Crustal structure of the convergent plate-boundary zone, eastern Taiwan, assessed by seismic tomography

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ABSTRACT

The three-dimensional P-wave velocity structure of the obliquely convergent zone in the eastern Taiwan area has been determined by using traveltimes of seismic waves from 1826 local earthquakes and air-gun shots recorded by the Central Weather Bureau Seismographic Network, and 8334 earthquakes have been relocated for better understanding of the current tectonics. The possible location of the plate boundary between the Eurasian and Philippine Sea plates, characterized by a sharp gradient in the velocity structure, is found beneath the eastern flank of the Central Range to the north of 23.5°N, eastern Taiwan. To the south of 23.5°N, this boundary is generally along the Longitudinal Valley fault and its southern projection. The distribution of the relocated earthquakes also shows a spatial pattern closely related to the boundary and the state of plate collision. To the east of the boundary, a prominent high-velocity anomaly in the middle to lower crust is found beneath the Longitudinal Valley and the Coastal Range in eastern Taiwan; this anomaly could be interpreted as the oceanic crust of the Luzon forearc. To the west of the boundary, the Central Range has a relatively low velocity at the same depth. The velocity structure and relocated seismicity have led to the recognition of interaction between the materials on opposite sides of the boundary. The relatively high P-wave velocity of the Luzon forearc suggests that it can accumulate strain energy and then release it as brittle failure. However, the relatively low P-wave velocity of the Central Range implies that it responds to the convergence by silent or ductile deformation.

INTRODUCTION

East of Taiwan, the Philippine Sea plate is subducting beneath the Eurasian plate along the Ryukyu Trench (Fig. 1). South of Taiwan, the South China Sea lithosphere is subducting eastward under the Philippine Sea plate. Connecting these two subduction zones, the active convergent margin in the eastern Taiwan area is characterized by rapid crustal movement (Yu et al. 1997), regional-scale crustal faulting (e.g., Barrier and Angelier, 1986), high seismicity (e.g., Tsai, 1986), and the Luzon volcanic arc. The oblique collision of the Luzon volcanic arc against the edge of the Asian continent resulted in the uplift of...
Figure 1. Tectonic framework and main structural units in Taiwan (geodynamic setting in the upper right). Bathymetry is in kilometers. Major thrust faults at sea and on land are also shown with open triangles on the upper side. Thick lines indicate subduction with solid triangles on the overriding plate. Several thrust faults located in the eastern and southeastern Taiwan offshore area were proposed by Malavieille et al. (this volume). BR—Backbone Range, CF—Chuchih fault, CR—Coastal Range, HR—Hsuehshan Range, HuR—Huatung Ridge, HenR—Hengchun Ridge, LF—Lisan fault, Longitudinal Valley—Longitudinal Valley, LVF—Longitudinal Valley fault, SLT—Southern Longitudinal Trough, TC—Tananao Complex, TT—Taitung Trough, WF—Western Foothills.
the Taiwan mountain belt to more than 3 km above sea level in central Taiwan. Continuous GPS (Global Position System) monitoring between 1990 and 1995 shows that, in the area of eastern Taiwan, shortening rates of about 3 cm/yr are measured across the Longitudinal Valley (Yu et al., 1997). Such oblique convergence often creates arc-parallel migration of the forearc (e.g., McCaffrey, 1994) and produces extreme seismic hazard as a consequence of the relative motions of forearc blocks (e.g., Kanamori, 1995). Three-dimensional velocity models using natural earthquake data from the Taiwan area have been constructed and discussed (Roecker et al., 1987; Chen, 1995; Rau and Wu, 1995; Ma et al., 1996). However, their resolution is not good enough to reveal the crustal structure of the Luzon forearc, which is likely to have played a significant role in both the collision that built the mountain belt and the seismogenic zone of the convergent boundary.

In this study, we determined the three-dimensional P-wave velocity structure of the convergent zone in eastern Taiwan by using travel times of seismic waves from local earthquakes and air-gun shots recorded by the Central Weather Bureau Seismicographic Network (CWBSN). We also relocated the earthquakes for more reliable seismicity data based on the obtained P-wave velocity structure. Our goal was to answer the following questions: (1) In the velocity structure, what is the characteristic velocity feature of the Luzon forearc? (2) How does the forearc behave during collision? (3) What is the role of the forearc in the plate tectonics?

GEOLOGIC SETTING

Taiwan is the result of active, oblique collision between the Eurasian and Philippine Sea plates. It has two main tectonic provinces divided by the Longitudinal Valley (Fig. 1). To the east of the Longitudinal Valley, the Coastal Range, a part of the Luzon arc, is mainly composed of Miocene to Pliocene andesitic volcanic units and associated flyschoid and turbiditic sedimentary deposits (Ho, 1986). To the west of the Longitudinal Valley, the Central Range and the Hsiuhsien Range are composed of a pre-Tertiary metamorphic basement overlain by Paleogene sedimentary rocks metamorphosed at low grade, Neogene folded and thrust-faulted sedimentary rock layers, and Quaternary alluvial deposits. The Hsuhsien Range is separated from the Central Range by the Lisan fault, which branches off from the Chuchih fault. The Chuchih fault is a major up-thrust fault that follows the contact between the Slate Belt and the fold-and-thrust belt of the Western Foothills region (Ho, 1982). The Western Foothills is a province of typical cover tectonics in which only upper Tertiary and Quaternary rocks are involved (Fig. 1). In addition to the exposed part in Taiwan, deformed rock sequences of the orogenic structural features are thought to extend northeastward and southward to offshore Taiwan (e.g., Liu et al., 1997).

The southeastern Taiwan area is a transitional zone between an intensive mountain building due to the collision of the Luzon arc against the Eurasian plate and the typical eastward subduction of the South China Sea lithosphere. On the basis of a morphologic study, Chen and Juang (1986) divided the southeastern offshore area of Taiwan into five physiographic zones: the Hengchun Ridge, the Southern Longitudinal Trough, the Huatung Ridge, the Taitung Trough, and the Lanhsu Ridge, from west to east, respectively (Fig. 1). By using magnetic and gravity data, Liu et al. (1992) determined that the material of the basement of the Taitung Trough belongs to a volcanic arc, whereas the basements of the Southern Longitudinal Trough and Huatung Ridge do not. The Taitung Trough, the northern part of the North Luzon Trough, narrows and shallows toward the north and ends at the southern Coastal Range on eastern Taiwan (Page and Suppe, 1981). Lutao and Lanhsu are the two northernmost islands of the Lutao-Babuyan Ridge of the Luzon volcanic arc (Bowin et al., 1978). The Luzon arc presumably continues northward to include the Chimei Igneous Complex in the middle of the Coastal Range of Taiwan (Ho, 1986). Radiometric dating shows a southward younging of volcanic ages in this ridge belt (Richard et al., 1986). In this part of the Luzon arc, the main volcanic activity ceased in the middle Miocene (Ho, 1982, 1986).

SEISMIC DATA AND ANALYSIS

The purpose of this study is to obtain a high-resolution wave-velocity structure by using earthquake and air-gun data and a three-dimensional (3-D) tomographic technique (Thurber, 1983, 1993; Eberhart-Phillips, 1990) for delineating the plate-boundary structure between the Eurasian and Philippine Sea plates beneath eastern Taiwan. In eastern Taiwan, the CWBSN stations cover a long and narrow area with high seismicity. We thus divide the study area into four subareas from north to south (Fig. 2), in order to increase the model resolution. For an earthquake with magnitude larger than 4.5 that occurs at a distance of less than 50 km, the amplitude of the P-coda always is saturated and makes the S-wave reading difficult and unreliable owing to the limited dynamic range of the velocity-type sensor used by the CWBSN. For this reason, we consider only the P-wave arrivals (and only those for earthquakes with magnitude greater than 4.5) to be reliable. Without an S-wave reading, we are doubtful about the accuracy of earthquake location, especially the hypocentral depth. Although the wave-velocity modeling of a broad area would decrease the resolution because of omitting most minor earthquakes or a number of moderate earthquakes, the small-area analysis used in this study can include minor to moderate earthquakes with well-defined P- and S-wave arrivals and increase model resolution.

It must be emphasized that we want to provide the highest resolution in the middle crust instead of either the deeper crust or upper mantle. Therefore, most of the earthquakes selected in this study are crustal events with focal depth generally shallower than 40 km in depth. Because the deeper events occur
offshore in areas east of Taiwan that are outside the CWBSN and far from the study area, the model solution would be contaminated owing to the location uncertainty and long travel paths outside the study area if the traveltimes of the deeper earthquakes were used. On the other hand, the large quantity of local crustal events can be better located by the CWBSN, which permits selection of high-quality data sets. Moreover, the Lanhsu and Lutao stations situated on the Luzon arc (Fig. 2) keep a large number of the selected crustal events inside the CWBSN network, yielding a good opportunity to investigate the lateral crustal variation across a volcanic island, forearc basin, and subduction complex.
Traveltime data

Two types of traveltime data were used in this study: (1) first-arrival times from air-gun shots for subarea D (Fig. 2) and (2) the arrival times of P- and S-waves generated by earthquakes occurring in the vicinity of Taiwan. Air-gun sources were released by the R/V Maurice Ewing on the southeastern offshore area of Taiwan in September 1995 (e.g., Yeh et al., 1998) and recorded by the CWBSN stations in subarea D. In addition, the air-gun signals recorded by an ocean bottom seismometer (OBS) (Chen and Nakamura, 1998) were also included in the data set for the 3-D inversion. A study of the crustal structure using air-gun and earthquake data in subarea D can provide us with a detailed velocity model from shallow to deeper crust that permits us to study the crustal deformation associated with the transition from subduction to collision.

The earthquake data used in this study are P- and S-wave arrivals of local earthquakes recorded in real time by the CWBSN. The CWBSN uses three-component short-period digital seismographs having velocity-type sensors with an adjustable natural frequency of from 0.75 to 1.1 Hz (Shin, 1993). The earthquakes were selected to provide a set of hypocenters with the best available high-quality ray coverage of the subareas. They are digital data recorded by the CWBSN during 1991 to 1997. Events were restricted to those with at least 12 arrival times (both P and S waves) and with an azimuthal gap of less than 180° between stations. In order to represent the full spatial distribution of the arrival data, offshore events with at least six high-quality P arrivals were included that improve the spatial distribution of the data set. The Lutao station on the Luzon arc was shut down at the end of 1991. Thus, the earthquake data recorded at the Lutao station during 1986–1991 were also used. Furthermore, 110 events recorded in 1995–1996 by a temporary strong-motion array deployed in the Hualien area are included in the data to provide a denser coverage of stations for better resolution in modeling of the northern Coastal Range (Fig. 2). In addition, those strong-motion seismometers also provide well-defined S-wave arrivals near the Hualien area even for a moderate earthquake. The traveltime data were weighted according to their accuracy in forming and the smearing in evaluating resolution for a node, with independent data sets and velocity parameterizations (Fig. 2). The grid spacing was decreased from the coarse grid to a fine one in the study subareas during inversion. The model calculated at each step was used as the input model for the following step of inversion. We performed a trade-off analysis (Eberhart-Phillips, 1986) of the traveltimes and the model variances in order to choose the most suitable damping parameter to be used in the damped least-squares inversion. Finally, a damping value that reduced the data variance with only a moderate increase in solution variance was selected for each subarea as shown in Table 1.

The inversion procedure was carried out for each subarea with independent data sets and velocity parameterizations (Fig. 2). The grid spacing was decreased from the coarse grid to a fine one in the study subareas during inversion. The model calculated at each step was used as the input model for the following step of inversion. We performed a trade-off analysis (Eberhart-Phillips, 1986) of the traveltimes and the model variances in order to choose the most suitable damping parameter to be used in the damped least-squares inversion. Finally, a damping value that reduced the data variance with only a moderate increase in solution variance was selected for each subarea as shown in Table 1.

We measured the solution quality by computing a spread function (Michelini and McEvilly, 1991). As explained by Toomey and Foulger (1989) in detail, the spread function can describe the resolution in a better way than by solely examining the diagonal element. Because it combines the amount of information and the smearing in evaluating resolution for a node, the spread function does not have physical units. The higher

Table 1. Summary of Inversion Parameters

<table>
<thead>
<tr>
<th>Area</th>
<th>Total stations</th>
<th>Total events</th>
<th>P-wave arrivals</th>
<th>S-wave arrivals</th>
<th>Air-gun arrivals</th>
<th>Damping value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>43</td>
<td>294</td>
<td>4910</td>
<td>2607</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>49</td>
<td>537</td>
<td>10069</td>
<td>6009</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>19</td>
<td>400</td>
<td>5365</td>
<td>2764</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>D</td>
<td>14</td>
<td>595</td>
<td>4401</td>
<td>1917</td>
<td>641</td>
<td>30</td>
</tr>
</tbody>
</table>
the value of the spread function, the smaller the quantity of information coming from the data.

RESULTS

The 3-D velocity structure in the middle crust of eastern Taiwan is displayed by map views at 13, 17, and 25 km depths in Figure 3 and by a series of east-trending cross sections, arranged from north to south in Figure 4. Both figures reveal particularly strong velocity variations in the middle crust where the spread function indicates that the model resolution is good. The S-wave velocity model obtained (but not shown) reveals the same interesting features as those in the P-wave velocity model. We discuss only the latter in this paper.

Velocity anomalies and crustal blocks

The tomographic model in Figures 3 and 4 defines two main crustal units. The eastern unit extends from the eastern flank of the Central Range to the offshore area in eastern Taiwan. It can be further separated in the two subunits, the Luzon arc subunit in the east and the forearc subunit in the west, seen most clearly in Figure 4F. The forearc subunit shows a high P-wave velocity \( V_p \) feature in the shape of a north-south–elongated body in the middle crust beneath the Longitudinal Valley, the Coastal Range, and the Southern Longitudinal Trough (shown in Fig. 3, subareas B, C, and D). The velocity of the high-\( V_p \) volume varies from about 6.4 to 7.3 km/s at 17 km depth. The resolution is good, so the existence of the forearc high-velocity zone is reliable. The hypocenters of the events used in the inversion within a 10 km distance from each cross section are also plotted in Figure 4. The distribution of the hypocenters shows that inside the forearc high-\( V_p \) volume there are fewer earthquakes. The low-velocity material, lying above the forearc high-\( V_p \) volume, is about 10 km in thickness.

The two CWBSN stations (Lutao and Lanhsu stations) deployed on the northern Luzon arc (Fig. 1) provide us with two important sites to resolve the velocity structure of the Luzon arc subunit. The typical structure of the Luzon arc is the lenticular body beneath the Lutao islet as shown in Figure 4F. An interesting feature shown in Figure 4 is that the Coastal Range and Huatung Ridge are underlain by the forearc high-\( V_p \) crust in eastern Taiwan. Although the Coastal Range is thought to be the remnant of a westward-facing Neogene island arc on the leading edge of the Philippine Sea plate (Biq, 1972; Bowin et al., 1978; Chi et al., 1981), our observation suggests that the core of the Coastal Range is probably the uplifted forearc basin sediment, which filled in after the formation of the forearc basin; the forearc basin was then shortened and diminished. Our profiles of \( V_p \) show that the upper part of the Coastal Range above 10 km in depth corresponds to the part of the sediment filled in (Figs. 4D to 4F).

The second main unit, the Central Range, bounded on the west by the Chuchih fault and on the east by the Longitudinal Valley fault (Fig. 4), has a large middle-crustal region with low \( V_p \). The velocity of the Central Range unit is about 0.1 to 0.6 km/s lower than average velocities in subareas B, C, and D. The spatial distribution of the low-\( V_p \) volumes beneath the Central Range indicates that they are continuous from south to north. In the area between 23.5\(^\circ\)N and 24\(^\circ\)N, there is a high-velocity zone beneath the western flank of the Central Range (Figs. 4B and 4C). Wu et al. (1997) also reported the high-velocity zone, which they speculated represents the extrusion of high-velocity materials from the middle or lower crust to shallow depth. North of 24\(^\circ\)N, the velocity contours are relatively flattened beneath the Central Range (Fig. 4A).

Relocation of earthquakes

The 3-D velocity model was used to relocate 8334 earthquakes recorded by the CWBSN during 1991 to 1997. The epicenters of these events are plotted in Figure 5. When the relocated hypocenters are compared with the positions of the same earthquakes determined by the CWBSN, significant systematic changes are apparent. The horizontal changes vary from 0 to 15 km and move landward in a direction of northwest to southeast for subareas B, C, and D, as shown by the rose diagrams in Figure 5. The reason for this systematic variation in the forearc high-\( V_p \) structure has not been taken into account in the CWBSN 1-D velocity model. The vertical changes are mostly in the range of 0 to 5 km.

COMPARISON WITH GRAVITY ANOMALIES

In order to check the tomographic inversion results and enable estimation of crustal densities associated with the forearc high-\( V_p \) volume in eastern Taiwan, we perform 3-D gravity modeling directly from the 3-D velocity structure (Figs. 3 and 4). Gravity anomalies can be calculated and compared with observed gravity values, if an assumption is made about the relationship between velocity and density. We assume that lateral perturbations to velocity and to density are linearly related. In addition, because the digital elevation model offshore Taiwan is available (Liu et al., 1998), it might be more correct to compare the results with Bouguer than free-air anomalies at sea. Therefore, we determined the Bouguer gravity anomaly in eastern Taiwan from the 3-D \( V_p \) model by finding the velocity-contrast layers and then calculating the anomalies for each layer by using the formula of Parker (1972). In spite of some discrepancies between the observed (Yen et al., 1995) and model-derived gravity anomalies in the area of the Luzon arc (Fig. 6), they show many similarities in the spatial pattern, in particular the location of the on-land gravity high in eastern Taiwan. The implication of Figure 6 is that the source of the gravity high in eastern Taiwan may be the forearc high-\( V_p \) volume. In addition, although the gravity high is continuous along the strike of the Longitudinal Valley, its amplitude decreased from the 40–80 mgal values east of Longitudinal Valley to about 10 mgal to...
Figure 3. Results of three-dimensional inversion for P-wave velocities. Velocities are shown in map view at three slices at 13, 17, and 25 km for each subarea. Major faults are also shown. Average velocity for each depth slice is shown in upper-right corner. See Figure 2 for reference map. The area for which the spread function is 4.0 or smaller (inside the dashed lines) is also shown. Spread function smaller than 4.0 (i.e., inside the contour lines) indicates that the velocity value is well resolved and spatially well determined.
the west (Fig. 6). This amplitude change could correspond to the transition from the forearc (oceanic crust) to the Central Range (continental crust).

**LUZON FOREARC SLIVER**

The most prominent velocity feature of the 3-D velocity model is the elongated forearc high-velocity volume along the strike of the Longitudinal Valley beneath eastern Taiwan (Figs. 4 and 5). It is evident that the forearc high-velocity volume narrows northward and extends at least 200 km in eastern Taiwan. The head waves generated from 10 events that occurred in eastern Taiwan (Fig. 7) confirm the existence of the narrow forearc high-$V_p$ volume in the middle crust. The high-$V_p$ volume is also the possible mass that generates the gravity high in that area.

In a convergent zone, the existence of such a high-$V_p$ volume is not unusual; examples include the imbricated oceanic crust near the Contact fault zone, southern Alaska (Wolf et al., 1991; Fuis et al., 1991), the shattered oceanic crust near the Santa Lucia Escarpment in central California (Howie et al., 1993), and the remnant oceanic crust beneath Vancouver Island, western Canada (Spence et al., 1985). By using a temperature
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Figure 4. Cross sections A—A’ to G—G’ (locations shown in the top reference map) of 3-D velocity structure contoured at 0.5 km/s intervals. Relocated hypocenters of events used in velocity inversion to 35 km depth are also shown. Diamonds—events of magnitude 5.0 or more. Open circles—events of magnitude 4.0–4.9. Topography of each cross section is shown on top. Plots to the right of each cross section show the spread function. CenR—Central Range, HsR—Hsüehshan Range, CF—Chuchih fault, LF—Lisan fault, CR—Coastal Range, HR—Huatung Ridge, LVF—Longitudinal Valley fault, PLVF—southern prolongation of Longitudinal Valley fault.

versus depth model derived from thermal-gradient data (Lee and Chang, 1986) and velocity-depth functions for various rocks (Christensen and Mooney, 1995), Cheng et al. (1998) concluded that the high-velocity volume beneath the Longitudinal Valley corresponds to a trapped oceanic crustal sliver of the Luzon forearc. In the forearc sliver, the oceanic crust was covered with deformed ocean-floor sediments, uplifted trench-floor and trench-slope sediments, and the depositional fills of subsiding forearc basins during the convergence of Eurasian and Philippine Sea plates. Because of the various lithologies represented, the crustal velocity structure of the forearc sliver shows a signature differing from that of a typical oceanic crustal section.

The dense clusters of background seismicity in eastern Taiwan show that the forearc sliver is almost coincident with a less seismic area delineated by two subparallel seismic zones (Fig. 5). The locations of high-moment release events appear to correlate well with the high-$V_p$ volume, which is consistent with the positive correlation between increasing velocity and increasing ability of the materials to accumulate strain energy and release it as brittle failure (Michael and Eberhart-Phillips, 1991). In contrast, the low-$V_p$ zone beneath the central and northern Central Range, which is also a relatively quiescent zone of seismicity, might imply that the crustal material of the Central Range is ductile or weak and deforms and uplifts silently in response to the plate convergence. We thus conclude that the forearc sliver plays an important role in the arc-continent collision in the Taiwan area and in the tectonic evolution of the Central Range uplift.

A velocity cross section along the strike of the Longitudinal Valley is plotted in Figure 8. The plate interface and dip angle of the subducted Philippine Sea lithosphere are taken from a local seismicity and source-parameter study in the southernmost Ryukyu-Taiwan area (Kao et al., 1998), by approximately delineating the upper envelope of the dipping seismic zone (e.g., Isacks and Barazangi, 1977). The forearc high-$V_p$
Figure 5. Map of relocated epicenters of earthquakes that occurred during 1991 to 1997. Hypocenters are relocated with the 3-D velocity model. Diamonds—events of magnitude 5.0 or more. Open circles—events of magnitude 4.0–4.9. Major faults are also shown. Shaded area outlines the region with $V_p$ generally greater than 6.5 km/s. The southern extension of the high-velocity zone cannot be resolved in this study. Rose diagrams shown on right indicate horizontal variations and azimuths between initial (located by CWBSN) and relocated positions of events.
Figure 6. Map of (A) observed and (B) calculated gravity. Observed is from Yen et al. (1995) and shows Bouguer values at sea and on land. Right shows Bouguer values calculated from the 3-D velocity model. Shaded areas indicate Bouguer values greater than +10 mgal.

The oblique collision between the Luzon arc and the Eurasian continental shelf started near the Hualien area at ca. 4 Ma and moved progressively southward to reach the Taitung area in southeastern Taiwan by ca. 1 Ma (Lee et al., 1991). As shown in Figure 1, the spacing between the Luzon arc and the Longitudinal Valley is about 50 km in the Taitung area (measured from Lutao to Taitung city) and decreases to less than 20 km in the Hualien area. The northward narrowing of the spacing between the Luzon arc and the Longitudinal Valley is similar to that of the forearc high-\(V_p\) volume. A feasible interpretation for the northward-narrowing feature is that most of the forearc sliver has been shortened or plunged into the mantle. Chemenda et al. (1997) had justified this interpretation as one of the possible evolutions for the Taiwan collision on the basis of physical modeling.

The low-\(V_p\) zone beneath the Central Range coincides with the region of most intense active deformation (e.g. Yu et al., 1997), suggesting that it is relatively weak. In contrast, the \(V_p\) of the Luzon forearc sliver is relatively high in the middle to lower crust (Fig. 3). Thus, when the Luzon forearc sliver collides with the crust of the Central Range, the former may play a role as a backstop in the dynamics of the Taiwan orogeny. Such an occurrence may in turn result in a rapid rising of crustal materials to shallow depths, seen most clearly in Figure 4, B to E. The rapid uplift of the crustal material beneath the Central Range should have been accompanied by normal faulting along the eastern flank of the Central Range. The normal faulting observed in two transects along the Central and Southern Cross-Island Highways (Crespi et al., 1996) can be ascribed to the push of the forearc sliver.

**PLATE BOUNDARIES**

The plate boundaries between oceanic regions are narrow, such as the Mariana convergent plate margin (e.g., Fryer, 1996). Plate boundaries increase to hundreds of kilometers when they are between oceanic and continental lithospheres, such as the New Zealand subduction zone (e.g., Walcott, 1998) and the Cascadia subduction zone of the western United States (e.g., Goldfinger et al., 1997). However, seismicity and active faulting in continental regions are commonly dispersed over thousands of kilometers, such as Central Asia (Molnar and Tapponnier, 1988). The tectonic setting and width of the seismogenic zone in eastern Taiwan (Fig. 5) is generally consistent with the boundary between the oceanic and continental lithospheres. Although the Longitudinal Valley fault is generally accepted as
the plate boundary between the Eurasian and Philippine Sea plates (Biq, 1972; Chai, 1972; Karig, 1973; Wu and Lu, 1976; Tsai et al., 1981; Chi et al., 1981; Hsu and Sibuet, 1995), the detailed geometry and nature of the plate boundary are difficult to evaluate from the highly deformed crust in the Taiwan region. Controversial opinions on the plate boundary in Taiwan naturally exist (e.g., Biq, 1972; Bowin et al., 1978).

In this study, based on the relocated seismicity and the obtained 3-D velocity structure, the possible location of the plate boundary could be generally outlined. It is characterized by a sharp across-fault velocity variation, which is a primary feature in the 3-D velocity structure (Figs. 3 and 4). It generally marks a boundary between the oceanic and continental crusts. To the south of 23.5°N, this boundary is generally along the mapped Longitudinal Valley fault trace and its southern prolongation (Fig. 4, E to G). To the north of 23.5°N, it seems to
move westward from the mapped trace of the Longitudinal Valley fault to the eastern flank of Central Range (Fig. 4, C and D). The east dip in the shape of the forearc high-$V_p$ volume implies that the boundary may dip to the east along with the Luzon forearc sliver.

CONCLUSIONS

The three-dimensional P-wave velocity structure of the convergent zone in eastern Taiwan has been obtained by inversion of local earthquake and air-gun traveltimes. A large-volume high-velocity zone is observed in the middle to lower crust between the Central Range and Luzon arc in eastern Taiwan (i.e., beneath the Coastal Range and Longitudinal Valley). The high-velocity zone narrows northward and extends to at least 24°N; it can be interpreted as the oceanic crust of the Luzon forearc sliver. The Luzon forearc sliver is almost coincident with a less seismic area delineated by two subparallel seismic zones revealed by the relocated epicenters. The locations of high-moment release events appear to correlate well with the high-velocity volume, which is consistent with the positive correlation...
between increasing velocity and increasing ability of the material to store strain energy and release it as brittle failure.

West of the forearc high-velocity zone, the overall shape and location of the low P-wave velocity zone beneath the Central Range corresponds well to the mapped surface geology where deformation has been the most active. This low-velocity zone also corresponds to the relatively quiescent zone of seismicity in the central and northern Central Range. These results imply that the crustal material of the Central Range is weak or ductile and that when it collides with the Luzon forearc sliver, it might respond to the collision by silent or ductile deformation and crustal thickening.

Between the Luzon forearc sliver and the Central Range is the boundary between the oceanic and continental plates, which can be represented by a sharp velocity gradient in the three-dimensional crustal-velocity structure. This plate boundary is situated beneath the eastern flank of the Central Range to the north of 23.5°N and along the Longitudinal Valley to the south of 23.5°N and its southern prolongation in the offshore area. It may dip to the east along with the Luzon forearc sliver.

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