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Decoupled Transcurrent Faults in the Offshore Area South of Taiwan

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ABSTRACT

A simple shear deformation model is proposed to interpret the observed strike-slip faults in the Luzon subduction-Taiwan collision zone south of Taiwan. Seismic reflection data, gravity and magnetic anomaly, and previous solution of focal mechanism are analyzed to study the feasibility of decoupling hypothesis. Three sets of strike-slip faults are recognized in the collision-subduction zone of the offshore area south of Taiwan: the left-lateral strike-slip fault system associated with the Luzon volcanic arc, the right-lateral strike-slip fault system within the arcside of the accretionary wedge and forearc basin, and the left-lateral strike-slip faults located at the frontal portion of the accretionary wedge. The left-lateral strike-slip fault system associated with Luzon volcanic arc and the left-lateral fault system located at the frontal portion of the accretionary wedge can be explained as the decoupled transcurrent faults. The right-lateral strike-slip faults located within the arc-side of the accretionary wedge and forearc basin are induced from these two bounding transcurrent faults, which caused the forearc block rotation.

INTRODUCTION

Taiwan is the site of present-day Arc-continent collision between the Luzon Arc of the Philippine-Sea Plate and the Chinese continental margin. The collision is oblique because the arc is oriented north-south whereas the continental margin is oriented N61° E (Suppe, 1984). A model for oblique convergence between plates of lithosphere has been proposed by Fitch (1972) in which the slip component parallel to the plate margin causes transcurrent movements on a nearly vertical fault along a weak zone of overriding plate. The Semangko fault in Sumatra, the Atacama fault in Chile and the Philippine fault are examples of these transcurrent movements. In the extreme case of complete decoupling, only the slip component normal to the plate margin can be inferred from underthrusting. Becker (1983) studied the mechanism of tectonic transport in zones of oblique subductioin and sugoested that the condition for Sunda-type tectonics:

$$\tan \gamma > (\gamma_t/\gamma_s)\sin \Delta \qquad (1)$$

where γ = convergence angle,

Δ = dip of the subducting slab,

γ_s = resistance to slip per unit area along oblique-slip,

γ_t = resistance to motion on the transcurrent movements (Fig. 1).

Given γ_t=γ_s and subduction angles of roughly 30^o, Sunda-style tectonics should be favored when the angle of oblique convergence exceeds 20^o. The γ_s and γ_t will decrease for a time after the subduction zone becomes established, since fluid pressure build up in response to dehydration reactions in subducting surficial rocks. Thus increasing age of the subduction zone favors Sunda-style tectonic. The most dramatic and rapid reduction in γ_t, would be in the neighborhood of the magmatic arc or within zones of weakness.

The Philippine-Sea Plate is moving toward the Eurasian Plate in an N55^{o}W direction (Seno, 1977) and the Luzon arc is oriented roughly north-south; the convergence angle is thus about 35^o for this Luzon subduction system. Such convergence angle is sufficient to cause the decoupled transcurrent tectonics. One of the goals of this study is thus to: check feasibility of decoupling hypothesis and identify the possible strike-slip faults (transcurrent faults) in the Luzon Arc area.

The geometry and style of structures associated with strike-slip faulting depend on several factors: the nature of the rock being deformed, the configuration of pre-existing structures, the amount of horizontal slip, and the strain rate (Sylvester, 1990). Two principal mechanisms may explain the geometric and dynamic relations among strike-slip faults and associated structures: pure shear and simple shear. Pure shear produces relatively short, typically conjugate sets of strike-slip faults and bulk shear is irrotation. Simple shear has rotational component of bulk strain and accounts for the kinematics of strike-slip faults at all dimensions. The main zone of modern strike-slip is narrow, but the zone of pervasive simple shear is wide and heterogeneous over geological time.

The area south of Taiwan where the Luzon subduction system gets into contact with Asian continental margin may be an area where the simple shear deformation is occurring. This is because the changing thickness of the subducting plate from oceanic lithosphere of the South China Sea into continental lithosphere of the Chinese continental margin may generate another set of transcurrent faults in the frontal portion of the accretionary wedge, similar to that observed in southern end of the Philippine Trench where the East Morotai Plateau has terminated the subduction process and activated a series of strike-slip faults (Nichols, *et al.,* 1990). This study thus will also investigate the existence of strike-slip faulting at the trench side of the Luzon subduction complex and look for evidence of block rotations in the accretionary wedge in order to evaluate the proposed simple shear deformation model for the offshore area south of Taiwan.

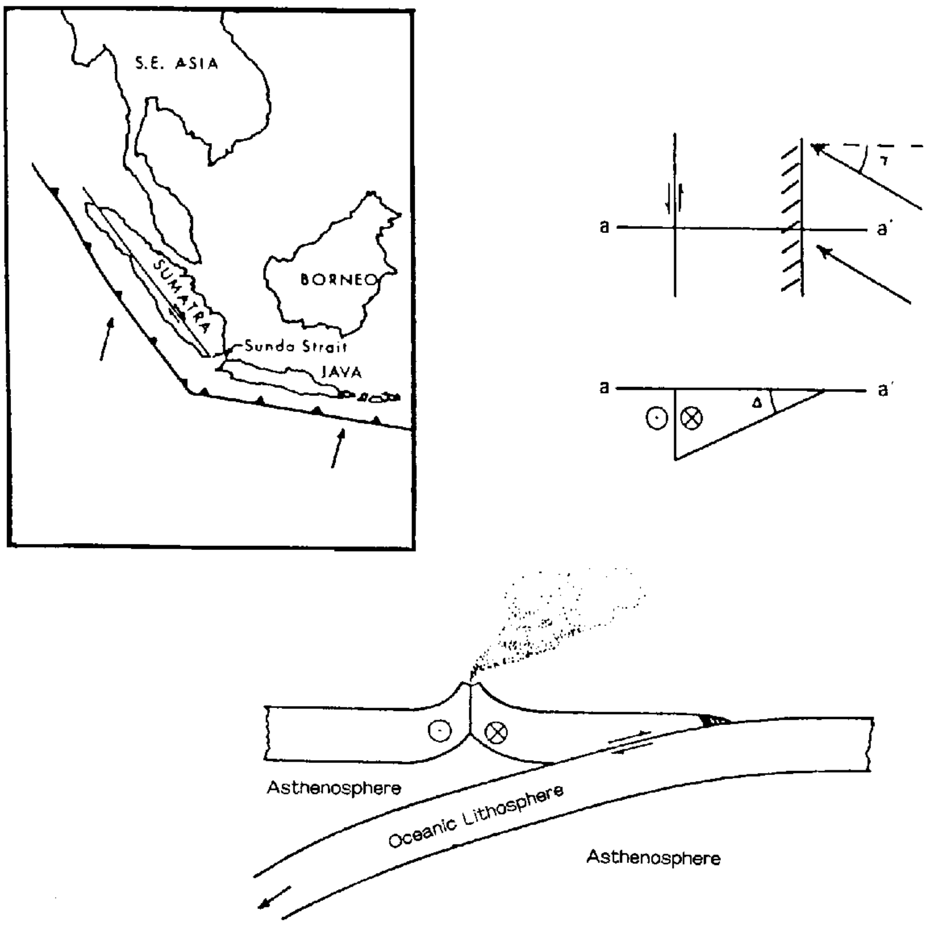

Figure 1. Geometrical relations of Sunda-style plate margin. (a) Simplified tectonic configuration of the Sunda subduction zone. West of Sunda Strait, a subduction-zone transcurrent-fault pair was formed because of the highly obique convergence between the Indian and Asian Plates (arrows); (b) is a cartoon illustrating the geometry of a Sunda-style margin, ã and Ä are the angle of the Benioff-Wadati zone, respectively; (c) is a more geological version of the lower half of (b) and illustrates formation of the transcurrent fault along a thermally-thinned zone coincident with the axis of the magmatic arc (adopted from Becker, 1983).

TECTONIC BACKGROUND

A shaded seafloor relief diagram (Fig. 2) reveals finer features of the tectonic elements of the Luzon subduction-Taiwan collision zone in the study area (Liu *et al.,* 1992). Typical subduction trench-accretionary wedge-forearc basin-volcanic arc type configuration is observed in the southern part of the study area, as represented by the Manila Trench, Hengchun Ridge, North Luzon Luzon Trough, and the Luzon volcanic arc, respectively. The western half of the Hengchun Ridge can be divided into a gently dipping lower-slope area and a steeper upper-slope area. The eastern side of the accretionary prism approaches the North Luzon Trough with a steep scarp. On-going arc-continent collision is proceeding in the northern part of the study area. North of 21° 20'N, the Huatung Ridge narrows the forearc basin into a steep trough (the Taitung Trough). Between the Hengchun peninsula and the Huatung Ridge lies the Southern Longitudinal Trough.

Previous studies have suggested that strike-slip faults may exist in the study area. Fitch (1972) used Taiwan as an example for his oblique convergent-decoupling hypothesis. Karig(1973) proposed the existence of some left lateral strike-slip faults of NE-SW trend in the offshore area between Taiwan and Luzon based solely on the bathymetry data. Using both bathymetry data and some focal mechanism solutions, Lewis and Hayes (1989) proposed the existence of some left lateral strike-slip faults of NW-SE trend but not in detail. The physiographic diagram (Fig. 2) indicates that the closure of the forearc basin near 21° 30'N and, 121° E is abrupt rather that gradual, therefore some strike-slip faults should exist near the area where this abrupt change occurs. However, none of the previous studies have provided detail and sufficient evidence for the locations of the strike-slip faults. Integrated interpretation of seismic reflection data, gravity and magnetic anomalies, and focal mechanism solutions provide more detail and sufficient evidence to locate these strike-slip faults.

EVIDENCE OF THE STRIKE-SLIP FAULTS

This study is based primarily on the analyses of geophysical data collected by the R/V Moana Wave in May/June of 1990 off south Taiwan. Data analyzed included 6-channel digital seismic reflection profiles, and gravity and magnetic anomaly data. The coverage of the study area is from 22° 50'N to 20° 30'N, and the E-W extent of it is from 122° E to 119° E (Fig. 3) Most of the 6-channel seismic reflection data were processed at UC Santa Cruz through 4-fold stack followed by F-K migration using a constant velocity of 1500 m/sec (Reed *et al.,* 1992) and some profiles are processed at the Institute of Oceanography, National Taiwan University (NTU). Gravity and magnetic data were processed and analyzed at the NTU and the Academica Sinica (Kuo *et al.,* 1991; Liu *et al.,* 1992). The major structural pattern revealed from the seismic interpretation emphasizing thrust domain, and a double vergent thrusts model of the accretionary wedge was proposed (Reed *et al.,* 1992). In this study, seismic interpretation will focus on simple shear domain. Total of over 5000 kilometers of seismic reflection profiles (Fig. 3) have been interpreted and the results are mapped. The gravity and magnetic anomaly data and some focal mechanism solutions are incorporated into the seismic interpretations.

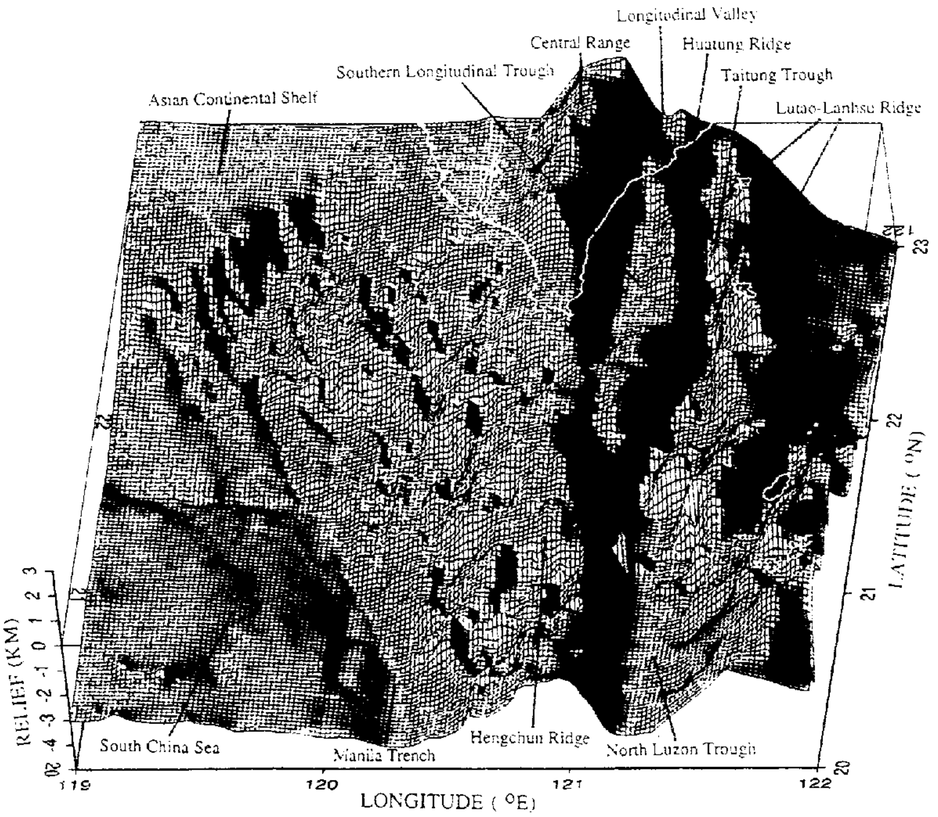

Figure 2. Physiographic diagram of the subduction to arc-continent collision zone south of Taiwan (adopted from Liu *et al*., 1992).

Strike-slip faults could be identified on a seismic section by features such as systematic vertical offset of near-horizontal reflectors, near-vertical zones along which reflector packets with different dips convergence, vertical offset of sea floor, near-vertical zones of broken and discontinuous reflectors, elongate fault-bounded welt forms above the zone of principal displacement, the positive flower structure and negative flower structure, etc. (Harding, 1985; Lewis, *et. al.*, 1988; Richard, *et al.*, 1991; Pinet and Stephan, 1990). Due to the chaotic nature of the pre-existed accretionary wedge structure or the relict morphology of the ocean bottom, the strike-slip faults in the study area are not easily identifiable. Consecutive eruption of the volcanos can also destroy previous fault traces. Most of the strike-slip faults onshore seem composing of minor lateral movement, thus some of the strike-slip faults identified in our study might be a temporally structural style which overprint the pre-existed thrusts.

Three sets of strike-slip faults have been recognized in this study: those associated with the Luzon volcanic arc, those identified on the arc-side of the accretionary wedge and those located along oceanward of the transitional crust boundary in the frontal portion of the accretionary wedge. Evidences of these strike-slip faults are presented as follows:

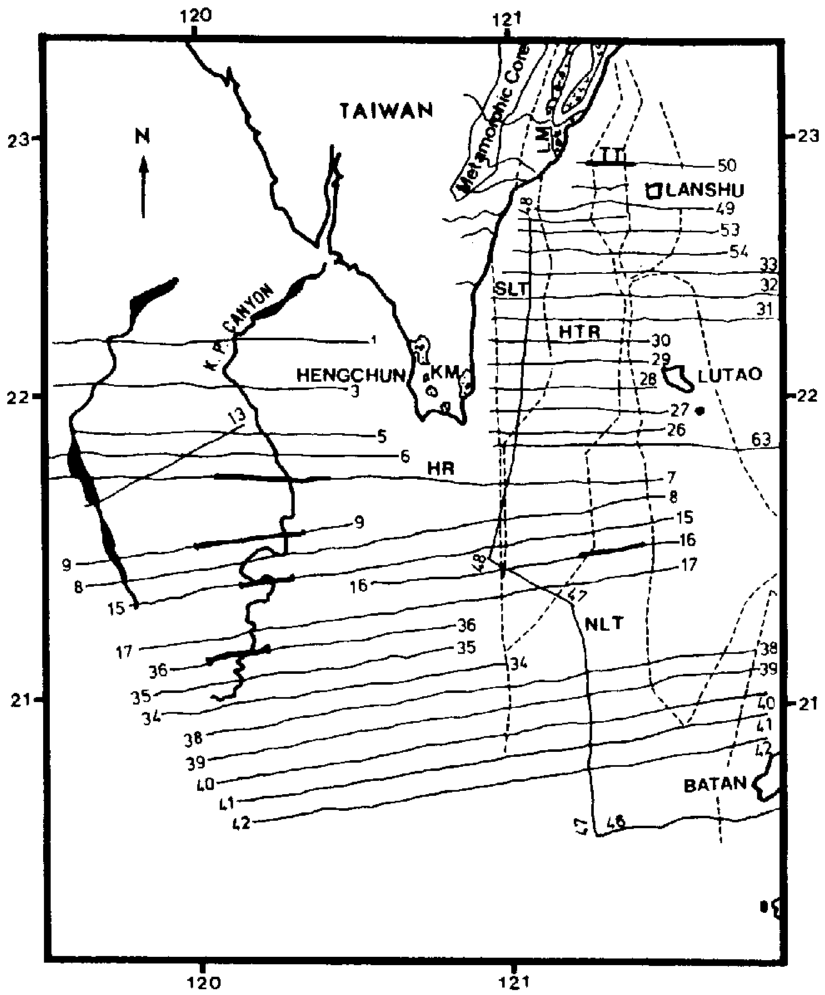

Figure 3. The location map of the seismic lines. The portion of the show lines are highlighted.

The Strike-Slip Fault System Associated with the Luzon Volcanic Arc

Several seismic profiles which run across the Luzon volcanic arc reveal that a left-lateral strike-slip fault system (marked as A in Fig. 4) might exist along the volcanic arc in the eastern part of the study area. Near the Batan Island, the observed strike-slip fault has an N-S trending. It turns into north-northwest trend near Lanshu Island. Due to lack of seismic data coverage, there is a large gap for the observation of this fault system between 21° 10'N and 22° N. Numerous previous studies of earthquake focal mechanism have shown that there were left lateral movement of north-northwest trend occurred at east of the Lanshu Island and along it (Kstsumata and Sykes, 1969; Seno and Kurita, 1978; Lin and Tsai, 1981; Chen and Wang, 1986; Cheng and Yeh, 1991). The numerical simulation of collision process in eastern Taiwan (Song, 1993) is predicted that the collision boundary on land tends to turn southeast at its southern corner. The southward extension of this predicted collision boundary coincides with the northern part of our interpreted strike-slip fault system along arcs. The left-lateral movement of the Longitudinal Valley Fault (Barrier, 1986- Yu and Liu, 1980; Yu and others, 1990) is consistent with the left-lateral movement of this fault. Seismic profiles of line 50 running across this strike-slip fault system are shown in Figure 5. The corresponding seismic line location is highlighted in Figure 3. Abrupt vertical offset of the sea floor, vertical offset of near-horizontal reflectors and convergent fault zone can be observed in these figures. The experimental result on fault reactivation in strike-slip mode conducted by Richard (1991) is very similar to the structure observed in Figure 5. As shown in Figure 4, we have also mapped two secondary left lateral wrench faults of northwest trending located to the west of the Lutao Island and to the northwest of the Banta Island respectively. The thrust faults related to this strike-slip fault system trends north-northeast. Compared with the tectonic map of the Central Rocky mountain area by Stone (1969), the deformation mechanism related to this strike-slip fault system is inferred to be simple shear and left lateral, which is consistent with the focal mechanism solutions mentioned above. The modern strike-slip is narrow, but the zone of pervasive simple shear may be as wide as 30 km (Fig. 4).

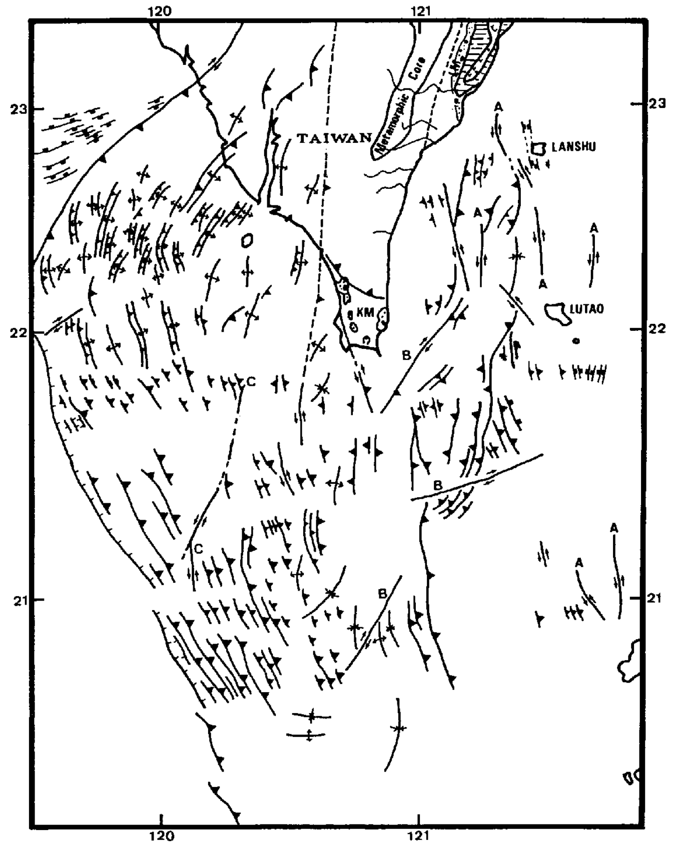

Figure 4. The structural map of the study result. The strike-slip faults along arcs are marked as “A”, the strike-slip faults in the crest area of the accretionary wedge are marked as “B” and the strike-slip faults sub-parallel to the transitional-oceanic crust boundary are marked as “C”.

The Strike-Slip Faults Associated with the Accretionary Wedge

Some NE-SW trending right-lateral strike-slip faults are identified in the crest area and the arc-side of the accretionary wedge (marked as B in Fig. 4). The interpreted seismic line 16 running across one of these faults are shown in Figure 6. The Reflector C, interpreted as the volcanic arc basement, is offset nearly vertically at least 200 msec on seismic line 16 (Fig. 6). The N-S trending high amplitude magnetic anomaly at 121° E (Fig. 7) is offset by one of these right-lateral strike-slip faults at about 21° 20'N. The Free-air gravity anomaly map (Fig. 8) appeared the same way as the magnetic anomaly at the place where this strike-slip fault is located. South of this strike-slip fault, the forearc basin sediments are strongly underthrust by the westward lateral movement of the volcanic basement dipping to the west. Further south, another right-lateral strikeslip fault identified over several E-W trending seismic profiles near 121° E. The obvious cranks on the sea floor are the characteristics on all these seismic section where the strike-slip fault passes. The results from experimental modeling of the oblique convergence in Taiwan, conducted by Lu and Malavirille (1994), also show these phenomena.

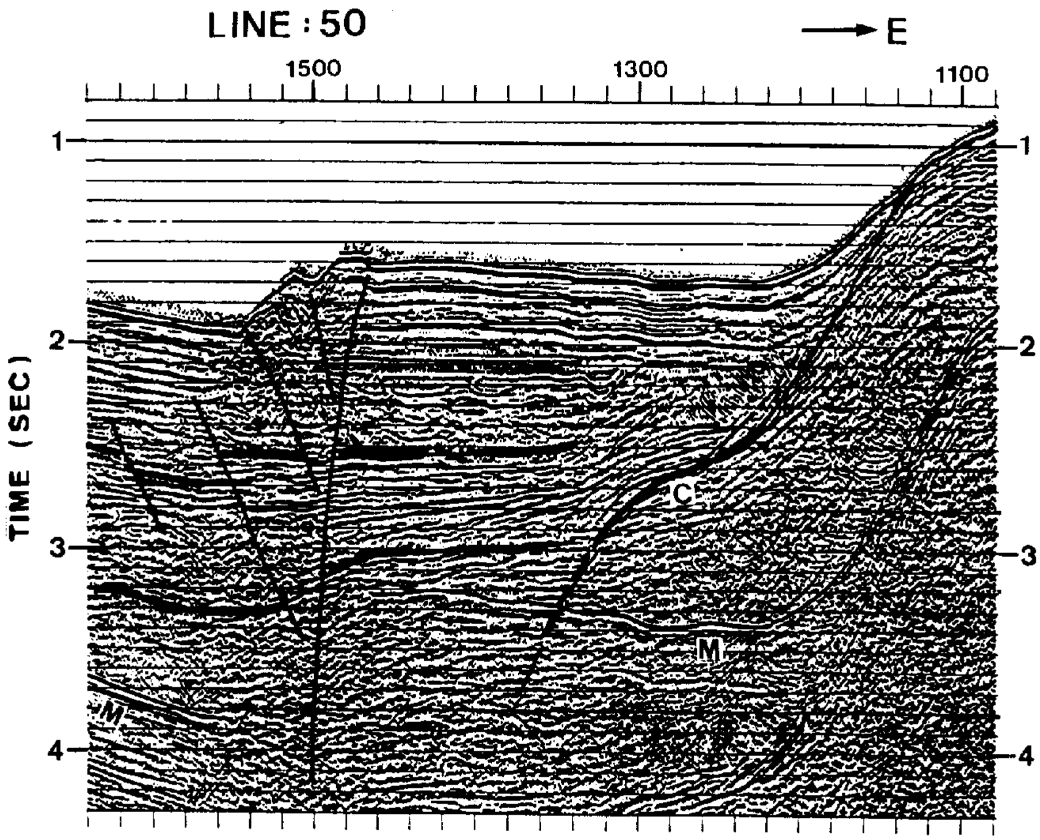

Figure 5. Seismic section of line 50 (location is indicated in Fig. 3). The strike-slip fault on this section traversed by fault A is evidenced by: offset of the basement, vertical offset of nearly horizontal reflectors, converged fault zone and vertical offset of the sea floor. Reflector C is the volcanic arc basement and reflector M is multiple of sea floor.

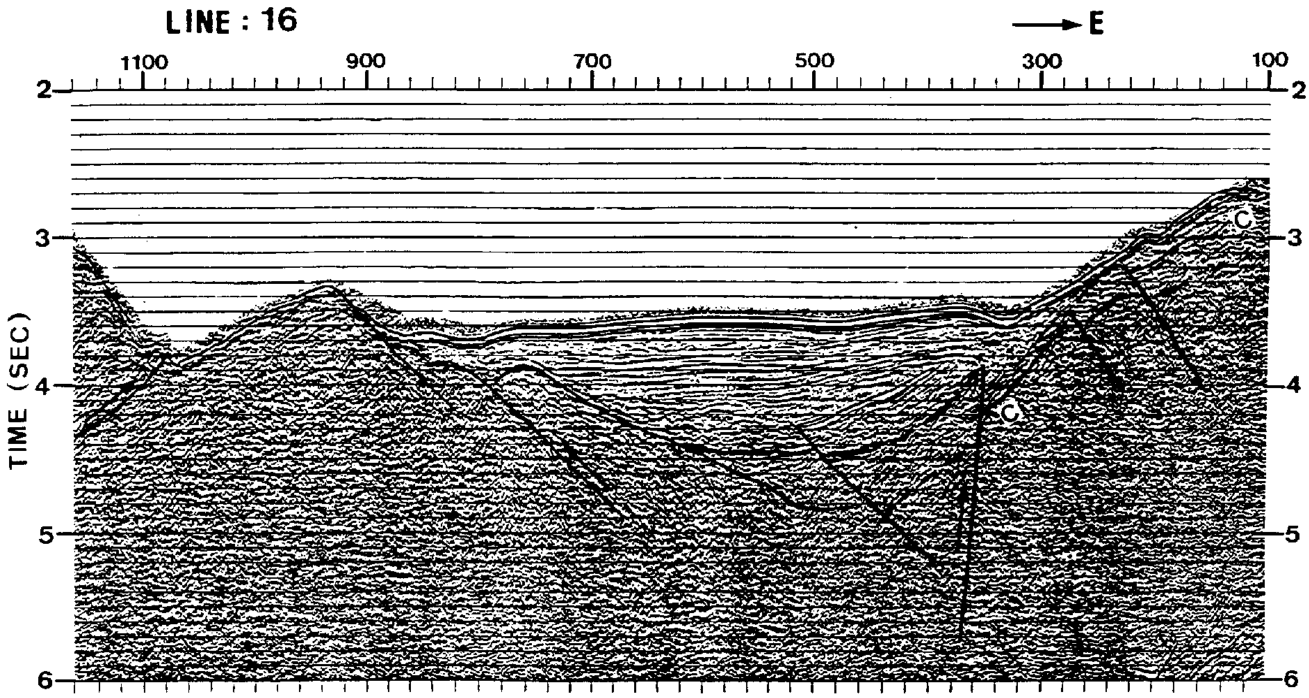

Figure 6. Seismic section of line 16 (location is indicated in Fig. 3). The strike-slip fault in the crest area of the wedge traversed this section near REP 320. The volcanic arc basement top, reflector C, is offset by 200 msec vertically.

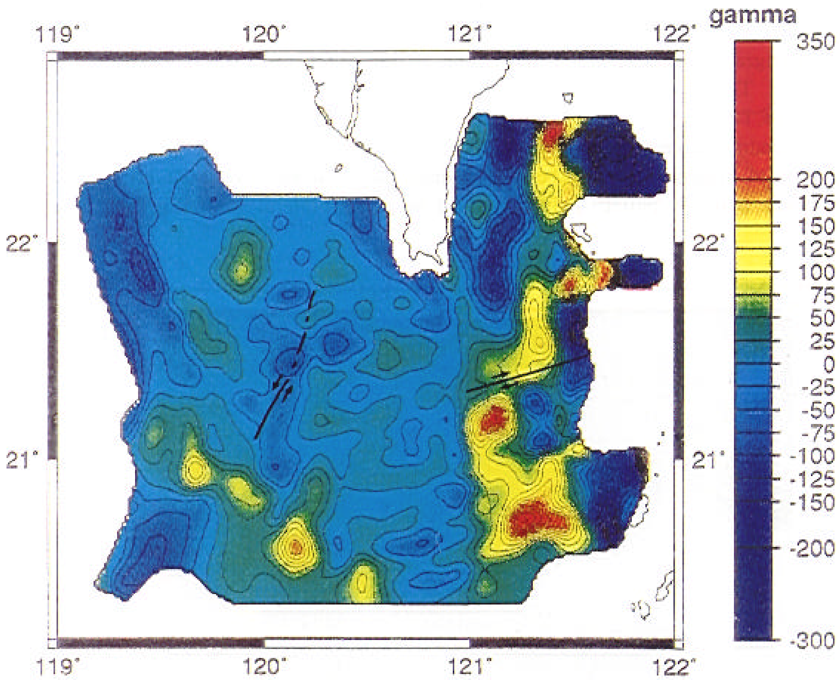

Figure 7. The magnetic anomaly map (after reductin to the pole) of the study area. The anomaly low (contour of 25 mgal), observed in the southwestern portion of Figure 9, is closely related to the boundary separating the transitional and the oceanic crust. The linear trend of magnetic high in the eastern part of the study area is offset sharply by one of our interpreted strike-slip fault.

The Strike-Slip Faults Located at the Frontal Portions of the Accretionary Wedge

A NNE-SSW trending left-lateral strike-slip fault system (marked as C in Fig. 4) was identified from several seismic sections across the lower slope domain of the accretionary wedge. The characters of near vertical fault, vertical offset of nearhorizontal reflectors, vertical offset of sea bed and the converged fault patterns are used to delineate the strike-slip faults on these seismic lines. The slumping at west flank of the Kaopiric, Canvon observed on seismic profile 9 (Fig. 9) and the Canyon base being dragged downward to the east indicate the existence of this strike-slip fault. On line 9 (Fig. 9), the sea bed to the east of the Kaoping Canyon has a sharp relief of 900 msec. Usually, a thrust sheet with this kind of thrown, the down thrown strata would be dragged upward; especially the pull-up effect is added. On this section, we observed flat strata underneath the canyon rather than dragged upward strata. The contact between this flat strata and the eastern flank of the highly deformed thrust sheet thus is more likely to be a vertical zone along which reflector packets with different dip convergence. All these phenomena suggest that a strike-slip fault exists at this location. The structure on seismic line 36 (Fig. 9) clearly demonstrates a basement involved negative flower structure. The meandering of the lower stream of the Kaoping Canyon

(Liu *et al.*, 1993), which is almost superimposed on our interpreted strike-slip fault system, is very likely to be controlled by the lateral movement of this strike-slip fault system. Example of the zigzag or meandering of the streams related to the strike-slip faults are also found on land. The left-lateral strike-slip fault suggested by Lin and Tsai (1981) in the area south of Taiwan from focal mechanism solution may be related to this fault system. A N-S trending magnetic anomaly low (contour of 25 mgal) observed in the southwestern portion of Figure 9 may also be used to delineate the location of this fault system. This magnetic anomaly pattern may be caused by the left-lateral strike-slip fault described above (Hoyton, *et. al.*, 1984). However, it could only reflect the trend of different nature of the crust (Hutchinson *et al.*, 1982-, Ranalli and Murphy, 1987).

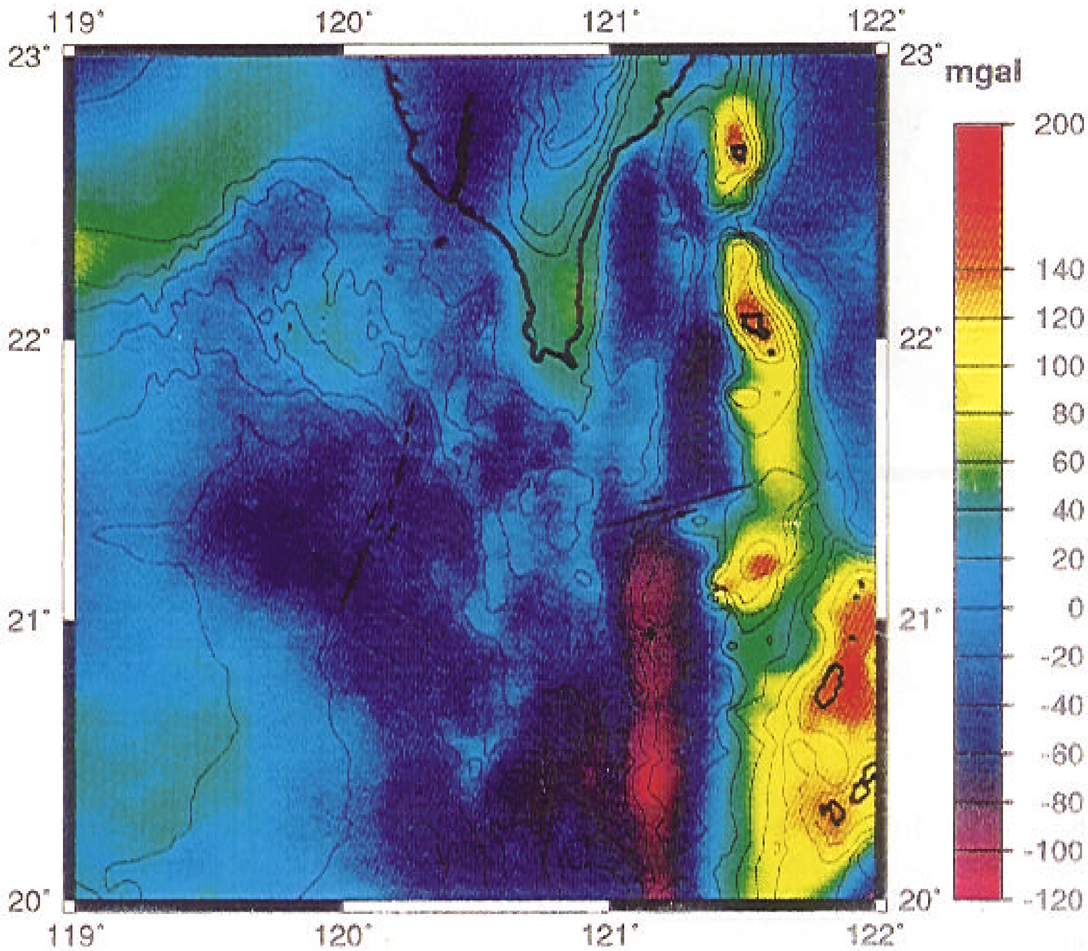

Figure 8. The Free-air gravity anomaly map overlaid with bathymetric contours in 500 m interval of the study area. The contour of 40 mgal turns sharply (nearly 90°) at about 21°20' N where the strike-slip fault is located (adopted from Liu, *et al.*, 1992).

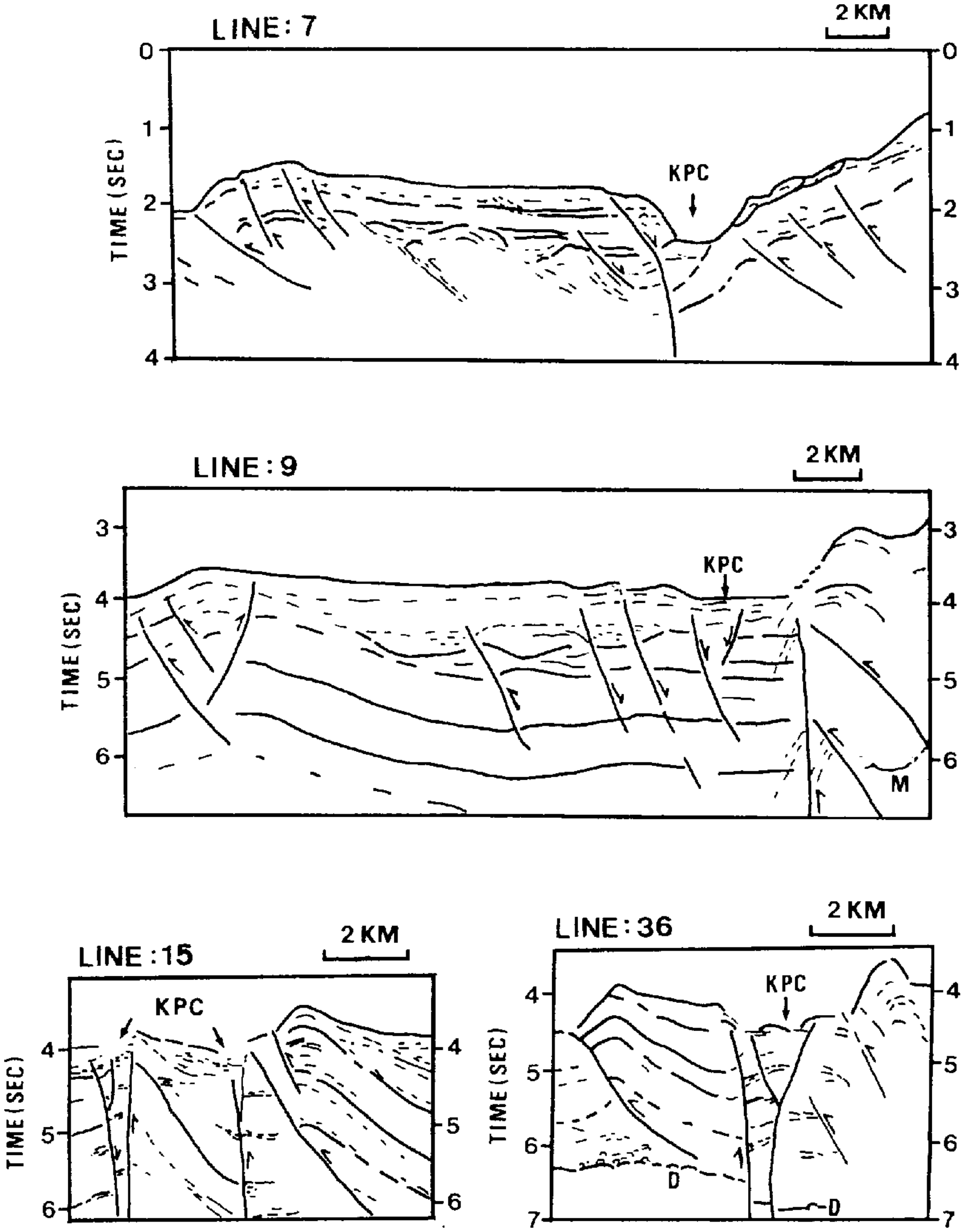

Figure 9. Line drawings of seismic reflection profiles crossing Kaoping Canyon. KPC = Kaoping Canyon, M = multiple. Meandering of the Kaoping Canyon is controlled by the strike-slip faults.

a. Fault associated with continent-ocean boundary b. fault associated with volcanic arc

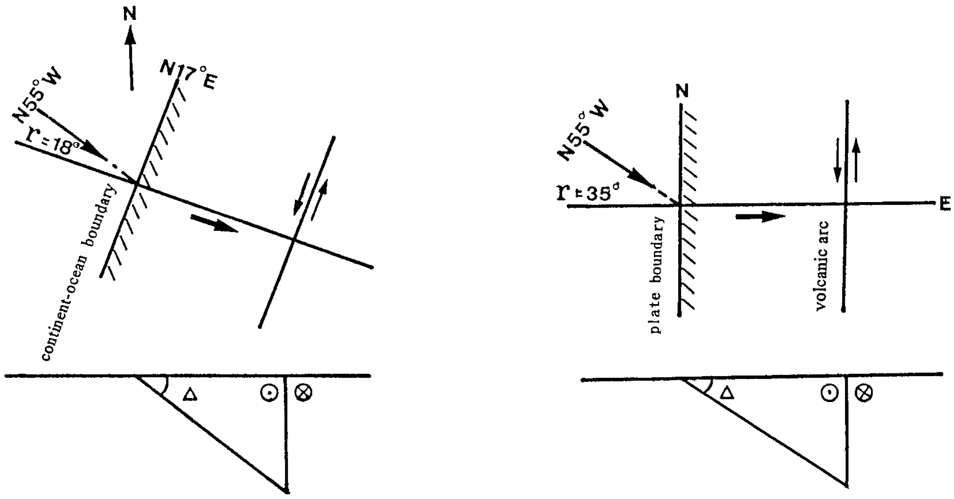

Figure 10. Decoupled transcurrent faults in the offshore area south of Taiwan. Movement between Eurasian Plate and Philippine Sea Plate is N55°W, heavy arrows represent decoupled normal stress, double arrows represent decoupled transcurrent movements, convergence angle associated with Luzon Arc is 35° and those associated with continent-ocean boundary is 18°. (a) decoupled transcurrent fault associated with continent-ocean boundary; (b) decoupled transcurrent fault associated with the Luzon volcanic arc.

Decoupled Transcurrent Movements in the Offshore Area South of Taiwan

According to Becker (1983), conditions favoring decoupled transcurrent movements are; (1) a high angle of oblique convergence; (2) a low angle of subduction; and (3) relative thermal " softening " of the magmatic-arc or increasing age of the subduction zone. These conditions exist in southern offshore Taiwan for the following reasons: (1) The Luzon Arc is oriented north-south whereas the Philippine Sea Plate is moving toward the Eurasian Plate in an N55º W direction, the convergence angle is thus 35º (Fig. 10a). Subduction angle inferred from seismicity (Pezzopane, *et al.*, 1989; Cheng, *et al.*, 1991) in study area is of roughly 45º ; given $\gamma_t = \gamma_s$ (as discussed earlier), inequality (a) implies that Sunda-style tectonics should be favored for such convergence angle, (b) on-going arc-continent collision is proceeding in the northern part of the study area, this means that buoyant Eurasian continental plate is approaching the Luzon subduction zone. This has the same effect of increasing buoyancy by lowering the subduction angle, (c) the Luzon volcanic arc plays as a weak zone in the overriding plate. The strike-slip fault system associated with Luzon Arc (as discussed earlier) is very likely the decoupled transcurrent fault as described by Fitch (1972) and Becker Jr. (1983). As to the strike-slip fault system located at the frontal portion of the accretionary wedge, we discuss as follows: the buoyancy of subducting plate is increased by approaching of the Eurasian continental lithosphere, if a weak zone would exist in subducting plate, the decoupled transcurrent movements would also be possible to be existed within it. A linear magnetic anomaly trending N17^{o} E is proposed to be related to the boundary separating oceanic from continental crust. The boundary is a transition zone considered to be either thinned continental crust or thickened oceanic crust. The crust of this transition zone is of relict rift-stage crust, which has been heated, thinned, faulted and extensively intruded (Hutchinson, 1982). Thus the transition zone provide as a possible weak zone within subducting plate. Besides, due to variation of crustal type, physical properties and thickness across the continent-ocean boundary, stress is possible to be decoupled along this boundary. Fluid pressure built up, due to dehydration reaction in surficial rocks of the accretionary wedge, will reduce slip resistance(γ_t, γ_s) and thus advance the decoupling process. The strike-slip faults located at the frontal portion of the accretionary wedge is thus another set of decoupled transcurrent fault.

The two sets of strike-slip faults associated with the Luzon Arc and the continent-ocean boundary, respectively, Act as two bounding faults which caused rotation of forearc block as described in schematic diagram of Figure 11. The right-lateral strike-slip faults observed within the arc-side of the accretionary wedge and the forearc basin are thus induced from block rotations.

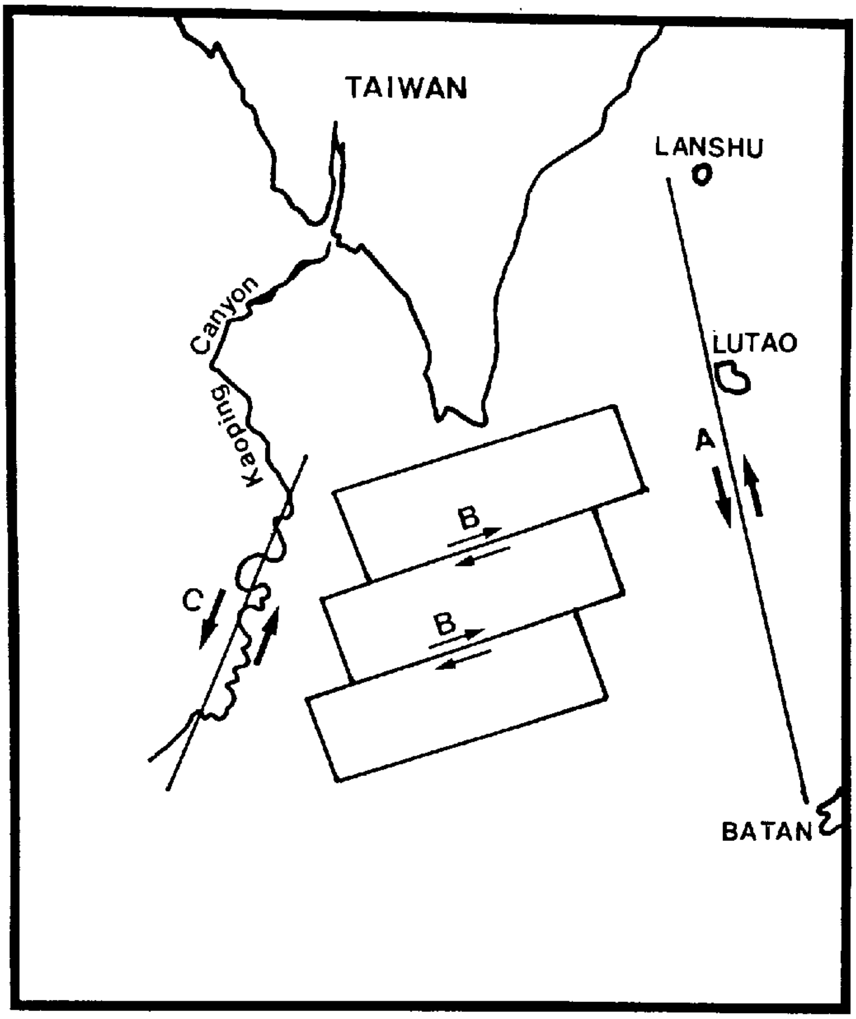

Figure 11. Schematic diagram shows the roles which strike-slip faults in the southern offshore Taiwan play in collision related rotation tectonic. Strike-Slip faults associated with volcanic arcs and those controlling the meandering path of the Kaoping are the bounding faults of forearc block rotation. The right-lateral strike-slip faults observed within the arc-side of the accretionary wedge delineated in our study may result from this rotation.

CONCLUSIONS

- Three sets of strike-slip faults are observed in the collision-subduction zone in the offshore area south of Taiwan: (1) the left-lateral strike-slip fault system associated with the Luzon volcanic arc; (2) the right-lateral strike-slip faults located within the arc-side of the accretionary wedge and forearc basin, and; (3) the left-lateral strike-slip faults located at the frontal portion of the accretionary wedge.
- The decoupling hypothesis is feasible for oblique convergence in the offshore area south of Taiwan.

- The left-lateral strike-slip fault system associated with the Luzon volcanic arc and those located at the frontal portion of the accretionary wedge can be explained as the decoupled transcurrent faults.
- The right-lateral strike-slip faults located within the arc-side of the accretionary wedge and forearc basin induced from the two bounding transcurrent faults, which caused the forearc block rotation.

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摘　要

本研究提出一單剪(simple shear)變形模型來解釋在呂宋隱沒一台灣碰撞帶所觀察到之橫移斷層。反射震測、重力及磁力異常及前人研究中所分析之地震機制解被用以分析研究區域內解耦合假說之可能性。三組橫移斷層在台灣南部海域之碰撞一隱沒帶被辨認出：和呂宋島弧相關之左移橫移斷層，在增積岩體及弧前盆地靠火山島弧西側內之右移橫移斷層，及位於增積岩體前側之左移橫移斷層。和火山島弧相關及位於增積岩體前側的兩組左移橫移斷層可解釋為解耦合橫推斷層。在火山島弧西側之增積岩體及弧前盆地內之右移橫移斷層則由前述兩組橫推界斷層所引起之弧前地塊轉動所造成。