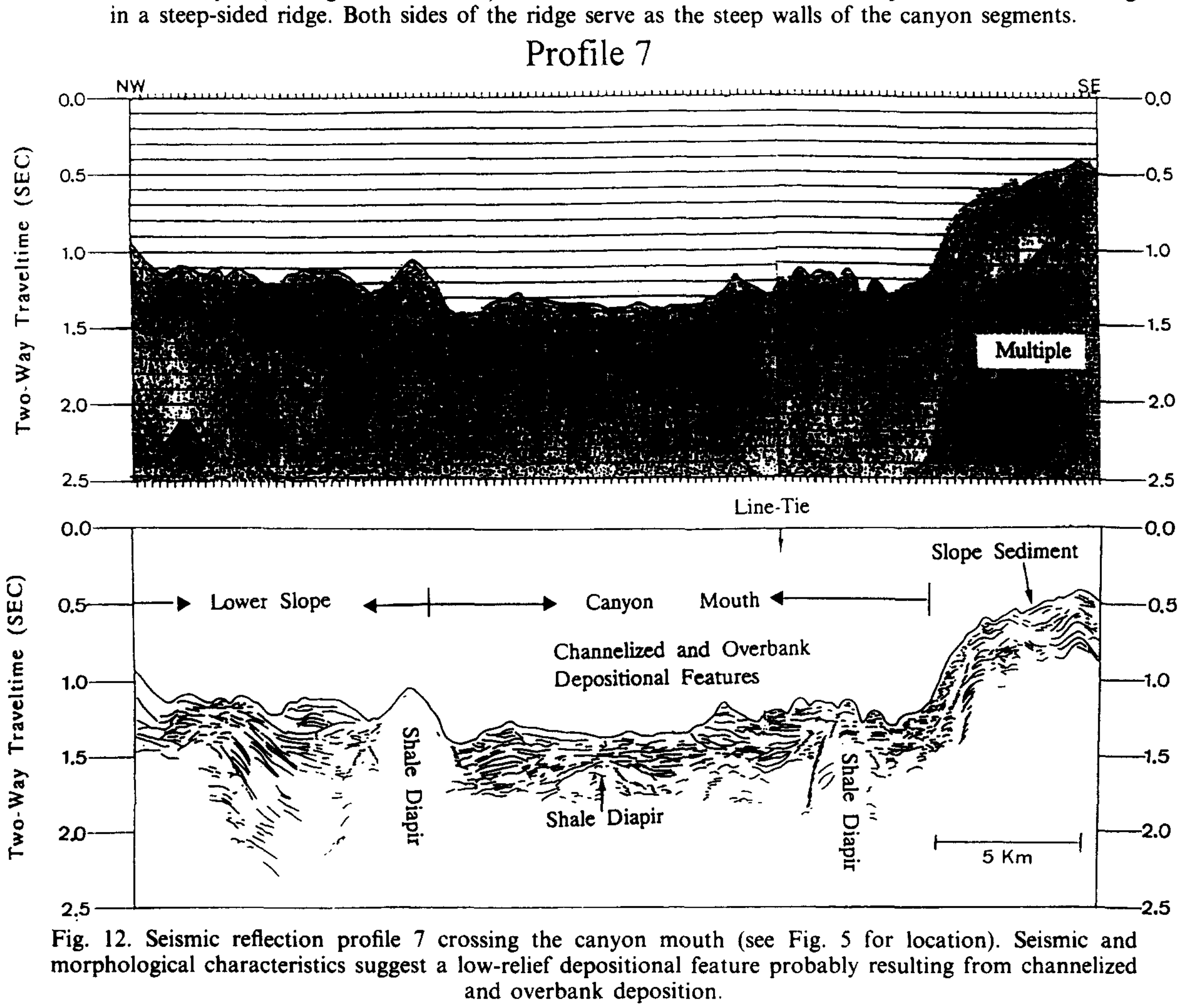


Fig. 12. Seismic reflection profile 7 crossing the canyon mouth (see Fig. 5 for location). Seismic and morphological characteristics suggest a low-relief depositional feature probably resulting from channelized and overbank deposition.

Discussion

The identifications of the faults associated with shale diapirs and canyon margins in several seismic profiles are open to other interpretations. Faults related structural features shown in Profiles 4, 5 and 8 may be interpreted as rotational fault blocks on listric faults which lie on the western sides of both canyons, implying both the canyon strands and the diapirs being localized along faults. On the other hand, Huang (1993) and Sun and Liu (1993, Fig. 5) suggested that many of the shale diapirs in the offshore area of southwestern Taiwan have moved up along thrust faults. The interpretation of thrust faults accompanied by diapiric intrusions is compatible with the regional tectonic compressive stress. The seismic interpretations of fault style from the profiles across the Fangliao Canyon need to be integrated into other geologic observations. In the immediate future the task is to thoroughly investigate the relationship between diapirism and faulting in the study area. The interpretation of the faults associated with the Fangliao Canyon is preliminary and may be revised with more information.

Conclusions

Fangliao Canyon is a relatively small, young (< 3 Ma) continental slope canyon which begins at the shelf edge, ends at the upper slope and is not related to river valleys onland. The bathymetric data reveal that Fangliao Canyon is divided into two morphologically contrasting parts: an upper canyon, a relatively straight one ending at approximately the 600 m isobath, and a lower canyon, consisting of two segments separated by active shale diapirism.

The interaction of sedimentary processes (mainly erosion, sliding and slumping) and tectonic processes of tilting of the continental slope and local uplift of the shale diapir and associated faulting operating on the continental slope off southwestern Taiwan form the present Fangliao Canyon.

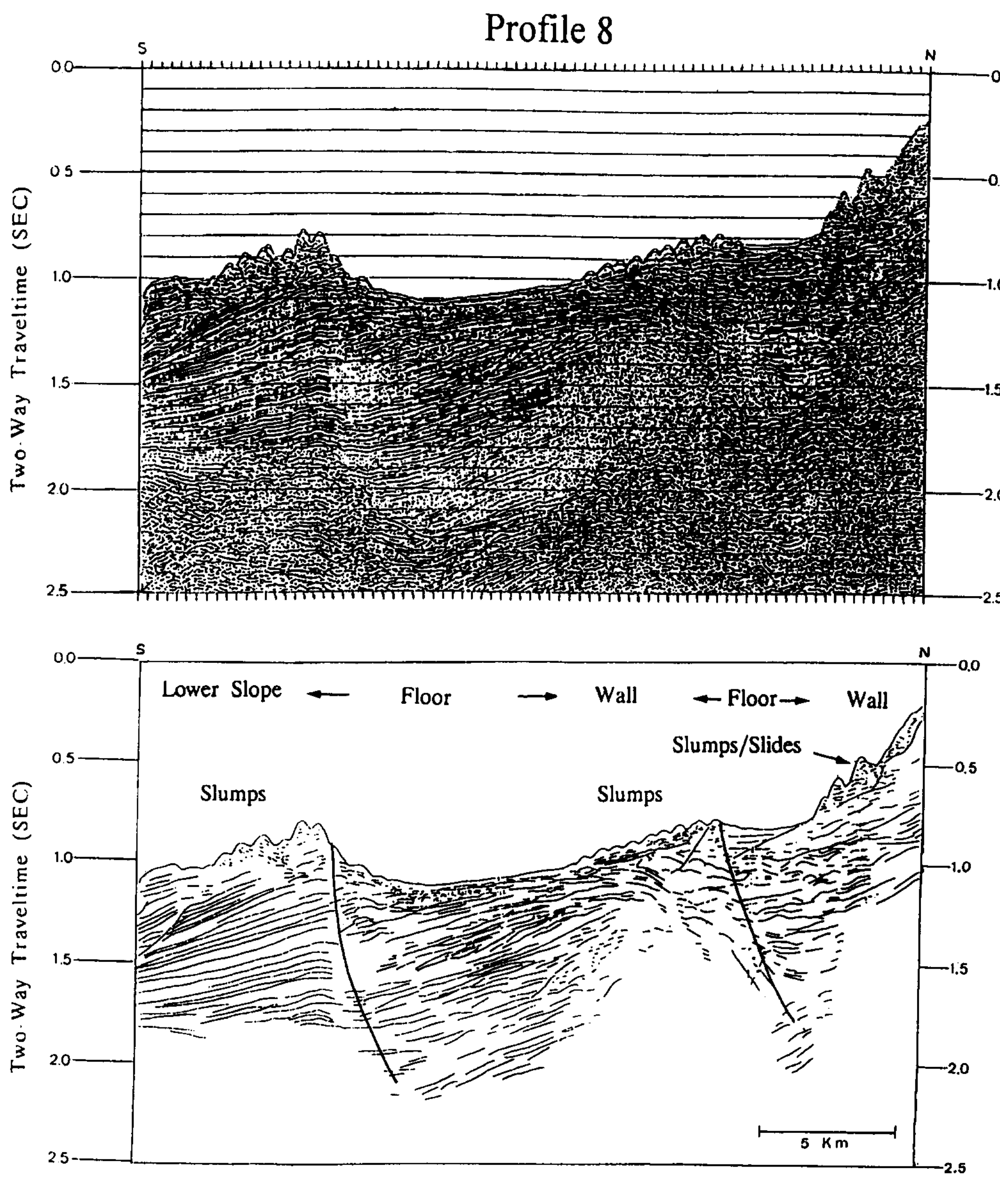


Fig. 13. Seismic reflection profile 8 extending from the upper canyon wall, crossing the canyon floor and ending at the lower slope (see Fig. 5 for location). The canyon walls and slope strata are characterized by slumping/sliding features with irregular surfaces. The seismic characteristics of the canyon floor exhibit a smooth continuous reflector, suggesting an erosional/depositional bedform. This seaward dipping profile shows great topographic relief.

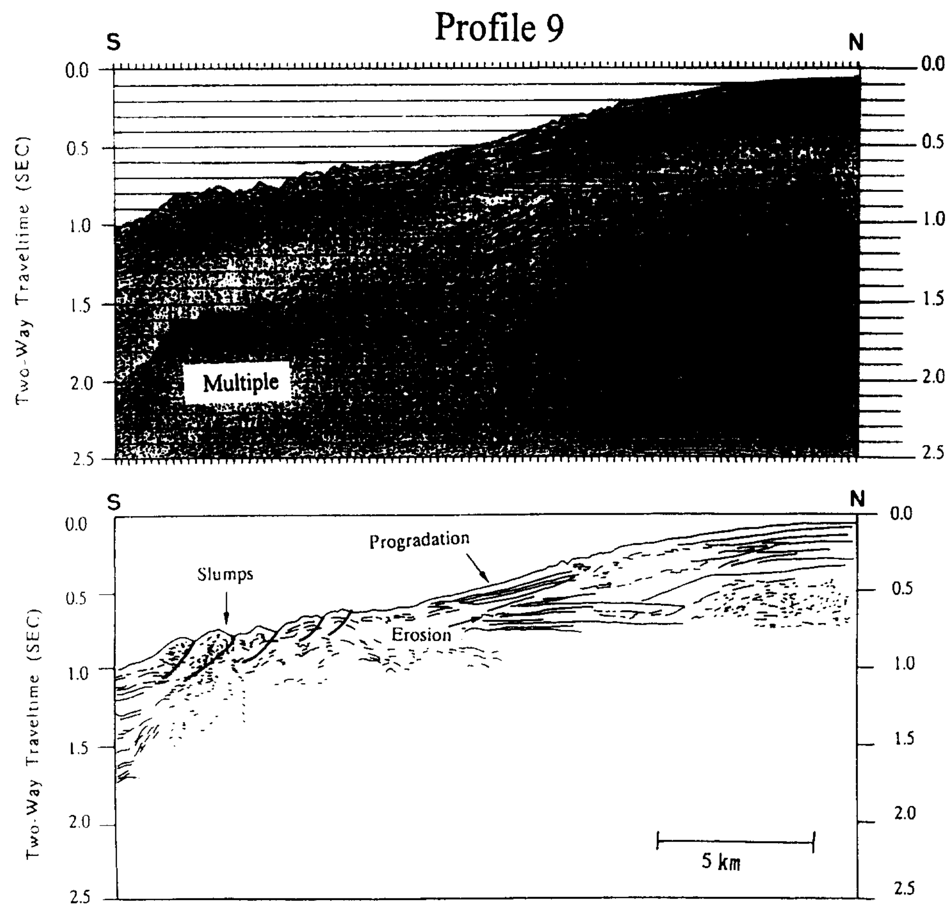


Fig. 14. Seismic reflection 9 extending from the shelf to the upper continental slope (see Fig. 5 for location). Seismic characteristics suggest that the slope may be built by erosion and progradation processes. The sea floor is represented by a convex upward sloping surface whose upper part being a strong and smooth reflector and lower part being a strong irregular reflector. This part of slope is not cut transversely by submarine canyons.

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