Marine Geophysical Researches
Volume 27, Number 1 / mars 2006: 95-107
http://dx.doi.org/10.1007/s11001-006-8182-3

The original publication is available at http://www.springerlink.com

Tectonic Significance of the Taitung Canyon, Huatung Basin, East of Taiwan

Jean-Claude Sibuet[1], Shu-Kun Hsu[2] and Alain Normand[1]

(1) Ifremer Centre de Brest, B.P. 70, 29280 Plouzané Cedex, France
(2) Institute of Geophysics, National Central University, Chung-Li, Taiwan, 32054

Abstract:

Since the beginning of formation of Proto-Taiwan, the subducting Philippine (PH) Sea plate has moved continuously through time in the N307° direction with respect to Eurasia (EU), tearing the EU plate. The subducting EU plate includes a continental part in the north and an oceanic part in the south. The boundary B between these two domains corresponds to the eastern prolongation of the northeastern South China Sea ocean-continent transition zone. In the Huatung Basin (east of Taiwan), the Taitung Canyon is N065° oriented and is close and parallel to B. Seismic profiles show that the southern flank of the canyon corresponds to a fault with a normal component of a few tens of meters in the sediments and possible dextral shearing. Several crustal earthquakes of magnitude >%6 are located beneath the trend of the Taitung Canyon and focal mechanisms suggest that the motion is right-lateral. Thus, faulting within the sedimentary sequence beneath the Taitung Canyon is a consequence of underlying dextral strike-slip crustal motions. As the continental part of the EU slab located north of B has been recently detached, some subsequent dextral strike-slip motion might be expected within the EU slab, along the ocean-continent transition zone, which is a potential zone of weakness. We suggest that the dextral strike-slip motion along the ocean-continent boundary of the EU slab might trigger the observed dextral strike-slip motion within the overlying PH Sea crust and the associated faulting within the sediments of the Huatung Basin, beneath the Taitung Canyon.

Keywords: Taitung Canyon - right lateral strike-slip fault - underlying slab deformation along trasition zone

1. Introduction

Since the beginning of formation of the proto-Taiwan during late Miocene (9 Ma), the subducting Philippine (PH) Sea plate moved continuously through time in the N307° direction at a 5.6 cm/s velocity with respect to Eurasia (EU), tearing the EU plate (Sibuet and Hsu, 2004). Thus, the torn EU plate has two boundaries (relict T1 in Figure 1): one is the upper plate trench edge of the Ryukyu Arc, the other is the deeply subducted border of the EU slab, underlying the PH Sea plate (Lallemand et al., 2001). The subducting EU plate includes a continental part in the north and an oceanic part in the south with the ocean-continent transition zone (OCT) (labeled B in Figure 1) in between. B corresponds to the eastern prolongation of the northeastern South China Sea (SCS) OCT. The Taitung canyon starts on the east Taiwan continental shelf. It is N065° oriented in the deep Huatung Basin. Several moderate to large earthquakes of magnitude larger than 6 have been reported and are located along the trend of the deepest part of the Taitung canyon. These earthquakes occur within the PH Sea plate lithosphere and their focal mechanisms suggest that the motion is right-lateral. The purpose of this paper is to demonstrate that faulting along the Taitung canyon is associated with dextral shear within the underlying crustal PH Sea plate, itself triggered by dextral strike-slip motion along the OCT of the underlying subducting EU plate.

2. Geological setting

The Taiwan mountain belt is one of the youngest mountain in the world. Whatever are the proposed models to explain its formation, all authors agree that the uplift of Taiwan results from the collision of the Luzon Arc with the Eurasia (EU) margin. The Luzon Arc is an intra-oceanic volcanic arc, which belongs to the Philippine (PH) Sea plate, outcrops in the Coastal Range and whose contact with the EU plate is the Longitudinal Valley. Davis et al. (1983) and Suppe (1984) demonstrate that the collision of the Luzon Arc with EU was propagating southward slightly faster than that of the convergence rate, which means that moving south 90 km along the collision is analogous to viewing development of the collision 1 Ma earlier. Thus, most authors (*e.g.* Teng (1990) and Malavieille et al. (2002)) suggest that the evolution through time of Taiwan mountain building is a continuum, which could be represented by a series of cross-sections from the present-day Manila subduction system to the south (before collision), through middle Taiwan (collision) and northeast of Taiwan, across the southern Okinawa Through and Ryukyu subduction system (post-collision). However, this notion of continuum from subduction to collision and finally to collapse might be taken with caution as clear tectonic boundaries have been identified both in the subducting slabs and the overlying plates (Sibuet and Hsu, 2004; Sibuet et al., 2004, in press).

We call A the western boundary of the PH Sea plate (Figures 1 and 2). In its northern part A follows the western border of the Ryukyu subducted plate edge delineated from either the distribution of intermediate-depth and/or deep focus seismicity (Font et al., 1999; Kao et al., 2000) or high velocity anomaly on tomographic images (Rau and Wu, 1995). East of A, within the EU plate above the Ryukyu slab, shallow crustal extensional earthquakes occur in the southwestern Okinawa Trough and Ilan Plain. On land, several active faults with a normal component have been identified (Hsu and Chang, 1979; Tsai, 1986; Lee and Wang, 1987; Lee and Wang, 1988). West of A, compressive earthquake mechanisms and reverse faults testify to solely contractional motions within the upper plate. Consequently, in northern Taiwan, A, the surface projection of the PH Sea plate boundary is associated with a zone of strain change in the EU crust (extensional in the Okinawa Trough and northeastern Taiwan and contractional in the rest of Taiwan). South of Hualien (Figure 3), A follows the Longitudinal Valley (Figures 1 and 2a), as suggested by numerous authors (e.g. (Lu and Hsü, 1992; Malavieille et al., 2002)). South of the Longitudinal Valley, the location of A, though poorly defined, has been arbitrarily located west of the Luzon Arc and adjacent forearc basins. In this scheme, the Manila accretionary prism corresponds to deformed sediments belonging to the EU plate (South China Sea), the rest of the EU plate subducting beneath the PH Sea plate (Figures 1 and 2). The Manila trench is prolonged northwards by the deformation front considered as the western boundary of the Taiwan deformed zone. Similarly, the Central Range and Foothills are considered as a continental accretionary prism, which includes sediments and upper crustal material belonging to the EU plate, the rest of the EU plate subducting beneath the PH Sea plate.

Recent studies of the structure of the lithosphere and mantle in East Asia based on seismic tomographic images (Tajima et al., 1997; Bijwaard et al., 1998; Rangin et al., 1999; Lallemand et al., 2001; Kuo et al., 2003) show that the Manila slab is a continuous feature extending northwards up to the latitude of Hualien and down to 500-600 km (Rangin et al., 1999). However, the deep seismicity associated with the Manila slab only occurs south of B and is almost absent north of B. On tomographic images, a slight change in the orientation of the slab occurs at the latitude of B, as well as an increase of the slab steepness north of B

(Rangin et al., 1999; Lallemand et al., 2001). South of B, the distribution of seismicity at depths >80 km represents the geometry of the Manila slab and there is a good correspondence between the geometries of the slab deduced from both tomographic images and the location of deep earthquakes. However, north of B, the paucity of deep earthquakes suggests that the portion of the slab imaged on tomographic data might be detached (Lallemand et al., 2001). B is approximately located in the northeastward prolongation of the northern continental margin of the South China Sea, suggesting that the slab is of continental and oceanic nature north and south of B, respectively. In other words, within the EU slab, B would follow the OCT zone and might underline the southern limit of the possible detached portion of the slab (Figures 1 and 2b). The considerable intraplate deformation occurring north of B would be consistent with the tectonic setting of the regional collision of the Luzon Arc with EU, and a continental subduction, whereas the seismicity pattern in the south would correspond to the subduction of the oceanic part of the EU lithosphere (South China Sea) and the formation of the intra-oceanic Luzon Arc. In conclusion, B is an important feature of the subducting EU plate. The Luzon intra-oceanic arc is only formed south of B, above the subducting EU oceanic lithosphere, while the collision of the Luzon Arc with EU only occurs north of B.

3. Morphology of the Taitung canyon

The Huatung Basin is located in the northwestern corner of the PH Sea (Figure 3). To the west, it is bounded by the Eurasian margin, which consists of the portion of Luzon Arc colliding with EU. To the north, the Huatung Basin deepens in direction of the Ryukyu Trench and is bounded by the Ryukyu accretionary prism and forearc (Liu et al., 1998). To the east, the basin is bounded by the 350-km long linear Gagua Ridge. This aseismic ridge is N-S trending, 30 km wide, culminates about 3-4 km above the seafloor, 4-5 km above the oceanic basement and is flanked on its western side by a smaller chain of seamounts. NNW-SSE crests and troughs identified on the swath bathymetric survey of the Gagua Ridge have been interpreted as Riedel shears, not only suggesting the existence of a N-S strike-slip zone but also that the Gagua Ridge was a former transform plate boundary at the time of formation of the adjacent oceanic domains (Deschamps et al., 1998; Sibuet et al., 1998). The juxtaposition of a large gravity high below the ridge and a large gravity low to the west (Hsu et al., 1998) also suggests the existence of a former compressive component along the Gagua Ridge, which would explain part of the large abnormal elevation of the ridge above the adjacent oceanic basement. To the south, the Gagua Ridge merges the Luzon Arc, closing the Huatung Basin. The age of the Huatung Basin is Eocene (Hilde and Lee, 1984; Sibuet et al., 2002), though it has been proposed an early Cretaceous age (Deschamps et al., 2000) based on the age of three samples, which in fact do not belong to the Huatung Basin *sensu stricto* (see discussion in Sibuet et al. (2002)).

The morphology of the Taitung canyon has been described in great detail by Schnürle et al. (1998). A large volume of sediments derived from the Taiwan mountain belt is transported in the Huatung Basin through several canyons. The most prominent one is the Taitung canyon, which originates from the southern end of the Longitudinal Valley, east of the Taitung city (Figure 3). It first runs to the south between the coast and the Luzon Arc (Lundberg, 1988) and then turns sharply to the east through a topographic low, between the Lutao and LanHsu islands, which belong to the Luzon Arc (Schnürle et al., 1998). From the base of the slope, the Taitung canyon runs N065° for about 100 km in direction of the Gagua Ridge, where it abuts and turns north in direction of the Ryukyu Trench. It then turns eastward around the northern extremity of the Gagua Ridge before entering in the Philippine Sea and following the Ryukyu Trench further east. The Hualien canyon is the northern canyon in the deep Huatung Basin (Figure 3). Its head is located at the northern end of the Longitudinal Valley, near Hualien city. It follows the Ryukyu Trench and merges the Taitung canyon close to the northern end of the Guagua Ridge. Between the Taitung and Hualien canyons, two unnamed canyons run from the Coastal Range to the deep Huatung Basin. Their deepest parts are also N065° oriented before merging the Taitung canyon.

4. A crustal tectonic feature in the Huatung Basin

In the Huatung Basin, between 122°E and 123°E, the density of intraplate crustal earthquakes is considerably reduced (Figure 4) and there is no significant deformation within the crust and sediments, except along the trend of the Taitung canyon (Schnürle et al., 1998). Figure 5 shows epicenters and focal mechanisms of 13 large to moderate size earthquakes (M≥6) that occurred between 1964 and 1998, indicating strike-slip solutions in an area where other solutions (not represented on Figure 4) give thrust faulting. Determinations were done by Lin and Tsai (1981), Cheng (1995), Huang (1997), Cheng et al. (1998), and Kao and Jian (1999). Though using different techniques of source parameter inversions, results are consistent and similar to those already found by Sibuet and Hsu (1997) and later on by several authors (Cheng et al., 1998; Kao et al., 2000), who suggested the existence of a dextral strike-slip feature coinciding with the surface expression of the Taitung canyon (Figure 5). Epicenters of these 13 earthquakes are located between 121°E and 123°E, that is between the Hengchun Peninsula and the Gagua Ridge. Most of them are aligned along a N065° oriented linear trend (B' in Figure 5), which is determined with a precision of about 30 km in the N-S direction. Because dextral strike-slip solutions are parallel to the N065° trend of this feature, B' must be a dextral strike-slip fault. A slight additional downward vertical motion of the northward compartment is also suggested by focal mechanism solutions, which is compatible with the fact that the slab is detached and sinking.

5. Sedimentary deformation beneath the Taitung canyon

During the “active collision in Taiwan” cruise (ACT, May-June 1996) of the R/V l’Atalante (Lallemand et al., 1997), an integrated geophysical survey of East Taiwan was conducted as part of an ongoing cooperative project between France and Taiwan. A series of 25 profiles trending N-S were acquired from a few kilometers east of the Taiwan coastline to east of the Gagua ridge. Using two GI (generator/injector) guns operated in harmonic mode (Pascouet, 1991), 6-channel high speed (10 knots) seismic data were collected. The following processing sequence was applied to all seismic profiles: F-K filter, 4-12 Hz; 35-40 Hz band-pass filter, 3-fold stack with a constant velocity of 1480 m/s, Kirchoff migration with a constant velocity of 1420 m/s. Figure 6 shows 12 portions of seismic profiles (located in Figure 5b) cutting across the Taitung canyon both in the Huatung Basin and on the east Taiwan continental slope.

In the deep Huatung Basin, the southern wall of the Taitung canyon corresponds to the location of a few tens meters vertical offset of the subsiding northern Huatung Basin with respect to the southern Huatung Basin (ACT profiles 42 to 85, Figures 5b and 6). As the vertical offset is less than 100 m and acoustic reflectors partly mimic the topography of the southern wall, one can suggests a pull down artifact. However, depth migrated sections with sedimentary velocities varying from 1.7 to 2.4 km/s show that this slight vertical offset still persists whatever is the adopted velocity. For example, a vertical offset of 20 meters is obvious in the deepest portion of seismic profile 71 (Figure 7), but such a small offset cannot be evidenced in the rough basement topography. Schnürle et al. (1998) have already noticed the presence of small offset normal faults beneath the Taitung canyon on several seismic profiles. However, we cannot exclude that the motion along the sedimentary fault could also present a shear component, which cannot be resolved by seismic reflection data. We have seen that earthquake mechanisms display dextral strike-slip solutions and a slight downward vertical motion of the northward compartment. As the dispersion of 13 earthquake locations around the Taitung canyon is about 10 km, we suggest that they might occur beneath the southern wall of the N065° trending Taitung canyon. In addition, the type of sedimentary deformation established from seismic reflection profiles is compatible with the type of crustal deformation established from the earthquake focal mechanisms. However, due to its weak expression on seismic profiles, this feature seems to be a very recently activated feature.

On the continental slope, west of 121°45’E, the Taitung canyon changes direction (N115°) and presents a V-shape morphology different from its U-shape morphology in the deep basin. The western ACT profile on which an active north-facing normal fault is identified beneath the bottom of the canyon is profile 42.

On the upper continental slope, west of 121°15’E, in the region where several dextral strike-slip crustal earthquakes are reported (Figure 5), the location of the deformation is not obvious. It might follow a N065° subsidiary of the Taitung canyon (ACT profiles 45 to 48 on Figures 5b and 6), which is approximately parallel to the portion of the Taitung canyon located in the Huatung Basin (Figure 5). On the western displayed profile (ACT 49), as well as on four other N-S profiles located landward but not displayed in Figure 6, the active deformation seems is absent. Thus, the western end of the tectonic feature associated with the deep Taitung canyon and its slope canyon subsidiary is located offshore Taiwan, east of the location of the westernmost earthquake showing a strike-slip mechanism (121°E, Figure 5). We call B’ such a tectonic feature.

Using swath-bathymetric and seismic data, Deschamps et al. (1998) have shown that the northern 50 kilometers of the Gagua ridge are right-laterally offset north of B'. However, because there is no indication of surface sedimentary deformation in the oceanic domain located east of the Gagua ridge, B' does not extend northeastward, in the direction of the Ryukyu Trench. Figure 5c summarizes the information concerning the location, lateral extent and nature of B’: it consists of a N065° oriented dextral strike-slip fault; a transtensional motion with a downward vertical subsidence of the northward compartment is observed on the seismic profiles; the mean orientation of B’ is parallel to B.

6. Discussion

Though B is not precisely located, it is parallel to B' and located a few tens of kilometers north of B'. The two features do not seem to be geographically coincident. However, B' does not continue from the eastern coast of the Hengchun Peninsula to the Manila deformation front, and B is not evidenced east of 122°E, where the deep crustal strike-slip earthquakes have been recorded. However, we suggest that B and B' are genetically related. Since 15 Ma, B is a permanent feature (OCT) located within the EU slab (Sibuet and Hsu, 2004). The continental part of the EU slab located north of B seems to be recently detached (Lallemand et al., 2001). If this portion of slab is detached as suggested in Figure 1, some related dextral strike-slip motion might be expected along the OCT boundary of the EU slab because OCT zones are generally considered as weak zones and potential areas of strain deformations (Whitmarsh et al., 1993).

As motions along the OCT zone inside the EU slab and within the overlying PH Sea crust, beneath the Taitung canyon, seem to be both dextral strike-slip motions, we propose the following scenario: 1) The motion of the detached continental portion of EU slab with respect to the rest of the EU slab induces dextral strike-slip motion along B. 2) The coupling of the two portions of EU slab with the overlying PH Sea lithosphere generates differential motions inside the PH Sea lithosphere, which trigger dextral strike-slip motion along B' within the brittle upper PH Sea crust. 3) The identification of minor normal faulting with a possible minor dextral shear component within the overlying sedimentary sequence suggests that this phenomenon has been recently initiated. 4) The location of the Taitung canyon within the Huatung Basin was initially controlled by a sea-bottom topographic offset due to the sedimentary faulting and was followed by the excavation of the canyon.

B' is a crustal feature, which belongs entirely to the PH Sea plate. As the PH/EU motion occurred in the N307° direction since the beginning of Taiwan uplift (Sibuet and Hsu, 2004), that is obliquely to the trend of B, B' cannot stay above B through time and might jump within the upper PH Sea lithosphere in order to remain in the close vicinity of B. The N065° general trend of the Taitung canyon and the associated strike-slip crustal feature are not parallel to Huatung Basin fracture zones or seafloor spreading rift directions, oriented N-S and E-W respectively (Hilde and Lee, 1984; Hsu et al., 1998). Thus, the N065° direction is a post-seafloor spreading trend. Unnamed canyons located in the deep Huatung Basin, north of the Taitung canyon, are parallel to the Taitung canyon, at least before merging the Taitung canyon (Figure 3). These N065° trends might have been in the past the location of previous superficial expressions of motions along B. However, no signs of normal or strike-slip faulting have been identified within the sedimentary cover, north of the Taitung canyon.

7. Conclusions

The main conclusions of this study are:

1) Since the beginning of formation of the proto-Taiwan, the subducting PH Sea plate moved continuously through time in the N307° direction with respect to EU, tearing the EU plate. The subducting EU plate includes a continental part in the north and an oceanic part in the south. The boundary B between these two domains corresponds to the eastern prolongation of the northeastern South China Sea OCT zone. As the continental part of the EU slab located north of B seems to be recently detached, some related dextral strike-slip motion might be expected within the EU slab along the OCT boundary, a potential zone of weakness.

2) In the Huatung Basin (east of Taiwan), the Taitung canyon is N065° oriented and is close and parallel to B. Seismic reflection profiles show that the southern flank of the canyon corresponds to a sedimentary fault with a vertical offset of a few tens of meters and with a possible dextral shear component.

3) Several crustal earthquakes of magnitude >6 are located beneath the trend of the Taitung canyon. Focal mechanisms suggest that the motion is right-lateral. Faulting within the sedimentary sequence beneath the Taitung canyon is a consequence of underlying strike-slip crustal motions.

4) The dextral strike-slip motion along the OCT zone of the EU slab might trigger the observed dextral strike-slip motions within the overlying PH Sea crust and the associated faulting within the sediments of the Huatung Basin. The location of the Taitung canyon was initially controlled by the resulting seafloor topographic offset.

5) One of the main results of this work is that faint bathymetric features evidenced by detailed swath bathymetric surveys can help to resolve deep tectonic processes, as a slab detachment in this study.

Acknowledgments. Original data presented in this paper were acquired during the ACT cruise (May-June 1996) on board the Ifremer R/V l'Atalante as part of an ongoing cooperative project between France and Taiwan. M.-O. Boulanger kindly extracted earthquakes from the ISC catalogue. The GMT software package was used to display some of the figures (Wessel and Smith, 1991). This is a contribution of the France-Taiwan cooperation program supported by the French Institute in Taipei and the National Science Council in Taiwan. Comments from P. Schnürle and an anonymous reviewer greatly helped to revise the manuscript.

References

Bijwaard, H., Spakman, W. and Engdahl, E. R., 1998, Closing the gap between regional and global travel time topography, J. Geophys. Res., **103,** 30,055-30,078.

Cheng, S.-N., 1995, The study of stress distribution in and around Taiwan, Ph. D. Thesis, National Central Univ., Chung-Li, Taiwan, 215 p.

Cheng, W.-B., Wang, C., Shyu, C.-T. and Shin, T.-C., 1998, A three-dimensional Vp Model of the southeastern Taiwan area and its tectonic implications, TAO, **9,** 425-452.

Davis, D., Suppe, J. and Dahlen, F. A., 1983, Mechanics of fold-and-thrust belts and accretionary wedge, J. Geophys. Res., **88,** 1153-1172.

Deschamps, A., Monié, P., Lallemand, S. E., Hsu, S.-K. and Yeh, K. Y., 2000, Evidence for early Cretaceous oceanic crust trapped in the Philippine Sea plate, Earth Planet. Sci. Lett., **179,** 503-516.

Deschamps, A. E., Lallemand, S. E. and Collot, J.-Y., 1998, A detailed study of the Gagua Ridge: a fracture zone uplifted during a plate reorganisation in the mid-Eocene, Marine Geophysical Researches, **20,** 403-423.

Font, Y., Lallemand, S. and Angelier, J., 1999, Etude de la transition entre l'orogène actif de Taiwan et la subduction des Ryukyu - Apport de la sismicité, Bull. Soc. Géol. France, **170,** 271-283.

Hilde, T. W. C. and Lee, C.-S., 1984, Origin and evolution of the west Philippine basin: a new interpretation, Tectonophysics, **102,** 85-104.

Hsu, S.-K., Liu, C.-S., Shyu, C.-T., Liu, S.-Y., Sibuet, J.-C., Lallemand, S., Wang, C. and Reed, D., 1998, New gravity and magnetic anomaly maps in the Taiwan-Luzon region and their preliminary interpretation, TAO, **9,** 509-532.

Hsu, T.-L. and Chang, H.-C., 1979, Quaternary faulting in Taiwan, Geol. Soc. China, **3,** 155-165.

Huang, K. C., 1997, Earthquakes beneath southern Taiwan: a case of collision between Luzon arc and Taiwan, Master Thesis, National Taiwan Univ., Taipei, Taiwan, 160 p.

Kao, H., Huang, G.-C. and Liu, C.-S., 2000, Transition from oblique subduction to collision in the northern Luzon arc-Taiwan region: constraints from bathymetry and seismic observations, J. Geophys. Res., **105,** 3059-3079.

Kao, H. and Jian, P.-R., 1999, Seismogenic patterns in Taiwan region: Insight from source parameters inversion of BATS data, *Active subduction and collision in southeast Asia: data and models*. International conference and 4th France-Taiwan symposium, Montpellier, 10-12 May 1999. Mémoires Géosciences Montpellier, Institut des Sciences de la Terre, **14,** 199-202.

Kuo, B.-Y., Li, A., Forsyth, D., Kao, H., Pan, H.-H. and Chen, C.-R., 2003, Lithospheric structure beneath Taiwan: array analysis of Rayleigh waves, European Geophysical Society 2003, Geophys. Res. Abst., **5,** 5405.

Lallemand, S., Font, Y., Bijwaard, H. and Kao, H., 2001, New insights on 3-D plates interaction near Taiwan from tomography and tectonic implications, Tectonophysics, **335,** 229-253.

Lallemand, S., Liu, C.-S., Angelier, J., Collot, J.-Y., Deffontaines, B., Dominguez, S., Fournier, M., Hsu, S.-K., Le Formal, J.-P., Liu, S.-Y., Lu, C.-Y., Malavieille, J., Schnürle, P., Sibuet, J.-C., Thareau, N. and Wang, F., 1997, Swath bathymetry reveals active arc-continent collision near Taiwan, EOS Trans., AGU, **78,** 173-175.

Lee, C.-T. and Wang, Y., 1987, Paleostress due to the Pliocene-Quaternary arc-continent collision in Taiwan, Geol. Soc. China, **9,** 63-86.

Lee, C.-T. and Wang, Y., 1988, Quaternary stress changes in northern Taiwan and their tectonic significance, Geol. Soc. China, **31,** 154-168.

Lin, M.-T. and Tsai, Y.-B., 1981, Seismotectonics in Taiwan-Luzon area, Bulletin of the Institute of Earth Sciences, Academia Sinica, **1,** 51-82.

Liu, C.-S., Liu, S.-Y., Lallemand, S., Lundberg, N. and Reed, D. L., 1998, Digital elevation model offshore Taiwan and its tectonic implications, TAO, **9,** 705-738.

Lu, C.-Y. and Hsü, K. J., 1992, Tectonic evolution of the Taiwan mountain belt, Petr. Geol. Taiwan, **27,** 21-46.

Lundberg, N., 1988, Present-day sediment transport paths south of the Longitudinal valley, southeastern Taiwan, Acta Geologica Taiwanica, **26,** 317-331.

Malavieille, J., Lallemand, S., Dominguez, S., Deschamps, A., Lu, C.-Y., Liu, C.-S., Schnürle, P. and ACT scientific crew, 2002, Geology of the arc-continent collision in Taiwan: marine observations and geodynamic model, Geol. Soc. Amer. Special Issue, **358,** 187-211.

Pascouet, A. P., 1991, Something new under the water, the bubbleless air gun, The leading edge, **10,** 79-81.

Rangin, C., Spakman, W., Pubellier, M. and Bijwaard, H., 1999, Tomographic and geological constraints on subduction along the eastern Sundaland continental margin (South-East Asia), Bull. Soc. Géol. France, **170,** 755-788.

Rau, R.-J. and Wu, F. T., 1995, Tomographic imaging of lithospheric structures under Taiwan, Earth Planet. Sci. Lett., **133,** 517-532.

Sandwell, D. T. and Smith, W. H. F., 1994, New global marine gravity map/grid based on stacked ERS1, Geosat and Topex altimetry, EOS Trans.,AGU, **75,** 321.

Schnürle, P., Liu, C.-S., Lallemand, S. and Reed, D., 1998, Structural controls of the Taitung canyon in the Huatung basin east of Taiwan, TAO, **9,** 453-472.

Sibuet, J.-C., Deffontaines, B., Hsu, S.-K., Thareau, N., Le Formal, J.-P. and Liu, C.-S., 1998, The southwestern Okinawa Trough backarc basin: tectonics and volcanism, J. Geophys. Res., **103,** 30,245-230,267.

Sibuet, J.-C. and Hsu, S.-K., 1997, Geodynamics of the Taiwan arc-arc collision, Tectonophysics, **274,** 221-251.

Sibuet, J.-C. and Hsu, S.-K., 2004, How was Taiwan created?, Tectonophysics, **379,** 159-181.

Sibuet, J.-C., Hsu, S.-K. and Debayle, E., 2004, in press, Geodynamic context of the Taiwan orogen, Ocean-Continent Interactions in the East Asian Marginal Seas, Clift, P. and Hayes, D. E. (Eds), AGU, Washington, D.C., Geophysical monograph.

Sibuet, J.-C., Hsu, S.-K., Le Pichon, X., Le Formal, J.-P., Reed, D., Moore, G. and Liu, C.-S., 2002, East Asia plate tectonics since 15 Ma: constraints from the Taiwan region, Tectonophysics, **344,** 103-134.

Suppe, J., 1984, Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan, Geol. Soc. China, **6,** 21-34.

Tajima, F., Fukao, Y., Sakurai, T. and Niu, F., 1997, Characteristics of the upper mantle transition zone structure in the northwestern Pacific and a comparison with ISC P-wave tomographic images, EOS Trans., AGU, **78,** 456.

Teng, L. S., 1990, Late Cenozoic arc-continent collision in Taiwan, Tectonophysics, **183,** 57-76.

Teng, L. S. and Lee, C.-T., 1996, Geodynamic appraisal of seismogenic faults in northeast Taiwan, Geol. Soc. China, **39,** 125-142.

Tsai, Y.-B., 1986, Seismotectonics of Taiwan, Tectonophysics, **125,** 17-37.

Wang, C., Young, M.-L., Chou, C.-P. and Lee, C.-S., 1999, Tectonic structure at the western end of Ryukyu subduction zone for westward extension of Okinawa Trough, Active subduction and collision in southeast Asia: data and models. International conference and 4th France-Taiwan symposium, Montpellier, 10-12 May 1999. Mémoires Géosciences Montpellier, Institut des Sciences de la Terre, **14,** 137-138.

Wessel, P. and Smith, W. M. F., 1991, Free software helps map and display data, EOS Trans., AGU, **72,** 441-446.

Whitmarsh, R. B., Pinheiro, L. M., Miles, P. R., Recq, M. and Sibuet, J.-C., 1993, Thin crust at the ocean-continent transition off Iberia and ophiolites, Tectonics, **12**, 1230-1239.

Yu, S.-B., Chen, H. Y. and Kuo, L.-C., 1997, Velocity field of GPS stations in the Taiwan area, Tectonophysics, **274,** 41-59.

Legend of figures

Figure 1: Sketch showing the 3-D shape and extent of the Eurasian (EU) slab after removal of the Philippine (PH) Sea plate (modified from Lallemand et al. (2001) and Sibuet et al. (2004, in press)). Thin lines approximately every 100-km give the scale of the EU subducted slab. A is the trace of the western boundary of the PH Sea plate. East of A, EU is torn by the westward motion of the PH Sea plate inside EU and thus has two boundaries (relict T1). B is the boundary between the oceanic (dark gray) and continental (light gray) parts of the EU slab located in the prolongation of the South China Sea ocean-continent transition zone. LV, Longitudinal Valley; OJ, Okinawa-Japan plate; OT, Okinawa Trough.

Figure 2: (a, b and c): Present-day plate tectonic context and types of deformation for each of the three Philippine Sea, Eurasia and Okinawa-Japan plates (Sibuet and Hsu, 2004; Sibuet et al., 2004, in press). EU, Eurasia; NLT, Northern Luzon Trough; OCT, ocean-continent transition; OJ, Okinawa-Japan; PH, Philippine; SLT, Southern Longitudinal Trough. A is the western boundary of the PH Sea plate and B is the OCT zone within the EU slab (in the prolongation of the South China Sea OCT). Relict fault T1 is located beneath the transcurrent fault localized at the rear of the present-day Ryukyu accretionary prism. Based on the distribution and magnitude of earthquakes (Kao et al., 2000) and GPS displacements (Yu et al., 1997), areas of diffuse extension exist in northern Taiwan, in the Okinawa Trough and in the Manila accretionary prism. The portion of Taiwan Island west of A and the northern part of the Manila accretionary prism are moderately deformed by compressive stress. The northern Luzon, Coastal Range and the Manila forearc basins (SLT and NLT) are severely deformed by compressive stress; the Okinawa Trough, northern Taiwan (east of A) and the southern portion of the Manila accretionary prism are under extension (Teng and Lee, 1996; Kao et al., 2000). The PH Sea plate is in blue and the Philippines islands to northern Taiwan accretionary prism is in light blue. The EU plate is in green for its oceanic part and in yellow for its continental part. The OJ plate is in orange and the Ryukyu accretionary prism in light orange. (d) Green dashed lines are locations of the four synthetic profiles, which show the nature and boundaries of EU, PH Sea and OJ plates (Sibuet and Hsu, 2004; Sibuet et al., 2004, in press). In green, EU oceanic lithosphere; in yellow, EU continental lithosphere; in blue, PH Sea oceanic lithosphere, in orange, OJ lithosphere. In light blue, Manila to northern Taiwan

accretionary prism; in light orange, Ryukyu accretionary prism. The scale of profile 4 is half the one of other profiles.

Figure 3: N120° shaded bathymetric map of the Huatung Basin extracted from a new grid (grid spacing, 150 m) established at Ifremer and including all available swath bathymetric data available from French and Japanese oceanographic ships (Sibuet et al., in preparation). The topography is extracted from the Taiwan DTM (B. Deffontaines, personal communication). The shelf and upper slope data are from conventional soundings (Wang et al., 1999) and were compiled by F. Wang (personal communication). Bathymetric curves every kilometer. This map shows the canyon trends from Taiwan to the deep Huatung Basin. CR, Coastal Range; LA, Luzon Arc; LV, Longitudinal Valley.

Figure 4: General bathymetric map and topography around Taiwan every 1000 m from Liu et al. (1998) and Sandwell and Smith (1994), earthquake epicenters (ISC catalogue from 1963 to 1998, M≥3.0) (dots) and dextral strike-slip solutions for events occurring near the Taitung canyon (stars). A is the western boundary of the Philippine Sea plate, B the ocean-continent transition zone of the Eurasian slab and B' the crustal dextral strike-slip fault which coincides with the Taitung canyon. LV, Longitudinal Valley.

Figure 5: a) N300° shaded bathymetric map of southern Taiwan and Huatung Basin (Liu et al., 1998) showing epicenters of earthquakes (ISC catalogue from 1963 to 1998, M≥3.0) (dots) and dextral strike-slip fault plane solutions of earthquakes in the area of the Taitung canyon (stars) (Lin and Tsai, 1981; Cheng, 1995; Huang, 1997; Cheng et al., 1998; Kao and Jian, 1999) plotted in equal area projections of the lower hemispheres of focal spheres. Compressional quadrants are shaded. B is the ocean-continent transition zone of the Eurasian slab. B' is the crustal dextral strike-slip fault, which coincides with the Taitung canyon. b) Bathymetry with 500 m spacing, except between 4000 and 5000 m where spacing is 100 m in order to underline the trend of the Taitung canyon. Locations of portions of ACT seismic profiles displayed in Figure 6. Stars are dextral strike-slip focal mechanisms of Figure 5a and black dots are the locations of sedimentary normal faults dipping northwards identified on seismic reflection profiles and corresponding to the southern flank of the Taitung canyon. c) Location of B'.

Figure 6: Time migrated seismic reflection profiles located in Figure 5b and aligned on the straight line B' (located in Figure 5b). Vertical exaggeration: 13. Interpretation of the 12 ACT seismic reflection profiles on the right-hand side. Normal faults are identified on ACT profiles 42 to 85. SP, shot point; s twtt, second two-way travel time.

Figure 7: Depth migrated portion of profile ACT 71 located in Figure 5b. Adopted velocity in the sedimentary column: 1.9 km/s.

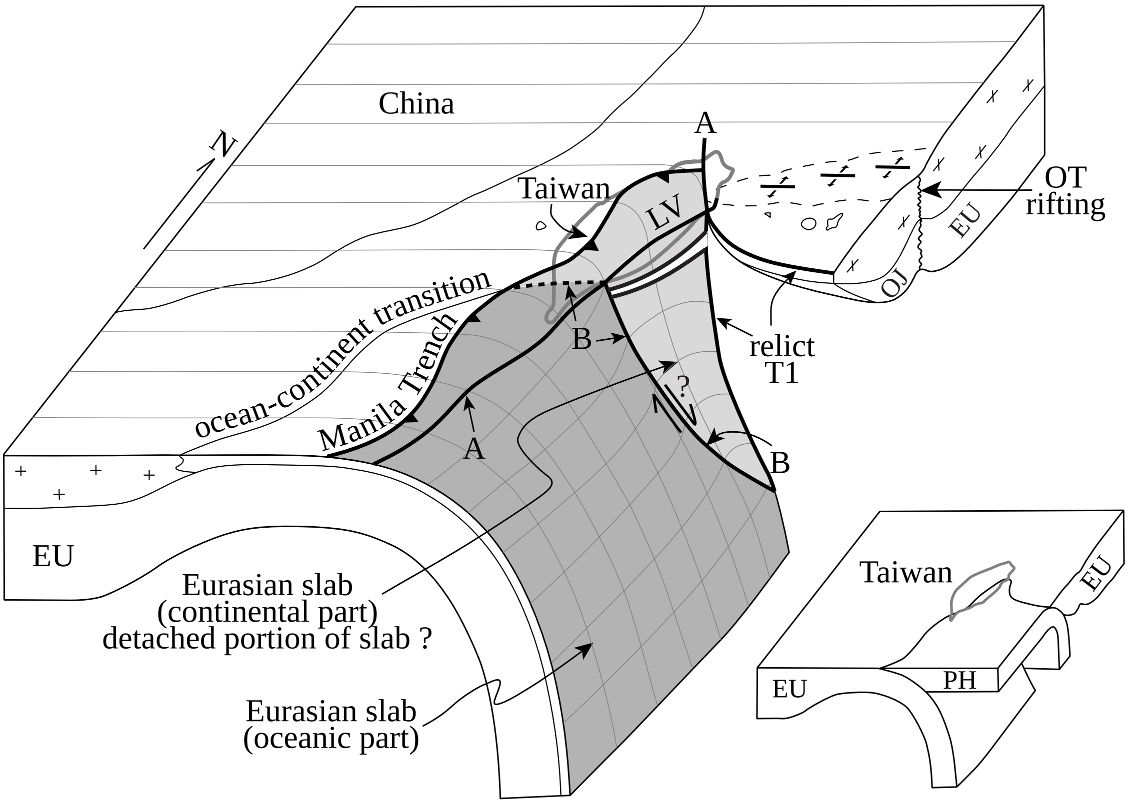
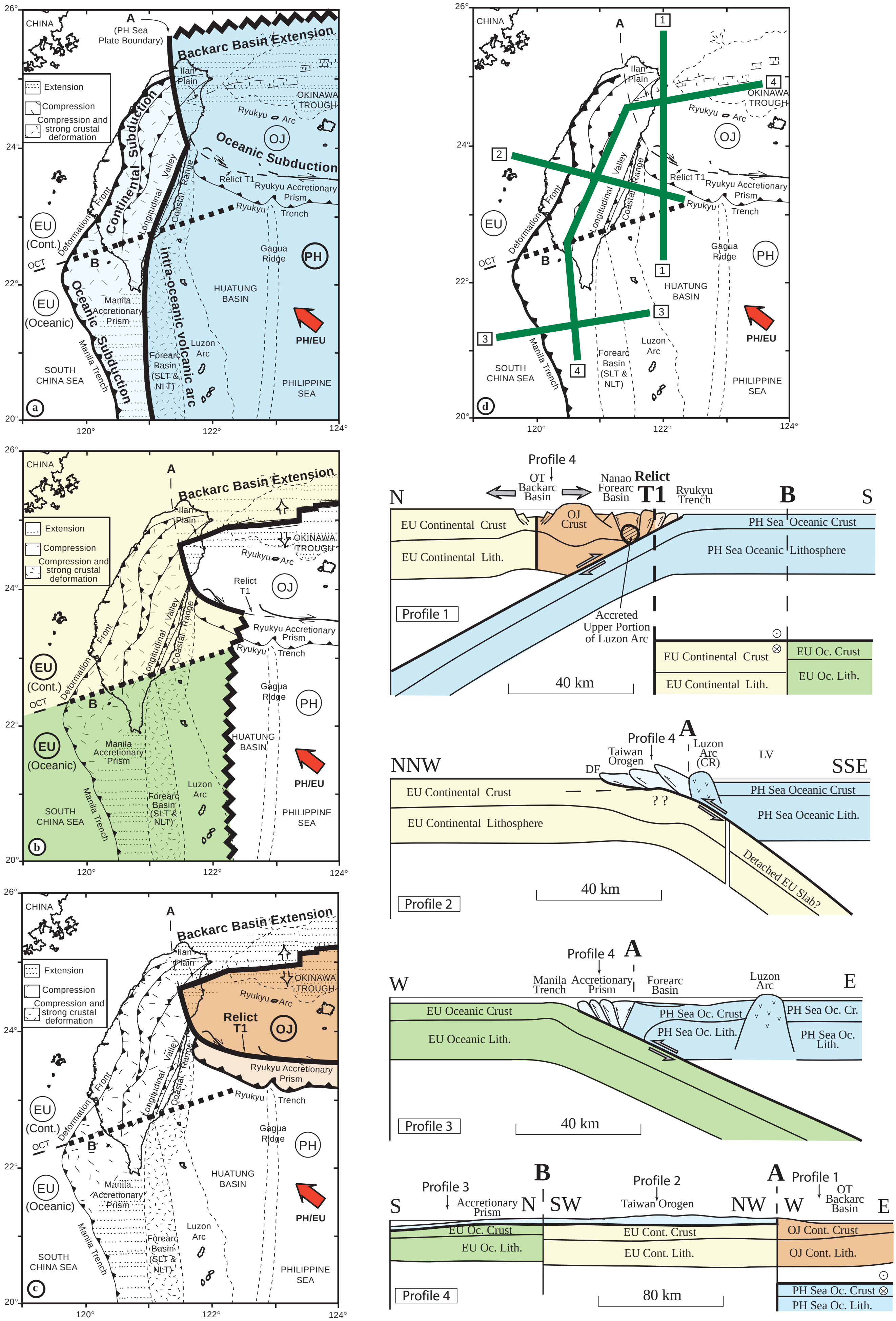

China
N
A
Taiwan
LV
OT
rifting
EU
OJ
relict
T1
ocean-continent transition
Manila Trench
B
A
?
B
EU
Eurasian slab
(continental part)
detached portion of slab ?
Eurasian slab
(oceanic part)
Taiwan
EU
EU
PH

Figure 1



CHINA
A
(PH Sea
Plate Boundary)
Backarc Basin Extension
Extension
Compression
Compression and
strong crustal
deformation
Ilan
Plain
OKINAWA
TROUGH
Ryukyu Arc
OJ
Oceanic Subduction
Continental Subduction
Valley
Longitudinal
Coastal Range
Relict T1
Ryukyu Accretionary
Prism
Ryukyu
Trench
EU
(Cont.)
Deformation Front
OCT
B
Gagua
Ridge
PH
EU
(Oceanic)
Oceanic Subduction
Manila
Accretionary
Prism
intra-oceanic volcanic arc
HUATUNG
BASIN
PH/EU
Forearc
Basin
(SLT &
NLT)
Luzon
Arc
SOUTH
CHINA SEA
Manila Trench
PHILIPPINE
SEA
a
b
c
d
20°
22°
24°
26°
120°
122°
124°
1
2
3
4
Relict
T1
Profile 4
OT
Backarc
Basin
Nanao
Forearc
Basin
Relict
T1
Ryukyu
Trench
N
S
OJ
Crust
EU Continental Crust
EU Continental Lith.
PH Sea Oceanic Crust
PH Sea Oceanic Lithosphere
Profile 1
Accreted
Upper Portion
of Luzon Arc
40 km
EU Continental Crust
EU Continental Lith.
EU Oc. Crust
EU Oc. Lith.
Profile 4
A
Taiwan
Orogen
Luzon
Arc
(CR)
LV
NNW
SSE
DF
EU Continental Crust
? ?
PH Sea Oceanic Crust
PH Sea Oceanic Lith.
EU Continental Lithosphere
Detached EU Slab?
Profile 2
40 km
Profile 4
A
W
E
Manila
Trench
Accretionary
Prism
Forearc
Basin
Luzon
Arc
EU Oceanic Crust
PH Sea Oc. Crust
PH Sea Oc. Cr.
EU Oceanic Lith.
PH Sea Oc. Lith.
PH Sea Oc.
Lith.
Profile 3
40 km
B
Profile 3
Accretionary
Prism
S
N
SW
Profile 2
Taiwan Orogen
NW
A
Profile 1
W
OT
Backarc
Basin
E
EU Oc. Crust
EU Oc. Lith.
EU Cont. Crust
EU Cont. Lith.
OJ Cont. Crust
OJ Cont. Lith.
PH Sea Oc. Crust
PH Sea Oc. Lith.
Profile 4
80 km

Figure 2

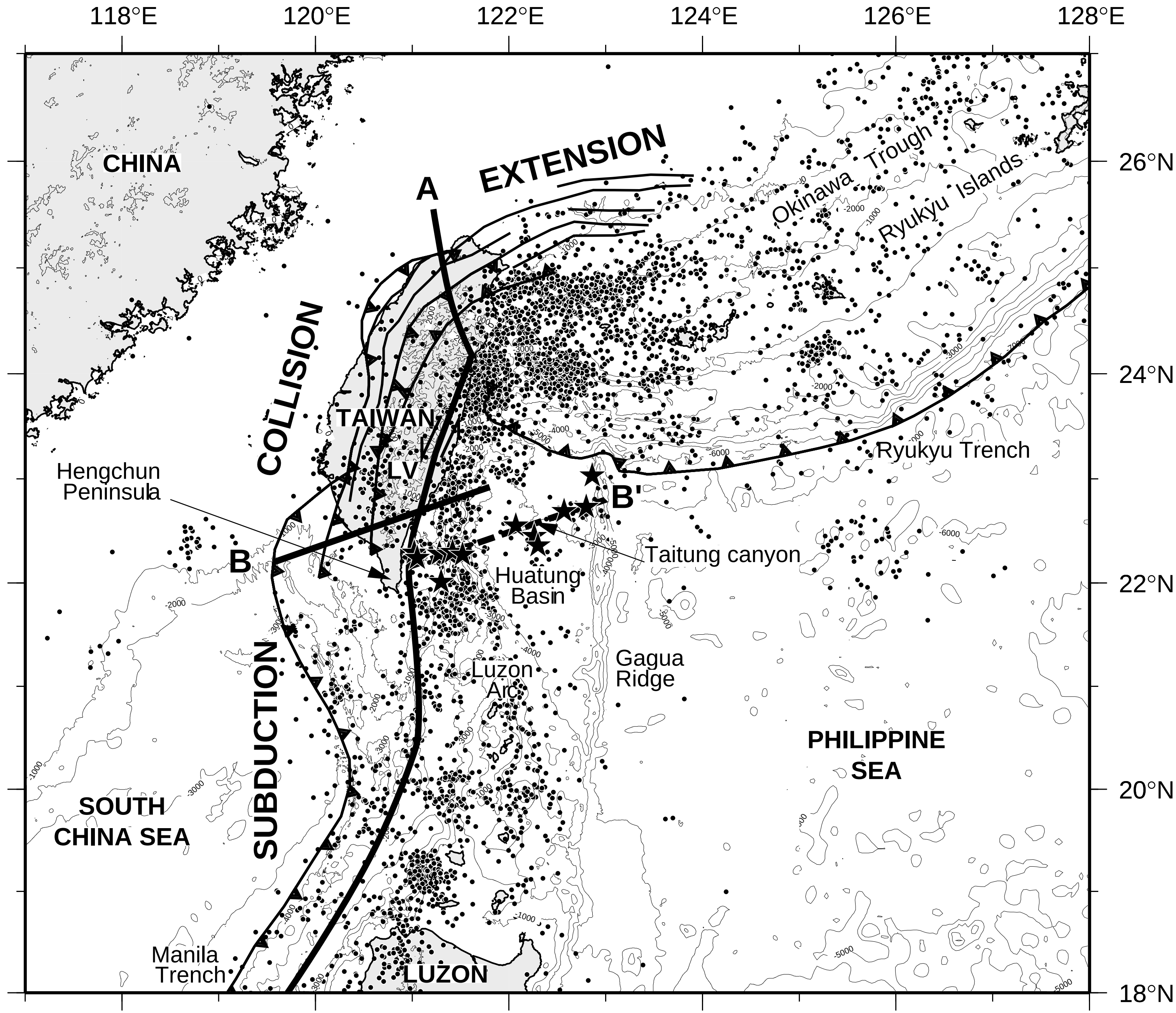

118°E
120°E
122°E
124°E
126°E
128°E
26°N
24°N
22°N
20°N
18°N
CHINA
EXTENSION
A
Okinawa Trough
Ryukyu Islands
COLLISION
TAIWAN
LV
Ryukyu Trench
Hengchun
Peninsula
B'
B
Taitung canyon
Huatung
Basin
Gagua
Ridge
Luzon
Arc
PHILIPPINE
SEA
SUBDUCTION
SOUTH
CHINA SEA
Manila
Trench
LUZON

Figure 4

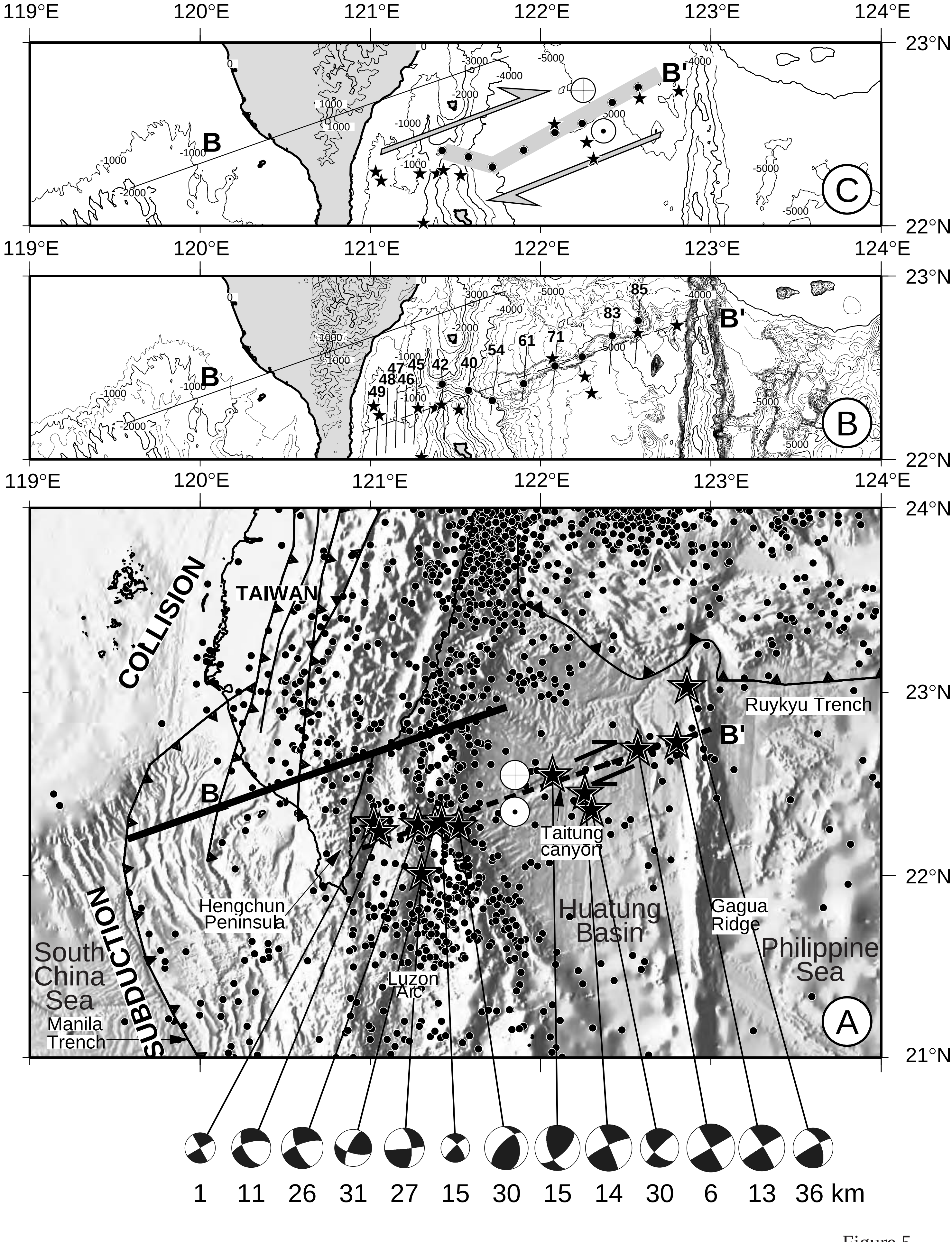

119°E
120°E
121°E
122°E
123°E
124°E
23°N
22°N
24°N
21°N
B
B'
C
A
TAIWAN
COLLISION
SUBDUCTION
Ruykyu Trench
Taitung canyon
Hengchun Peninsula
Huatung Basin
Gagua Ridge
South China Sea
Philippine Sea
Luzon Arc
Manila Trench
49
48
47
46
45
42
40
54
61
71
83
85
1 11 26 31 27 15 30 15 14 30 6 13 36 km

Figure 5

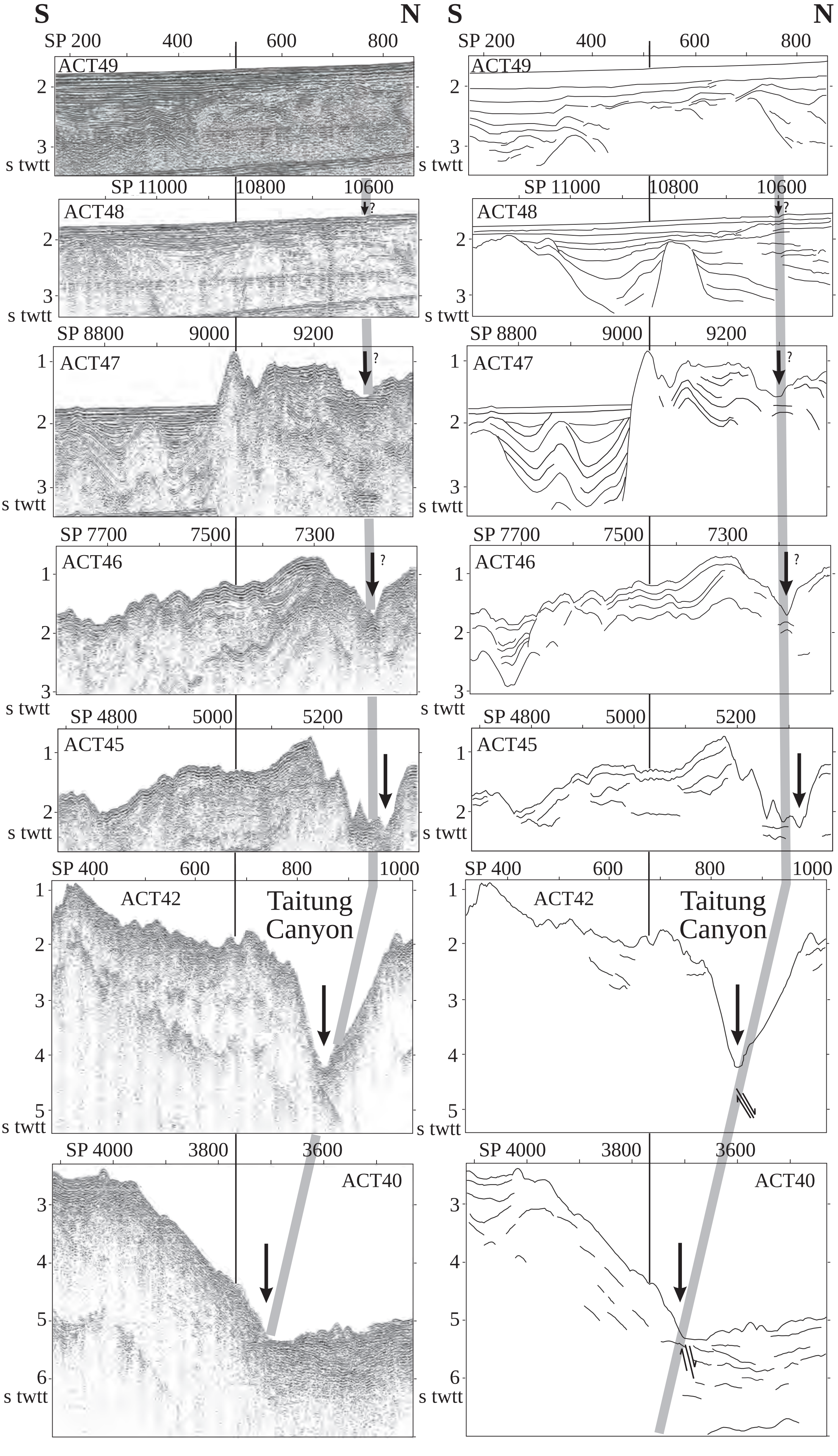

S
N
SP 200
400
600
800
ACT49
SP 11000
10800
10600
ACT48
SP 8800
9000
9200
ACT47
SP 7700
7500
7300
ACT46
SP 4800
5000
5200
ACT45
SP 400
600
800
1000
ACT42
Taitung Canyon
SP 4000
3800
3600
ACT40
s twtt

Figure 6

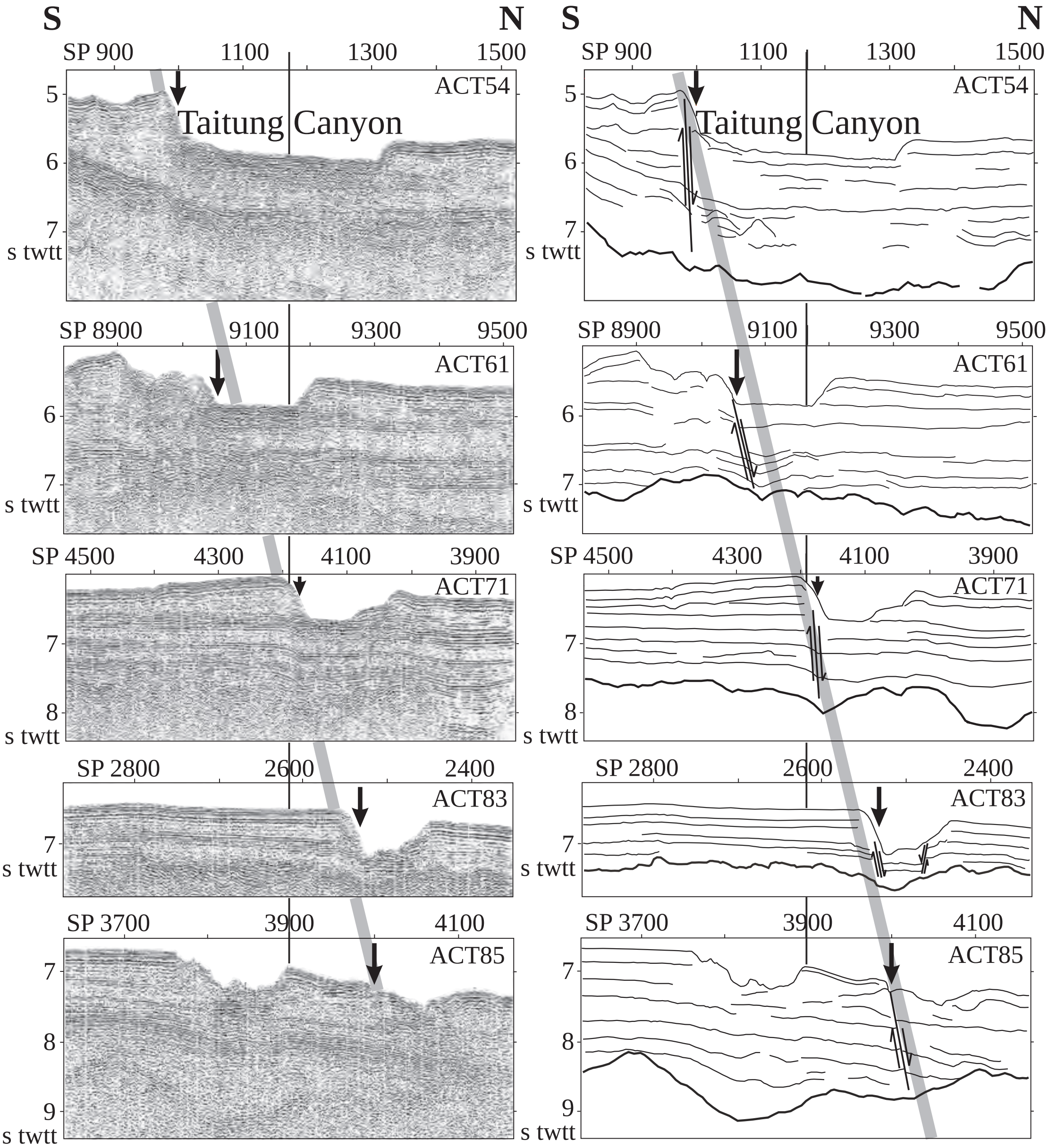


Figure 6 (following)

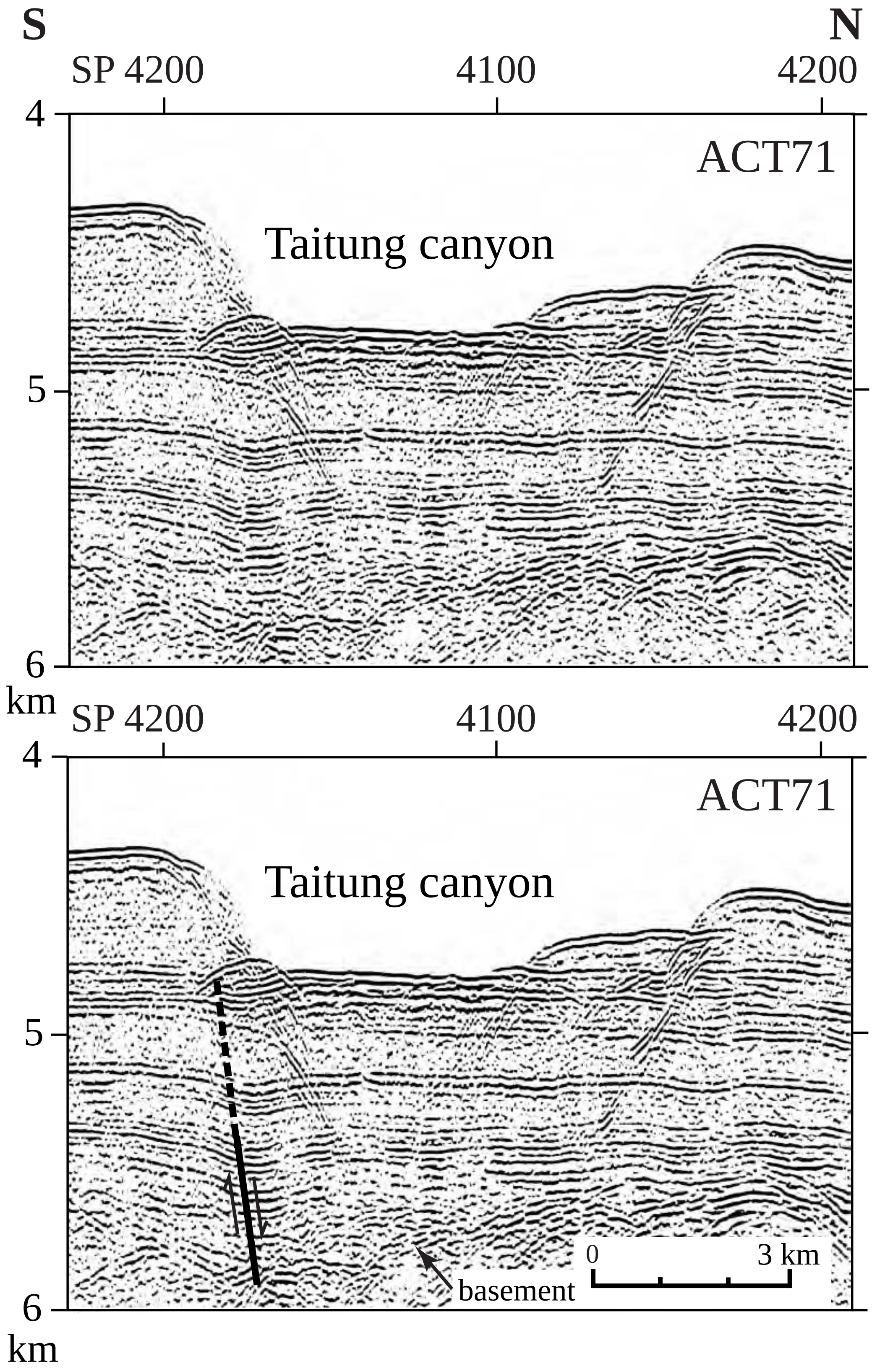

S
N
SP 4200
4100
4200
4
5
6
km
ACT71
Taitung canyon
SP 4200
4100
4200
4
5
6
km
ACT71
Taitung canyon
0
3 km
basement

Figure 7

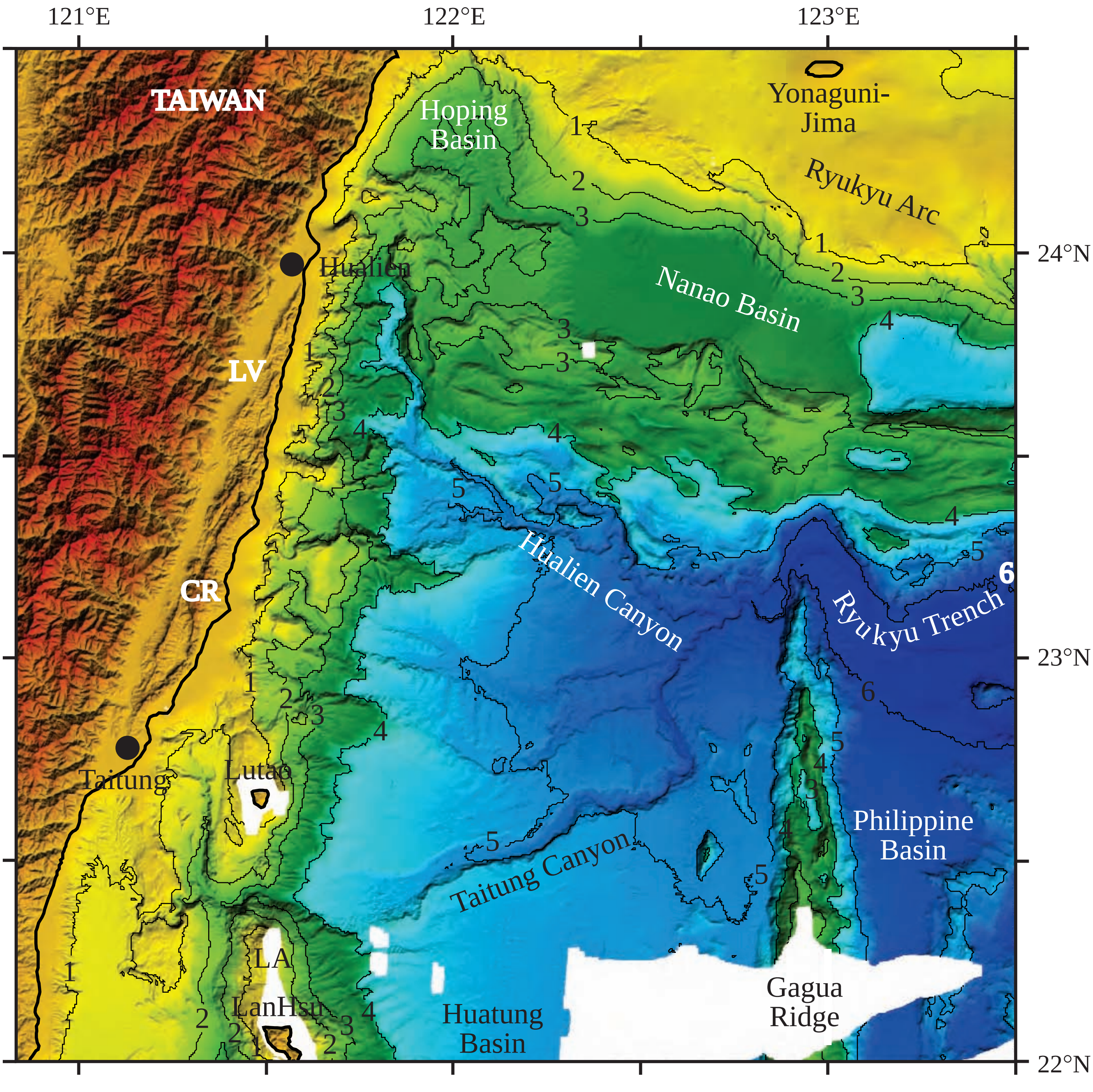

121°E
122°E
123°E
24°N
23°N
22°N
TAIWAN
Hoping Basin
Yonaguni-Jima
Ryukyu Arc
Hualien
Nanao Basin
LV
CR
Hualien Canyon
Ryukyu Trench
Taitung
Lutao
Philippine Basin
Taitung Canyon
LA
LanHsu
Huatung Basin
Gagua Ridge

Figure 3