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Trench-parallel stretching and folding of forearc basins and lateral migration of the accretionary wedge in the southern Ryukyus: A case of strain partition caused by oblique convergence

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Abstract. Detailed seafloor mapping in the area east of Taiwan revealed trench-parallel stretching and folding of the Ryukyu forearc and lateral motion of the accretionary wedge under oblique convergence. East of 122°40'E, a steep accretionary wedge is elongated in an E-W direction. A major transcurrent right-lateral strike-slip fault accommodates the strain partitioning caused by an oblique convergence of 40°. A spectacular out-of-sequence thrust may be related to the subduction of a structural high lying in the axis of the N-S trending Gagua Ridge. This asperity is likely responsible for the uplift of the accretionary wedge and forearc basement and may have augmented strain partitioning by increasing the coupling between the two plates. West of 122°40'E, the low-taper accretionary wedge is sheared in a direction subparallel to the convergence vector with respect to the Ryukyu Arc. The bayonet shape of the southern Ryukyu Arc slope partly results from the recent (re)opening of the southern Okinawa Trough at a rate of about 2 to 4 cm/yr. Right-lateral shearing of the sedimentary forearc with respect to the nonlinear Ryukyu backstop generates trench-parallel extension in the forearc sediment sequence at dilational jogs and trench-parallel folding at compressive jogs. The Hoping Basin lies above a diffuse trench/trench/fault (TTF) or TFF unstable triple junction moving toward the south along a N-S transform zone which accommodates the southward drift of the Ryukyu Arc with respect to Eurasia.

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1. Introduction

Strain partition has been documented in many subduction zones where the convergence vector makes an angle with the direction normal to the trench axis [e.g., *Fitch*, 1972]. Generally, transcurrent strike-slip faulting is observed near the volcanic arc because it corresponds to the weaker region of the overriding plate. Prime examples include the Great Sumatran Fault in Indonesia, the Median Tectonic Line in Japan, and the Philippine Fault [e.g., *Diament et al.*, 1992; *Jarrard*, 1986]. The southern Ryukyus offer an interesting geodynamic setting to study this process because (1) the obliquity exceeds 40°, (2) the southern Ryukyu Arc is nonvolcanic, and (3) the overriding plate undergoes backarc extension as attested by the opening of the Okinawa Trough.

On the basis of the geology of the Yaeyama Islands [*Kuramoto and Konishi,* 1989] and on earthquake slip vectors [*Kao et al.*, 1998], some authors argue for strain partitioning along the Ryukyu Arc. However, there are absolutely no indications of oblique rifting or spreading in the axis of the Okinawa Trough [*Sibuet et al.*, 1995]. In this study, we present new data collected along the Ryukyu forearc near Taiwan and discuss these data with regard to the other previous studies.

A joint French-Taiwanese cruise, called ACT cruise for active collision in Taiwan, in May and June 1996 on the R/V *L'Atalante* provided detailed structural images of the seafloor and crust around Taiwan, in particular along the westernmost 200 km of the Ryukyu forearc area [*Lallemand et al.*, 1997a]. The data collected during this cruise helped answer the following questions: Does strain partitioning occur in the forearc area, and if so, is the deformation localized or diffuse? Does deformation affect the arc slope, the forearc basins, or the accretionary wedge? Another topic addressed in this study is concerned with the interaction between the subducting Gagua Ridge and the southern Ryukyu margin: How does the Ryukyu forearc deform during ridge subduction and does it affect slip partitioning?

2. Data Acquisition

The study area (see location in Figure 1) was mapped with 100% bathymetric and backscattering coverage during the ACT cruise [*Lallemand et al.*, 1997a]. Tracks were generally oriented parallel to the structures along the Ryukyu and Luzon Arc slopes in order to keep the swath width constant and

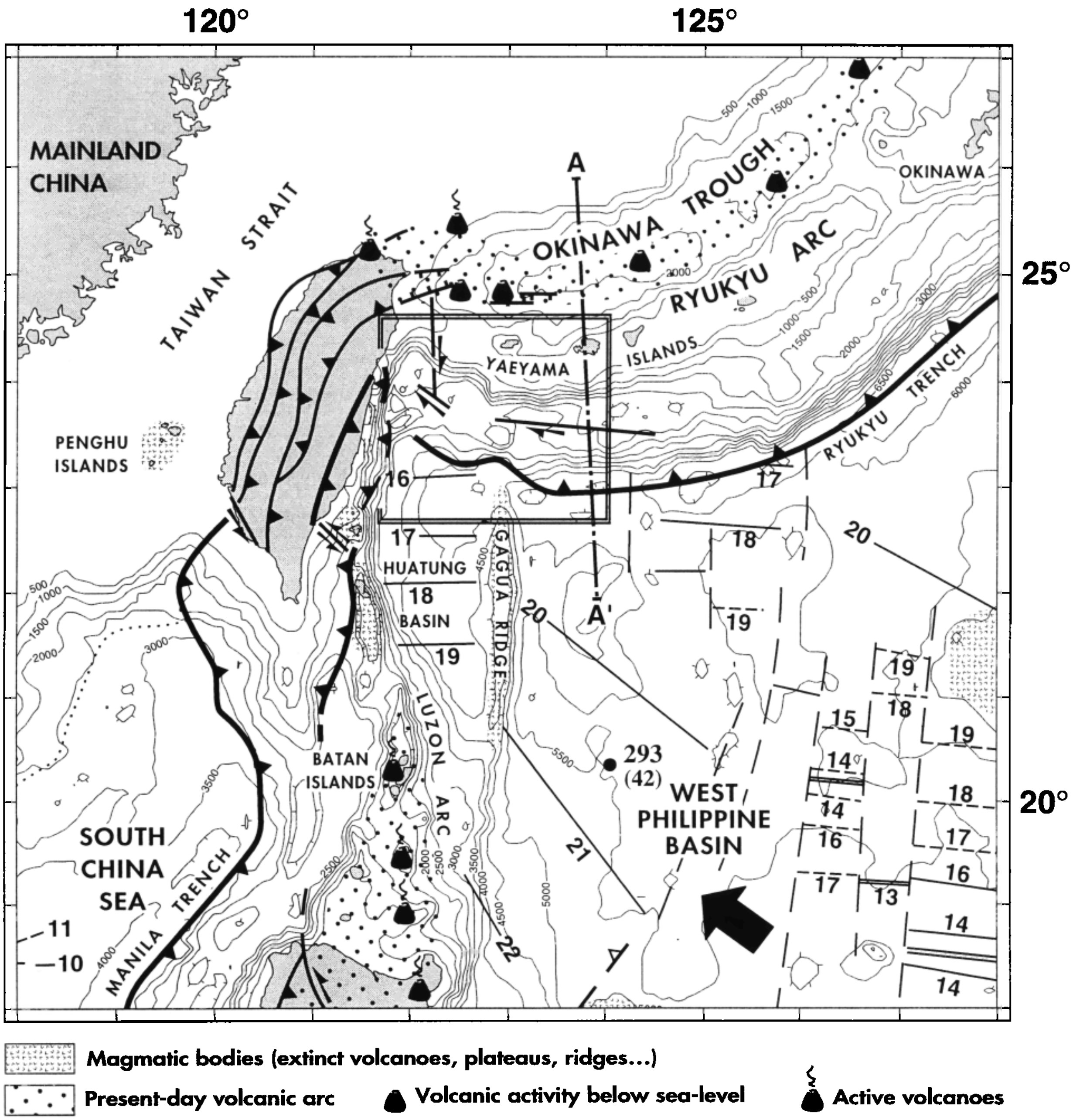

Figure 1. Geodynamic setting of the study area. The main tectonic features are represented, including the major results of the active collision in Taiwan (ACT) cruise. Magnetic lineations are from *Hilde and Lee* [1984] in the Philippine Sea and from *Briais and Pautot* [1992] in the South China Sea. Convergence arrow is 81 km long (1 m.y. of convergence) in the direction given by Global Positioning System (GPS) measurements [*Yu et al.*, 1997] relative to the South China Block (SCB). The line A-A' indicates the location of the lithospheric cross section of Figure 2. Deep Sea Drilling Program site number 293 is located in the Philippine Sea with absolute crustal age in parentheses. Isobaths are every 500 m.

because most previously acquired seismic lines were shot normal to the structures. The ship is equiped with SIMRAD EM12-Dual and EM950 (for depths shallower than 300 m) multibeam systems that enable swath mapping and side-scan imagery over a maximum 20-km-wide strip (151 simultaneous soundings) of seabed in a single pass. The side-scan imagery associated with EM12-Dual gives detailed information on the acoustic reflectivity associated with fine bathymetric features and with variations in the nature of the seafloor. Subbottom (3.5 kHz) and reflection seismic profiling and magnetic and gravity data were also recorded along the 20-km-spaced parallel ship tracks for great depths and along more closely spaced ship tracks for shallower depths. We deployed a six-channel streamer with two 1230-cm^3 generator/injector (GI) guns at a pressure of 160 bars. The guns were fired in harmonic mode to genèrate a source signature centered on 20 Hz for deep penetration. Shot intervals were ~ 50 m. Seismic data were processed using ProMAX software to obtain poststack time-migrated profiles.

3. Geological Setting of the Southern Ryukyus Near Taiwan

The relative plate convergence between Eurasia and the Philippine Sea Plate (PSP) is oblique along the two major plate boundaries which meet in Taiwan (Figure 1). One is the N-S trending Manila subduction zone along which a transition occurs between an eastward dipping oceanic subduction (South China Sea) south of 21°40'N and southeast dipping continental subduction (Chinese shelf) north of this latitude. The other is the north dipping Ryukyu subduction zone along which the PSP is subducting beneath the Ryukyu Arc, rifted from the Chinese margin. At the junction between these two opposite subductions, the Taiwan orogen is actively growing.

3.1. Philippine Sea

The oceanic crust of the PSP near Taiwan belongs to the Paleogene West Philippine Basin. East-west trending magnetic lineations, observed in the small Huatung Basin near Taiwan, were tentatively identified by *Hilde and Lee* [1984] as anomalies 16 to 19 on the magnetic reversal scale. They represent the youngest stage (middle to late Eocene) in the opening of the West Philippine Basin (Figure 1). According to the magnetic lineations map in the West Philippine Basin (Figure 1), the 37 Ma fossil spreading center, north of anomaly 16 in the Huatung Basin, should be buried beneath the Ryukyu accretionary wedge near latitude 23°30'N. It should be noted that according to the satellite altimetry-derived gravity map of *Smith and Sandwell* [1997], the grain of the oceanic crust and the Central Rift Valley of the West Philippine Basin trend northwest-southeast rather than east-west as proposed by *Hilde and Lee* [1984]. The Huatung Basin is separated from the main Philippine Sea basin by the N-S trending Gagua Ridge which probably originated from a fracture zone [*Mrozowski et al.*, 1982; *Deschamps et al.*, 1997]. In addition to this prominent ridge, the PSP carries the Neogene Luzon volcanic arc, paired with the Manila subduction zone, as well as seamounts and oceanic plateaus. The PSP moves toward the northwest, with respect to the Eurasian Plate as indicated by global kinematics [e.g., *Seno*, 1977]. *Yu et al.* [1997], on the basis of geodetic data issued from a 5-year Global Positioning System (GPS) survey, propose a current convergence of 80 to 83 mm/yr in an azimuth of N306° ± 1° of the Lanyu Island (representative of the PSP) relative to the Penghu Islands (representative of the South China block (SCB)). *Heki* [1996] proposed that the SCB was extruded from the stable Asian continent at a rate of 11 mm/yr in the direction N112°, following the model of *Tapponnier et al.* [1982]. After accounting for the relative motion between the SCB and stable Eurasia, the relative convergence between the PSP and Eurasia is in excellent agreement with *Seno et al*'s [1993] model.

3.2. Okinawa Trough and Ryukyu Arc

The Chinese continental shelf suffered back arc extension from Taiwan to Kyushu (Japan) above the Philippine Sea slab. The Ryukyu Arc is thus a rifted fragment of continental crust. Back arc extension in the Okinawa Trough may have started as early as middle Miocene according to *Park* [1996]. Other authors argued for a late Miocene first phase of opening [e.g., *Letouzey and Kimura*, 1985]. In any case, *Sibuet et al.* [1995] suggested that the opening ceased from 6 to 2 Ma and resumed since 2 Ma. On the basis of GPS measurements on the Yaeyama Islands over a few years [*Imanishi et al.*, 1996], Yonaguni (the closest island from Taiwan) is moving toward the south (N184°) at a rate of about 40 ± 5 mm/yr, whereas Ishigaki and Hateruma are moving at a lower rate of 22 and 24 ± 5 mm/yr toward the south (N172°) and SSE (N150°), respectively, with respect to the SCB, that is, after correcting for the relative motion between the SCB and stable Eurasia given by *Heki* [1996]. Such significant rates of opening necessarily have important consequences with regard to the recent tectonic

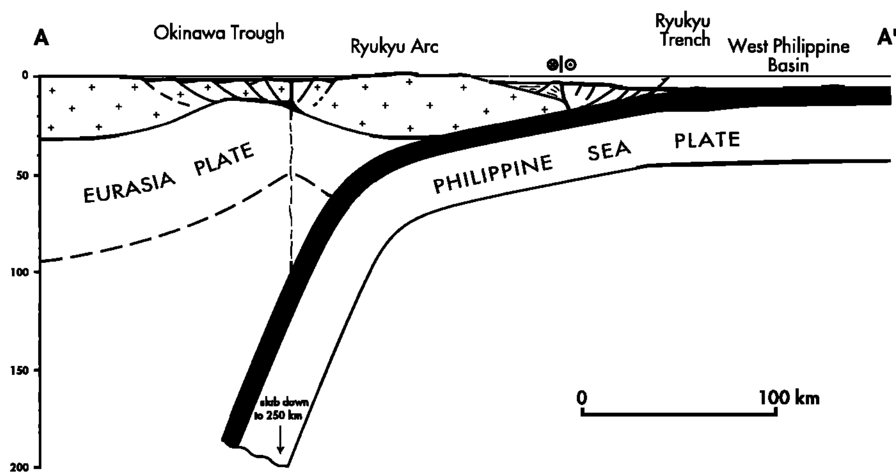

Figure 2. Interpretative geological cross section A-A' (shown in Figure 1). Interpretations include ACT cruise results such as strike-slip faulting at the rear of the Yaeyama Ridge or magmatism and active normal faulting along the southern side of the Okinawa Trough [*Sibuet et al.*, 1998].

evolution of the Ryukyu Arc [*Lallemand and Liu*, 1998], and the relative convergence between the PSP and the Ryukyu margin in the study area occurs at a rate of 10.7 cm/yr in a N325° direction.

The Ryukyu subduction started during the Late Cretaceous according to *Lee and Lawver* [1995]. Ryukyu arc volcanism is expressed on the morphological arc north of Okinawa, and in the axis, or on the southern side of the Okinawa Trough from Okinawa to Taiwan [*Sibuet et al.*, 1987]. The Ryukyu Arc is thus nonvolcanic south of Okinawa Island. The back arc basin is about 2-km deep near Taiwan, and seismic activity, faulting, and magmatism presently occur along the southern part of the trough as revealed during the ACT cruise [*Sibuet et al.*, 1998] (see cross section A-A' on Figure 2). South of the Yaeyama Islands, the southern Ryukyu forearc system consists of a steep arc basement slope, a series of forearc basins (East Nanao, Nanao, and Hoping Basins), and an accretionary wedge (Yaeyama Ridge).

4. New Insights From the ACT Geophysical Survey

4.1 Subducting Philippine Sea Plate

Detailed analyses of the ACT reflection seismic lines, together with previously recorded seismic profiles, reveal that the basement of the basin is very rough with N-S trending ridges and troughs [*Deschamps*, 1997]. The maximum depth of the basin floor is 4800 m. It shallows gently westward toward the arc to a depth of 4000 ± 500 m, because all sediments are supplied from the Taiwan mountain belt through numerous canyons (Figures 3 and 4). The mean sediment thickness in the Huatung Basin is 1600 m, increasing to more than 2000 m toward the mouth of the Hualien and Chimei Canyons (Figure 4).

The Gagua Ridge rises above the surrounding seafloor by up to 4 km. It is a 300- to 350-km-long, and 20- to 30-km-wide, linear asymmetric ridge. The highest peak, 1520 m below sea

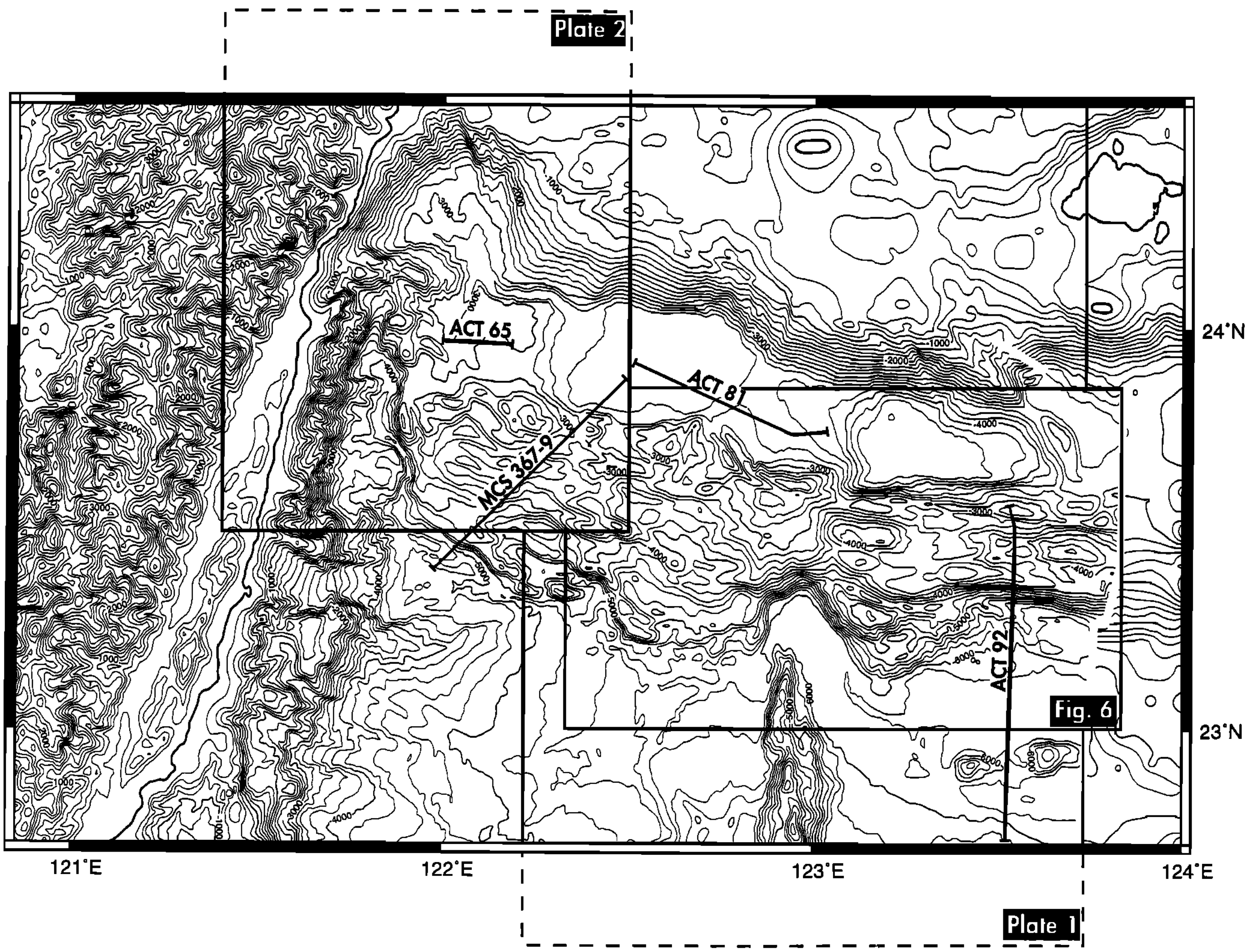

Figure 3. Multibeam bathymetry of the study area at 200-m contouring. In the vicinity of the Yaeyama islands (upper right corner) and in the left side of Figure 3, the gaps are filled using the available bathymetric data of the area. On land, the topography is given at a resolution of 500 m with 200-m contouring. Plates 1 and 2 and Figure 6, ACT seismic lines, and another seismic line (MCS 367-9) shown in this study are located.

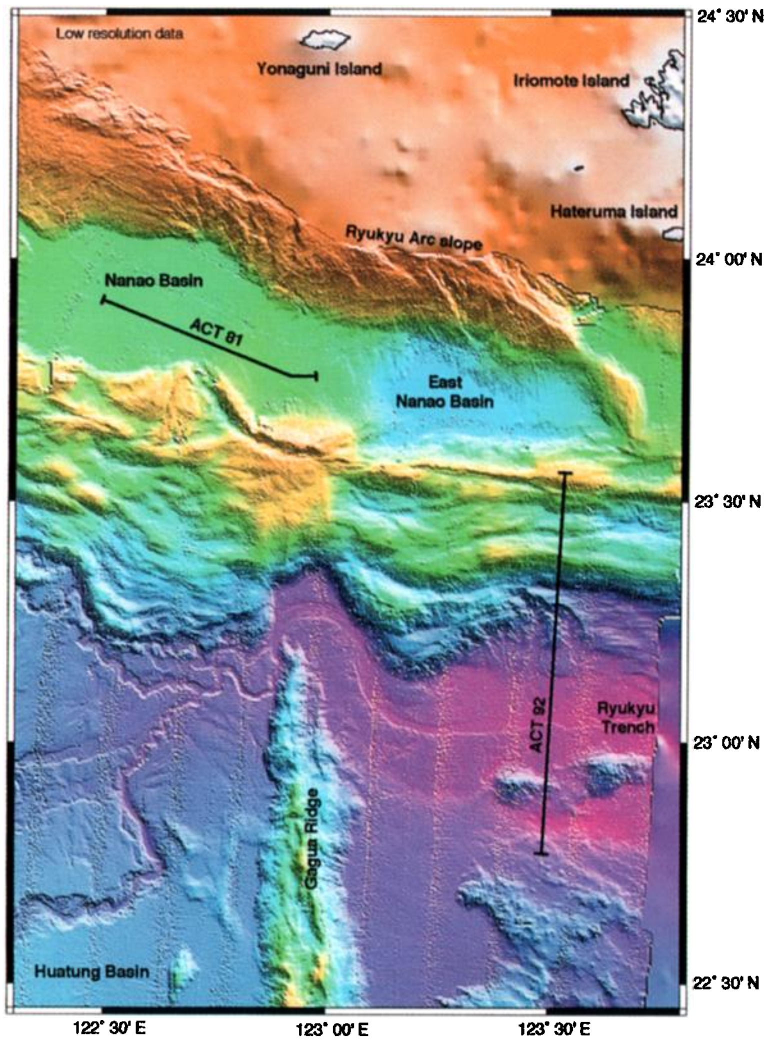

Plate 1. Shaded view of swath bathymetry acquired during the ACT cruise. See location of the box on Figure 3. Note the junction of Hualien and Taitung Canyons in the Ryukyu Trench, just west of the Gagua Ridge, and the eastward course of the resulting channel after passing round the northern end of the ridge. Note also the prominent linear strike-slip fault, paralleling the trench at the rear of the accretionary wedge and the uplift of the accretionary wedge and forearc basin in the axis of the Gagua Ridge. The different morphology of the accretionary wedge east and west of 122°40'N is clearly visible: to the west, a broad gentle wedge with closely tight spaced thrusts and to the east, a narrow, steeper wedge with wider thrust spacing. Seismic lines ACT 81 and ACT 92 shown in this study are located on the map.

level, is located near 22°05'N of latitude. The crest deepens from this latitude toward the north and south. The ridge dams the sediments and turbidites coming from the west, except in the north where it vanishes in the Ryukyu Trench (Plate 1). This feature partly explains why the seafloor in the sedimentary basins is 400 m deeper east of the ridge. Another reason for the depth difference could be related with the 4 m.y. younger oceanic crust of the Huatung Basin with respect to the adjacent West Philippine oceanic crust [*Hilde and Lee*, 1984]. In fact, the Gagua Ridge parallels the N-S trending fracture zones of the West Philippine Basin (Figure 1). It thus probably originated from an old fracture zone of the West Philippine Basin. Dredged rocks recovered on the western flank near 21°N include gabbros, amphibolites, and basalts with slickensides, which *Mrozowski et al.* [1982] interpreted as an up-faulted sliver of oceanic crust bounding a fracture zone.

The northwesternmost part of the West Philippine Basin is very rugged east of the Gagua Ridge, with little sediment. Some seamounts crop out through the 2-km-thick trench fill. The Ryukyu trench axis beyond 200 km east of Taiwan is filled with up to 2 km of turbidites flowing from west of the Gagua Ridge (Figure 4 and Plate 1). These orogenic sediments are derived from the Central and Coastal Ranges mostly through the Hualien, Chimei, and Taitung Canyons.

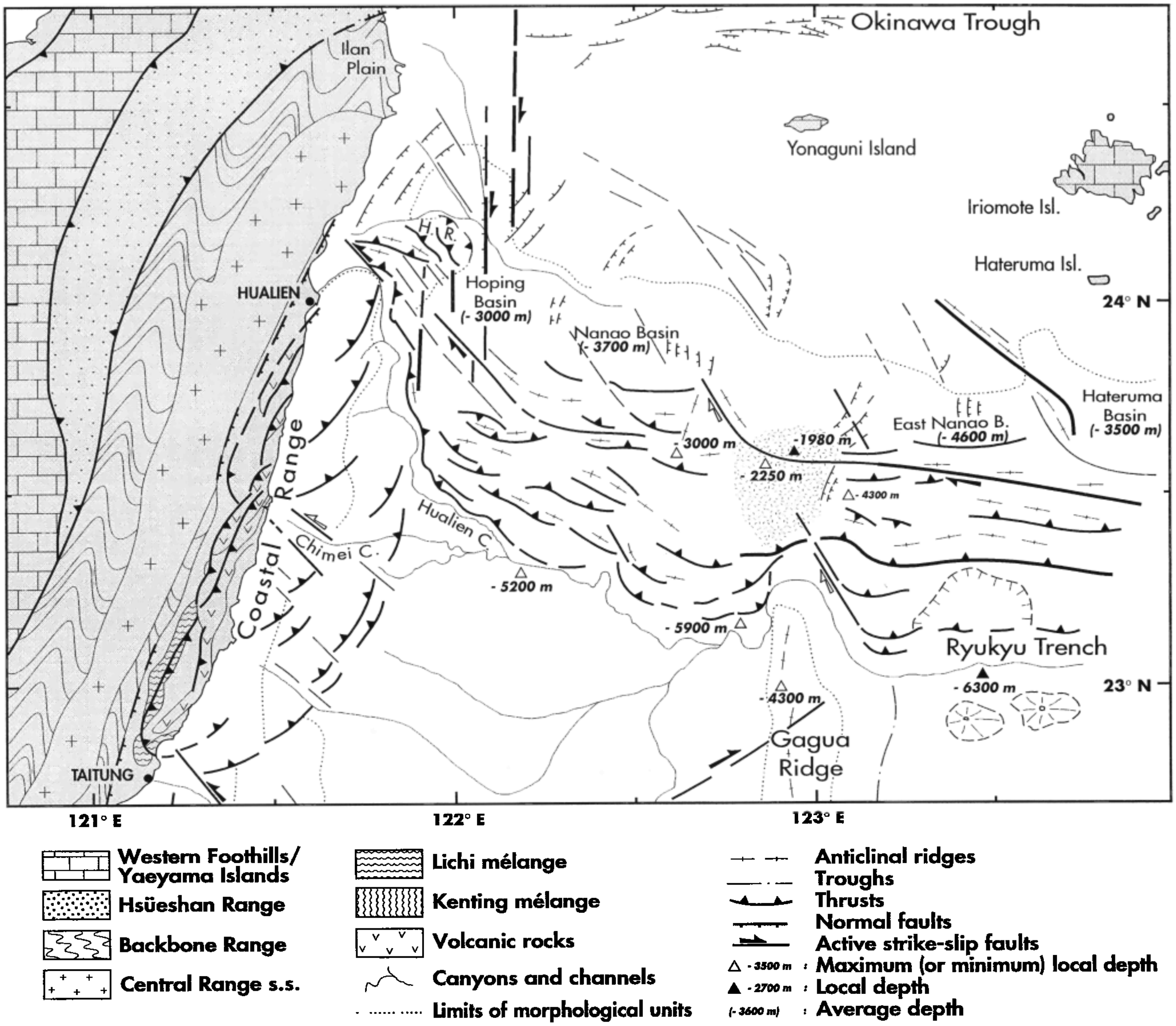

Figure 4. Simplified structural map of the study area offshore east of Taiwan, based on the analysis of all the ACT seismic lines, as well as 1/100,000 scale bathymetric charts. Simplified geology is given on land with more details along the Coastal Range. The stippled area represents the uplifted part of the accretionary wedge and forearc basin north of the Gagua Ridge. Normal faults in the Okinawa Trough are based on *Sibuet et al.* [1998]. HR is Hsincheng Ridge.

4.2. The Ryukyu accretionary wedge

South of the Yaeyama Islands, a classical sequence of arc slope, forearc basins, and accretionary wedge is observed. For a long time, the wedge was improperly called "Yaeyama Ridge." In fact, it was proven, after a cruise on board the R/V *Jean Charcot*, that the Yaeyama Ridge is a typical accretionary wedge (J.-F. Stéphan et al., unpublished POP2 cruise report, 1985).

4.2.1. East of 122°40'E. The accretionary wedge is 50 to 60 km wide with numerous slope breaks corresponding to the emergence of thrust ramps. There is a pronounced thrust front, that we interpret as an active out-of-sequence thrust within the wedge, along latitude 23°20'N, east of the Gagua Ridge (see the ACT line 92 on Figure 5). The frontal scarp dips 15° trenchward and is about 2 km high (Figures 3 and 5). The front of the wedge is steeper and rougher east of the Gagua Ridge (Figure 4). The morphology of the lower slope in this area suggests material collapse down to the trench (Figure 4 and Plate 1). Oversteepening of the frontal wedge and gravitational collapse of the margin indicate either an increased effective basal friction along the décollement [*Gutscher et al.*, 1998] or the recent subduction of an oceanic high [*Lallemand et al.*, 1994]. According to the roughness of the oceanic basement south of the Ryukyu Trench (Plate 1) and to the existence of positive magnetic anomalies beneath the wedge [*Hsu et al.*, 1996a], we propose that oceanic asperities are responsible for both instabilities of the frontal accretionary wedge. North-south reflection seismic profiles acquired during the TAICRUST cruise [*Schnürle et al.*, 1998] and the ACT cruise

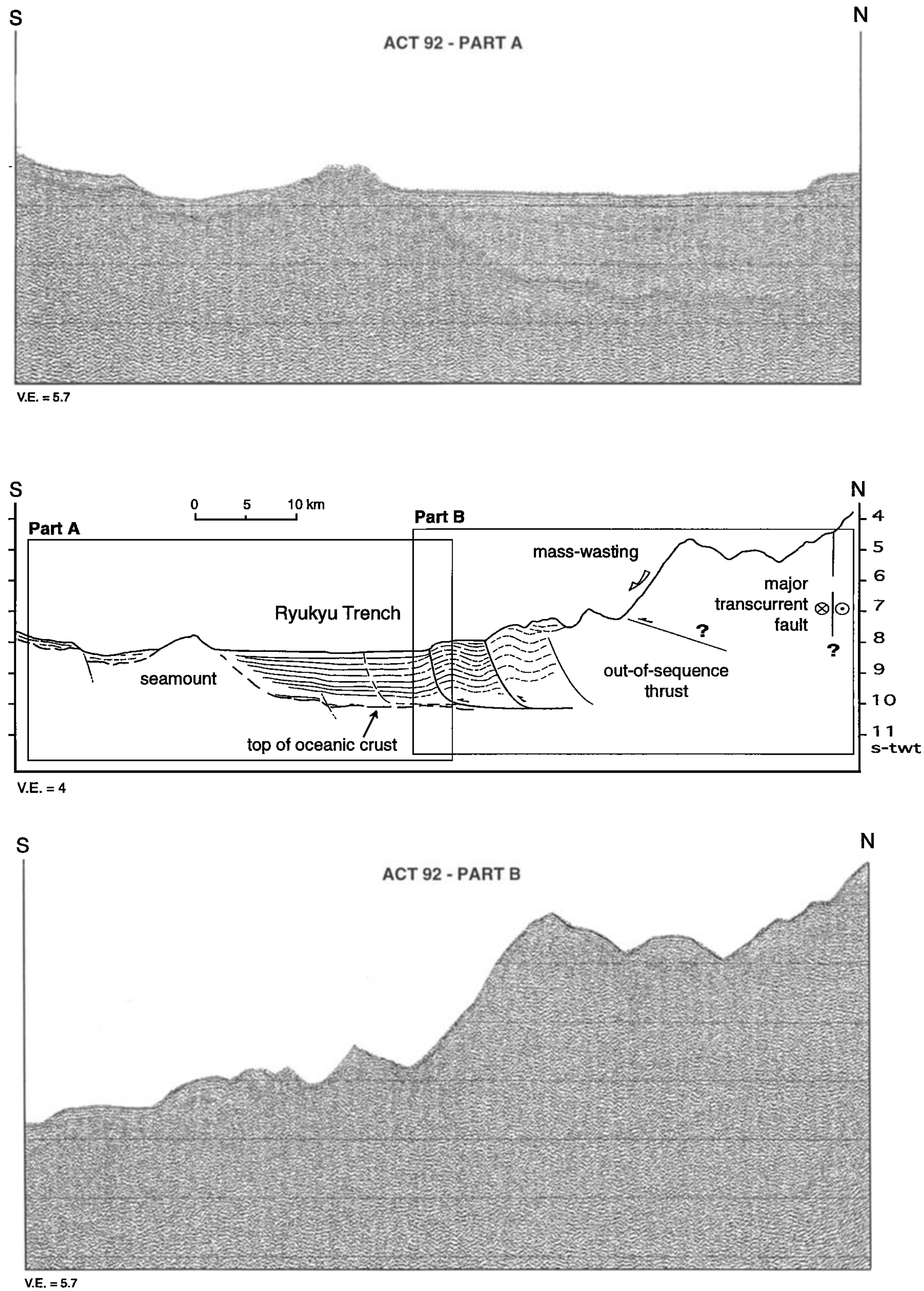

Figure 5. Portion of N-S time-migrated 6-channel seismic line ACT 92 across the Ryukyu Trench and accretionary wedge, east of the Gagua Ridge. Note the depth of the décollement in the trench, which almost coincides with the top of the oceanic basement. The emergence of an out-of-sequence thrust is suspected at the base of the main inner wall scarp, and, on the basis of bathymetric studies, the major transcurrent fault is located at the top of the wedge. Vertical exaggeration is ~ 5.7 at seafloor. Location is shown in Figure 3 and Plate 1.

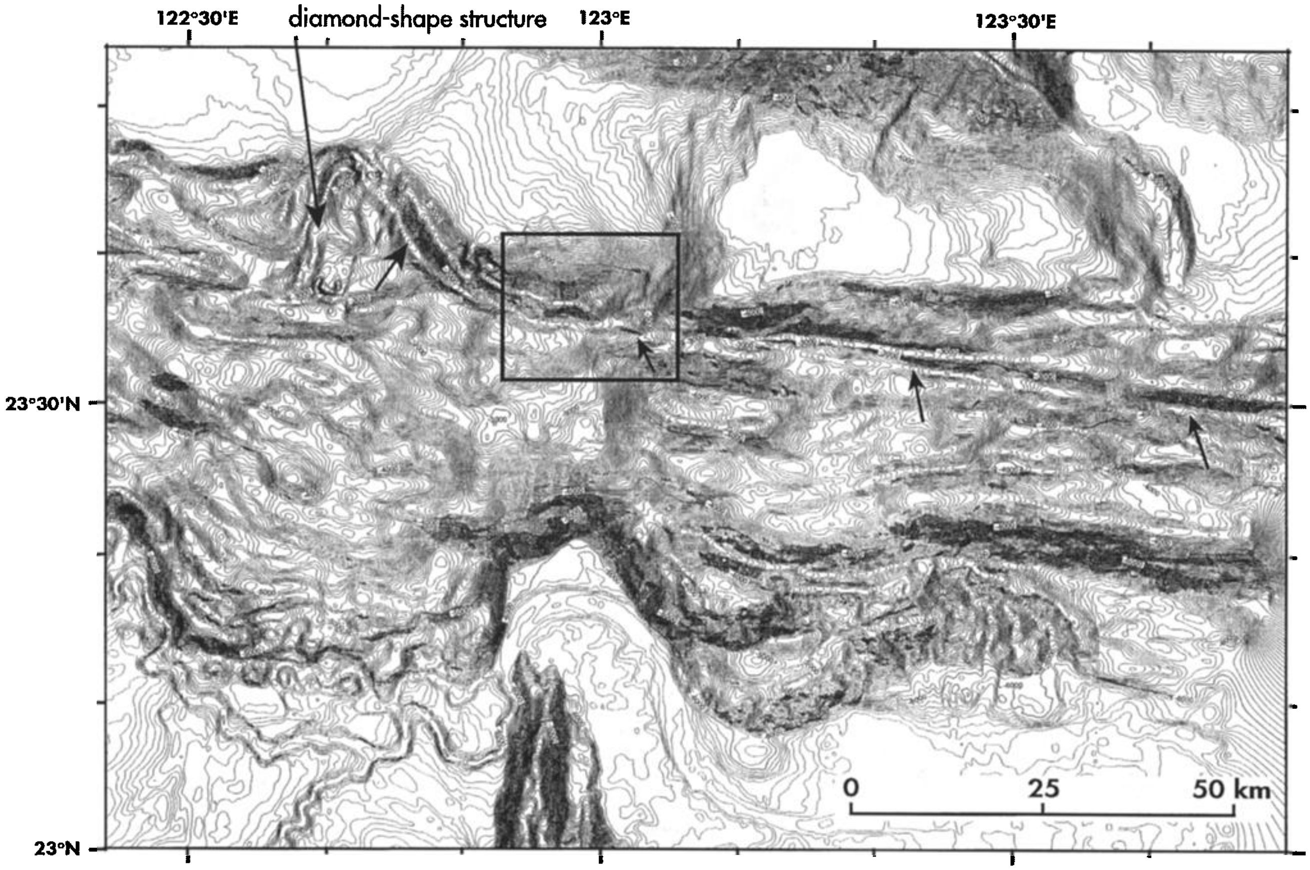

Figure 6. Bathymetric map of the Yaeyama accretionary wedge in the region of apparent interaction between the Gagua Ridge and the margin (see location in Figure 3). Isobaths are every 20 m. Note the strike-slip fault at the rear of the wedge (small arrows) and the steepness of deformation fronts in and east of the reentrant along the emergence of the out-of-sequence thrust. A particular structure is observed at the rear of the wedge near 122°40'E, refered as the diamond-shaped structure in this paper (see explanations in the text). Location of Figure 7 (box).

(Figure 5) both reveal that the entire sedimentary section, 2- to 3-km-thick, of the Ryukyu Trench is presently offscraped at the front of the wedge east of the Gagua Ridge.

Transcurrent faulting is localized at the rear of the wedge along a single major fault which is poorly resolved on seismics (Figure 5) but nicely imaged on bathymetry (Plate 1). Indeed, a spectacular N95° trending strike-slip fault is observed at the rear of the accretionary wedge, east of the Gagua Ridge (Figure 4 and Plate 1). Its morphological expression is a linear, 1 ± 0.5-km-wide, up to 650-m-deep, 100-km-long trough and associated narrow ridge to the north (Figures 6 and 7a). The backscattering image shows a series of parallel fractures, interpreted as Riedel shears (Figure 7b), producing a right-lateral displacement across the main fault. Consequently, the accretionary wedge moves toward Taiwan with respect to the Ryukyu Arc. Results from sandbox experiments indicate that oblique slip along a dipping basement fault with predominant strike slip and additional component of reverse dip slip (by opposition with pure strike slip) causes synthetic Riedel shears, with an upward convex shape, that are preferentially located above the downthrown side of the basement fault [*Mandl*, 1988, p. 142]. These experimental observations are in very good agreement with the existence and location of most splays, south of the main E-W trending shear zone (Figure 7c), because the downthrown basement block presumably belongs to the plate subducting northward. The upthrown basement block probably corresponds to the basement of the Ryukyu Arc. A local change in the dip of subducting basement in the vicinity of the shear zone (Figure 7c) is suggested by the associated regional high in the accretionary wedge north of the Gagua Ridge (Figures 4 and 6 and Plate 1). West of 123°E, the N95° trending strike-slip fault turns toward the north, reaching N33°W in azimuth (Figure 6). The curvature of the fault is also marked by what could be a curved drag fold to the north and a "diamond-shaped structure" to the east (Plate 1 and Figure 6, crossing of a N-S and an E-W fold).

The Ryukyu deformation front has been indented about 15 km in front of the Gagua Ridge. The reentrant consists to the east of a N30°W striking scarp, which is parallel to the termination of the right-lateral strike-slip fault at the rear of the wedge (Figures 4 and 6 and Plate 1). The 3-km-high frontal slope dips about 30°, close to the angle of repose of the accreted sediment, and is consequently highly unstable. A portion of the wedge about 30 km in diameter is uplifted by about 1000 to 1500 m with respect to the surrounding seafloor (Plate 1 and stippled area on Figure 4). The highest point,

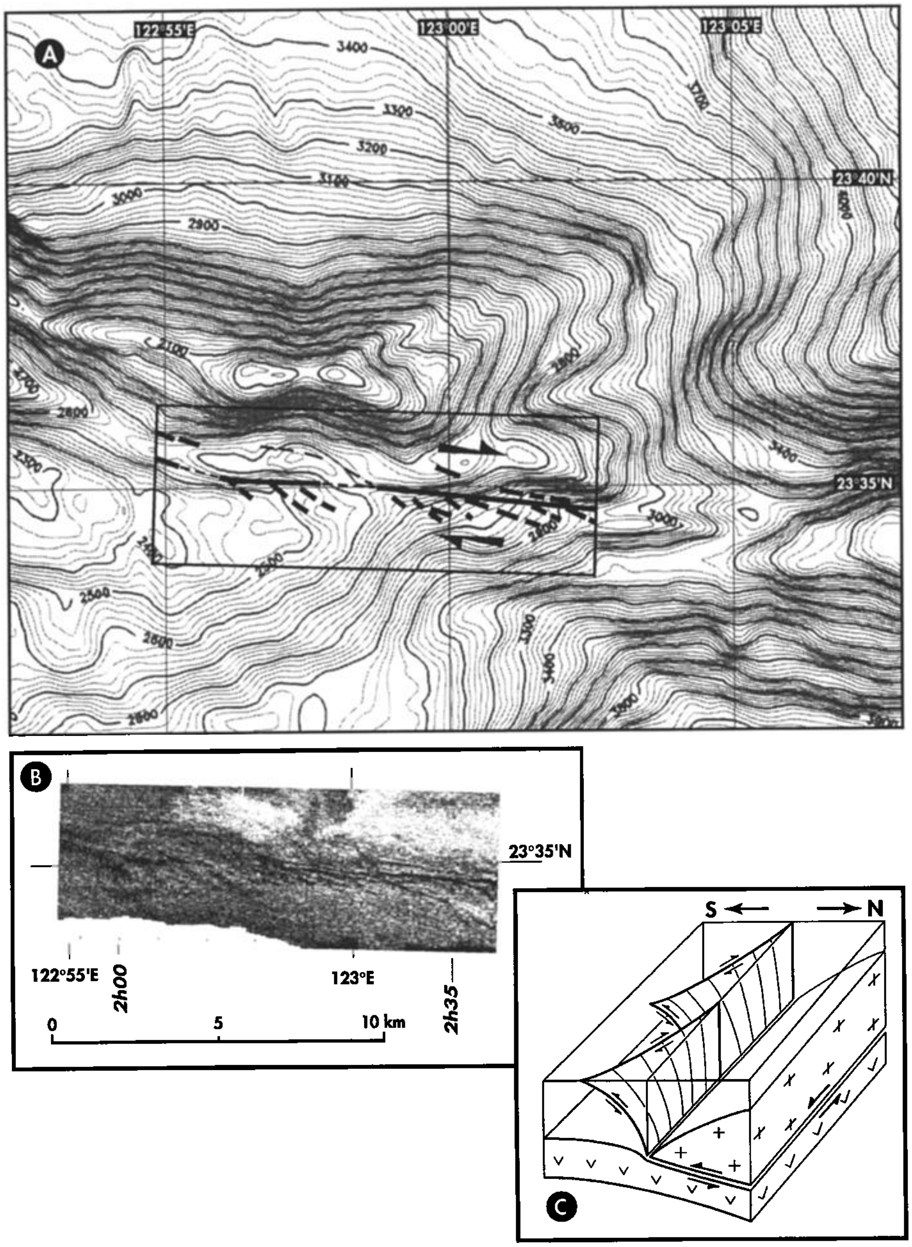

Figure 7. (a) Bathymetric map of the uplifted region which is cut by the major strike-slip fault. Isobaths are every 20 m. (b) Onboard display of real-time backscattering image of the major strike-slip fault located on Figure 7a. Note the Riedel shears mainly on the southern side of the shear zone. (c) Interpretative cartoon showing the geometry of the Riedels, adapted from *Mandl* [1988].

1980 m deep, is located north of the main N95° shear zone (Figures 4, 6, and 7a).

4.2.2. West of 122°40'E. West of the Gagua Ridge, evidence for active accretion at the trench is less convincing, except close to the ridge. The frontal taper is much lower (Figure 8) and the frontally accreted unit is crosscut by meandering channels (Plate 1). As already observed during previous Taiwanese cruises [*Liu et al.*, 1996, 1997], oblique thrusting and strike slip prevail in the wedge as attested by linear and lenticular structures of troughs and anticlines which are subparallel to the convergence vector (Figures 4 and 8 and Plate 1). A NW-SE trending right-lateral strike-slip fault is clearly visible in the bathymetry (Figure 9a) on shaded perspective views (Plate 2) and on the onboard display of reflectivity along the ship's route (Figure 9b). The fault can be traced over more than 40 km on the detailed bathymetric map (Figure 9a). Its precise trend, that is, N313°, is close to that of the convergence vector between PSP and Taiwan (SCB) [*Yu et al.*, 1997]. Because the strike-slip faults are linear with respect to the complex structure of the adjacent accretionary wedge and forearc basin, we think that they recently cut through the previous features rather than reactivating old thrusts.

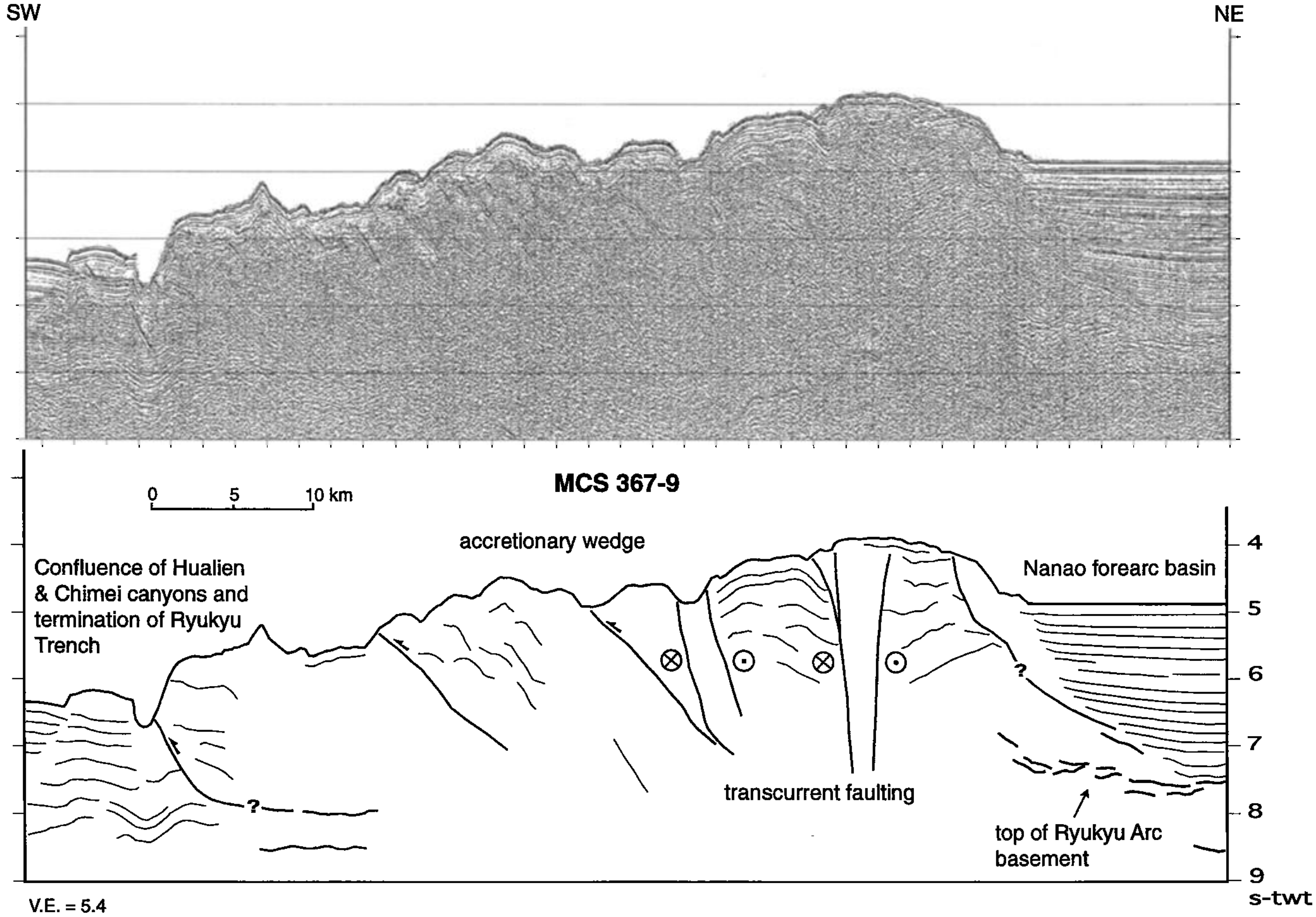

Figure 8. Portion of the NE-SW time-migrated 56-channel seismic line 367-9, acquired in 1993 on board the Taiwanese R/V *Ocean Researcher I*, across the westernmost part of the Ryukyu trench and accretionary wedge. Note the low taper compared with line ACT 92 (Figure 5), and the presence of transcurrent dextral faults at the rear of the wedge. Vertical exaggeration is ~ 5.4 at seafloor. Location is shown in Figure 3.

The Hualien Canyon outlines the physical boundary between the accreting Luzon Arc and the accretionary wedge. It deeply incises the sedimentary mass of the wedge (Plate 2).

4.3. Ryukyu Forearc Basins

The ACT survey revealed what was previously considered a single forearc basin to be, in fact, a series of forearc basins arrayed in an along-strike staircase geometry. The basins shallow westward from 4600 m in the East Nanao Basin to 3700 m in the Nanao Basin and to 3000 m in the Hoping Basin. They also shallow eastward to 3400 m in the Hateruma Basin (Figures 3 and 4 and Plate 1). This basin was named after the ACT cruise, using the name of the nearest Japanese island south of Iriomote (Figure 4).

On the basis of ACT reflection seismic lines, as well as on previous lines [*Liu et al.*, 1996, 1997; *Schnürle et al.*, 1998], it became possible to propose a relative chronology for the tectonic evolution of the Nanao and East Nanao Basins. Present-day sedimentation in the Nanao Basin is primarily turbidites coming from the Ilan area (Lanyang Hsi River, Figure 4), whereas the Hoping Basin deposits are now eroded and reworked [*Lallemand et al.*, 1997b]. Little deposition occurs in the East Nanao Basin, and the Hateruma Basin may be fed by sediments coming from the Yaeyama Islands through a NW trending valley (Figures 3 and 4 and Plate 1). The maximum thickness of 3.7 s two-way travel time (twt) of horizontal deposits has been observed in the Nanao Basin. In fact, there are two adjacent basins, a western one 3-s thick and an eastern one 3.7-s thick, separated by a 1.8-s deep basement high, in the E-W trending Nanao Basin [*Schnürle et al.*, 1998]. Numerous normal faults, N-S to NNW-SSE striking, affect the forearc basins sediment as seen on seismic line ACT81 (Figure 10) or on other trench-parallel seismic lines along the forearc basins.

There is a broad uplifted area rising 200 m above the 3700-m-deep Nanao Basin (Plate 1 and Figure 10) and 1100 m above the 4600-m-deep East Nanao Basin (Plate 1 and Figure 6) in the axis of the ridge and uplifted wedge.

The structure of the Hoping Basin appears more complex. It is likely controlled by the ongoing arc-continent collision in Taiwan. A tremendous, negative free-air gravity anomaly of about -200 mGal and a sediment thickness of more than 4 s (twt) characterize the basin area [*Lallemand et al.*, 1997b].

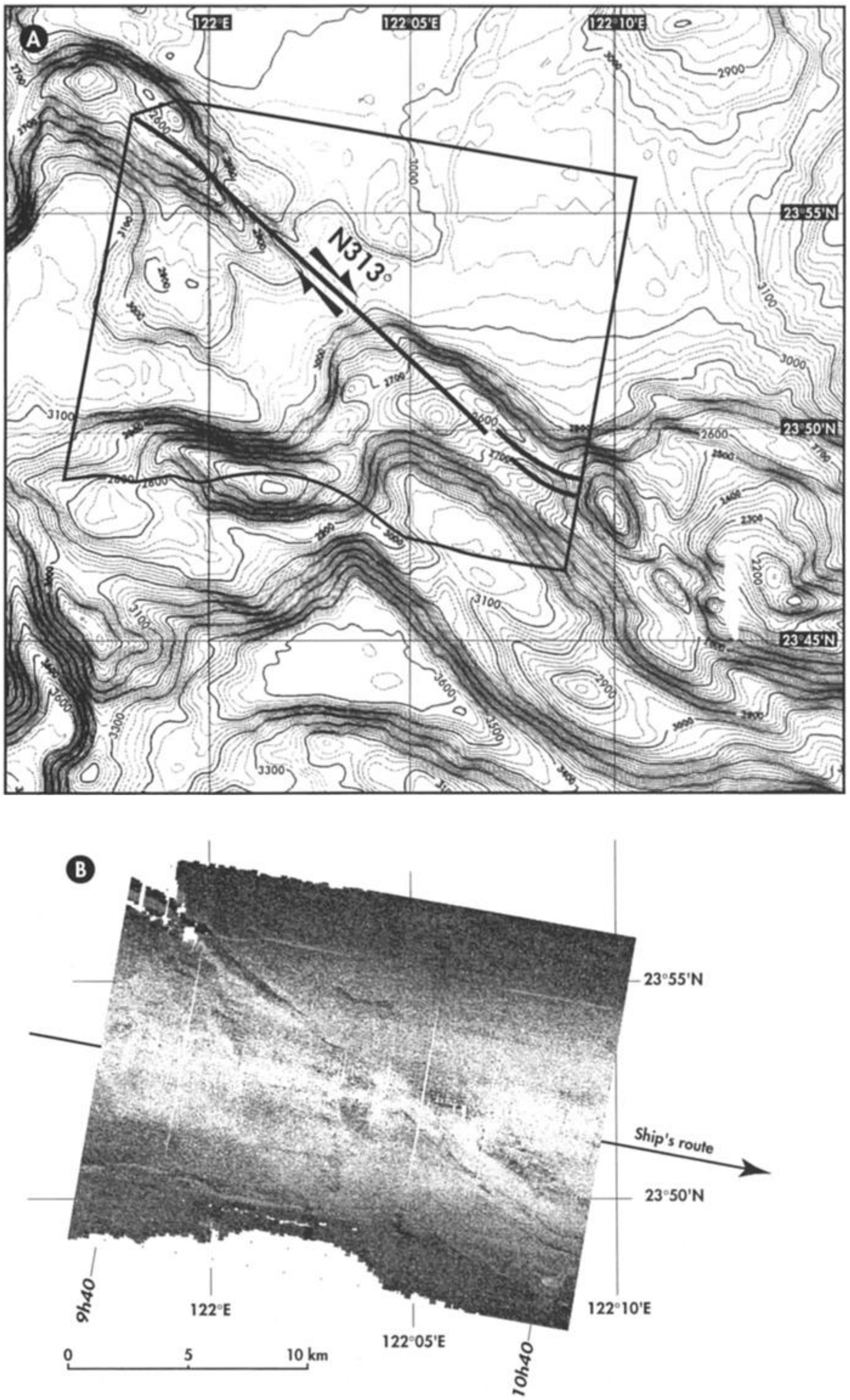

Figure 9. (a) Bathymetric map in the region of N313°-strike-slip faulting offshore of Hualien. Location shown in Plate 2. Isobaths are every 20 m. (b) Onboard display of real-time backscattering image of the strike-slip fault located on Figure 9a.

NW-SE lineaments are observed across the E-W trending Hsincheng Ridge in the Hoping Basin (Figure 4 and Plate 2) and were reported following previous cruises [*Lallemand et al.*, 1997b; *Liu et al.*, 1996, 1997]. The ridge is nonmagnetic [*Hsu et al.*, 1996a], and both southwestward and northeastward verging thrusts have been interpreted from several reflection seismic lines (Figure 4). It is located immediately north of the Coastal Range and could thus be related with the subduction of the northermost portion of the volcanic arc.

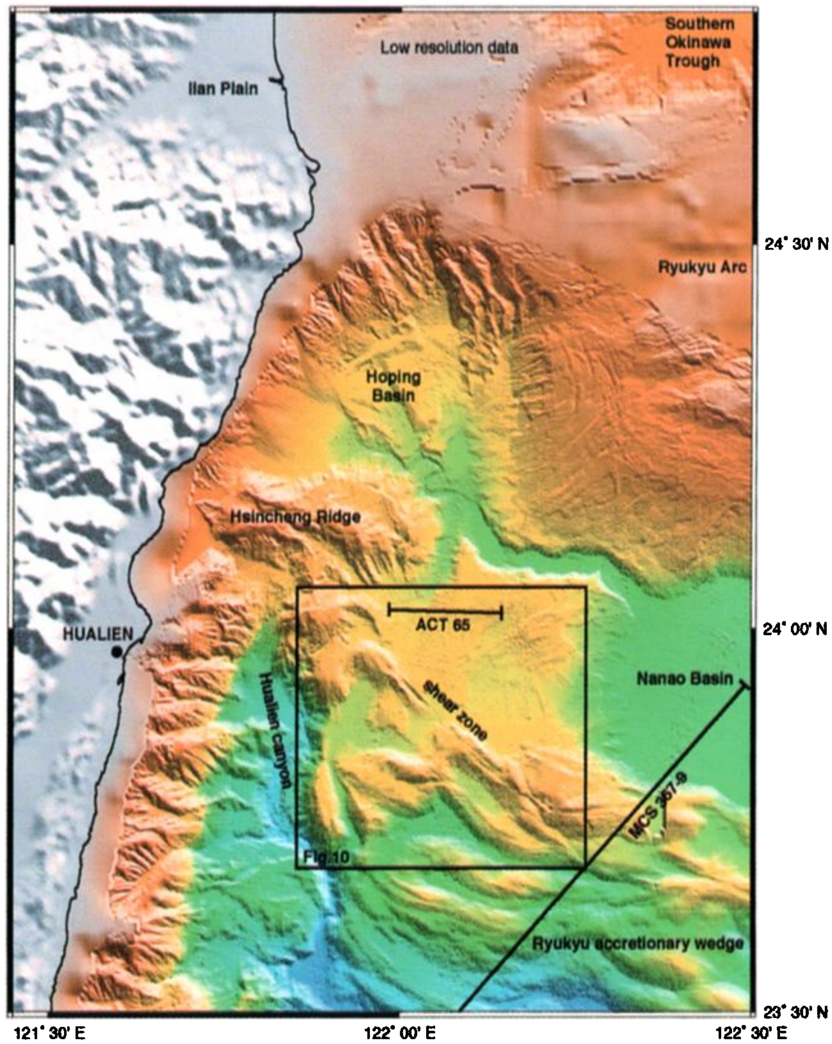

Plate 2. Shaded view of swath bathymetry acquired during the ACT cruise in the Hoping Basin off Hualien. See location of the box in Figure 3. Note the E-W trending Hsincheng Ridge and the N313° trending shear zone. Location of Figure 9a (box) and seismic line ACT 65 are shown in this study. Unfiltered swath bathymetric data were used in order to enhance fine structural details; thus some north-south artefacts remain in the image.

4.4. Ryukyu Arc Slope

The Ryukyu Arc slope exhibits a bayonet geometry in map view (Figures 3 and 4), with segments apparently offset right laterally along N-S to NW-SE strike-slip faults. On the basis of this observation, *Hsu et al.* [1996b] interpreted the southern Ryukyu Arc and back arc as being dissected by three N27°W trending strike-slip faults controlling the location of canyons in the northern margin of the Okinawa Trough. The detailed swath bathymetry acquired during the ACT cruise confirms at least part of this interpretation in the sense that the southern arc slope shows N30°W trends north of the Nanao Basin interpreted as old strike-slip faults subparallel to those observed in the accretionary wedge north of the Gagua Ridge (Figures 3 and 4 and Plate 1). The arc slope also exhibits N-S to NNE-SSW spoon-shaped normal faults visible on the bathymetric map (Figure 3) merging on WNW-ESE trending lineaments, subparallel to the convergence vector (Figure 4).

From west to east, the following is known:

1. The N30°E to N45°E striking steep slope, north of the Hsincheng Ridge (Figures 3 and 4), belongs to the Central Range as indicated by the simplified geological map of Figure 4. It is very likely affected by normal faulting as observed by authors along the coastal road on land and as predicted by GPS measurements [*Yu et al.*, 1997].

2. The detailed ACT bathymetry allowed us to trace several en échelon dextral strike-slip faults from the Okinawa Trough axis to the Hoping forearc basin (Figure 4). One of the faults is associated with an east facing scarp in the Okinawa Trough (24°50'N, 122°13'E, see the complete ACT survey bathymetric map of *Lallemand et al.* [1997a] or *Sibuet et al.* [1998]) and with a right-lateral offset of structural highs on both sides of about 15 km (Plate 2). The fault continues southward across the arc basement and splits into several N-S trending branches in the Hoping Basin (Figure 4). The isobaths are systematically

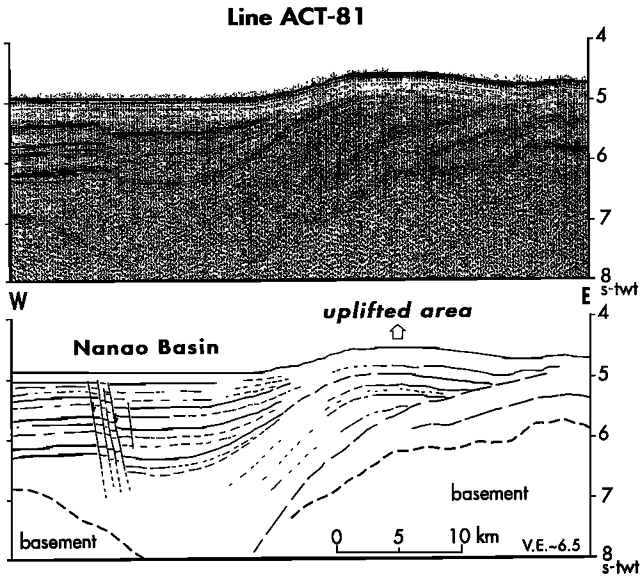

Figure 10. Portion of E-W time migrated 6-channel seismic line ACT 81 across the Nanao forearc basin and the uplifted area between the former basin and the East Nanao Basin. Note the normal faults in the Nanao Basin and the progressive uplift of the seafloor above the subducting asperity as indicated by onlap of sediments. Vertical exaggeration is ~ 6.5 at seafloor. Location is shown in Figure 3 and Plate 1.

deflected along longitude 122°04'E between 23°44'N and 24°32'N, that is, over 85 km (Figure 3 and Plate 2). A flower structure is seen along the E-W line ACT-65 crossing the shear zone in the Hoping Basin on both seismic and 3.5 kHz profiles (Figure 11).

3. The prominent N50°W trending spur and associated narrow valley, south of Iriomote Island (Figure 4 and Plate 1), has remained enigmatic for a long time because it is highly oblique to the strike and it seems to offset left laterally the Ryukyu Arc slope, that is, in a sense opposite to the other offsets.

5. Discussion and Interpretations

5.1. Lateral Transport of the Ryukyu Accretionary Wedge Caused by High Convergence Obliquity

On the basis of GPS measurements, the present-day convergence between the PSP and the southern Ryukyu margin in the study area has an obliquity of 40° east of 122°40'E and 60° west of this longitude [*Lallemand and Liu.*, 1998]. Slip partitioning between closer-to-trench normal thrusting and trench-parallel strike-slip faulting has been postulated from the study of earthquake slip vectors [*Kao et al.*, 1998] at least along the arc segment between 122°E and 123°E. Because the selected earthquakes (interface seismic zone) are located between 24°N and 24°20'N beneath the Ryukyu arc slope, transcurrent faulting must occur landward, that is, in the arc itself or in the Okinawa Trough, to account for the slip deflection. The lack of E-W compressional stress at the western boundary of the presumed Ryukyu forearc sliver and, conversely, evidence of southeastward motion in the northeastern area of Taiwan and on Yonaguni Island with respect to SCB [*Yu et al.*, 1997; *Imanishi et al.*, 1996] indicate that a westward motion of a Ryukyu forearc sliver is incompatible with geodetic data and stress regime of the upper plate.

For instance, transcurrent faulting is well documented in the accretionary wedge, but it cannot have any influence on slip vectors. NW-SE diffuse shearing characterizes most of the wedge west of 123°E, whereas a major E-W strike-slip fault,

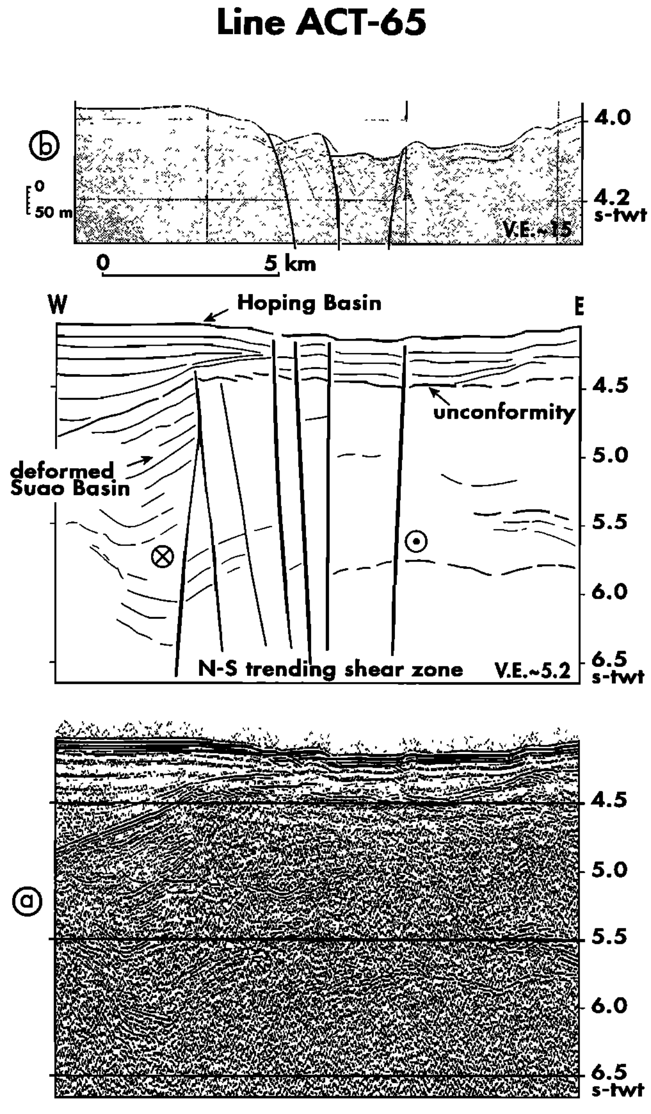

Figure 11. (a) E-W time-migrated 6-channel seismic line ACT 65 across the southern part of the Hoping Basin. The Hoping Basin sequences are thinning toward the east above the highly deformed Suao Basin strata [see *Lallemand et al.*, 1997b]. The vertical strike-slip faults might belong to the N-S transform zone which allows the Ryukyu Arc to drift southward with respect to the SCB (see Figure 4). (b) A kind of flower structure is visible on the 3.5 kHz profile. The horizontal scale is the same as Figure 11a but vertical exaggerations differ. Vertical exaggeration is ~ 5 at seafloor on the seismic line and is ~ 15 on the 3.5 kHz profile. See location on Figure 3 and Plate 2.

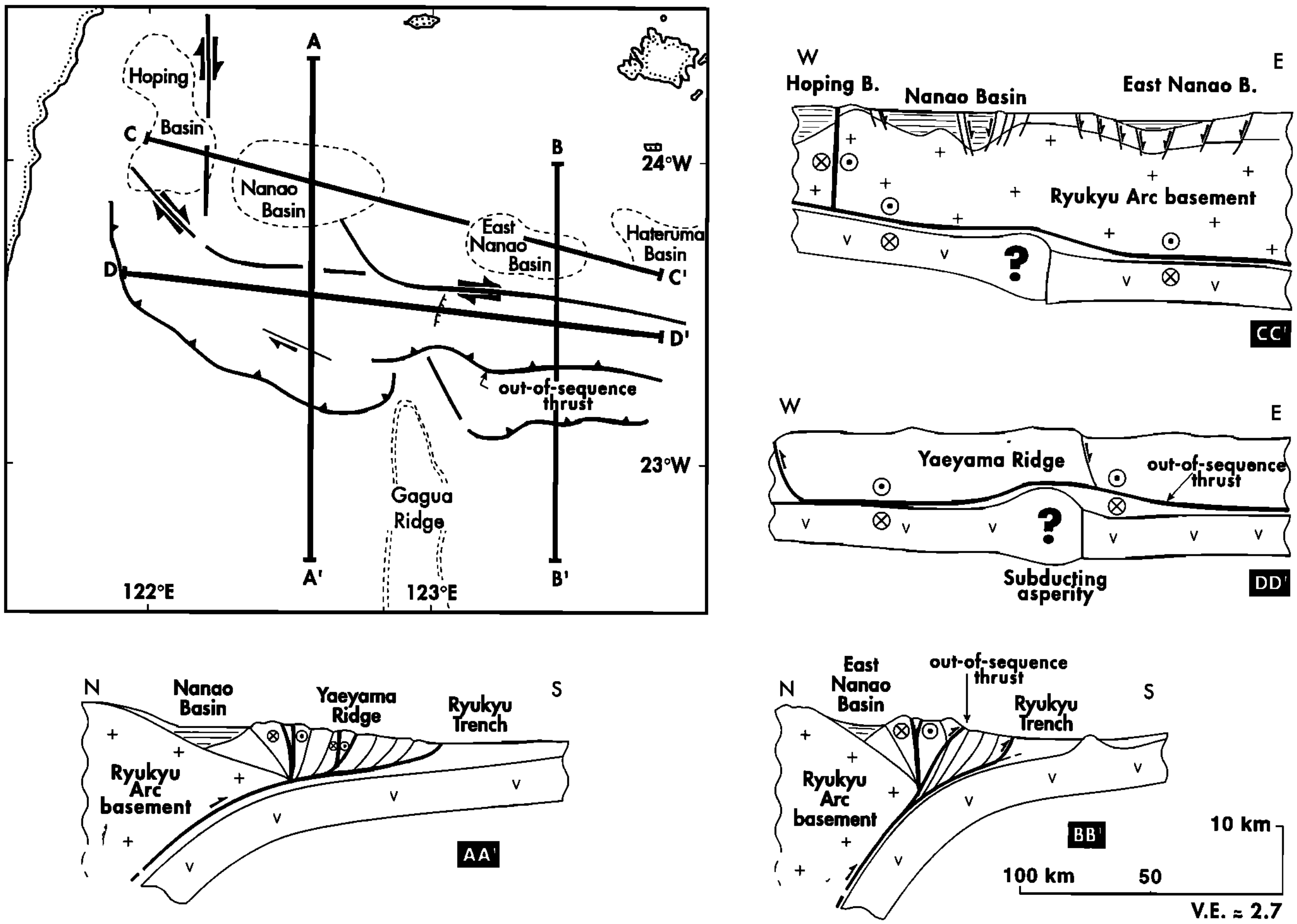

Figure 12. Four sections across and along the Yaeyama accretionary wedge and forearc basins. These interpreted sections are based on seismic line interpretations and detailed bathymetry from M. Ewing cruise [*Schnürle et al.*, 1998] and this cruise for shallower parts. Interpretations at deeper levels, such as the geometry of the subducting plate and out-of-sequence thrust are deduced from sandbox experiments [*Lallemand et al.*, 1992]. The deepening of the subducting Philippine Sea Plate (PSP) away from Taiwan is suggested by geometrical considerations of the PSP near Taiwan, seismicity [*Kao et al.*, 1998], and refraction studies [*Wang et al.*, 1996].

associated with southward thrusting prevails to the east (see Figure 4 and synthetic cross sections A-A' and B-B' on Figure 12).

Near 122°40'E, the major N95° transcurrent fault is deviated toward the north and exhibits a N33°W segment which offsets the rear of the wedge (Figure 6). It duplicates the change in strike of the southern slope of the arc north of the Nanao Basin (Figures 3 and 4 and Plate 1). Assuming that the Ryukyu Arc basement acts as a rigid backstop controlling the growth of the wedge, we suppose that its bayonet shape is reflected in the accretionary wedge, especially at its rear. West of this segment at the tip of the N95° trending strike-slip fault, the diamond-shaped structure probably partly took up some intrawedge shortening. This particular structure may also represent an overlap zone, which transfers the displacement, with less clear trench-parallel strike-slip faults to the west (Figures 4 and 6).

These right-lateral transcurrent faults accommodate strain partitioning within the accretionary wedge, parallel to the strike of the adjacent trench section, that is, roughly E-W east of 122°40'E and WNW-ESE west of 122°40'E.

Inasmuch as only 20% of the convergence between PSP and SCB is taken up on land in the Hualien area [*Yu et al.*, 1997], the westward displacement of the wedge, if significant, should be counterbalanced by shortening in the wedge (see the N-S trending fold east of the Hualien Canyon, Figure 4 and Plate 2 and cross section D-D' on Figure 12) and/or erosion by the Hualien Canyon (see the 20° dipping, 1-km-high east wall of the canyon, Figure 3).

5.2. Gagua Ridge Subduction and Degree of Slip Partitioning

According to previous studies on subducting asperities [e.g., *Lallemand and Le Pichon*, 1987; *Lallemand et al.*, 1990, 1994], indentation of the deformation front by local blocking of the décollement. and interruption of frontal accretion with significant uplift of the margin are generally interpreted as evidence for subduction of a structural high. In this case, the top of the subducting high should be located beneath the highest point in the wedge (-1980 m, see Figures 4, 6 and 7).

Because the more-than-300-km-long Gagua Ridge seems to terminate at the trench (its height with respect to the surrounding basement decreases from 5 km in the south to less than 1 km in the trench), we consider that either (1) the ridge extends to the north with a low at the trench or (2) the ridge ends at the trench and a subducted seamount lies in the axis of the ridge north of it. In any case, the subduction of a bathymetric high is certainly responsible for the indentation of the margin front.

Now, we consider the two extreme cases with respect to the amount of strike slip absorbed on the N95° transcurrent fault. (1) If there is no lateral slip (degree of partitioning is 0), then the trail of the subducted high must coincide with the azimuth of present-day convergence between the PSP and the local Ryukyu margin, that is, N325°. (2) If the total lateral component of the oblique convergence is accommodated along the N95° transcurrent fault (degree of partitioning is 1), then the trail of the subducted high must be normal to the strike of the trench, that is, N5°.

As we can see on the bathymetric map (Figure 6), the reentrant is asymmetric, and the visible part of the Gagua Ridge is located on the western side of the reentrant. This means that there is some degree of slip partitioning accommodated along the transcurrent fault. The distance between the asperity (below the highest point in the wedge) and the present margin front is about 50 km. The magnitude of the normal-to-the-trench component of the relative convergence vector (PSP/Ryukyu margin) is about 81 km/m.y. [*Lallemand and Liu*, 1998]. This implies that the asperity passed through the deformation front about 0.6 m.y. ago and even less if we account for frontal accretion during this period of time (see Figure 5). Thus, during the last 600,000 years, the lateral slip along the N95° strike-slip fault may have reached a maximum of 42 km in the case of total slip partitioning.

On the basis of observations in the wake of a subducting asperity, we have shown that strain partitioning was efficient within the wedge at least during the last 400,000 to 600,000 years. Detailed morphological investigations supported by sandbox models are currently being performed [*Dominguez et al.*, 1996] to propose a kinematic analysis of this sector and estimate the contribution of the subducting seamount/ridge in the coupling between the two converging plates and thus the degree of partitioning.

5.3. Trench-Parallel Stretching and Folding in the Forearc Basins and Relations With the Arc Framework

The forearc basins shallow systematically from 123°30'E to Taiwan. The same general trend is observed for the accretionary wedge and the subducting oceanic basement (sections C-C' and D-D' in Figure 12). The shallowing cannot be entirely caused by the nearby collision zone where the PSP overthrusts the Eurasian Plate along the Longitudinal Valley Fault because (1) the shallowing is not progressive but occurs step by step, (2) there are structural highs between the various basins, and (3) the easternmost Hateruma Basin is 1200 m shallower than the East Nanao Basin. Boundaries between the basins are thus probably structurally controlled.

We have seen that the forearc basins are arranged in an en échelon array, as is the Ryukyu Arc slope. GPS measurements indicate that the "Yonaguni" Ryukyu Arc segment (YS) is

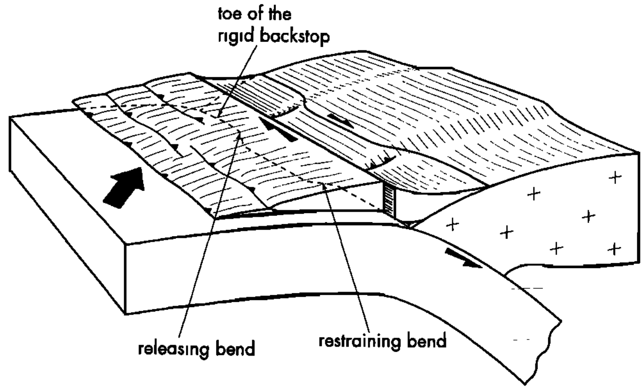

Figure 13. Perspective cartoon illustrating the geometry of releasing and restraining bends of the toe of the rigid backstop underlying the forearc basin sediments. The accretionary wedge is moving laterally along a major transcurrent fault located at the rear of the prism. This motion induces some dextral shearing within the forearc sedimentary section with stretching above the releasing bends and folding above the restraining bends of the arc basement.

moving toward the south (with respect to SCB) 1.6 to 1.8 cm/yr faster than the "Iriomote" Ryukyu Arc segment (IS) which moves toward the south-southeast. This present-day kinematics is reflected in the bathymetry (Figure 3), as illustrated by the YS which is offset right laterally with respect to northern Taiwan along a N-S transform fault zone, whereas the IS is apparently offset left laterally with respect to the YS along a NW-SE fault zone (Figure 4). In fact, the N50°W trending spur and associated narrow valley north of the East Nanao Basin (Figure 4 and Plate 1) probably originate from extension perpendicular to their trace according to the respective motion of Hateruma with respect to Yonaguni. The amount of extension has been estimated to be about 2.4 cm/yr by *Lallemand and Liu* [1998]. The differential southeastward motion of both Ryukyu Arc segments results in an apparent left-lateral offset of the southern Ryukyu Arc slope.

A right-lateral motion of the sedimentary forearc (basin and wedge) with respect to an underlying bayonet-shaped rigid backstop may generate trench-parallel extension above releasing bends and compression above restraining bends as illustrated on Figure 13. On the basis of the structural map, dilational jogs or bends (incipient pull-apart) are found beneath the forearc basins near 122°10'E, 122°30'E, and 122°50'E where normal faults are observed, whereas a compressive jog (pop up) may exist at 123°40'E between the East Nanao and Hateruma Basins, where a fold is observed in the forearc sediments (Figures 3 and 4 and Plate 1).

Some lineaments subparallel to the convergence vector are observed in the Ryukyu Arc slope suggesting some discrete right-lateral motion within the arc. The geometry of the forearc basins, the numerous normal faults within the recent sediment fill and on the slopes of the basins which connect with NW-SE lineaments, and the associated free-air gravity minima are interpreted as indications of a transtensional regime. It is associated with subsidence of the forearc basins in a context of right-lateral shearing or lateral displacement of the accretionary wedge with respect to the arc basement.

Trench-parallel stretching has already been documented along the Sumatra or Aleutians subduction zones [*McCaffrey*, 1991; *Ryan and Coleman*, 1992; *Bellier and Sébrier*, 1995]. Such extension is generally caused by an increase of convergence obliquity and thus of the slip rate along the trench. This explanation can be invoked for the present study because the convergence obliquity increases from 40° east of 122°40'E to 60° west of this longitude. The lateral component of the relative convergence vector thus increases from 7 to 10 cm/yr for the case of total strain partitioning. This mechanism supposes that the degree of partitioning remains more or less constant along the accretionary wedge and it only explains trench-parallel extension in the wedge, not in the forearc basins. The particular geometry of the toe of the backstop together with the shearing of the overlying sedimentary forearc is thus probably a second factor of trench-parallel extension and compression.

5.4. Hoping Basin: A Diffuse Triple Junction?

The most prominent feature which is associated with the right-lateral offset of the arc basement is the N-S trending shear zone close to Taiwan (Figure 4). On the basis of GPS and very long baseline interferometry studies [*Imanishi et al.*, 1996; *Yu et al.*, 1997; *Heki*, 1996], the present-day kinematics of the southern Ryukyu Arc area is such that about 1.2 to 1.3 cm/yr of right-lateral displacement must be absorbed along a N170° trending transform fault zone somewhere between the Ilan Plain and Yonaguni (Figure 4) [*Lallemand and Liu*, 1998].

The deformed Hoping Basin presently trends N-S or NNW-SSE rather than E-W like the other forearc basins. There are several reasons for this geometry, among which is its particular location at the complex junction between (1) the western tip of the Ryukyu Trench, (2) the northern end of the Longitudinal Valley Fault, known on land as the suture between PSP and SCB, and (3) the transform zone along which the Ryukyu Arc moves southward with respect to SCB (Figure 4). If we consider that these three features represent plate boundaries, then the basin is located on top of an unstable trench-trench-transform fault triple junction or a trench-fault-fault triple junction, inasmuch as the Longitudinal Valley Fault is rather a high-angle reverse fault than a subduction thrust. The diffuse junction migrates toward the south since the start of activity along the N-S transform zone. After restoring the Ryukyu Arc to its former position (about 15 km back to the north corresponding to the lateral offset of structural highs on Plate 2, i.e., about 1 m.y. of activity at the present rate), the Hoping Basin unbends and joins the E-W alignment of the other forearc basins.

The Hsincheng Ridge is located exactly at the intersection of (1) the northern end of the Longitudinal Valley Fault, (2) the northwestern extension of the NW-SE strike-slip faults affecting the accretionary wedge, and (3) along a major N-S transform zone. This is the reason why it is so difficult to seismically image structural features in it, even with multichannel seismics. *Lallemand et al.* [1997b] have shown that the upper sequence of the ridge consists of deformed sediment of the Hoping Basin. The ridge is thus presently growing. Seismic data and morphological studies allow us to infer that it undergoes strong compression. The ridge is also located in the extension of the Coastal Range, so that its deeper parts can be constituted of the Luzon Volcanic Arc, which could be downfaulted to the north along an E-W tear fault [*Lallemand et al.*, 1997b].

6. Conclusion

It has been shown in this study that slip partitioning, caused by oblique convergence, was either localized along a major transcurrent fault at the rear of the accretionary wedge for an obliquity of 40° or distributed over the width of the sedimentary wedge when obliquity increased to 60°. The influence of a subducting ridge or seamount on the degree of strain partitioning needs to be further investigated using analog modeling, and no definitive conclusion can be reached yet. The forearc basin sediments appear to be slightly sheared between the rigid underlying arc basement and the moving accretionary prism. Trench-parallel stretching and folding is thus observed above the bayonet-shaped toe of the rigid arc.

Unlike the Sumatra and Hikurangi cases where transcurrent faulting also occurs onshore near the volcanic line, our observations from the southern Ryukyu show that no significant transcurrent features were revealed in the arc. This absence within the southern Ryukyu Arc basement could result from the lack of any volcanism (no weakness zone) and/or the extensional regime of the overriding plate (Okinawa Trough opening).

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References

Bellier, O., and M. Sébrier, Is the slip rate variation on the Great Sumatran Fault accommodated by fore-arc stretching ?, *Geophys. Res. Lett.*, *22* (15), 1969-1972, 1995.

Briais, A., and G. Pautot, Reconstructions of the South China Sea from structural data and magnetic anomalies, in *Marine Geology and Geophysics of the South China Sea*, edited by J. Xianglong, H.R Kudrass, and G. Pautot, pp. 60-69, China Ocean Press, 1992.

Deschamps, A., Signification tectonique de la ride de Gagua en subduction près de Taiwan, Master's thesis, Montpellier 2 Univ., Montpellier, France, 1997.

Deschamps, A., S. Lallemand, and J.-Y. Collot, The tectonic significance of the Gagua Ridge near Taiwan, paper presented at Tectonics of East Asia (TEA) International Conference, Natl. Cent. Univ., Chung-Li, Taiwan, Nov. 3-5, 1997.

Diament, M., H. Harjono, K. Karta, C. Deplus, D. Dahrin, M. T Zen Jr., M. Gérard, O. Lassal, A. Martin, and J. Malod, Mentawai fault zone off Sumatra: A new key to the geodynamics of western Indonesia, *Geology*, *20*, 259-262, 1992.

Dominguez, S, S. Lallemand, C.-S Liu, and the ACT Scientific Crew, The southern Ryukyu arc-trench system and the Gagua Ridge subduction. Preliminary results of the ACT cruise (abstract), *Eos Trans AGU*, *77*(46), Fall Meet. Suppl., F731, 1996.

Fitch, T. J, Plate convergence, transcurrent faults, and internal deformation adjacent to southeast

Asia and the western Pacific, *J. Geophys. Res.*, *77* (23), 4432-4460, 1972.
Gutscher, M.-A., N. Kukowski, J. Malavieille, and S. Lallemand, Episodic imbricate thrusting and underthrusting: Analog experiments and mechanical analysis applied to the Alaskan accretionary wedge, *J. Geophys. Res.*, *103* (5), 10161-10176, 1998.
Heki, H., Horizontal and vertical crustal movements from three-dimensional very long baseline interferometry kinematic reference frame: Implication for the reversal timescale revision, *J. Geophys. Res.*, *101* (2), 3187-3198, 1996.
Hilde, T.W.C., and C.-S. Lee, Origin and evolution of the West Philippine Basin: A new interpretation, *Tectonophysics*, *102*, 85-104, 1984.
Hsu, S.-K., S.-Y Liu, C-S. Liu, C.-T. Chyu, S. Lallemand, J-C. Sibuet, C. Wang, B. Karp, and the ACT Scientific Crew, New compilation of magnetic and gravimetric data around Taiwan (abstract), *Eos Trans. AGU*, *77*(46), Fall Meet. Suppl, F732, 1996a.
Hsu, S.-K., J.-C. Sibuet, S Monti, C.-T. Shyu, and C-S. Liu, Transition between the Okinawa Trough backarc extension and the Taiwan collision: New insights on the southernmost Ryukyu subduction zone, *Mar. Geophys. Res.*, *18*, 163-187, 1996b.
Imanishi, M, F. Kimata, N. Inamori, R. Miyajima, T. Okuda, K. Takai, and K. Hirahara, Horizontal displacements by GPS measurements at the Okinawa-Sakishima Islands (1994-1995) (in japanese), *Earthquake*, *2* (49), 417-421, 1996.
Jarrard, R. D., Terrane motion by strike-slip faulting of forearc slivers, *Geology*, *14*, 780-783, 1986.
Kao, H., S.-S. J. Shen, and K.-F. Ma, Transition from oblique subduction to collision: Earthquakes in the southernmost Ryukyu Arc - Taiwan region, *J. Geophys. Res.*, *103* (4), 7211-7229, 1998.
Kuramoto, S., and K. Konishi, The southwest Ryukyu Arc is a migrating microplate (forearc sliver), *Tectonophysics*, *163*, 75-91, 1989
Lallemand. S E., and C.-S. Liu, Geodynamic implications of present-day kinematics in the southern Ryukyus, *J. Geol Soc China*, *41* (4), 551-564, 1998.
Lallemand, S., and X. Le Pichon, Coulomb wedge model applied to the subduction of seamounts in the Japan Trench, *Geology*, *15*, 1065-1069, 1987.
Lallemand, S., J.-Y Collot, B. Pelletier, C. Rangin, and J.-P. Cadet, Impact of oceanic asperities on the tectogenesis of modern convergent margins, *Oceanol. Acta*, *10*, 17-30, 1990.
Lallemand, S.E., J. Malavieille, and S. Calassou, Effects of oceanic ridge subduction on accretionary wedges: Experimental modeling and marine observations, *Tectonics*, *11* (6), 1301-1313, 1992.
Lallemand, S.E., P. Schnürle, and J. Malavieille, Coulomb theory applied to accretionary and non-accretionary wedges - Possible causes for tectonic erosion and/or frontal accretion, *J Geophys. Res.*, *99* (6), 12033-12055, 1994.
Lallemand, S.E., C-S. Liu, and the ACT scientific crew, Swath Bathymetry Mapping Reveals Details of the Active Arc-Continent Collision Offshore Taiwan, *Eos Trans. AGU*, *78* (17), 173-175, 1997a
Lallemand, S.E., C.-S. Liu, and Y. Font, A tear fault boundary between the Taiwan orogen and the Ryukyu subduction zone, *Tectonophysics*, *274* (1/3), 171-190, 1997b.
Lee, T.-Y., and L. A. Lawver, Cenozoic plate reconstruction of Southeast Asia, *Tectonophysics*, *251*, 85-138, 1995.
Letouzey, J., and M. Kimura, Okinawa Trough genesis: Structure and evolution of a back-arc basin developed in a continent, *Mar. Pet. Geol*, *2*, 111-130, 1985.
Liu, C-S., S. E. Lallemand, and S.-J. Lin, Structural characteristics and possible boundary between the Taiwan collision zone and the Ryukyu arc-trench system, paper presented at Geological Symposium in Memory of Professor T P. Yen, Nat. Cent Univ., Chung-Li, Taiwan, May 24-25, 1996.
Liu C.-S., S. E. Lallemand, S.-J. Lin, P Schnurle, and D. L Reed, Forearc structures of the Ryukyu Subduction-Taiwan Collision zone from seismic reflection studies east of Taiwan (abstract), *Eos Trans AGU*, Fall Meet. Suppl., F718, 1997.
Mandl, G., Mechanics of tectonic faulting - Models and basic concepts, in *Developments in Structural Geology*, vol 1, 407 pp., Elsevier Sci., New York, 1988.
McCaffrey, R, Slip vectors and stretching of the Sumatran forearc, *Geology*, *19*, 881-884, 1991.
Mrozowski, C. L., S. D. Lewis, and D. E. Hayes, Complexities in the tectonic evolution of the West Philippine Basin, *Tectonophysics*, *82*, 1-24, 1982.
Park, J-O., Seismic stratigraphy and tectonic evolution of the southern Ryukyu island arc, Ph.D thesis, 145 pp., ORI, Univ. of Tokyo, Tokyo, 1996.
Ryan, H F, and P J. Coleman, Composite transform-convergent plate boundaries: Description and discussion, *Mar. Pet Geol.*, *9*, 89-97, 1992.
Schnürle, P., C-S. Liu, S. E. Lallemand, and D. L. Reed, Structural insight into the south Ryukyu margin: Effects of the subducting Gagua Ridge, *Tectonophysics*, *288*, 237-250, 1998.
Seno, T., The instantaneous rotation vector of the Philippine Sea plate relative to the Eurasian Plate, *Tectonophysics*, *42*, 209-225, 1977.
Seno, T., S. Stein, and A. E. Grip, A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geologic data, *J Geophys. Res.*, *98* (10), 17941-17948, 1993.
Sibuet, J.-C., et al., Back-arc extension in the Okinawa Trough, *J. Geophys. Res.*, *92* (13), 14041-14063, 1987.
Sibuet, J.-C., S.-K. Hsu, C.-T. Shyu, and C.-S. Liu C.-S., Structural and kinematic evolutions of the Okinawa Trough backarc basin, in *Backarc Basins: Tectonics and Magmatism*, edited by B. Taylor, pp. 343-379, Plenum, New York, 1995.
Sibuet, J.-C., B. Deffontaines, S.-K. Hsu, N. Thareau, J.-P. Le Formal, C.-S. Liu and the ACT party, Okinawa trough backarc basin: Early tectonic and magmatic evolution, *J. Geophys. Res.*, in press, 1998.
Smith, W.H F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956-1962, 1997.
Tapponnier, P., G. Peltzer, A-Y. Le Dain, R. Armijo, and P. Cobbold, Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine, *Geology*, *10*, 611-616, 1982.
Wang, T.-K., K. McIntosh, Y. Nakamura, and C.-S. Liu, OBS refraction survey and imaging offshore eastern Taiwan, *Eos Trans. AGU*, *77*(46), Fall Meet. Suppl., F720, 1996.
Wessel, P., and W.H.F. Smith, Free software helps map and display data, *Eos Trans. AGU*, *72* (41), 441, 445-446, 1991.
Yu, S.-B., H.-Y. Chen, and L.-C. Kuo, Velocity field of GPS stations in the Taiwan area, *Tectonophysics*, *274* (1/3), 41-59, 1997.

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