

Short Note

Anomalous P_n Waves Observed in Eastern Taiwan: Implications of a Thin Crust and Elevated Oceanic Upper Mantle beneath the Active Collision-Zone Suture

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Abstract Normal P_n waves are commonly observed in Taiwan from shallow regional earthquakes at epicentral distances larger than 120 km, similar to the observations in many other continental regions. However, the critical distances to observe P_n waves for shallow eastern Taiwan earthquakes vary with azimuth corresponding to a significant variation of crustal thickness. In particular, anomalous P_n waves are commonly observed for shallow eastern Taiwan earthquakes recorded on seismic stations at epicentral distances as small as 60 km along the collision zone suture, the Longitudinal Valley. For the same event, normal P_n waves are observed at other seismic stations elsewhere on the island. The apparent velocity of the anomalous and normal P_n waves from the same event is 7.8 ± 0.15 km/sec, which is consistent with the average P_n velocity in the Taiwan area. Thus, the unusually short critical distance for P_n waves in eastern Taiwan suggests that the crust beneath the collision zone suture must be very thin and the upper mantle beneath the Longitudinal Valley must be relatively elevated compared with that beneath the other parts of Taiwan. Assuming a simple 1D layered velocity model, the Moho depth beneath the suture zone can thus be estimated at $\sim 23 \pm 2$ km. This observation is consistent with the recent report from a high-resolution 3D tomographic inversion that a narrowly confined, anomalously elevated, and north-northeast–south-southwest elongated oceanic upper mantle was imaged beneath the Longitudinal Valley from Hualien in the north to Taitung in the south (Kim *et al.*, 2005, 2006). Furthermore, the preceding observations may also support the interpretation that the conduction of excess heat supply from the elevated hot oceanic upper mantle into the adjacent mid-to-lower continental crust over a long period of geological time may play an important role in the crustal deformation beneath the continent, including metamorphism, thickening, and uplifting.

Introduction

The Longitudinal Valley of central eastern Taiwan is sandwiched between the Central Range of the Eurasian plate and the Coastal Range of the Philippine Sea plate (Fig. 1). It is considered as the collision suture between the two fast-converging plates (Ho, 1986; Tsai, 1986). The Longitudinal Valley extends for about 160 km along the north-northeast–south-southwest orientation with less than 10 km width in most places and is filled up with Quaternary sediments. The crust and upper mantle structure and their associated earthquake activity across the suture zone are the keys to our understanding of how plates interact and deform along an arc-continent collision between two active subduction zones. In the past decade, lateral variations of crustal structure and P -

wave velocity beneath the Taiwan area were studied extensively by 3D tomography inversions of local earthquake data (e.g., Rau and Wu, 1995; Ma *et al.*, 1996; Cheng *et al.*, 2002; Kim *et al.*, 2005). To provide constraints on the uppermost mantle velocity around Taiwan, Ma and Song (1997), Huang *et al.* (1998), and Chen *et al.* (2003) analyzed travel times of the first P arrival (P_n phase) observed at epicentral distances in the range from 150 to 300 km. In general, the average P_n velocity in Taiwan region is about 7.8 km/sec (Yeh and Tsai, 1981) which seems to be slightly higher to the east and to the west of the Central Range (Huang *et al.*, 1998). Here, we report that anomalous P_n waves are observed at stations with epicentral distances as small as 60 km

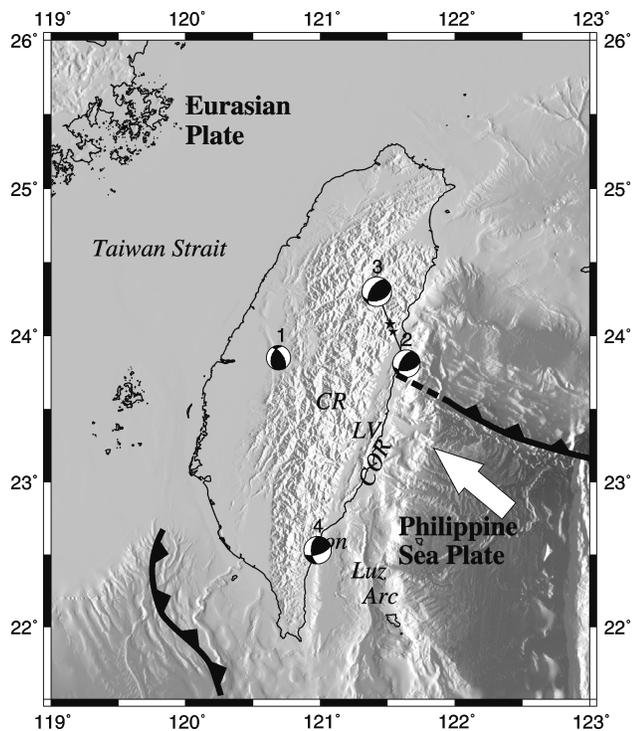


Figure 1. Tectonic setting around Taiwan. The Philippine Sea plate is being subducted underneath the Eurasian plate in northeastern Taiwan. The South China Sea plate (a subplate of the Eurasian plate) is being subducted underneath the Philippine Sea plate to the south of Taiwan. The Luzon arc of the frontal Philippine Sea plate collides with the continental margin of the Eurasian plate between the two subduction zones. CR, Central Range; COR, Coastal Range; LV, Longitudinal Valley. The locations of four earthquakes selected for this study are also shown with their corresponding focal mechanisms.

along the collision suture from shallow earthquakes located either at the northern or at the southern ends of the suture zone. For the same event, however, normal P_n waves are observed at other seismic stations outside the collision zone region. Thus, the crustal thickness beneath the suture zone must be anomalously thin and the oceanic upper mantle must be relatively elevated beneath the collision suture compared with that beneath other parts of Taiwan. The tectonic implications of the inferred contact between the elevated upper mantle beneath the suture zone and the adjacent mid-to-lower continental crust can thus be explored.

Data and Observations

Broadband and short-period waveform data from four recent shallow earthquakes recorded by the Central Weather Bureau Seismic Network (CWBSN) (Fig. 2) are selected and analyzed (Table 1). Among them, two events occurred at the northern end and one at the southern end of the Longitudinal Valley, and the fourth occurred at the western side of the

Central Range. As listed in Table 1, the four selected earthquakes are well recorded (quality A or B) with local magnitude $M_L \geq 4.0$ and all at shallow depths. The regional Centroid Moment Tensor (CMT) solution for all selected events was obtained by inverting the broadband waveform data recorded by the BATS (Broadband Array in Taiwan for Seismology). All four events show predominantly thrusting mechanisms (Liang *et al.*, 2004; <http://bats.earth.sinica.edu.tw>). The compression axes for the three eastern Taiwan earthquakes are systematically aligned along the northwest–southeast direction, which is consistent with the direction of plate convergence, whereas the one located to the west of the Central Range in the aftershock region of the disastrous 1999 Chi-Chi earthquake displays an almost east–west direction of compression.

Anomalous P_n Waves

An example of an anomalous P_n wave occurs in the vertical-component broadband waveform of event 3 recorded at the station TWG, which is located at a 146.5-km epicentral distance in the southern Longitudinal Valley, shows a small-amplitude P_n arrival followed by an impulsive large-amplitude second P -wave arrival (Fig. 3). However, the time of the first P_n arrival at station TWG is clearly ~ 4 sec earlier than that recorded at station SGS (see Fig. 2), which is located at the same epicentral distance as the station TWG but on the western side of the Central Range. Similarly, for the stations TWF1 and TWQ1 at the same epicentral distance of 83 km, not only the first arrival at TWF1 is more than 3 sec earlier than that at the TWQ1, but it is also clear that P_n arrivals can be seen at the TWF1 but not at TWQ1. TWF1 is located above the suture zone and TWQ1 is on the western side of the Central Range.

Two plots of arrival time versus epicentral distance for event 3 are displayed: one for stations along the collision zone suture (Fig. 4a) and the other for the rest of the stations (Fig. 4b). A small-amplitude first arrival preceding an impulsive second arrival can be observed at stations with epicentral distances greater than 60 km along the collision suture (Fig. 4a) and at stations with epicentral distances greater than 120 km elsewhere in the Taiwan region (Fig. 4b). The apparent velocity of the small-amplitude first arrivals observed in both cases is $\sim 7.8 \pm 0.15$ km/sec, confirming our interpretation that the small-amplitude first arrivals are the P_n waves. Apparently, the P_n -arrival time at stations along the collision suture is consistently 3 to 4 sec faster than those observed at stations elsewhere in the Taiwan region, as shown by the constant separation between the parallel solid and dashed lines (Fig. 4), revealing a dramatic difference of crustal thickness beneath the collision suture and elsewhere.

The distinctive and large-amplitude P arrivals observed as the first arrival at closer stations and as the second arrival following the P_n arrival at stations beyond the critical distance are characterized by apparent velocities ranging from 6.0 to 6.3 km/sec along a hyperbolic curve (Fig. 4a

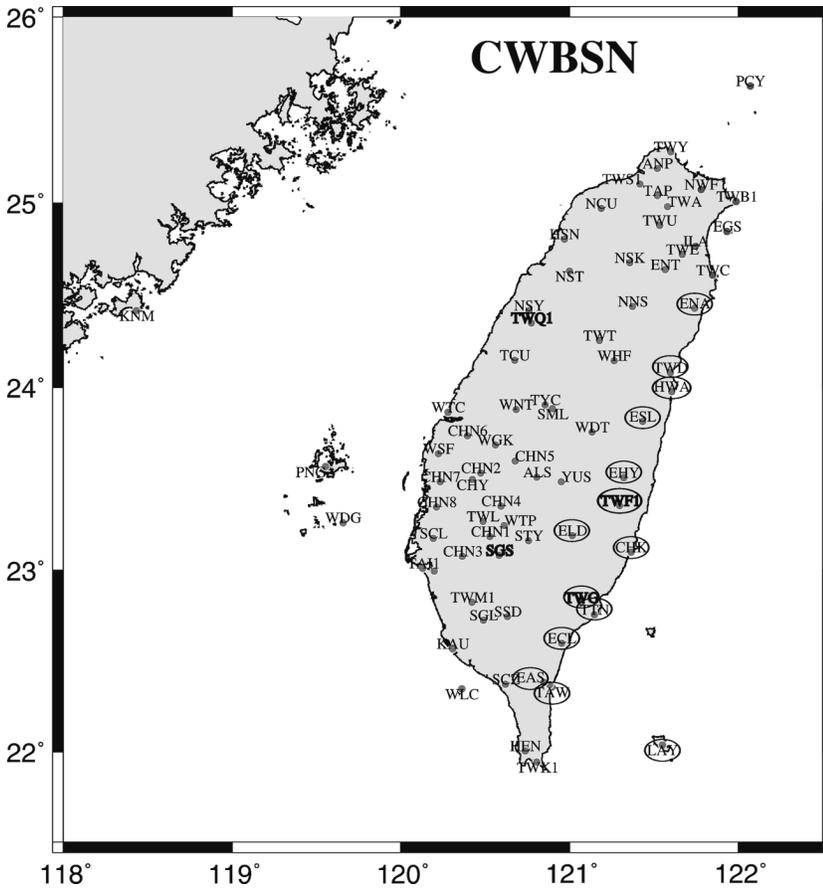


Figure 2. Map showing the locations of CWBSN stations in the Taiwan region. Anomalous P_n waves from shallow eastern Taiwan earthquakes are commonly observed at those stations marked with large circles, mainly along the collision zone suture. Anomalous P_n waves can also be observed at stations ENA, TWD, TWA, and ESL to the north of the collision zone suture from earthquakes that occurred in the southern collision zone area, e.g., earthquake 4 in Table 1. Waveform examples in Figure 3 are recorded at stations in boldface font (TWG, SGS, TWQ1, and TWQ1).

Table 1

Source Parameters of the Four Selected Earthquakes

No.	Origin Time	Latitude (° N)	Longitude (° E)	Depth (km)	M_L	BATS CMT Solution	Region
1	2000/08/02 14:19	23.84	120.69	26.40	4.14		Nantou
2	2002/06/24 01:12	24.03	121.54	19.88	4.70		Hualien
3	2004/05/01 07:56	24.08	121.53	21.55	5.25		Hualien
4	2004/06/06 00:09	22.53	120.97	7.49	4.99		Taitung

and b). They are interpreted as the direct P_g waves traveling through the upper and middle crust. The arrival time of the direct P_g waves for stations along the suture zone (Fig. 4a), marked by the hyperbolic curve, is clearly 1 to 2 sec earlier than those stations in other areas of Taiwan (Fig. 4b) corresponding to slightly higher velocity in the upper and middle crust along the collision zone suture than elsewhere in Taiwan.

Figure 5 shows arrival time versus epicentral distance plots for the four selected earthquakes (Table 1). It is clear that both anomalous and normal P_n waves can be observed only from crustal earthquakes that occurred in eastern Taiwan (e.g., earthquakes 2, 3, and 4) but not from other lo-

cations (e.g., earthquake 1). The average crustal velocity (V_c) can be estimated ~ 6.3 km/sec from the fitting of P_g -arrival times with a hyperbolic curve in all four cases. The anomalous P_n waves with apparent velocity of $\sim 7.8 \pm 0.15$ km can be clearly identified at seismic stations as close as 60 km and beyond along the collision zone suture and normal P_n waves with similar apparent velocity can be observed at stations elsewhere in the Taiwan region. The apparent velocity for both anomalous and normal P_n waves obtained here corresponds to the average P_n velocity reported from other previous independent studies (e.g., Yeh and Tsai, 1981).

P_n Velocity and the Moho Depth

As revealed in the arrival-time versus epicentral distance plots for the three eastern Taiwan events (earthquakes 2, 3, and 4) listed in Table 1, the apparent velocity of the P_n waves (V_p) along the collision suture can be derived from the slope of the linear fitting of the P_n arrivals, which is estimated to be about 7.8 ± 0.15 km/sec (Fig. 5). By assuming a 1D velocity structure with an average crustal velocity (V_c) of 6.3 km/sec (e.g., Ma *et al.*, 1997; Chen *et al.*, 2003), the Moho depth (H) can be estimated from the observed P_n velocity through the following relationship:

$$H = [T_p \times V_p \times V_c / \sqrt{V_p^2 - V_c^2} + d] / 2.0, \quad (1)$$

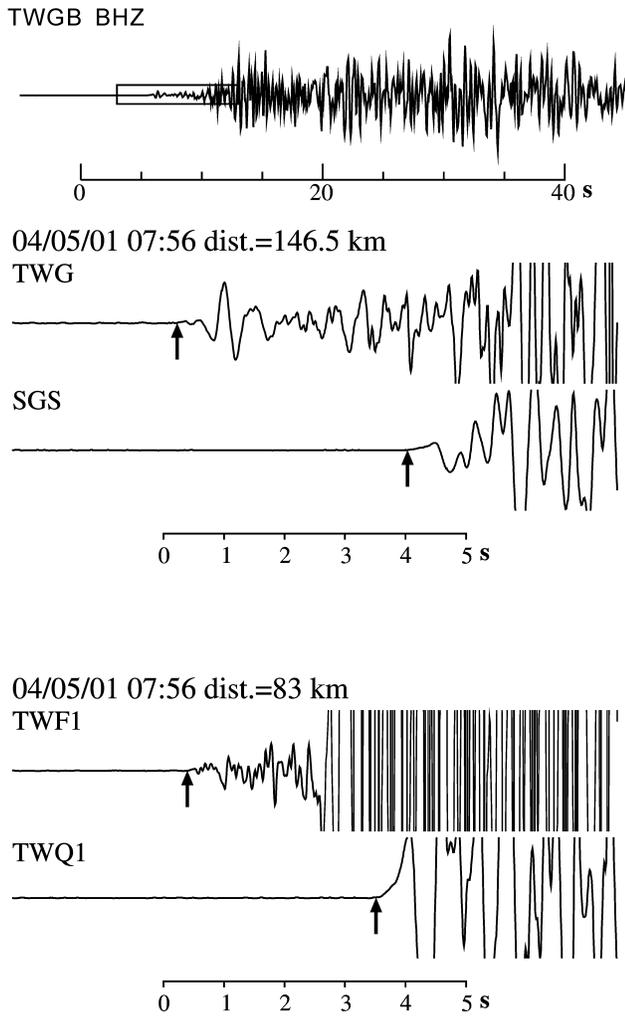


Figure 3. Example of a broadband vertical-component seismogram from event 3 and recorded at TWG at an epicentral distance of 146.5 km showing small-amplitude P_n arrivals preceding a large-amplitude second P arrival (top). The enlarged seismogram for the first 10 sec marked by the rectangular box at the top trace is displayed along with another station (SGS) with similar epicentral distance (middle). Similar displays for the TWF1 and TWQ1 stations at epicentral distance of 83 km are also shown (bottom). These four stations are highlighted in Figure 2 in boldface font.

where T_p is the intercept time and d is the focal depth. Based on the information shown in Figures 4 and 5, the inferred Moho depth is about 23 km beneath the Longitudinal Valley, which is about 10–30 km shallower than in other parts of Taiwan (Kim *et al.*, 2005). When given a 5% perturbation to V_c and d independently or considering the uncertainties of V_c and d , the perturbations of the estimated Moho depth are less than 2 and 1 km, respectively. Therefore, these uncertainties will not alter or modify our interpretation of a thin crust with $\sim 23 \pm 2$ km thickness beneath the Longitudinal Valley.

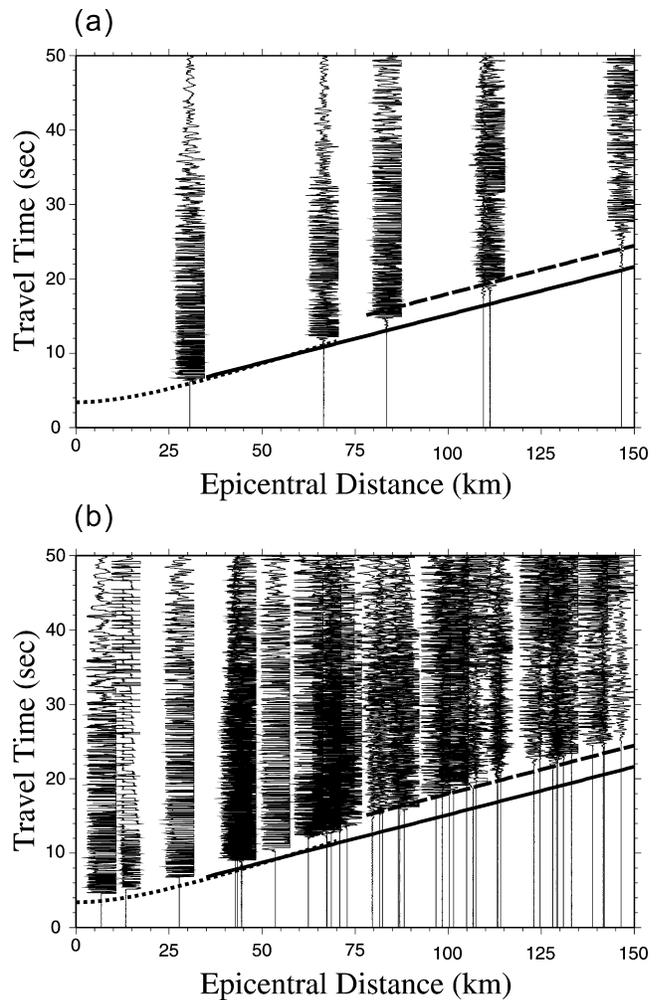


Figure 4. Travel time versus epicentral distance plots for event 3 (1 May 2004, Table 1) showing seismograms for stations along the collision suture zone (a) and for stations elsewhere in the Taiwan region (b).

Chen *et al.* (2003) obtained a P_n velocity of 7.9–8.0 km/sec in the eastern Taiwan region and estimated a Moho depth ~ 38 km using a relatively coarse cell size ($\geq 0.6^\circ$) that probably lacks spatial resolution in local scale. Results from previous onshore/offshore wide-angle seismic profiling studies have also failed to provide enough resolution to resolve the transition-zone structure across the collision suture in the eastern Taiwan region (e.g., Hetland and Wu, 1998; Yang and Wang, 1998; Yeh *et al.*, 1998; McIntosh *et al.*, 2005). However, the crustal thickness of the Luzon Arc offshore of the eastern Taiwan region is estimated to be ~ 24 km from marine seismic-line data (e.g., Yang and Wang, 1998). It may correspond to a thickened and deformed oceanic crust associated with the arc-continent collision (Hetland and Wu, 1998; Lin, 2002; McIntosh *et al.*, 2005).

Recently, results from high-resolution 3D tomography studies of the Taiwan region (Cheng *et al.*, 2002; Kim *et al.*,

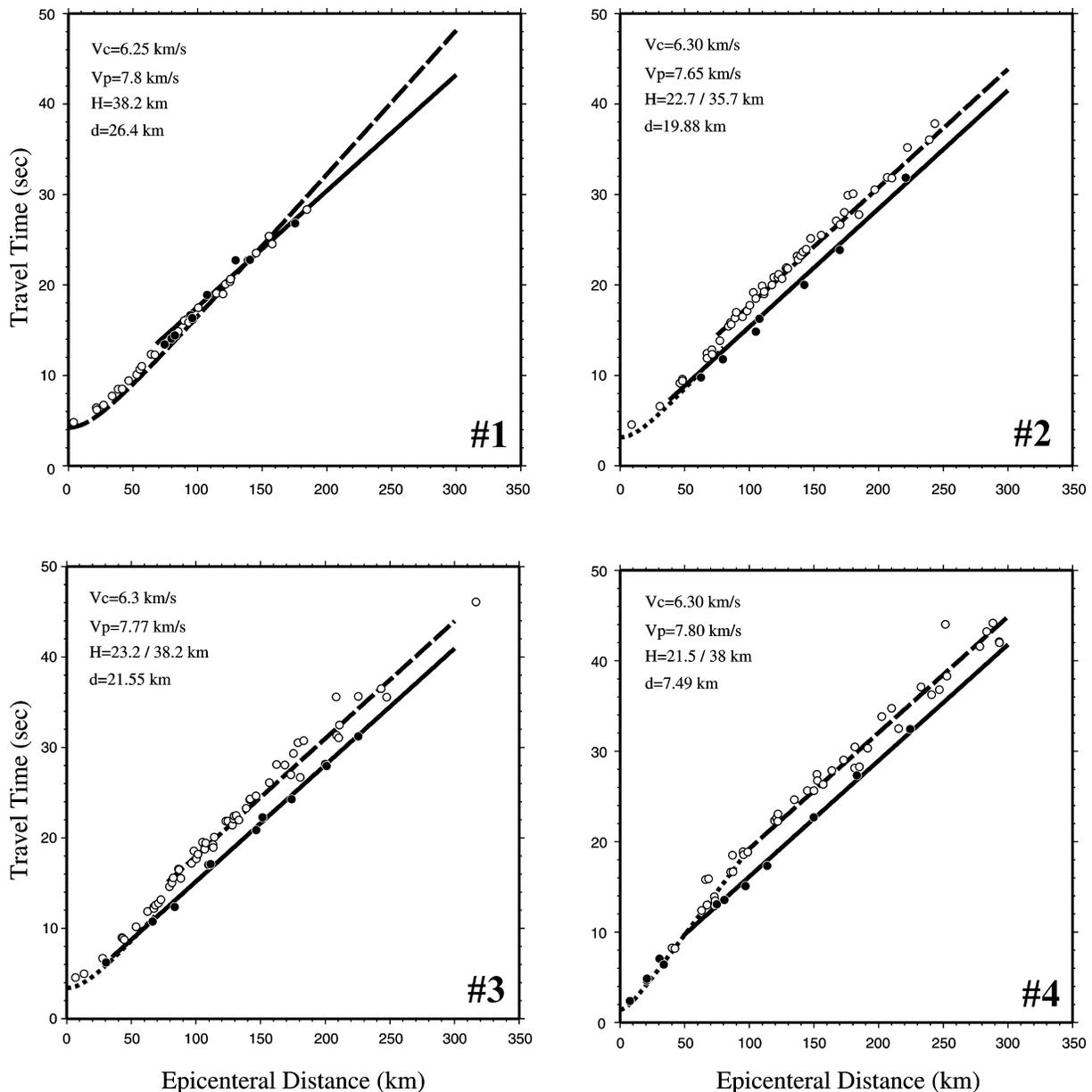


Figure 5. Arrival time versus epicentral distance plots for the four selected earthquakes (Table 1) showing the observed first arrival time at various stations (circles) and the best-fitting arrival time curves for Pg (dotted curve) and Pn waves (solid and dashed lines). Solid and open circles represent the observed first arrival times for stations along the collision zone suture and for stations elsewhere in the Taiwan region, respectively.

2005, 2006) reveal that a north-northeast–south-southwest-trending high-velocity oceanic upper mantle is elevated beneath the collision suture, the Longitudinal Valley, from Hualien in the north to Taitung in the south (Fig. 6). The depth of the Moho inferred from 3D structural images (Kim *et al.*, 2005, 2006) is consistent with the result from this study that a thin crust and an elevated oceanic upper mantle beneath the Longitudinal Valley is responsible for the observed anomalous Pn waves in eastern Taiwan.

Preliminary Tectonic Implications

Combining our results with 2D (e.g., McIntosh *et al.*, 2005) and 3D (Kim *et al.*, 2005, 2006) tomographic images, we infer that the crustal thickness beneath the Longitudinal Valley and the Coastal Range is about 23 ± 2 km, which is 10 to 30 km thinner than elsewhere beneath Taiwan. Because the Longitudinal Valley is commonly considered as the suture zone between the Philippine Sea Plate and the Eurasia continental margin (Ho, 1986), the oceanic/arc and

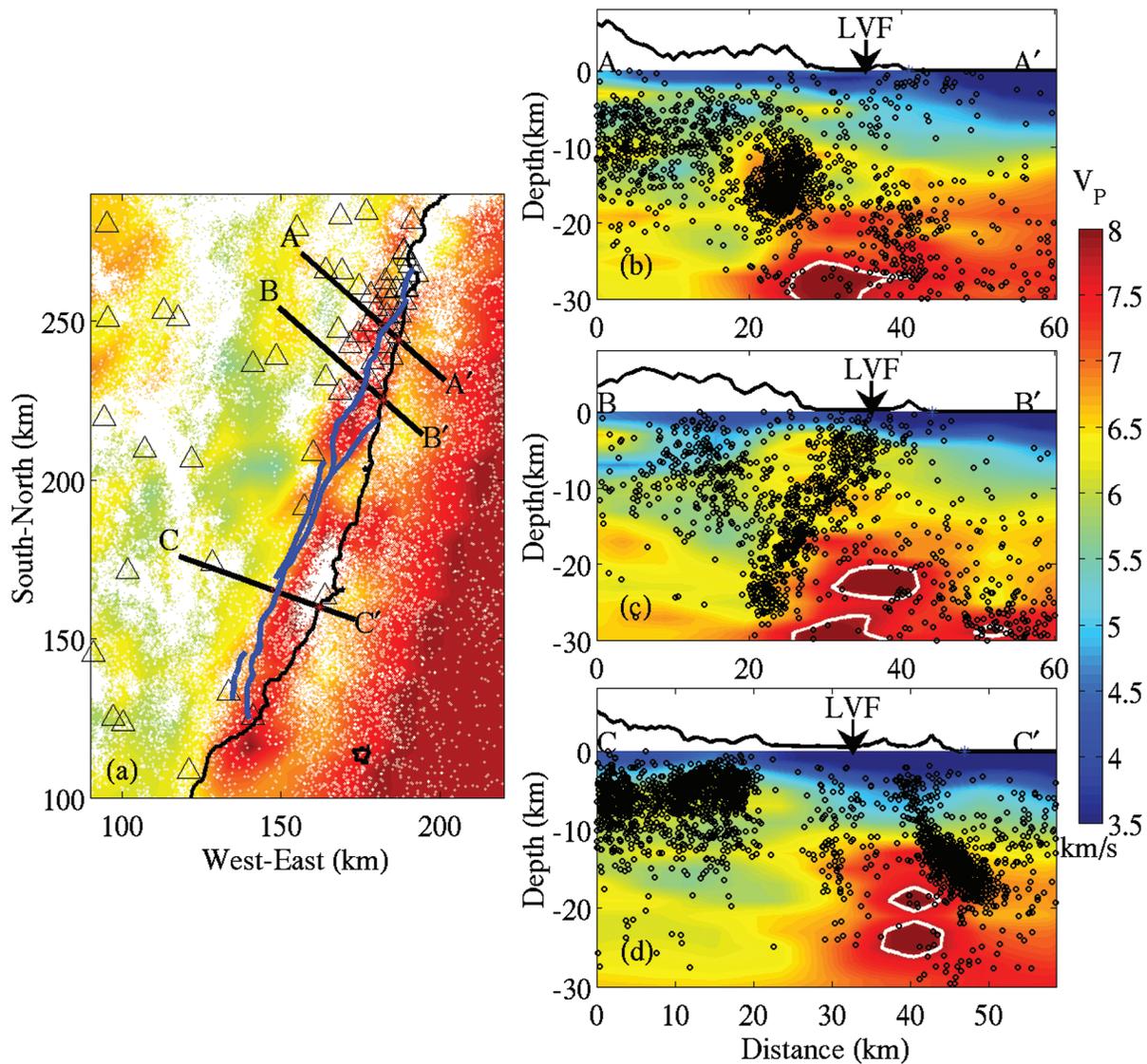


Figure 6. (a) Map view of the horizontally sliced P -wave velocity at the depth of 20 km. Blue lines indicate the surface traces of active faults, and the white dots mark the epicenter locations. (b)–(d) A few cross-sectional views of P -wave velocity images beneath the collision suture zone obtained from a high-resolution 3D tomography study (modified from Figures 5 and 8 of Kim *et al.*, 2006).

continental crusts are deformed, thickened, and uplifted across the collision suture. As a consequence, the crust beneath the suture zone is relatively thicker than normal oceanic crust (5–10 km) but the mantle underneath is still higher than the one beneath the Central Range by 10–30 km.

The possible impact of the relatively elevated oceanic upper mantle to the adjacent mid-to-lower continental crust and its role on the Cenozoic orogenic process in the Taiwan area is further explored here. Results of a few modern seismic tomography studies of Taiwan (Rau and Wu, 1995; Ma *et al.*, 1996; Kim *et al.*, 2005, 2006) consistently imply a thick middle to lower crust beneath the Central Range. This thickened mid-to-lower continental crust is also characterized by low velocity and a lack of seismicity and high at-

tenuation (e.g., Kim *et al.*, 2005). Surface geology shows that not only is a large area of the Central Range characterized by various degrees of metamorphism, but also the closer the area to the collision zone suture, the higher the degree of metamorphism (e.g., Ho, 1986). Thus, a better understanding of the subsurface structure beneath the collision suture and its transition to the thick continental crust provides insight and additional information with which we can further explore the potential thermal sources that may contribute to the high degree of metamorphism and active orogenic processes in the Taiwan region.

To understand the thermal properties beneath the Central Range, Song and Ma (2002) derived a first-order-approximation thermal model based on crustal thickening

followed by constant erosion processes. They concluded that the temperature might not be the only factor causing the observed lack of seismicity and low seismic velocity. Alternatively, Lin (2002) proposed that an exhumation of the detached and subducted continental crust in the eastern Central Range could account for the high grade of metamorphism, high heat flow, and Taiwan orogeny. Nevertheless, the elevated oceanic upper mantle and its close contact to the adjacent mid-to-lower continental crust discussed in this study and in Kim *et al.* (2006) have provided a new structural configuration beneath the collision zone suture to explore the deformation across the suture.

Across the collision suture, the hot and elevated oceanic upper mantle adjacent to the mid to lower continental crust serves as an additional heat source via heat conduction, although the penetrating width may be limited around the contact boundary and is also a function of time. Therefore, the consequence of continuously increasing heat input to the mid to lower crust beneath the Central Range, especially across the transition zone beneath the collision-zone suture, may include gradual thermal expansion of volume and eventually a reduction of density over a long period of geological time and over a large region. The region closer to the contact zone is expected to be subjected to a higher thermal effect and thus a higher degree of metamorphism. The result of volumetric change and reduction of rock density over time in the mid-to-lower crust beneath the Central Range is that the Central Range will be eventually uplifted because of buoyancy forces, especially between the two steeply west-dipping boundary faults (Kim *et al.*, 2005), to reach an isostatic balance status.

Conclusions

Anomalous *Pn* waves traveling along the collision suture between the Central Range and the Coastal Range of Luzon Arc are commonly observed in eastern Taiwan. The onset of the anomalous *Pn* waves can be identified at stations with an epicentral distance as small as 60 km along the collision suture, which is much shorter than for normal *Pn* waves observed elsewhere at epicentral distances greater than 120 km in Taiwan and other continental regions around the world. Thus, an unusually thin crust is expected beneath the collision suture compared to other parts of Taiwan. The apparent velocities of the anomalous *Pn* waves can be determined to be 7.8 ± 0.15 km/sec, which is similar to that observed elsewhere in the Taiwan region but at much deeper depth and are very close to the regional average (Yeh and Tsai, 1981).

Assuming 1D velocity structure with crustal velocity $V_c = 6.3$ km/sec, the Moho depth beneath the collision suture can be estimated to be $\sim 23 \pm 2$ km, which is about 10 to 30 km shallower than that beneath the high mountains of the Central Range immediately to the west. Therefore, the oceanic upper mantle beneath the collision suture is significantly elevated and is in close contact with the eastern part

of mid-to-lower continental crust beneath the Central Range. Across the transition boundary or the contact zone, the elevated oceanic upper mantle will provide additional heat sources via heat-conduction input to the adjacent mid-to-lower continental crust beneath the Central Range. As a consequence of heat conduction over a long period of geological time, the mid-to-lower crust beneath the eastern Central Range will be subjected to different degrees of thermal deformation; the closer the region to the contact zone, the higher the degree of thermal effect expected. This is consistent with the observed surface geology. Thus, high-heat flow or high-thermal activity may contribute to a significant regional volumetric expansion and a reduction of material density in the mid-to-lower continental crust that the Central Range deformed and uplifted (Kim *et al.*, 2005) as a consequence of buoyancy force developed over time.

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