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Keywords	transient fan, Kaoping canyon-fan system, complex slope, turbidity currents, Taiwan

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The modern Kaoping transient fan offshore SW Taiwan: Morphotectonics and development

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Abstract

Using bathymetry and seismic reflection profiles, this study examined and determined the transient nature of the Kaoping Fan located in the topographically complex slope offshore southwest Taiwan. The main body of the Kaoping Fan is located west of the lower reach of the Kaoping Canyon at the lower Kaoping Slope, ranging from 2,200 to 3,000 m in water depths, and has a relatively small areal extent restricted in the topographic lows confined by structural highs due to mud diapiric uplifting and thrust faulting. The Kaoping Fan shows an asymmetrical triangular fan-shaped bathymetric feature elongated in a NW-SE direction but with a strong skew toward the east. The fan deposits consist of three main seismic facies: layered high-amplitude reflections in the upper section and stratified, parallel to sub-parallel low-amplitude reflections with variable continuity and channel fill facies in the lower section. The vertical stacking seismic patterns suggest that the deposits of the Kaoping Fan recorded the onset of channelized and over-bank deposits in the lower part and layered turbidite facies in the upper part subsequently. The development of the Kaoping transient fan can be divided into three stages in terms of canyon activities and fan-feeding processes.

Initially, the Kaoping Fan developed as a slope fan, mainly fed by a point sediment source at the apex of the fan. The proto-fan deposits are mainly built up by channel fills. Secondly, the Kaoping Fan maintained as a slope fan, mainly fed laterally by over-spilled sediments from the canyon course rather than by a point source. Finally, the Kaoping Canyon completely passes through the Kaoping Fan and supplies over-spilled sediments laterally to feed the Kaoping Fan continuously, forming a typical transient fan with two major characteristics: canyon incision and sediment by-passing.

The accumulation of sediments and the growth of the Kaoping Fan are primarily controlled by inherited complex paleo-topography and the evolution of the Kaoping Canyon. The linear mud-diapiric ridge immediately east of the lower reach of the Kaoping Canyon prevents the eastward over-spilling of sediment flows from the canyon, resulting in preferential deposition of westward over-spilling sediment flows and forming a transient fan west of the Kaoping Canyon. The sediment delivery system of the Kaoping Fan is characterized by lateral supply of over-spilling sediment flows and sediments bypassing to and beyond the base of slope. It is implied that the Kaoping Fan together with the ponded Fangliao Fan in the topographically complex Kaoping Slope can be used as a type model for evaluating the topographic effects on the development of submarine fans on complex slopes in general.

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1 Introduction

Submarine canyons are prominent topographic features on the seafloor of both active and passive continental margins (Harris and Whiteway, 2011; Shepard, 1981). Submarine canyons serve as major sediment conduits for delivering terrestrial sediments to deep-sea basins, forming depositional features such as submarine fans and associated turbidite systems. For example, the Congo Canyon incises across the continental margin over hundreds of kilometers and delivers a great amount of sediments from Congo River drainage basin to the basin floor, forming one of the largest submarine fans in the world (Anka et al., 2009). In the extreme case, the submarine Bengal Fan with an area of 3,000,000 km^2 in the Indian Ocean forms the largest sediment accumulation on Earth (Ingersoll et al., 2003). In other words, submarine canyons not only produce negative seafloor features, but also produce positive depositional features on the seafloor, constantly shaping the morphology of continental margins by varying erosive and depositional processes. It appears that studies of submarine canyons and associated submarine fans are important subjects for understanding submarine geomorphology and sedimentary processes of continental margins. From an industry point-of-view, submarine fans are known to contain significant petroleum reserves and have great potential for further exploration around the world (e.g., (Weimer and Link, 1991).

Submarine fans are deep-sea sediment accumulations consisting mainly of terrestrial and shallow marine sediments delivered to slopes and basin floors by canyons and channels. They are characterized by a fan-shaped geometry or fan-like morphology in plain view (Bouma et al., 1985; Henry W. Menard, 1955; Nelson et al., 1978). Submarine fans developed on topographically and structurally complex continental slopes with contrasting characteristics compared to those on the basin-floor of passive margins (i.e., Congo Fan) have begun to gain attention in the last two decades (Adeogba et al., 2005; Dalla Valle and Gamberi, 2010; Gamberi and Rovere, 2011; Gamberi et al., 2014; Madof et al., 2009; Prather, 2003; Prather et al., 1998; Smith, 2004; Spychala et al., 2015; Wolak and Gardner, 2009). Continental slopes in active margins or slopes influenced by gravity tectonics such as salt or mud diapirism result in deformed seafloor with complex topography. As shown in Fig. 1a, the location, geometry, and architecture of submarine fans in topographically complex slopes are largely influenced by seafloor deformation and resulting topography which control the sequential filling-and-spilling of sediment dispersal down-slope across a series of topographic highs and lows in the complex slope. Small confined deep-sea fans, transient fans, or ponded fans are formed at mid slopes where sediment gravity flows, from the feeding canyon or channel, are confined or ponded by raised seafloor features before transporting to the lower slope or basin plains. For instance, a ponded fan is formed where gravity sediment flows fill and pond in topographically closed basins such as intra-slope basins formed by salt diapirism as in the Gulf of Mexico continental slope (e.g., Booth et al., 2003). A transient fan is formed where gravity sediment flows fill-in less confined topographic lows and excess sediment flows over-spill to the next basin farther down-slope and are ultimately deposited within terminal fans. For example, a transient fan was found on the Niger Delta continental slope characterized by deformation of shale diapirism (Adeogba et al., 2005; Wolak and Gardner, 2009) and ancient transient fans in California (Duvernay and Dykstra, 2012; Turner and Dykstra, 2011). Therefore, inherited seafloor topography and fill-and-spill processes of sediment dispersal down-slope are two major controls on the nature and formation of submarine fans in topographically complex slopes.

Submarine canyons incised the shelf and slope and represented the major physiographic features on the seafloor off the southwest Taiwan margin (Yu and Song, 2000). Several noticeable submarine canyons are developed on the narrow Kaoping Shelf and the broad Kaoping Slope from northwest to southeast along the shoreline (Fig. 2). The Kaoping Canyon with a length of about 260 km is the longest among these canyons, extending from its head near the Kaoping River mouth, crossing the shelf and slope seaward, and finally merging into the lower reach of the Penghu Canyon in a water depth about 3,500 m (Hsiung and Yu, 2011). Investigating the morphotectonics of the Kaoping Canyon, Chiang and Yu (2006) noticed that there exists a submarine fan which is fed by sediments from the middle reach to the west (Fig. 2). This submarine fan was tentatively named as the Kaoping Fan without descriptions of the morphology and discussions of its origin (Chiang and Yu, 2006). Later, Yu et al. (2009, p. 381) considered the Kaoping Fan at the lower reach as a fan fed by the Kaoping Canyon and being a temporary sediment sink for sediments transported by the Kaoping Canyon in terms of source to sink. The nature of the Kaoping Fan was not explicitly studied by Chiang and Yu (2006), neither by Yu et al. (2009). These previous studies were focused on the morphotectonics and sediment dispersal of the Kaoping Canyon rather than the nature of the Kaoping Fan. As a result, the significance of topographic effects on the formation of the Kaoping Fan was given little attention (Yu et al., 2009).

On the other hand, Hsiung et al. (2014) realized the importance of topographic effects on the development of submarine fans occurring on the topographically and structurally complex Kaoping Slope. They determined the submarine fan in front of the mouth of the Fangliao Canyon at the mid slope, the noticeable shelf-indenting canyon east of the Kaoping Canyon, to be a modern ponded fan (Figs. 1b and 2). The Fangliao

Fan begins at the mouth of the Fangliao Canyon at a water depth of 900 m and terminates down-slope along a linear escarpment at a water depth of 1,100 m where gravity sediment flows are prevented from transporting farther down-slope due to ponding against the bathymetric highs. Sediments from the canyon mouth and upslope are mainly transported by mass movement, filling an intra-slope basin at the upper Kaoping Slope, and forming a ponded fan within the partially-filled basin (Hsiung et al., 2014).

By analogy to the study of the Fangliao Fan, this paper emphasizes the topographic and structural effects on the development of the Kaoping Fan as fed by the Kaoping Canyon on the Kaoping Slope. Considering the location of the Kaoping Fan beginning at a morphologic break (i.e., a sharp bend) along the canyon course (Fig. 2), the presence of an incised canyon passing through, and sediments bypassing to the slope base, we suggest that the Kaoping Fan can be considered as a transient fan (Fig. 1c). This paper tries to provide a modern example of a canyon-transient fan system on the Kaoping Slope. Our results help to better understand the nature of transient fans on complex slopes, as Gamberi and Rovere (2011, p. 212) stated that in-depth studies of modern transient fans are currently not available (Gamberi and Rovere, 2011). Furthermore, the study of the Kaoping transient fan together with the ponded Fangliao Fan can be used as a type model for evaluating the topographic effects on the development of submarine fans on complex slopes in general. This study has a broad implication for making a small yet significant contribution to the compilation of global geomorphic features on seafloors of oceans. A new and up-to-date digital seafloor geomorphic feature map has been published to provide bases for geomorphologic and geologic analyses for global distribution of specific seafloor features (Harris et al., 2014). Submarine fans are major submarine features and included to be one of these major categories geomorphic features providing significant estimates of physiographic statistics (Harris et al., 2014). Currently, the submarine canyons (Harris and Whiteway, 2011) and submarine channels (Peakall and Sumner, 2015) are well studied and can be classified geomorphologically into distinct types by geomorphic characteristics and geological processes. As new data and better understanding of submarine fans become available, the geomorphologic classification of submarine fans can be possible in the future.

2 Geological setting

The Taiwan mountain belt, located at the junction between the Ryukyu and Luzon Arcs in the northwest Pacific (Fig. 2), was formed by oblique collision between the Luzon Arc and the Chinese margin beginning in Late Miocene-Early Pliocene (Suppe, 1981). Subsequently, the western Taiwan foreland basin developed by flexural bending west to the Taiwan orogen and received orogenic Pliocene-Quaternary sediments more than 5000 m in thickness (Covey, 1984, 1986; Sun and Liu, 1993; Wu, 1993). Regarding the characteristics of basin fills, the offshore region southwest of Taiwan was considered as an immature marine foreland basin distal to the Taiwan orogen (Covey, 1984; Yu, 2004). Structurally, this marine basin was suggested to be a wedge-top basin, a part of foreland basin system (DeCelles and Giles, 1996), as evidenced by these marine sediments syntectonically deformed into folds, thrusts, and mud-diapiric intrusions (Chiang et al., 2004). Furthermore, structural lows between these structures, especially mud-diapiric uplifts, form numerous intra-slope basins or mini-basins in the Kaoping Slope which are filled or partially filled by spill-over slope sediments (Hsu et al., 2013; Yu and Huang, 2006).

Physiographically, the offshore area of southwest Taiwan is characterized by a very narrow Kaoping Shelf (~ 10 km) and a relatively broad Kaoping Slope with a water depth more than 3,000 meters (Chiang et al., 2012). This slope is juxtaposed with the South China Sea Slope to the west. These two continental slopes are separated by the N-S trending Penghu Submarine Canyon (Fig. 2). The Kaoping Slope can be divided into the upper and lower slopes by linear prominent escarpments in water depths ranging from 1,200 to 2,000 m. The linear escarpments result from seaward thrust-faulting (Chiang and Yu, 2006; Liu et al., 1997; Yu and Song, 2000). The upper slope is extensively incised by submarine canyons trending NE-SW, whereas the lower slope is characterized by ridges and valleys, resulting mainly from slope strata deformed by folds, thrust-faulting, and mud-diapirism. Linear depressions produced by canyon incision and raised ridges resulting from thrust-faulting have resulted in great relief of the sea floor of the Kaoping Slope and have modified the Kaoping Slope into a topographically and structurally complex continental slope.

3 Method and data

The concepts of topographic effects, associated with structures and tectonics, on the development of submarine fans in topographically complex slopes (Adeogba et al., 2005; Gamberi and Rovere, 2011) and the down-slope fill-and-spill model forming submarine fans in the intra-slope basins in the Gulf of Mexico Slopes (Prather et al., 1998) are used to determine the canyon-transient fan system in the Kaoping Slope. Combined multi-beam bathymetric data and seismic profiles are used to determine the morpho-sedimentary features and processes for the development of the Kaoping transient fan terminating on the lower slope in a water depth around 3,000 m (Fig. 3).

The Multibeam bathymetric data were collected on Ocean Researcher V during cruises in 2013-2014, covering about 150,000 km^2 of seafloor off SW Taiwan. The ATLAS HYDROSWEEP DS is a high resolution multibeam echo sounder ideally suited for seabed mapping in deep water up to full ocean depth based on a sonar frequency between 14 kHz to 16 kHz. These data have been processed and edited with the NaviEdit Software from the Taiwan Ocean Research Institute, National Applied Research Laboratories.

Bathymetric data (Elac 4700 Echo Sounder) and seismic reflection profiles (Strata Visor NX 24, Geometrics) collected onboard the R/V Ocean Research I operated by National Taiwan University, covering the entire Kaoping Canyon along the length from the canyon head to the canyon mouth, were used for studies of morphotectonics and sediment dispersal systems of the canyon (Chiang and Yu, 2006; Yu et al., 2009; Fig. 3). In this study, these previously collected seismic data are re-examined and re-interpreted, focusing on the processes responsible for the development of the Kaoping Fan as a transient fan. Three transverse seismic profiles oriented in NW-SE direction and one longitudinal transect trending nearly E-W across the canyon-transient fan system are shown in Fig. 3.

4 Results

4.1 Fan morphology

The updated high-resolution bathymetric mapping of the Kaoping Fan shows that the bathymetric contours spread out laterally and asymmetrically from the apex of the Kaoping Fan, thereby outlining an asymmetrical triangular fan-shaped bathymetric feature elongated in a NW-SE direction but with a strong skew toward the east (Fig. 4). It is noted that the relatively fan-shaped smooth surface can be separated into two bathymetric lobes: a proximal fan and a distal fan. The boundary between the proximal fan and distal fan is placed at a small ridge trending northwest approximately following the 2,400 m isobath (Fig. 4). The arc length of the proximal part of the Kaoping Fan is about 60 km with an area about 135 km^2. The distal fan has an area about 1,300 km^2 and the arc length is about 85 km along the deformation front parallel to the course of the lower Penghu Canyon (Fig. 4). The Kaoping Fan is a small submarine fan with relatively low relief. This fan ranges from about 2,200 m to 3,000 m in water depth. The radius of the Kaoping Fan ranges from about 25 to 35 km, and the fan size is approximately 1,455 km^2 in plan view (Figs. 2 and 4). The average gradient of this fan is 0.015° (Table 1).

4.2 Seismic facies and morpho/tectonic features

This section describes major seismic facies and morpho/tectonic features from four seismic reflection profiles covering the Kaoping Fan. Four main seismic facies have been identified on the basis of reflection configuration patterns, amplitude intensity, lateral continuity and other characteristics (Table 2). Seismic facies I is characterized by parallel and even reflection configuration with high-amplitude reflections and relatively good lateral continuity. Facies II mainly consists of stratified, parallel to sub-parallel low-amplitude reflections with variable continuity. Parts of reflections are shown in wavy or undulation forms with varying reflection terminations. Some reflections are tilted in different directions. Seismic Facies III is channel fill facies, consisting of layered high-amplitude reflections confined by channels, and facies IV is characterized by chaotic or free reflection facies. The main body of the Kaoping Fan consists mainly of two seismic facies: layered parallel high-amplitude reflections in the upper section and stratified, parallel to sub-parallel low-amplitude reflections with variable continuity in the lower section.

Seismic profile 809-1 trending NW-SE and crossing the proximal fan near the apex of the Kaoping Fan shows a prominent bathymetric ridge that is located east of the Kaoping Canyon and characterized by disturbed and chaotic seismic reflectors caused by mud diapir intrusion (Fig. 5). West of the Kaoping Canyon, the surface of the Kaoping Fan is characterized by a smooth and flat seismic reflector, extending northwestward about 20 km. In general, the shallow successions below the fan surface are characterized by stratified continuous and parallel reflectors as layers which overlie the lower successions with sub-parallel low-amplitude reflectors with variable lateral continuity. It is noticed that channel fills with strong reflectors can be discerned in the lower part of the stratified low-amplitude reflections (Fig. 5). The upper section varies in thickness from 0.5 to 0.3 s TWT, thinning toward the northwest. The lower section shows the maximum thickness of about 0.4 s TWT with sub-parallel low-amplitude reflectors. A noticeable reflector at a TWT depth of about 4.7 s is presumed to be the base of the modern Kaoping Fan (Fig. 5). Sub-parallel and wavy reflectors are present below the bottom of fan deposits, suggesting the irregular paleo-slope basin was filled by fan deposits subsequently.

While parallel to profile 809-1, seismic profile 809-2 and 809-3 are cross-sections farther down-fan that show the fan deposits are characterized by relatively smooth surface and layered high-amplitude and continuous reflections in upper section and seismic facies with sub-parallel low-amplitude reflections in the lower section (Figs. 6 and 7). The inclined smooth fan surface in profile 809-2 shows an up-dip proximal fan about 15 km wide and down-dip distal fan about 24 km wide, separated by a small ridge (Fig. 6). The proximal fan deposits show layered seismic facies about 0.2 s TWT thick in the upper section, low-amplitude laminated reflections about 0.8s TWT in thickness in the lower section (Fig. 6). In the distal fan, layered high-amplitude seismic facies is about 0.2 s TWT thick and these layered continuous reflectors terminate against a low-relief ridge immediately east of the Penghu submarine canyon, showing onlap reflection termination. The lower stratified low-amplitude facies is about 0.6 to 0.8 s TWT thick. It is noted that several channel fill facies occur in the lower part of the laminated low-amplitude reflections. A noticeable reflector at a TWT depth of about 4.7 to 5.1 s is inferred to be the base of the modern Kaoping Fan (Fig. 6). The eastern part of profile 809-2 crossing meandering bends of the Kaoping Canyon shows a diapiric ridge and a small bulge in the center of canyon floor that are suggestive of relatively intense down-cutting of the canyon floor, deposition of sediments, and complex structure disturbance (Fig. 6). Seismic profile 809-3 farther south shows the distal fan only (Fig. 7). Unlike the fan surfaces in profile 809-1 and 809-2, the distal fan surface of profile 809-3 about 37 km wide consists of a 30 km wide smooth and flat surface in the northwest and a 7 km wide inclined and low-relief seafloor in the southeast (Fig. 7). The distal fan deposits show layered high-amplitude seismic facies about 0.1 to 0.2 s TWT in the upper section, and stratified low-amplitude facies about 0.3 to 0.6 s TWT in the lower section (Fig. 7). A noticeable reflector at a TWT depth of about 4.5 to 4.7 s is presumed to be the base of the modern Kaoping Fan (Fig. 7). The east part of profile 809-3 shows a narrow canyon with an asymmetrical V-shaped cross section and steep wall with little sediment accumulation in the canyon floor, suggesting dominance of erosional down-cutting processes and sediment by-passing. These three strike-aligned seismic profiles reveal that the fan body is mainly located west of the Kaoping Canyon and is characterized by stratified reflections with variable amplitude and lateral continuity, indicating fan deposits being undergone different sedimentary processes such as cut-and-fills by channels.

The dip-oriented seismic profile MW-1 extending about 40 km from the fan apex to the lower end bordered by the Penghu Canyon shows a gentle inclined smooth surface separated by a noticeable ridge formed by thrust faulting (Fig. 8). The proximal fan about 12 km wide is located up-dip of the ridge and the distal fan about 20 km wide is located down-dip of the ridge (Fig. 8). The Kaoping Canyon with relatively narrow and low-relief west wall is located immediately east of the Kaoping Fan. Seismic profile MW-1 shows similar seismic characteristics to those of the three strike-aligned profiles. The fan deposits are characterized by seismic facies of layered parallel high-amplitude reflections in the upper section ranging from 0.1 to 0.3 s TWT in thickness. The seismic facies in the lower section consist of stratified low-amplitude reflections about 0.2 to 0.5 s TWT thick in the proximal part and 0.1 to 0.3 s TWT thick in the distal part, respectively. A noticeable wavy reflector of varying TWT depths from about 4.2 to 4.7 s TWT is suggested to be the base of the modern Kaoping Fan (Fig. 8). The relatively smooth fan surface is disturbed by a noticeable linear low-relief ridge which is associated with westward thrusting in a compression regional tectonics (Fig. 8).

5 Discussions

5.1 Kaoping Fan morphology

The morphology of the Kaoping Fan is quite different from that of the classic submarine fans (Normark, 1970; Normark, 1978). Instead of being fed from a point source, the modern Kaoping Fan is mainly fed laterally by over-spilled sediments from the lower reach of the Kaoping Canyon east of the fan (Figs. 2 and 4), which show high-amplitude reflections and continuity in the upper section of the seismic profiles. Furthermore, being confined by mud-diapiric ridges immediately east of the Kaoping Canyon, the Kaoping Fan has adopted an asymmetrical triangular shape skewed to the east (Fig. 4). Therefore, the sediment delivery system characterized by lateral sediment supply from the Kaoping Canyon and the topographic effect of the rising ridges to the east on the tilting fan surface to the southwest are the two major factors governing the overall morphology of the Kaoping Fan. The low-relief ridge oriented NW-SE in a water depth about 2,400 m is formed by westward thrusting of the shallow successions of fan deposits (Figs. 8), separating the Kaoping Fan into the proximal fan and the distal fan, respectively (Fig. 4). This is further evidence of structural effect on shaping the morphology of the Kaoping Fan. The relatively flat and low-relief Kaoping Fan surface is probably due to deposition of sheet-like turbidites from the over-spilled sediment flows from the side canyon with limited sediment supply. This results in the absence of channels incising the fan deposits and forming the smooth surface of the Kaoping Fan on the tectonically active Kaoping Slope. The lower reach of the Kaoping Canyon passes through the Kaoping Fan and its canyon mouth merges into the Penghu Canyon where the sediments from the Kaoping Canyon are accumulated (Figs. 2 and 4). The relatively small size of the Kaoping Fan reflects the confinement of the sediments in the slopes with complex seafloor topography (in active margins) rather than forming large deep-sea fans along the basin plain of passive margins (Barnes and Normark, 1985; Gamberi and Rovere, 2011; Shanmugam and Moiola, 1988). Thus, the inherited paleo-topography of the lower Kaoping Slope is the dominant factor in controlling the size and shape of the Kaoping Fan with secondary contributions from lateral sediment supply.

5.2 Hypothesis of development

Submarine fans are relatively smooth, fan-like depositional features normally sloping away from the termination of a canyon or canyon system (Harris et al., 2014; IHO, 2008), indicating a close genetic relation between the sediment-feeding canyon and the resulting submarine fans. However, the modern Kaoping fan is not located in front of the Kaoping Canyon mouth, but is located west of the lower reach of the canyon. Finally, the Kaoping Canyon terminates and merges into the lower reach of the Penghu Canyon which flows southward and continues to the deep-sea Penghu Channel farther south (Figs. 1c and 2). The Penghu Canyon and deep-sea Penghu Channel serve as a longitudinal sediment transport pathway, delivering sediments from Taiwan orogen including the Kaoping Slope to the northern South China Sea and ultimately to the Manila Trench (Hsiung and Yu, 2011). The sediments from the Kaoping Canyon are emptied into the lower reach of the Penghu Canyon and then are moved and transported southward, resulting in no accumulation of submarine fan or fan lobes at the terminal of the Kaoping Canyon. The Tugela Canyon and submarine fan system in offshore South Africa could be an analogy to the Kaoping Canyon case. Sediments sourced from the Tugela River are delivered via the Tugela Canyon offshore and emptied into the abyssal Natal Valley where sediments are reworked and swept by the North Atlantic Deep Water current, resulting in a poorly and starved submarine fan (Wiles et al., 2013).

According to the seismic profiles and the modern morphology of the Kaoping Fan, we thought that the Kaoping Canyon systems is active and related to the development of the Kaoping Fan. Therefore, we propose a hypothesis of the development of the Kaoping Fan with three stages in terms of canyon activities and fan-feeding processes to explain the fan being not in front of canyon mouth (Fig. 9). In the initial stage of the fan development (Fig. 9a), the growth of the Kaoping Canyon was limited to the middle reach at the mid slope where the southward canyon course was blocked by structural highs and was deflected to the west with its canyon mouth opening to the west. Due to its head connecting to the large Kaoping River, the Kaoping Canyon receives large amounts of terrestrial sediments to be transported down-canyon (Yu et al., 2009). Therefore, adequate sediments available from the Kaoping Canyon flow westward to the relative low and smooth area, which is the Kaoping Fan in the initial stage. Chiang and Yu (2006) analyzed several bathymetric profiles of the Kaoping Canyon, showing that the middle reach of the Kaoping Canyon is characterized by typical V-shaped morphology with little sediment accumulation on the canyon floor, indicating the prevalence of erosion and sediment bypassing along the middle reach (Chiang and Yu, 2006; Yu et al., 2009). In this study, it also shows the typical V-shape in the Kaoping Canyon in the 809-3 profile across the distal fan that indicated that the Kaoping Canyon formed from north to south gradually, and the southern part may be younger and more active than the northern part in our study area. In other words, during the formation of the Kaoping Fan, the Kaoping Canyon may be constantly active, not only as the major feeder for the Kaoping Fan, but also as a major sediment conduit in transporting sediments to the lower Kaoping Slope southward. This paper infers that the sediment flows coming out of the Kaoping Canyon mouth are transported down-slope, spread unconfined laterally, deposited at the lower slope, infilling the channels, and forming a fan-like sedimentary feature. Another sediment input for the proto-Kaoping Fan likely came from the upslope sediment flows in the north region of the fan probably due to slope failures of the strata. The area extent of the proto-Kaoping Fan was limited by the available accommodation space in response to the paleo-topography of the lower slope. Figures 5 through 8 reveal that the lower part of the fan deposits is dominated by sub-parallel low-amplitude facies and presence of channel fills facies (fig. 6). In other words, the deposits in the lower fan are represented mainly by laminated reflections with only some local vertical or sub-vertical zones of high-amplitudes (these are interpreted to be submarine channels on the fan). The locations of axis of these channels could not be aligned or traced upslope or down-slope to show the presence of continuous courses of channels from our seismic cross sections. These channels have broad troughs without confined course and over-bank levees, suggesting younger channelized features in the initial erosion stage (Deptuck et al., 2007; Fildani et al., 2013). These channelized and over-bank sediments are probably deposited by turbidity currents in a submarine fan setting (Nelson et al., 1978). Sediment flows continued to be dispersed laterally and transported by incipient channels and down-slope processes farther down-slope. As a consequence, sediments began to be deposited and prolonged deposition, and eventually formed the proto-Kaoping Fan, mainly fed by a point sediment source of the mouth of the middle reach of the Kaoping Canyon (Fig. 9a).

It is highly postulated that the transition from stage1 of point source to stage2 of lateral source. We follow the hypothesis of Chiang and Yu (2006) which suggested that the lower reach of the Kaoping Canyon was rejuvenated due to an increase in gradient by structural uplift to accelerate the incision of canyon course and extended course to the south. The lower reach of the Kaoping Canyon continued to excavate seabed down-slope and transport sediments down-canyon, and sediments over-spilled out of the canyon course sporadically and were deposited laterally over the preceding Kaoping Fan (Fig. 9b). In the second stage, the Kaoping Fan may continue as a slope fan mainly fed laterally by over-spilled sediments from the canyon course rather than by a point source from the canyon mouth. In this stage, the deposits in the fan were characterized by stratified, parallel to sub-parallel low-amplitude reflections with variable continuity which resulted probably from deposition of sediments from over-spilled turbidity currents in the Kaoping Canyon to the east. It is noted that some reflections are tilted in different directions. Other reflections are shown in wavy or undulation forms with varying reflection terminations. Apparently, these fan deposits in the Kaoping Slope were possibly undergone deformation under regional compression in a collision setting, resulting in disruption of these stratified, parallel to sub-parallel reflections. The vertical distribution of seismic facies II and III of the fan deposits suggests that initially the accommodation space of the Kaoping Fan was mainly filled by channelized and over-bank sediments and down-slope transported deposits which were later overlain by laterally supplied over-spilled turbidite facies mainly from the Kaoping Canyon to the east. As a result, channelized and over-bank deposits with a point source gave way to laterally supplied sediments over-spilling out of the canyon during the development of the fan from stage 1 to stage 2. It is noticed that the dip profile MW-1 shows that deposits of the lower part in the proximal fan being thicker than that in the distal fan (Fig 8). It probably resulted from combined effects of sedimentation and paleo-topography. Spilled sediments out of the Kaoping Canyon are preferentially deposited in the proximal fan confined by the small ridge rather than to the distal fan farther down slope, resulting in thick accumulation of sediments. The small ridge separating proximal fan from distal fan serves as a topographic barrier for sediments transport down fan (Figs 1 and 3). Apparently, sediments from the feeding canyon fill in less confined proximal fan, and excess sediment flows over-spill to the distal fan farther down-slope.

In the final stage, the lower reach of the canyon broke the small ridge and extended about 100 km down slope, and it finally merged into the Penghu submarine canyon (Figs 3 and 9c). The upper section (I) of the reflection shows high-amplitude and good continuity, indicating that the over-spilled sediments from the lower reach are supplied continually and accumulate over the preceding Kaoping Fan to form layered turbidite facies (Figs. 5 through 8). Turbidite facies distinguished on the basis of stratified conformable reflectors is about 150 m thick in the upper part. Some moderate-amplitude layered facies on the bank along the west wall of the Kaoping Canyon can be regarded as deposits of levee formed by over-spilled sediment flows from the canyon (Fig. 6). It is likely that hemi-pelagic deposits draped the fan after events of turbidity currents over-spilling laterally from the Kaoping Canyon to the east. The conformable draped hemi-pelagic sediments could be too thin to be distinguished from layered turbidite sequences from our seismic profiles. The uppermost section of the fan is characterized by relatively flat continuous and conformable reflections which are confined or terminated by low-relief structural highs with distinct onlap termination pattern. For examples, onlap patterns of the uppermost sections appear at the NW end of the fan deposits on profile 809-2 (Fig. 6) and at the SE end on the profile 809-3 (Fig. 7), respectively. It is inferred that lateral over-spilled sediments from the Kaoping Canyon are dominated by fine-grained turbidites. Hemi-pelagic sediments together with fine-grained turbidites are mainly settled down by suspension and draped over the partially filled shallow intra-slope depression, resulting in flat continuous and conformable reflections against structural highs at depression margins with distinct onlap termination pattern. However, it is not ruled out that some over-spilled sediments from the Penghu Canyon make a contribution to the onlap feature. Typhoons and frequent earthquakes are considered as potential trigger mechanism for generating turbidity currents in the Kaoping Canyon. It is noted that frequent earthquakes and typhoon-flooding events in southern Taiwan, including the Kaoping Slope, (e.g., the 2006 earthquake and the 2009 Typhoon Morakot) resulted in slope failures causing breakage of communication cables and the generation of turbidity currents in the Kaoping Canyon (Hsu et al., 2008; Su et al., 2012). Therefore, it is inferred that the layered deposits of the fan originated from the laterally over-spilled turbidity currents in the Kaoping Canyon seems reasonable. The deposits of the Kaoping Fan in the shallow upper section consist of the distinct seismic facies: layered high-amplitude and continuous reflections. This seismic facies is comparable to the strata vertical stacking patterns of layered facies in the shallow successions of the deep-water slope settings in the Gulf of Mexico and the Niger Delta. The layered facies in the upper section has been interpreted as the turbidite-sheet sedimentary facies (Adeogba et al., 2005; Beaubouef and Friedmann, 2000; Prather et al., 1998). The Kaoping Fan has been incised by the lower reach of the Kaoping Canyon as it delivered sediments across the lower boundary of the Kaoping Fan and accumulated sediments in the topographically lower depression of the Penghu Canyon. The canyon course of the lower reach completely passes through the Kaoping Fan and supplies over-spilled sediments laterally from the canyon to feed the Kaoping Fan continuously, forming a typical transient fan with two major characteristics: canyon incision and sediment by-passing that cannot be seen in the terminal fan (Fig. 9c). It is emphasized here that the developing lower reach of the Kaoping Canyon is dominated by sediment bypassing with sediment flows excavating along the canyon length and crossing the transition fan.

5.3 Canyon-fan systems

In the east of the Kaoping Canyon, the nearby shelf-indenting Fangliao Canyon extends down-slope and terminates at the upper slope at a water depth around 900 m (Chiang et al., 2012). In front of the mouth of the Fangliao Canyon, sediment flows spread out radically and sediments from the point source accumulate to form a submarine fan at the mid-slope (Fig. 2). The Fangliao Fan is recognized as a ponded submarine fan, as sediment flows from the canyon mouth being prevented from farther down-slope transport due to ponding against a linear bathymetric ridge in a water depth about 1,100 m (Hsiung et al., 2014). Neither from the landward river nor from the littoral sediment cells of the shelf, the head of the Fangliao Canyon receives low sediment supply, which results in a starved ponded Fangliao Fan (Hsiung et al., 2014).

The topographically complex Kaoping Slope is characterized by the presence of two contrasting types of submarine fan. The Kaoping transient fan at the lower slope is mainly fed laterally by the Kaoping Canyon. Although the river-connecting Kaoping Canyon receives much sediment at its head, the canyon is dominated by sediment bypassing, resulting in absence of a terminal fan at the slope base, but a transient fan at the lower slope instead. In contrast, the ponded Fangliao Fan at mid-slope is associated with a shelf-indenting canyon with low sediment supply. Applying the model of fill-and-spill in slopes with complex topography to the evolution of the Fangliao Fan, this study suggests that the Fangliao Fan will be filled with sediments continually, excess sediments can spill over the linear ridge currently terminating the fan (Gamberi and Rovere, 2011; Prather et al., 1998). Hence, the ponded Fangliao Fan will evolve into a transient fan with time. These two types of canyon-fan systems, occurring in the Kaoping Slope, may serve as an analog for similar canyon-fan systems developed on topographically complex slopes elsewhere.

6 Conclusions

The Kaoping Fan was recognized as a general slope submarine fan associated with the Kaoping Canyon (e.g., Chiang and Yu, 2006; Yu et al., 2009). We re-interpreted the Kaoping Fan as a transient submarine fan, emphasizing topographic and structural effects on the development of the Kaoping Fan as being fed laterally by the Kaoping Canyon in the east. The modern Kaoping Fan is characterized by the presence of the incised lower reach of the Kaoping Canyon passing through and by sediments bypassing to and beyond the base of the Kaoping Slope. These are two distinct criteria for recognition of a transient fan formed in topographically complex slopes.

We infer that initially the Kaoping Fan is fed mainly from a point source at the apex of the fan. The proto-fan deposits are mainly built up by channel fills. The Kaoping Fan is later fed laterally by over-spilled sediments from the lower reach of the Kaoping Canyon and confined by mud-diapiric ridges in the east, forming an asymmetrical triangular shaped bathymetric feature skewed to the east. The vertical stacking seismic patterns of the fan deposits suggest that the Kaoping Fan recorded the onset of channelized and over-bank deposits in the lower part and layered turbidite facies in the upper part subsequently. The development of the Kaoping transient fan can be divided into three stages in terms of canyon activities and fan-feeding processes. Channelized and over-bank deposits with a point source gave way to laterally supplied sediments over-spilling out of the canyon during the development of the fan from stage 1 to stage 2. In the final stage, lateral over-spilled sediments from the lower reach of the canyon are supplied continually and accumulate over the preceding fan deposits to form layered turbidite facies.

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Captions

Fig. 1 (a) Four types of submarine fans occur on the slope and basin floor in both active and passive margins. The ponded and transient fans commonly appear in the upper slopes influenced by the topographic effects. (b) The pre-existing topography of the intra-slope basin at the upper slope controlled the shape and areal extent of deposits which are confined by mud-diapiric ridges, resulting in a ponded fan. (c) The canyon course of the lower reach completely passes through the Kaoping Fan and supplies over-spilled sediments laterally from the canyon to feed the Kaoping Fan continuously, forming a typical transient fan with two major characteristics: canyon incision and sediment by-passing.

Fig. 2 Submarine canyons are developed on the narrow Kaoping Shelf and the broad Kaoping Slope from northwest to southeast along the shoreline. PHC: Penghu Canyon, SSC: Shoushan Canyon, KHC: Kaohsiung Canyon, KPC: Kaoping Canyon, FLC: Fangliao Canyon. The Kaoping Canyon with a length of about 260 km is the longest among these canyons and the feeder for the Kaoping Fan. It is noted that sediments derived the Kaoping Canyon are transported farther down-slope to the deep-sea Penghu Channel and are finally deposited in the northern Manila Trench (modified from Hsiung and Yu, 2011). The inset at the lower left corner is the map of the regional tectonic setting of the Taiwan region. The box indicates the study area.

Fig. 3 The Kaoping Fan is shown as a triangular-shaped bathymetric feature coded in blue color, the Kaoping Canyon is coded in yellow color passing through the eastern part of the Kaoping Fan, and the lower slope in the study area is imaged by three strike-aligned seismic reflection profiles in NW- SE direction and one dip seismic section in the nearly E-W direction to determine the morpho-sedimentary features and processes for the development of the Kaoping transient fan terminated on the lower slope in a water depth around 3000 m.

Fig. 4 The color-coded bathymetric map shows that the Kaoping Fan has an asymmetrical triangular fan-shape feature elongated in a NW-SE direction but with a strong skew toward the east. This fan can be separated by a small ridge trending northwest approximately following the 2,400 m isobath into two bathymetric lobes: a proximal fan and a distal fan. Bathymetric map indicates that near the end of the middle reach of the Kaoping Canyon the southward canyon course is blocked by the ridge marked by Y, forced to turn sharply to the west, and then changes its course to the south again. In the lower reach the southward canyon course is blocked by the ridge marked by Z, turned sharply to the west, and then returns its southward course again. The Kaoping Fan has a relatively small areal extent restricted in the topographic lows confined by structural highs due to mud diapiric uplifting and thrust faulting. (modified from Chiang and Yu, 2006; Yu et al., 2009).

Fig. 5 Seismic profile 809-1 in a NW-SE direction crosses the proximal part near the apex of the Kaoping Fan which is bounded by the Kaoping Canyon and a rising diapiric ridge to the east. The surface of the

Kaoping Fan is characterized by a relatively smooth and flat seismic reflector. The fan deposits are mainly represented by the layered high-amplitude reflections overlying stratified, parallel to sub-parallel low-amplitude reflections with variable continuity. Parts of these low-amplitude reflections are shown in wavy or undulation forms and some reflections are tilted in different directions, resulting from regional compression effect. Channel fills with strong reflectors can be discerned in the lower part of the stratified low-amplitude reflections. The thickness of the fan deposits is about 0.8 second in TWT.

Fig. 6 Seismic profile 809-2 farther down-fan shows that the fan deposits consist of two distinct types of seismic facies: the shallow successions of high-amplitude layered facies overlying the successions of stratified, parallel to sub-parallel low-amplitude reflections and channel fills facies below. The thickness of the fan deposits is about 0.8 second in TWT. The surface of the fan is represented by a west tilting inclined reflector. There exists a small ridge which uplifts the fan surface and separates the fan into a proximal fan and a distal fan. It is noted that parts of sediments from the Kaoping Canyon are over-spilled to the east side of the canyon, forming a part of the Kaoping Fan.

Fig. 7 Seismic profile 809-3 farther down-slope crossing the distal fan shows that the fan deposits are characterized by high amplitude layered seismic facies about 0.2 second TWT in the upper section, and stratified, parallel to sub-parallel low-amplitude reflections and channel fills facies about 0.6 second TWT in the lower section. The fan surface is a relatively smooth reflector bounded by a broad structural high to the east.

Fig. 8 The dip-oriented seismic profile MW-1 extending from the fan apex to the lower limit bordered by the Penghu Canyon shows a gentle inclined smooth surface separated by a noticeable ridge formed by thrusting faults. The proximal fan is located up-dip of the ridge and the distal fan is situated down-dip of the ridge. The fan deposits consist of two main seismic facies: layered high-amplitude reflections in the upper section and stratified, parallel to sub-parallel low-amplitude reflections and channel fills in the lower section. KPC: Kaoping Canyon, PHC: Penghu Canyon.

Fig. 9 The development of the Kaoping transient fan can be divided into three stages in terms of canyon activities and fan-feeding processes. (a) In stage 1, the growth of the Kaoping Canyon was limited to the middle reach where the canyon mouth opens to the lower slope. Sediment flows coming out of the Kaoping Canyon mouth were transported down-slope, spread unconfined laterally, and deposited at the lower slope, forming the proto fan mainly fed by a point sediment source of the Kaoping Canyon. (b) In stage 2, the Kaoping Fan maintained as a slope fan fed laterally by over-spilled sediments from the lower reach of the Kaoping Canyon rather than by a point source from the canyon mouth. (c) In stage 3, the lower reach of the Kaoping Canyon was rejuvenated due to increasing gradient by structural uplift to accelerate the incision of canyon course and extend farther down-slope, and finally merges into the deep-sea Penghu Channel. The lower reach completely passes through the Kaoping Fan and supplies over-spilled sediments laterally from the canyon to feed the Kaoping Fan continuously, forming a typical transient fan. Arrows indicate sediment transport directions. Locations of submarine cable breakage are marked along the Kaoping Canyon and deep-sea Penghu Channel associated with events of 2006 Pingtung earthquake and 2009 Morakot typhoon and flooding. It is implied that frequent earthquakes and typhoon-flooding events in southern Taiwan resulted in generation of turbidity currents in the lower reach of the Kaoping Canyon which not only caused breakage of communication cables but also produced over-spilled sediments feeding the Kaoping transient fan laterally.

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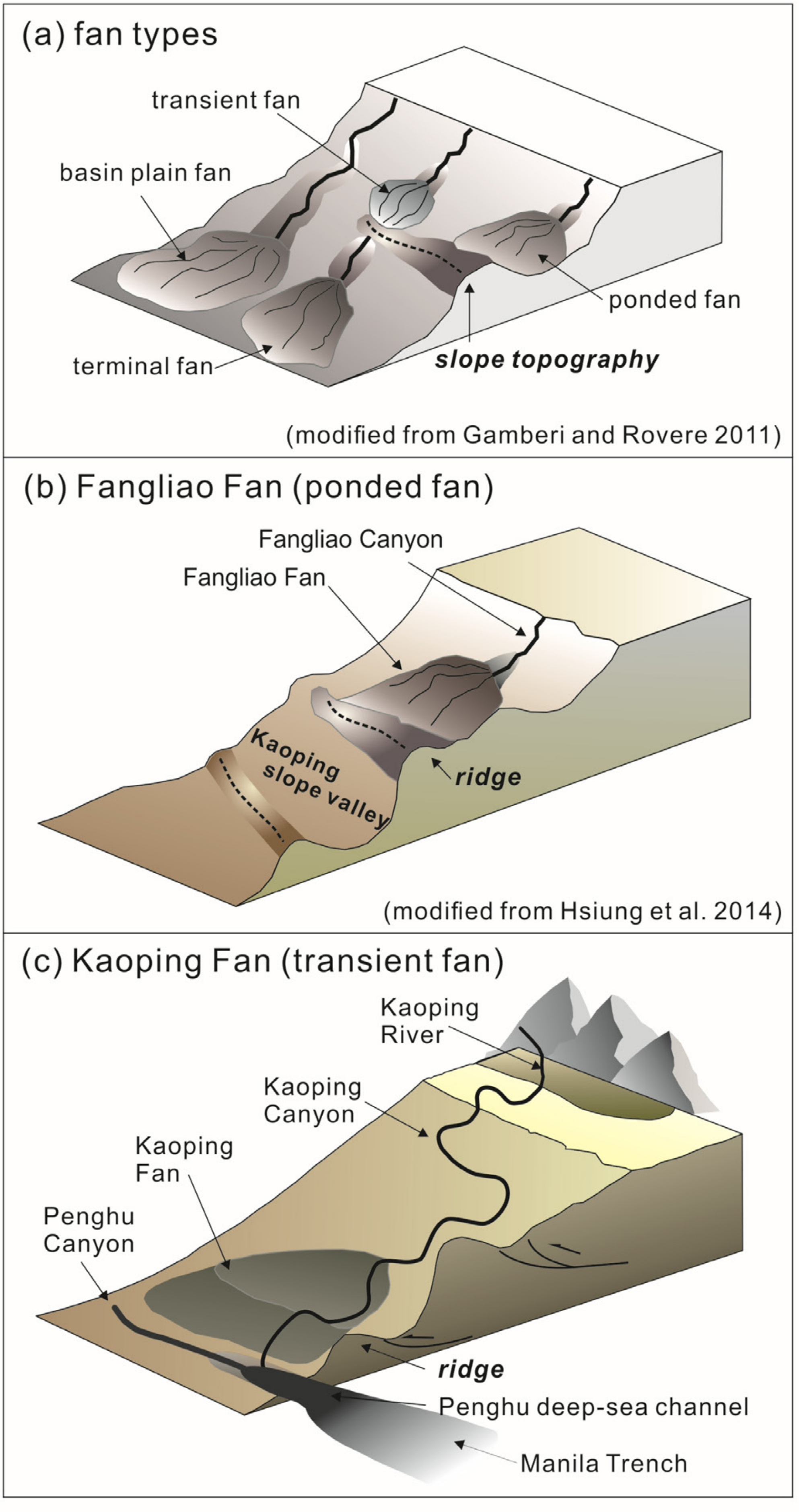
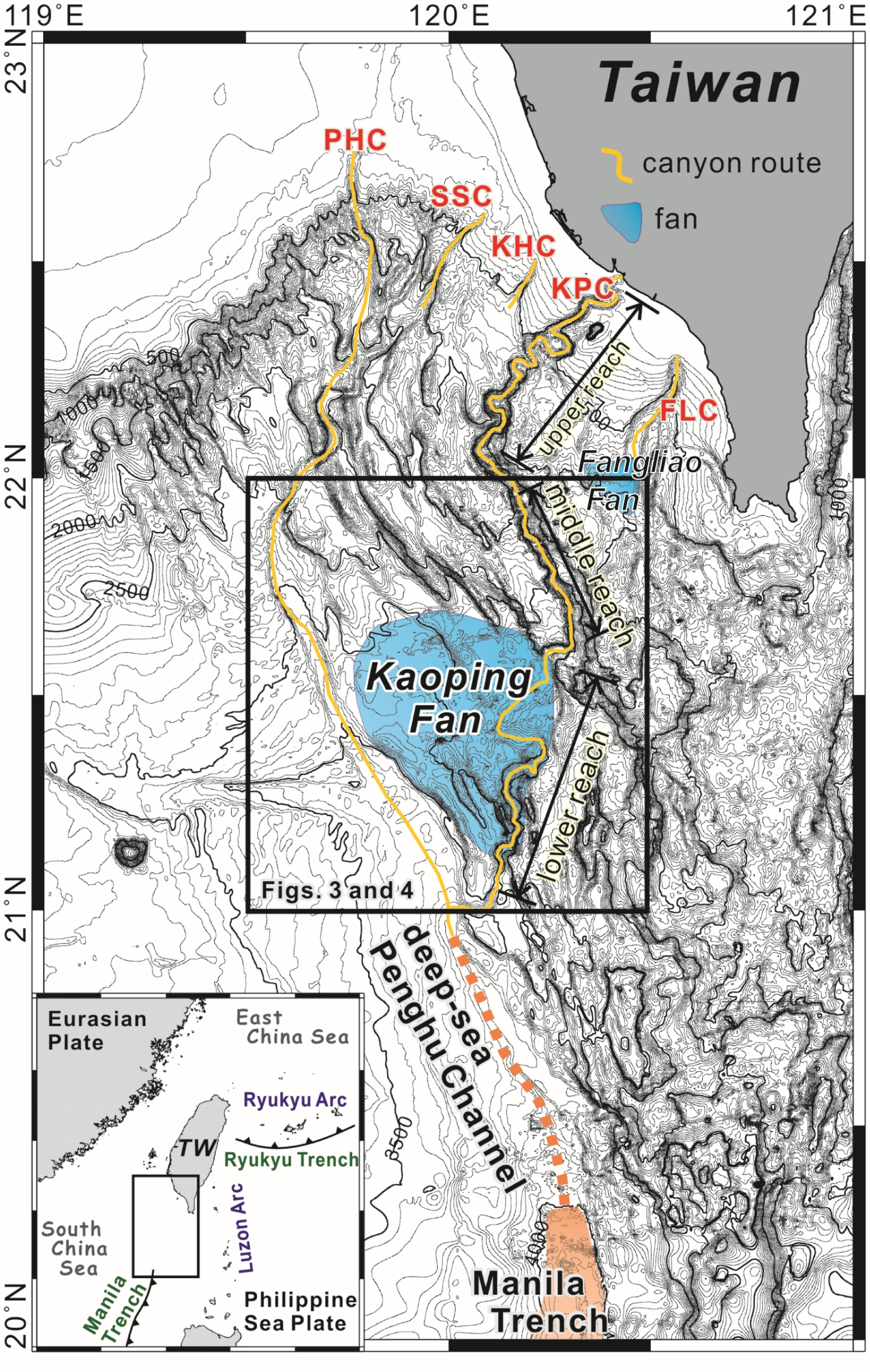
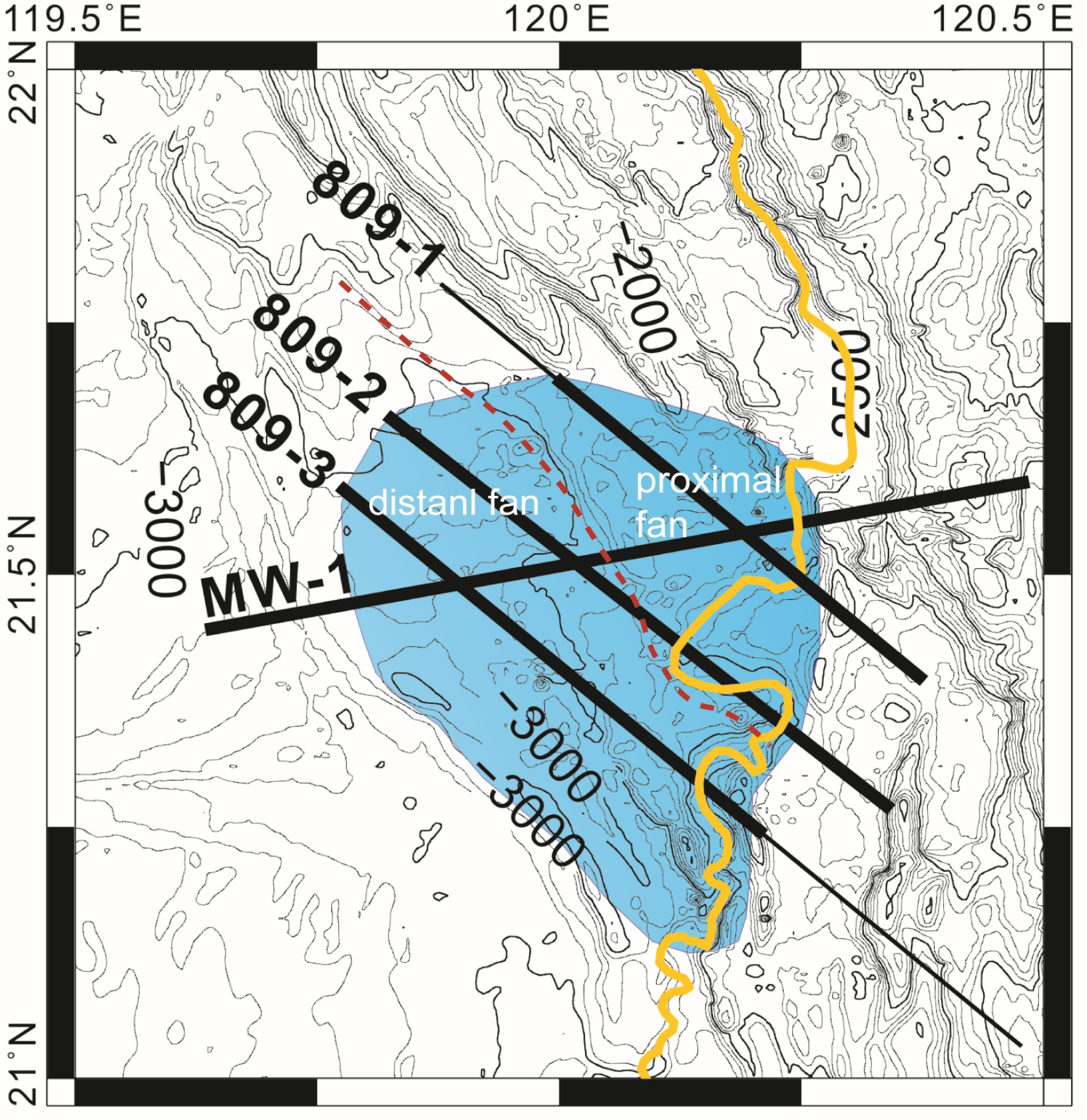
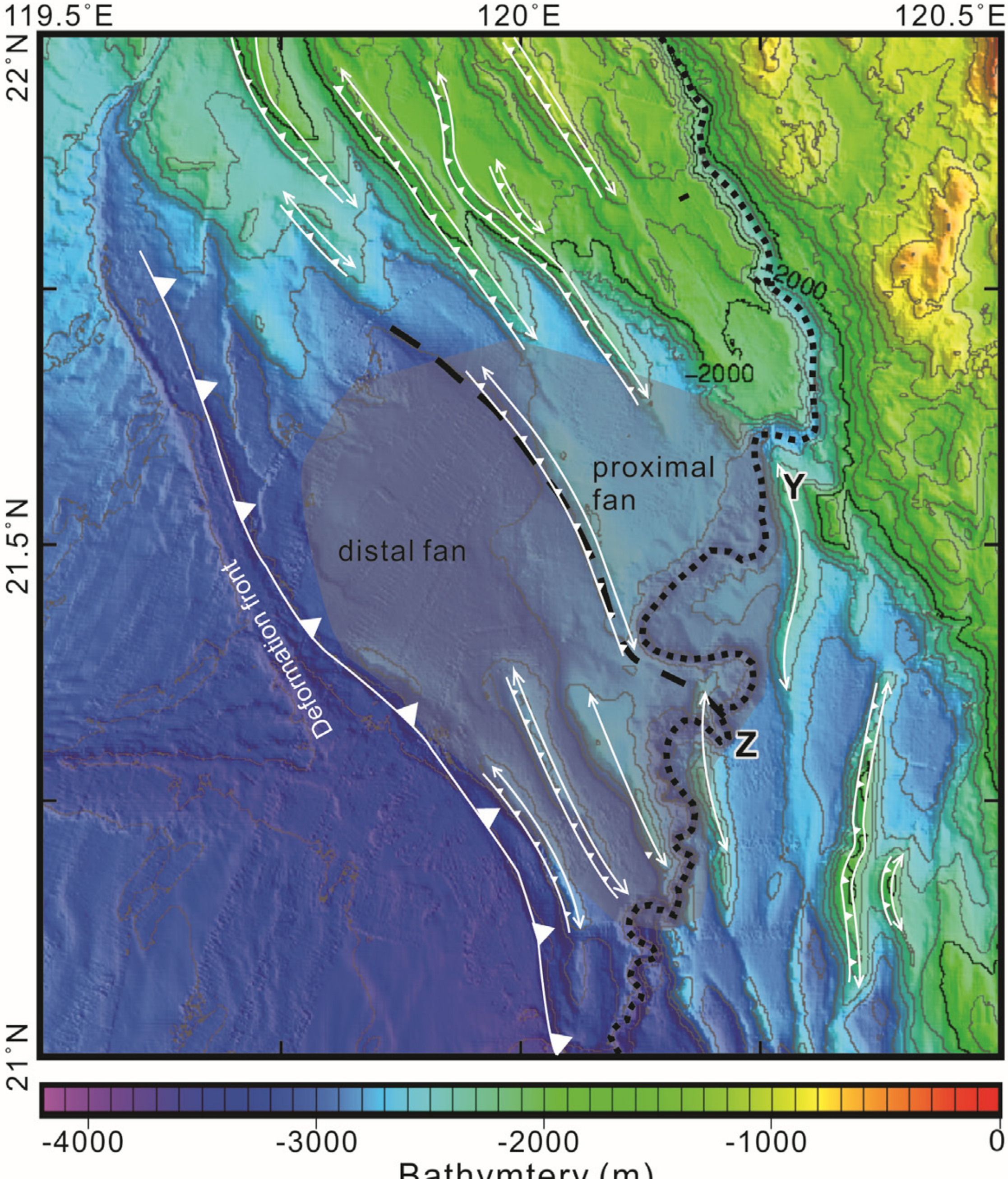

(a) fan types
transient fan
basin plain fan
ponded fan
terminal fan
slope topography
(modified from Gamberi and Rovere 2011)
(b) Fangliao Fan (ponded fan)
Fangliao Canyon
Fangliao Fan
Kaoping slope valley
ridge
(modified from Hsiung et al. 2014)
(c) Kaoping Fan (transient fan)
Kaoping River
Kaoping Canyon
Kaoping Fan
Penghu Canyon
ridge
Penghu deep-sea channel
Manila Trench



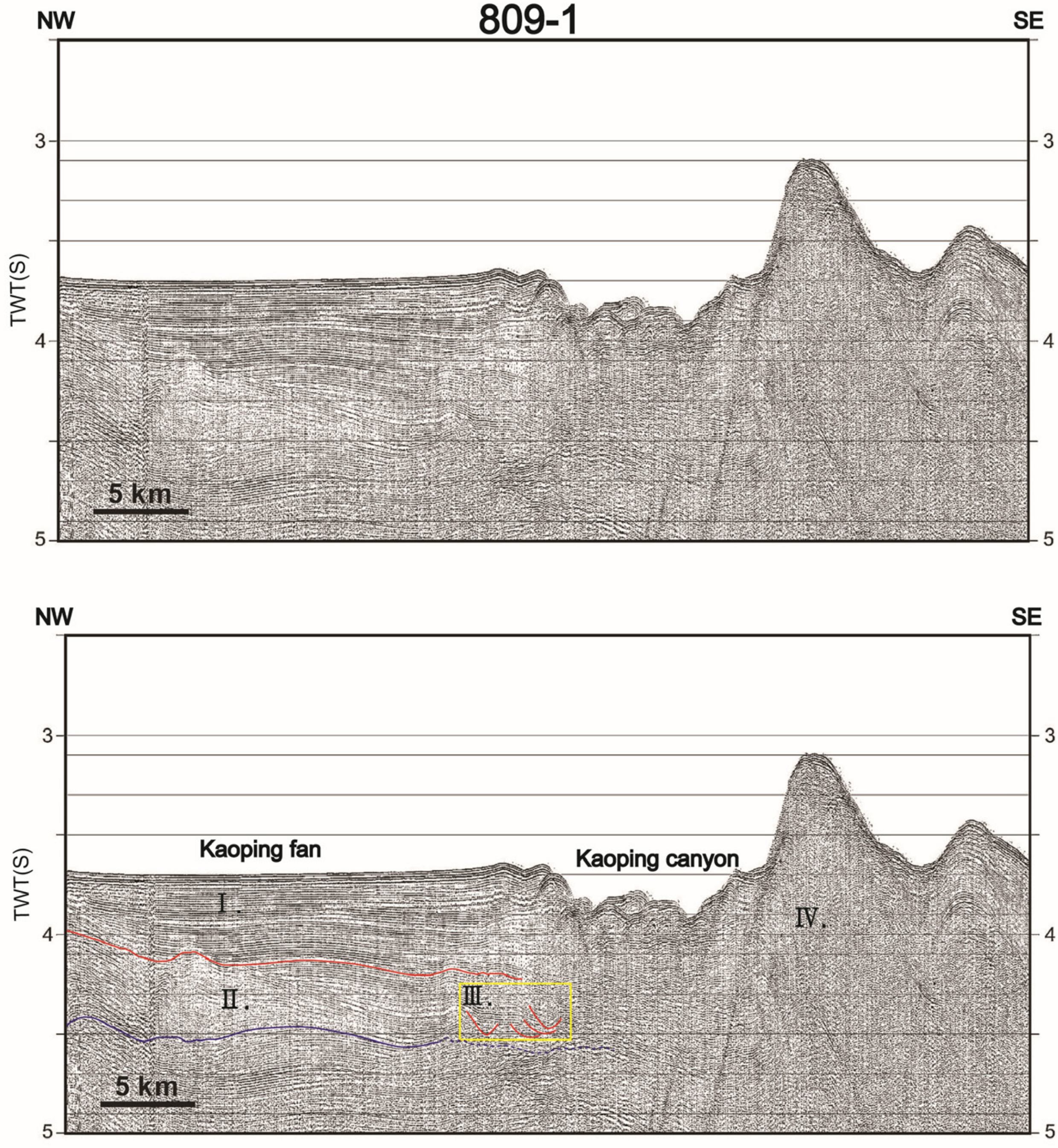
119˚E
120˚E
121˚E
23˚N
22˚N
21˚N
20˚N
Taiwan
canyon route
fan
PHC
SSC
KHC
KPC
FLC
Fangliao Fan
upper reach
middle reach
lower reach
Kaoping Fan
Figs. 3 and 4
deep-sea Penghu Channel
Manila Trench
500
1000
1500
2000
2500
3500
4000
Eurasian Plate
East China Sea
Ryukyu Arc
Ryukyu Trench
TW
South China Sea
Luzon Arc
Manila Trench
Philippine Sea Plate



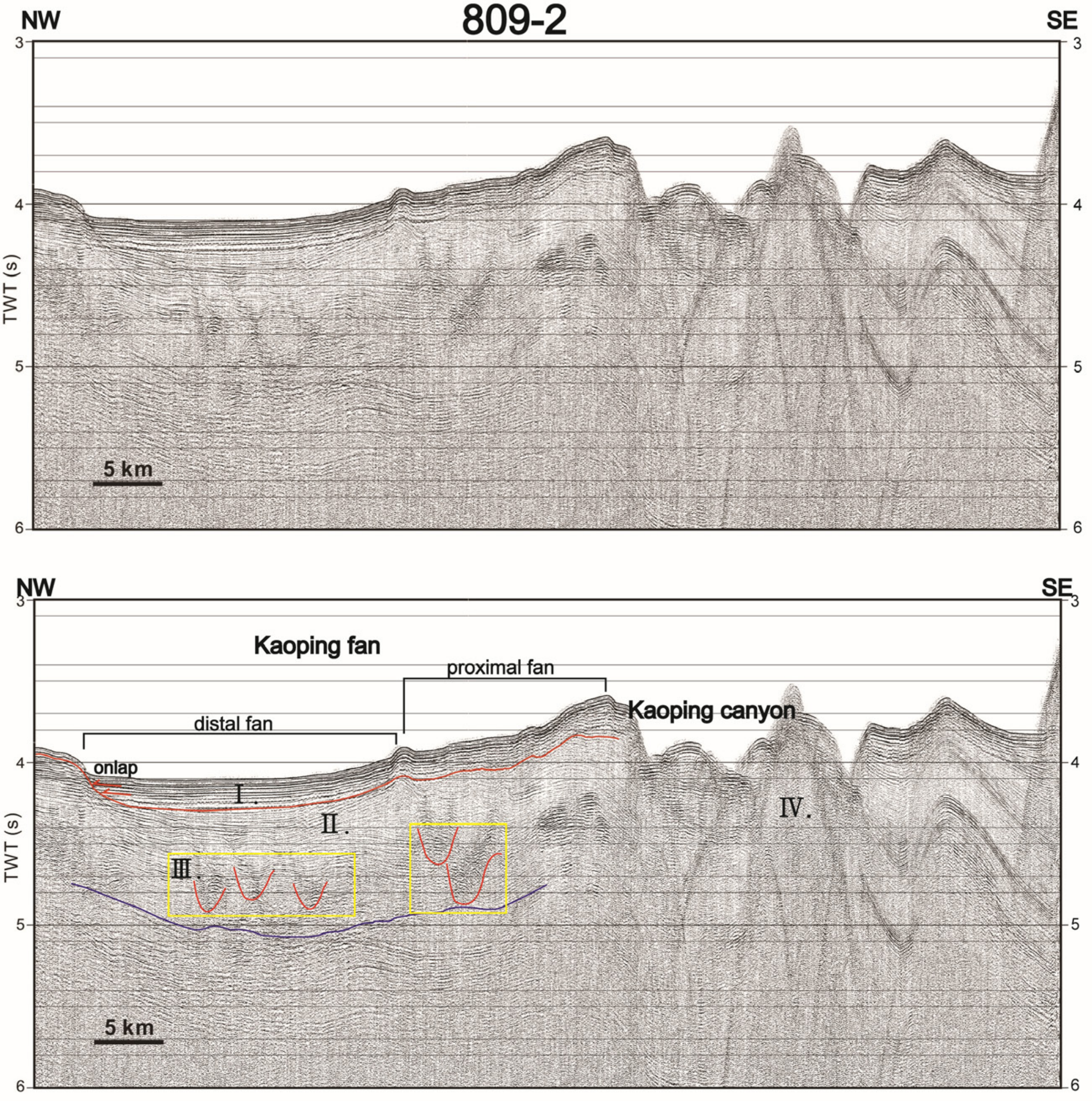
119.5˚E
120˚E
120.5˚E
22˚N
21.5˚N
21˚N
809-1
809-2
809-3
MW-1
−2000
2500
−3000
−3000
−3000
distanl fan
proximal
fan

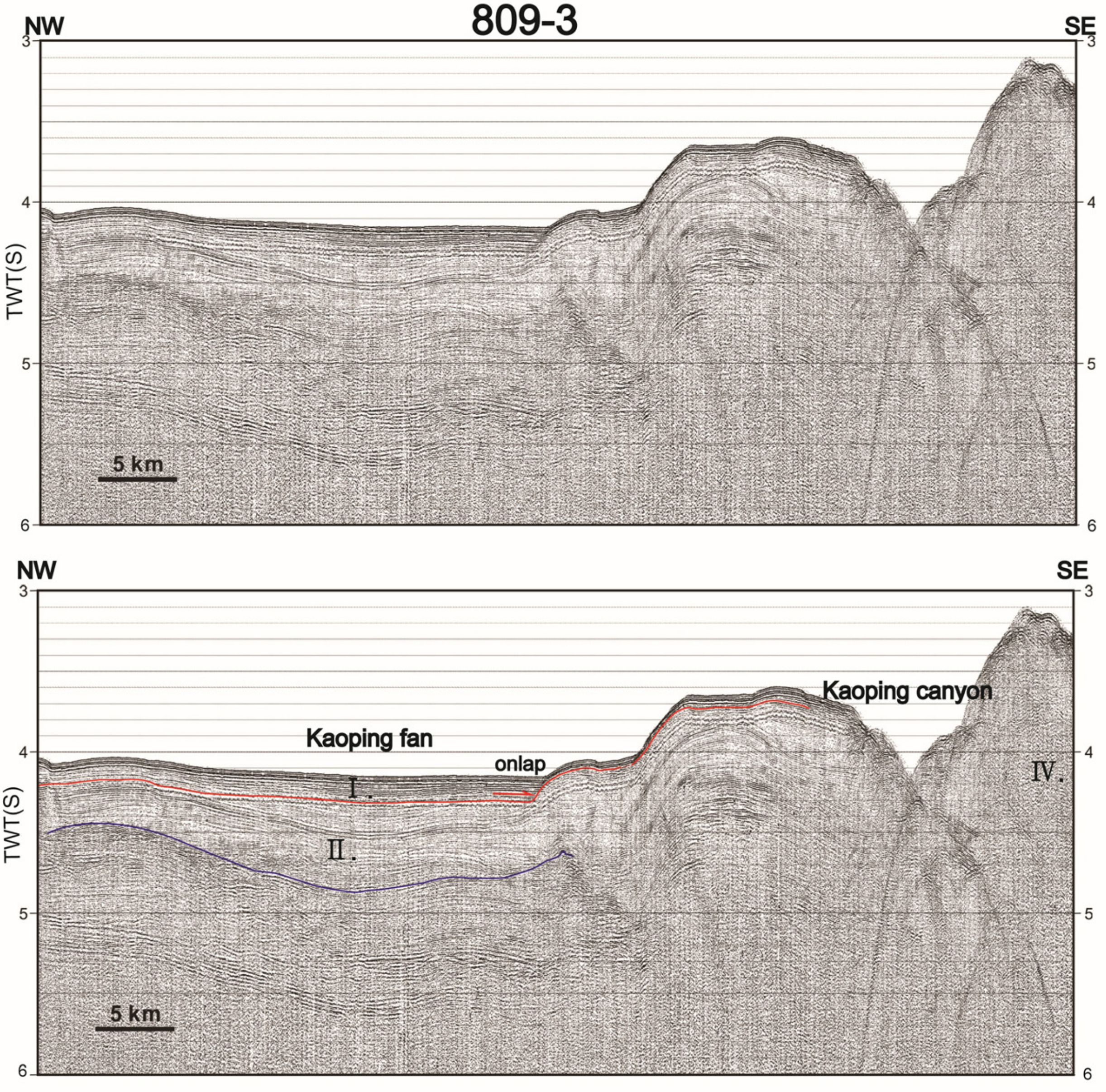


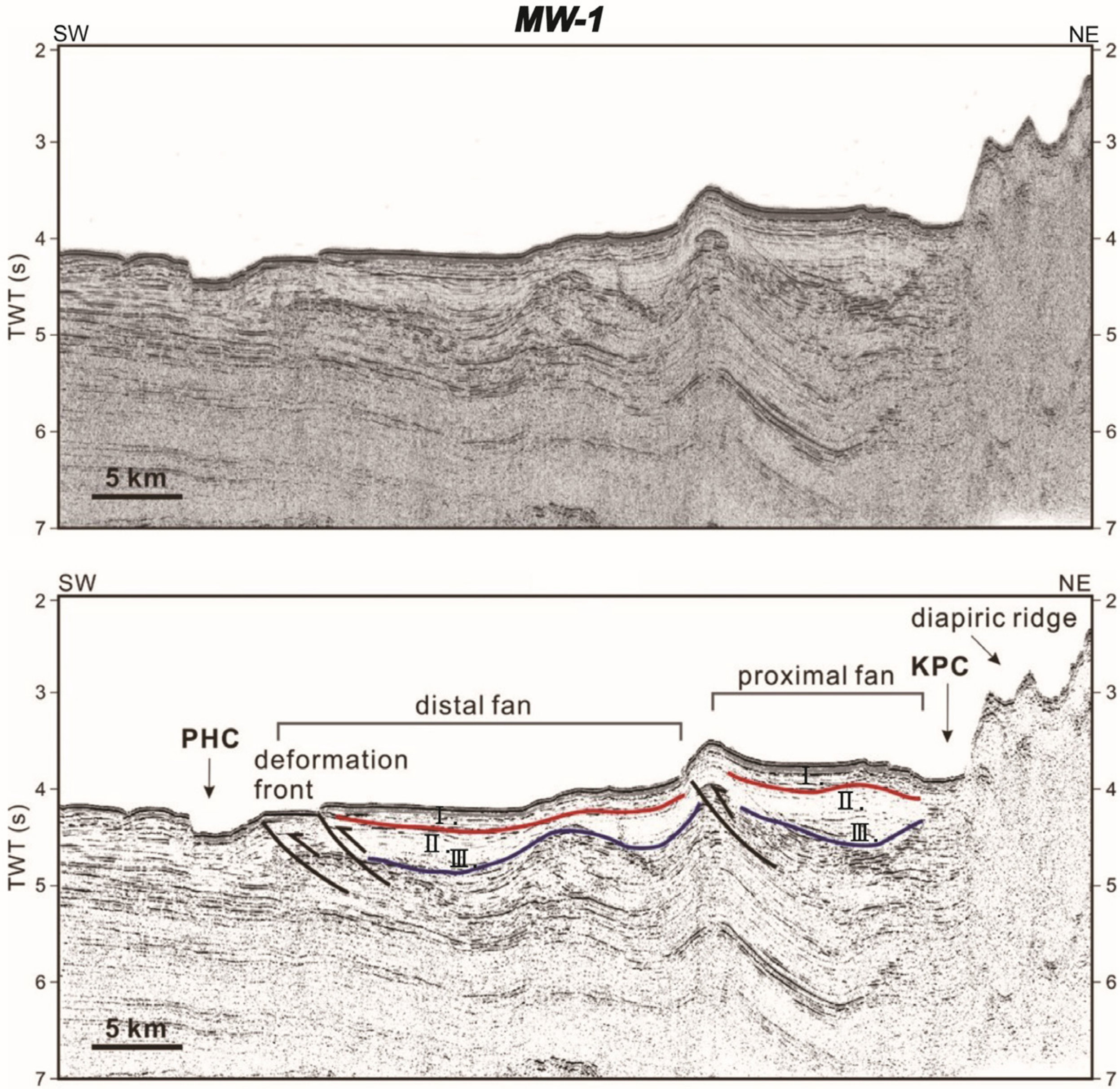
119.5˚E
120˚E
120.5˚E
22˚N
21.5˚N
21˚N
-2000
-2000
proximal fan
distal fan
Deformation front
Y
Z
-4000
-3000
-2000
-1000
0
Bathymtery (m)

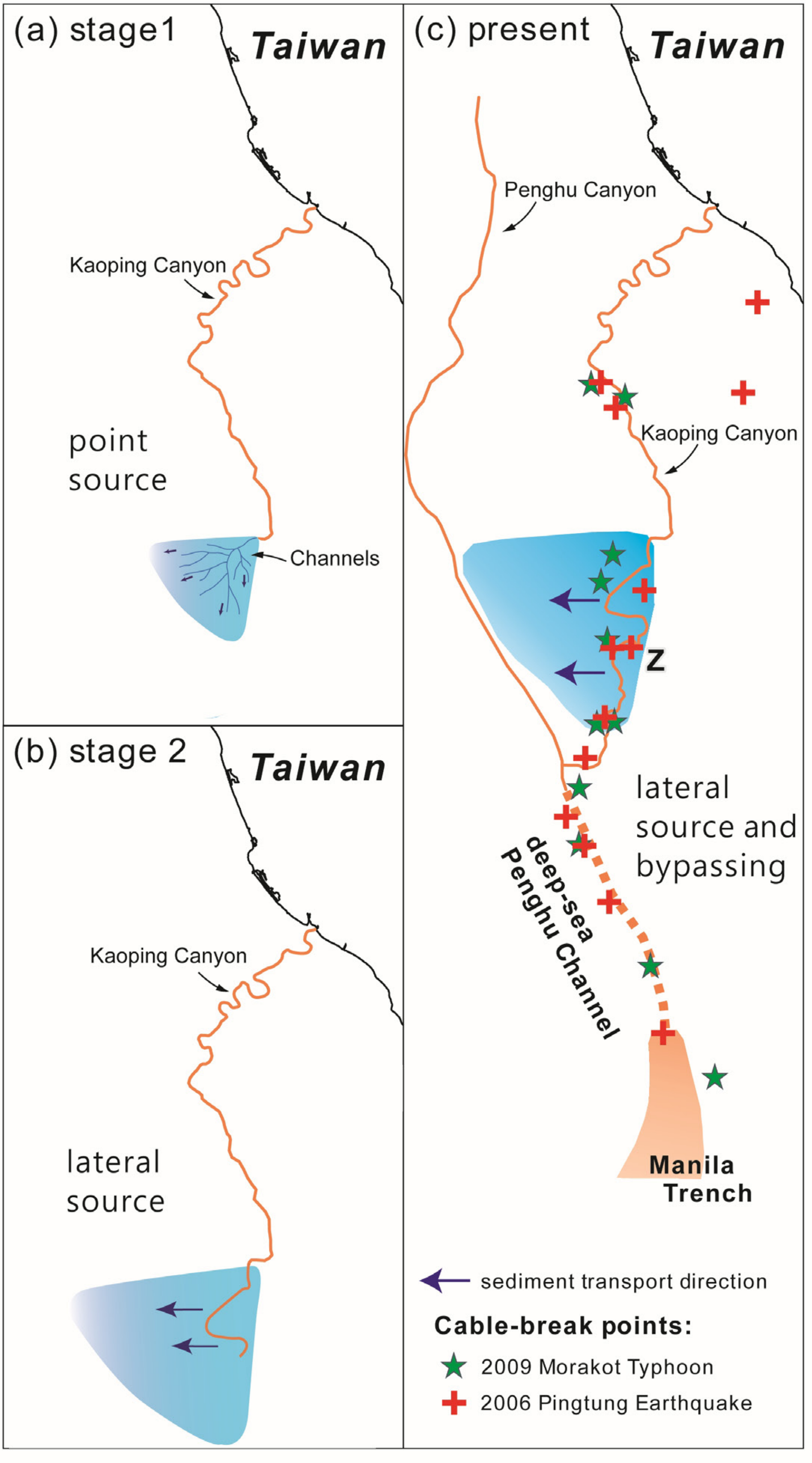


809-1
NW
SE
TWT(S)
3
4
5
5 km
Kaoping fan
Kaoping canyon
I.
II.
III.
IV.


809-2
NW
SE
TWT (s)
5 km
Kaoping fan
proximal fan
distal fan
Kaoping canyon
onlap
I.
II.
III.
IV.


809-3
NW
SE
TWT(S)
3
4
5
6
5 km
NW
SE
3
4
5
6
TWT(S)
Kaoping fan
Kaoping canyon
onlap
I.
II.
IV.
5 km


MW-1
SW
NE
TWT (s)
5 km
PHC
deformation front
distal fan
proximal fan
KPC
diapiric ridge
I.
II.
III.

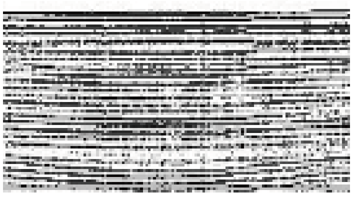
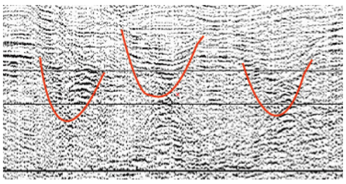


(a) stage1
Taiwan
Kaoping Canyon
point source
Channels
(b) stage 2
Taiwan
Kaoping Canyon
lateral source
(c) present
Taiwan
Penghu Canyon
Kaoping Canyon
Z
lateral source and bypassing
deep-sea Penghu Channel
Manila Trench
sediment transport direction
Cable-break points:
2009 Morakot Typhoon
2006 Pingtung Earthquake

Table 1 orphological variations in bathymetry, dimensions, and sediment thickness of the KaopingFan

Kaoping Fan	proximal part	distal part
bathymetry (m)	2,200 – 2,400	2,400 - 3,000
area (km^2)	135	1,320
arc length (km)	60	85
Layered parallel reflections (s, twt)	0.1 ─ 0.5	0.1 – 0.3
Laminated subparallel reflections (s, twt)	0.2 ─ 0.8	0.1 – 0.8

Table 2 Illustration of the four seismic facies and associated interpretation identified on the Kaoping Fan

Seismic facies		**Reflection configuration, amplitude and continuity**	**Interpretation**
☒.		Layered parallel reflections with high amplitude and good continuity (EVEN)	Overspill turbidites with hemipelagic deposits
II.		Laminated subparallel reflections with low amplitude and variable continuity	Unconfined channelized and overbank deposits
III.		Layered high-amplitude reflections occurring in channels	Channel fills
IV.		Chaotic or free reflection facies	Mud diapir