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Tectonic erosion and the removal of forearc lithosphere during arc-continent collision: Evidence from recent earthquake sequences and tomography results in eastern Taiwan

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ABSTRACT

A very common but important observation of collided and accreted volcanic arcs is that the forearc regions of these arcs are largely or even entirely missing. The processes and mechanisms responsible for the removal and transport of the forearc materials from the collisional belts are thus important issues in understanding tectonics and crustal growth. The young and ongoing collision between the Luzon volcanic arc and the Eurasian continental margin that forms the island of Taiwan provides a rare opportunity to examine these processes and mechanisms as they occur. From observations of a new detailed 3-D tomography combined with relocated hypocenters of two earthquake sequences occurred in 2003 and 2006, we found that the Luzon forearc lithosphere initially underthrusts westward after the collision began. As the collision proceeds, the forearc basement then subducts eastward beneath the colliding and accreting Luzon arc along a major fault system in eastern Taiwan. Thus the Luzon forearc lithosphere appears to be removed by tectonic erosion and is being transported eastward into the mantle. Our results from the active Taiwan orogen will provide important insights for interpreting rock records from many old arc-continent collisional belts in the world.

1. Introduction

When analyzing previously collided and accreted volcanic arc blocks in collisional belts worldwide, a common observation is that the forearc regions of those arcs are entirely or largely missing (e.g., Howell, 1989; Cloos et al., 2005). For example, the collided and accreted Jurassic Talkeetna–Bonanza arc in southern Alaska is missing almost all of its forearc materials (e.g., Clift et al., 2005). Since the forearc regions are usually more than 100 km wide (for example, the Sumatran forearc is ~200–250 km wide, and the Luzon forearc south of Taiwan before collision is ~100 km wide), a significant amount of lithospheric materials has to be removed from the collisional belt. The mechanisms responsible for the removal of these materials are therefore important in understanding collision and crustal growth processes.

Several different mechanisms are able to facilitate the removal of the forearc materials (e.g., Chemenda et al., 1997, 2001; Tang and Chemenda, 2000). Strike-slip movement between the continent and the colliding arc, for example, can also remove laterally these materials out of the collisional belt (e.g., Beck, 1983, 1986). However, laterally transported forearc materials will still be present somewhere near the later-developed suture. If the forearc is nowhere to be seen, it is likely that the forearc basement rocks have been transported down into the mantle by subduction processes. This mechanism is commonly referred to as tectonic erosion or subduction erosion (e.g., von Huene and Lallemand, 1990; von Huene and Scholl, 1991; Oncken, 1998; Clift and Vannucchi, 2004).

The island of Taiwan is the product of the ongoing convergence between the Eurasian and Philippine Sea plates and the collision between the Luzon volcanic arc and blocks of the Eurasian continental margin (e.g., Ho, 1986; Teng, 1987, 1990; Shyu et al., 2005a; and references therein; Fig. 1). In eastern Taiwan, the N–S elongated Longitudinal Valley marks the boundary between the metamorphic rocks of Taiwan's Central Range and the collided Luzon arc, and represents the suture between the continental basement and the accreted arc. Hence, at least the entire forearc basin of the Luzon arc, which is more than 50 km wide south of Taiwan at about 21°N (Fig. 1), is removed as the collision proceeds.

As a very young and developing arc-continent collision belt, the Taiwan orogen provides a rare opportunity to observe how the forearc materials are consumed in the collisional processes as it happens. In this paper, we combined a detailed tomography result

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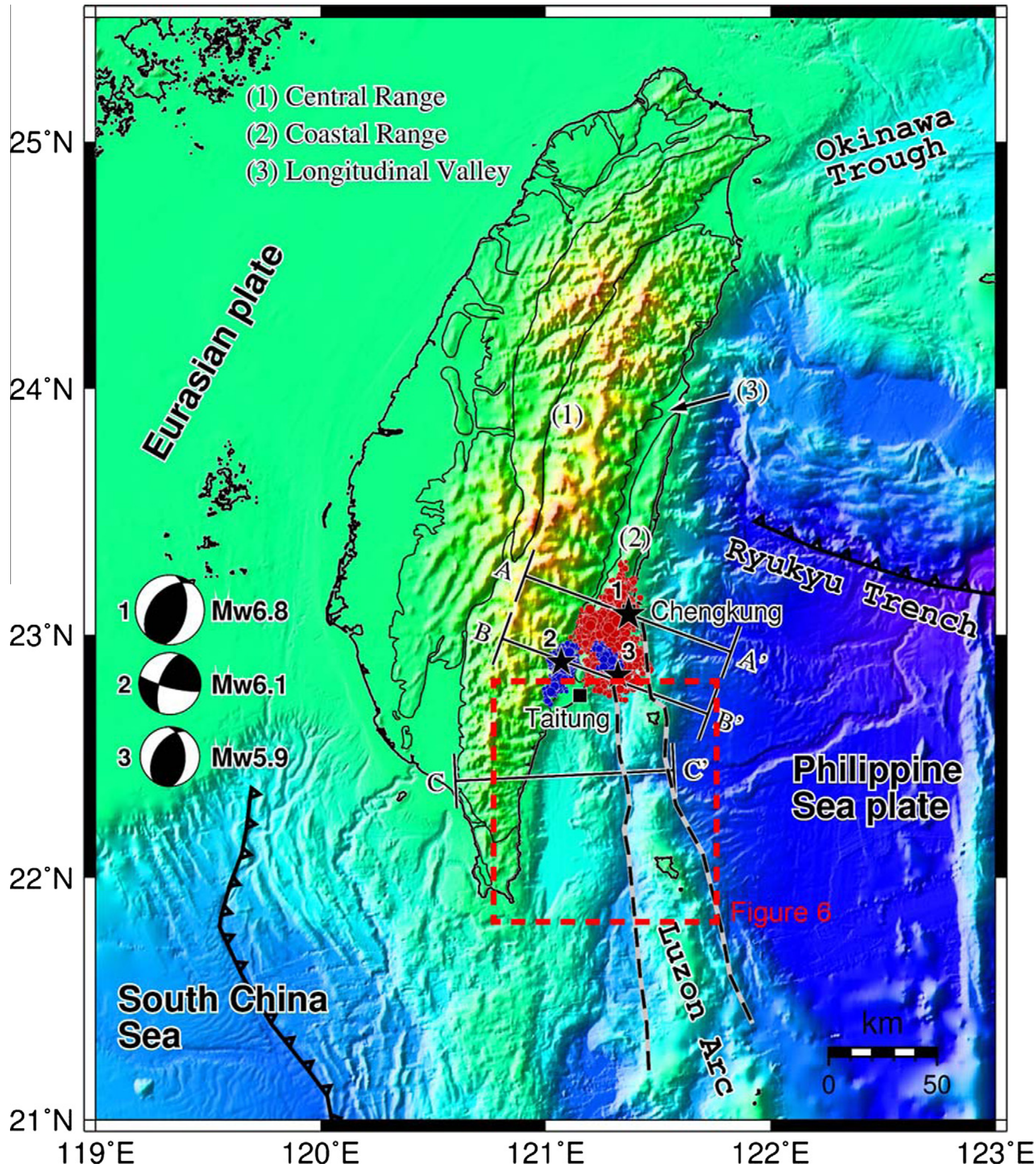

Fig. 1. Topography and major tectonic components of Taiwan and surrounding area. The Longitudinal Valley, between the Central and Coastal Ranges of Taiwan, is one of the most active plate sutures in the world. This suture is characterized by numerous active structures and earthquakes, including the 2003 Mw6.8 Chengkung earthquake (#1) and the 2006 Mw6.1 Taitung earthquake (#2). Red and blue circles indicate the relocated epicenters of the aftershock sequence of the Chengkung earthquake and the Taitung earthquake, respectively. Focal mechanisms of the Chengkung mainshock (Wu et al., 2006a; Kuochen et al., 2007), Taitung mainshock (Wu et al., 2006b), and a large aftershock of the Taitung earthquake (#3; Wu et al., 2006b) are also shown. Red dashed box indicates the area of Fig. 6.

of eastern Taiwan with relocated hypocenters of two recent earthquake sequences occurred in 2003 and 2006 to investigate the removal mechanism of the Luzon forearc basement as the arc collides with the Taiwan metamorphic basement. Our observations show that part of the forearc lithosphere may underthrust westward initially, and then it is clearly subducting beneath the collided Luzon arc as the Longitudinal Valley suture develops. Thus the development of the suture appears to be a clear example of tectonic erosion, and the Luzon forearc basement rocks are being removed and transported eastward into the mantle.

2. Tectonic background and the two recent earthquakes in eastern Taiwan

The convergence between the Eurasian and Philippine Sea plates that produces the Taiwan mountain belt is currently at a rate up to 80 mm/yr, according to GPS results (e.g., Yu et al., 1997). About half of this convergence is being absorbed in eastern Taiwan, on active structures along the Longitudinal Valley (Hsu et al., 2003). Therefore, the valley is one of the most tectonically active regions in the world, and is characterized by many active structures and earthquakes (e.g., Hsu, 1962; Bonilla, 1975, 1977; Shyu et al., 2005b, 2008).

Most of the earthquakes occurring along the Longitudinal Valley are associated with the two major structures bounding the two edges of the valley: the east-dipping Longitudinal Valley fault and the west-dipping Central Range fault (e.g., Kuochen et al., 2004, 2007; Shyu et al., 2006a,b, 2007; Wu et al., 2006a,b; Chung et al., 2008). Due to the fact that both of the faults are major structures of the suture, moderate to large earthquakes occurring on one fault may induce seismic activities on the other fault.

On 10 December 2003, the Chengkung earthquake (Mw6.8) occurred along the eastern coast of Taiwan near the town of Chengkung (Fig. 1). Based upon the results of earthquake relocation, focal mechanism determination, and coseismic deformation studies (Wu et al., 2006a; Kuochen et al., 2007), this event is believed to have occurred on the east-dipping Longitudinal Valley fault. The profile A–A′ in Fig. 2 shows the relocated hypocentral distribution of the Chengkung earthquake sequence. In the profile, there is an aftershock cluster of this earthquake sequence that is distinct from the east-dipping Longitudinal Valley fault and closer to the Central Range. West-dipping rupture planes are observed in this cluster (Kuochen et al., 2007). Thus this cluster may be associated with the Central Range fault. This result is in fact the first report that an earthquake occurred on one major structure of the Longitudinal Valley suture may have induced seismic activities on the other major structure of the suture.

About 2 years later, a Mw6.1 earthquake occurred on 1 April 2006 near Taitung (Fig. 1). This earthquake also produced significant coseismic ground displacements and a large number of aftershocks. Based on the dislocation model, mainshock focal mechanism and distribution of relocated aftershocks, the main shock was found to be located on the steeply west-dipping Central Range fault, with left-lateral strike-slip motion and minor thrust component (Wu et al., 2006b). The profile B–B′ in Fig. 2 shows the distribution of the relocated hypocenters of the Taitung earthquake sequence. Similar to the Chengkung earthquake, the aftershocks of the Taitung earthquake can also be grouped into two clusters. One of the clusters was onland and surrounding the main shock, and was correlated to the steeply west-dipping Central Range fault. The other cluster in the offshore region was located on a plane that is similar to the Cheng-kung earthquake rupture plane, and therefore is likely to be located on the Longitudinal Valley fault. The two clusters of the Taitung earthquake sequence are also temporally separate: The onland cluster underneath the western Longitudinal Valley occurred right after the main shock, but the offshore cluster occurred about 15 days later, with a large aftershock of Mw5.9 (#3 earthquake in Fig. 1).

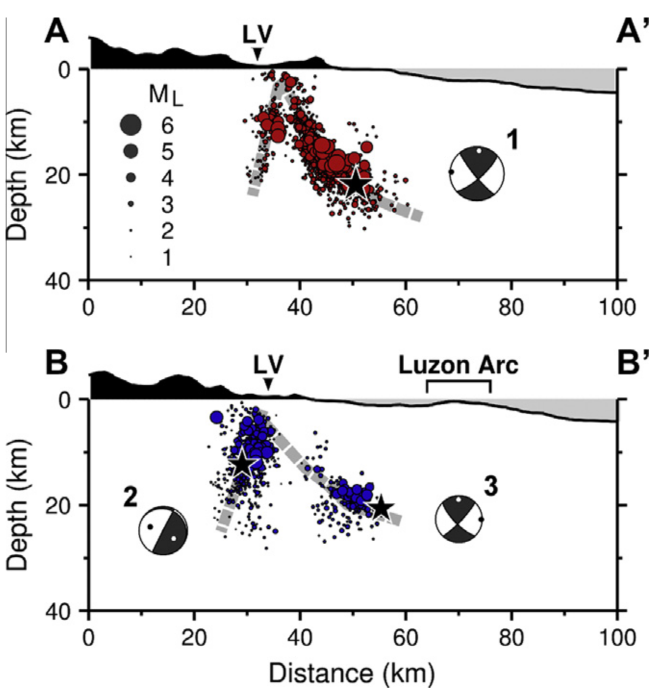

Fig. 2. East–west vertical profiles of the Chengkung earthquake sequence (A–A′) and the Taitung earthquake sequence (B–B′). All events above magnitude 2 of the two sequences (all red and blue circles in Fig. 1) were plotted. Focal mechanisms are plotted in lateral back-sided projection. Locations of the profiles are shown in Fig. 1. LV: Longitudinal Valley. No vertical exaggeration.

3. Tomography results in southeastern Taiwan

Recently, Wu et al. (2007) obtained a regional 3-D P-wave and Vp/Vs structure of Taiwan by combining a large dataset of S–P times from the Taiwan Strong Motion Instrumentation Program (TSMIP) records with the P- and S-wave arrival times from the Central Weather Bureau Seismic Network (CWBSN) stations. The TSMIP dataset, which includes more than 600 stations throughout the island, improves the source-station path coverage tremendously and provides much better constraints and resolution in the velocity structure determination. The new 3-D velocity model (Wu et al., 2007) motivated us to investigate the seismogenic structures of Taiwan in more detail than before. It also provided us constraints to conduct 3-D relocations of earthquakes in Taiwan. As a result, regional earthquakes in Taiwan from 1991 to 2007 were relocated using the 3-D velocity model (Wu et al., 2008a) and the focal mechanisms for most of $M_L > 4$ events were determined by genetic algorithm (Wu et al., 2008b). Together with the characteristics of the Chengkung and Taitung earthquake sequences, these datasets provide us an unprecedented opportunity to investigate the detailed collisional processes between the Luzon arc and the continental basement in eastern Taiwan.

Figs. 3–5 shows our new tomography models of Vp and Vp perturbation structures, Vp/Vs ratios, and our proposed interpretations along three east–west vertical profiles, together with relocated hypocenters of background seismicity and the Chengkung and Taitung earthquake sequences. Along the southernmost profile (C–C′), a distinct high Vp layer, up to 30 km thick, is visible in the eastern half of the section (Fig. 3). P-wave velocity of this layer indicates that it represents the Philippine Sea lithosphere (PSL) and the Luzon forearc lithosphere (FL) west of the arc. The FL appears to bend down to the west underneath the low Vp materials beneath southern Taiwan. Slightly above the west-dipping boundary between the high Vp forearc lithosphere and the low Vp materials, seismicity also appears to form a west-dipping belt (S).

Along profile B–B′, which is located near the southern end of the Longitudinal Valley, the geometry of the Luzon forearc lithosphere appears to be very different from that along profile C–C′ (Fig. 4). Between the Longitudinal Valley and the approaching Luzon arc, an east-dipping low Vp zone between two higher Vp blocks developed

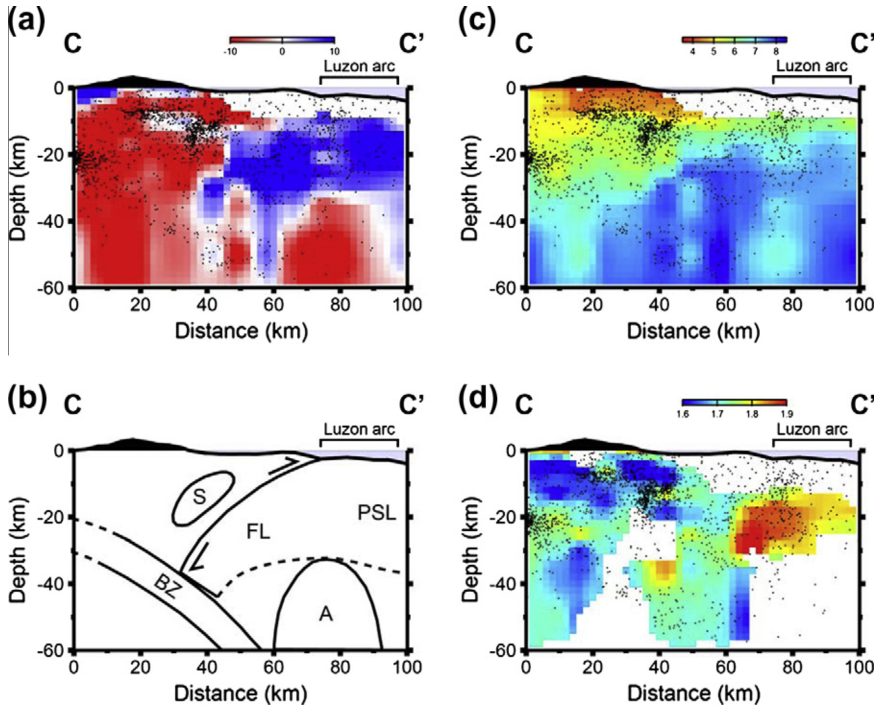

Fig. 3. A vertical E–W profile of Vp, Vp/Vs ratio, and our interpretations across southeastern Taiwan along line C–C′ in Fig. 1. (a) The Vp perturbation profile with relocated hypocenters of background seismicity. (b) Our interpretations based upon Vp perturbation structures. (c) P-wave velocity profile with relocated hypocenters of background seismicity. (d) Vp/Vs ratio profile with relocated hypocenters of background seismicity. See text for discussion. Relocated hypocenters distribution of the background seismicity, with many deeper earthquakes outside of the plot area, is from 1991 to 2007, with magnitude greater than 2. Width of the profiles is shown as the shorter lines on both sides of the cross-section line in Fig. 1, which is 20 km. FL: Luzon forearc lithosphere; PSL: Philippine Sea lithosphere; BZ: the Wadati-Benioff zone of the subducting Eurasian plate; S: the seismicity cluster that may correspond with the initial stage of the Central Range fault; A: low Vp body that may represents the shallow asthenosphere of the Philippine Sea plate or the upwelling magma beneath the Luzon arc.

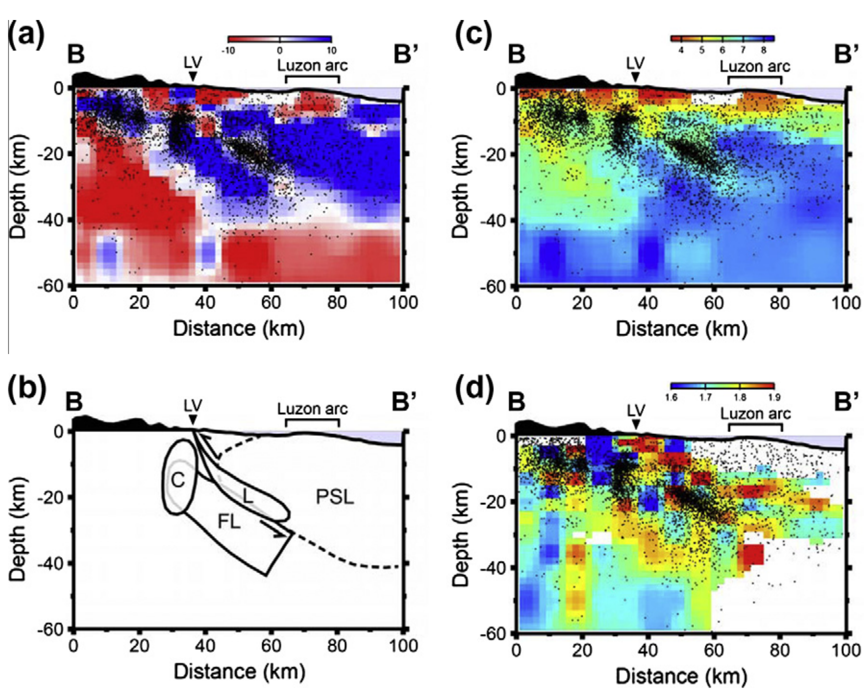

Fig. 4. A vertical E–W profile of Vp, Vp/Vs ratio, and our interpretations across southeastern Taiwan along line B–B′ in Fig. 1. (a) The Vp perturbation profile with relocated hypocenters of background seismicity and the Taitung earthquake sequence. (b) Our interpretations based upon Vp perturbation structures. (c) P-wave velocity profile with relocated hypocenters of background seismicity and the Taitung earthquake sequence. (d) Vp/Vs ratio profile with relocated hypocenters of background seismicity and the Taitung earthquake sequence. See text for discussion. Relocated hypocenters distribution of the background seismicity, with many deeper earthquakes outside of the plot area, is from 1991 to 2007, with magnitude greater than 2. Width of the profiles is shown as the shorter lines on both sides of the cross-section line in Fig. 1, which is 20 km. FL: Luzon forearc lithosphere; PSL: Philippine Sea lithosphere; L: the seismicity cluster that corresponds with the Longitudinal Valley fault; C: the seismicity cluster that corresponds with the Central Range fault.

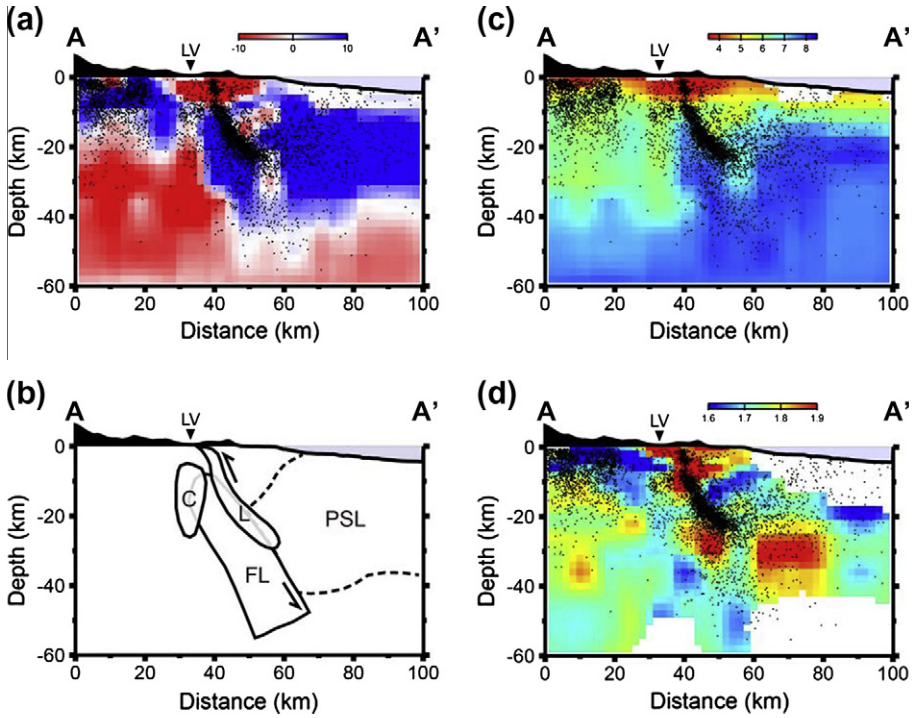

Fig. 5. A vertical E–W profile of Vp, Vp/Vs ratio, and our interpretations across southeastern Taiwan along line A–A′ in Fig. 1. (a) The Vp perturbation profile with relocated hypocenters of background seismicity and the Chengkung earthquake sequence. (b) Our interpretations based upon Vp perturbation structures. (c) P-wave velocity profile with relocated hypocenters of background seismicity and the Chengkung earthquake sequence. (d) Vp/V_s ratio profile with relocated hypocenters of background seismicity and the Chengkung earthquake sequence. See text for discussion. Relocated hypocenters distribution of the background seismicity, with many deeper earthquakes outside of the plot area, is from 1991 to 2007, with magnitude greater than 2. Width of the profiles is shown as the shorter lines on both sides of the cross-section line in Fig. 1, which is 20 km. FL: Luzon forearc lithosphere; PSL: Philippine Sea lithosphere; L: the seismicity cluster that corresponds with the Longitudinal Valley fault; C: the seismicity cluster that corresponds with the Central Range fault.

at a depth of about 20 km. P-wave velocity of the two high Vp blocks suggests that they are the Luzon forearc lithosphere (FL) in the west and the Philippine Sea lithosphere (PSL) in the east. The low Vp zone is coincident with a large amount of seismicity (L), including the offshore east-dipping aftershock cluster of the 2006 Taitung earthquake. The other aftershock cluster of the Taitung earthquake (C), which is steeply west-dipping, appears to be coincident with the western boundary of the FL.

Farther north along profile A–A′, the eastward underthrusting of the forearc lithosphere becomes more prominent (Fig. 5). The listric Longitudinal Valley fault, which is clearly illuminated by the aftershock cluster of the 2003 Chengkung earthquake as well as a large number of background seismicity, appears to follow the interface along which the forearc lithosphere subducts. The western boundary of the underthrusting forearc lithosphere is coincident with fewer earthquakes than those along profile B–B′.

4. The development of the Longitudinal Valley suture and the removal of Luzon forearc basement

One of the major advantages of studying the ongoing Taiwan collisional orogen is that we are able to observe the orogen in its different developing stages. From the geometry of the Taiwan orogen, Suppe (1981, 1984) calculated that the leading edge of the construction of the orogen is proceeding southward at about 90 mm/yr. Thus, latitude is grossly correlative to the development of collision in Taiwan. That is, if one wishes to understand what was happening at some point 1 Myr ago, one may get a good analogy from what is going on now 90 km to the south. Hence, the profiles shown in Figs. 3–5 not only represent current observations, but may also illustrate the development processes of the collision in eastern Taiwan.

Therefore, the downward bending of the western Luzon forearc lithosphere we observed along profile C–C′ in Fig. 3 suggests that the forearc lithosphere (FL) initially underthrusts westward after the collision began. The west-dipping seismic belt (S) may represent the initiation of the east-vergent Central Range fault zone in southernmost Taiwan. This is consistent with the observation in the basement rocks in southeastern Taiwan, in which a widespread series of east-vergent "backfolding" and "backthrust" is recorded (e.g., Stanley et al., 1981; Lu et al., 2001; Chang et al., 2009). Although the resolution of the Vp/Vs ratio data is not as good as the Vp data, the seismic belt appears to coincident with a slightly higher Vp/Vs zone (Fig. 3d). The surficial manifestation of this west-dipping structure is likely the major west-dipping thrust fault observed in the submarine topography at the western edge of the Luzon arc, east of the submarine Taitung Trough (e.g., Malavieille et al., 2002; Shyu et al., 2005b; Fig. 6). Along profile C–C′, the fault crops out at the slope break in the topography at distance 75 km (Fig. 3b). Marine sediments west of the arc appear to thrust eastward over the arc along this fault.

Along profile B–B′, however, the forearc lithosphere (FL) is clearly underthrusting eastward instead, and forms an east-dipping "extracting block" (Froitzheim et al., 2003, 2006; Fig. 4). The boundary between the FL and the Philippine Sea lithosphere (PSL) generally follows the east-dipping aftershock cluster of the 2006 Taitung earthquake (L in Fig. 4b), and shows high Vp/Vs ratio (Fig. 4d). Since the surface projection of the cluster is coincident with where the Longitudinal Valley fault crops out, we suggest that this zone represents the deeper part of the fault in its southernmost part. The other aftershock cluster of the 2006 earthquake (C in Fig. 4b), which we interpret to be along the Central Range fault,

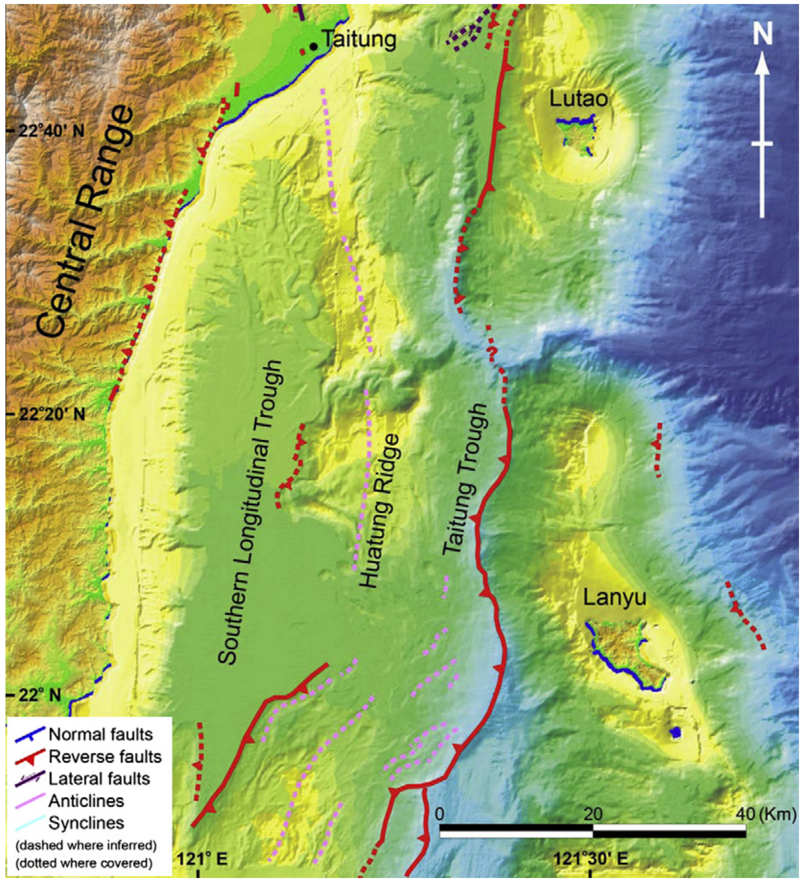

Fig. 6. Active structure map of the Lutao-Lanyu neotectonic domain, including southeastern Taiwan and the offshore area south of Taitung. One of the major structures in this area is a west-dipping thrust fault between the submarine Taitung Trough and the Luzon arc (Lutao and Lanyu). Modified from Shyu et al. (2005b).

appears to be coincident with the western boundary of the western high Vp layer. Thus we propose that this structure represents the western boundary of the Luzon forearc lithosphere. This geometry suggests that at the southernmost part of the Longitudinal Valley, the forearc lithosphere broke apart from the Philippine Sea plate, and began to be overridden by the colliding arc, creating the Longitudinal Valley fault system.

Although the Luzon forearc lithosphere appears to first underthrust westward as shown in profile C–C′, it would soon hit the subducting Eurasian plate, which is represented by the east-dipping Wadati–Benioff zone (BZ) in Fig. 3 (Wu et al., 2009a). We suggest that this is the reason that the forearc lithosphere changed its underthrusting polarity. Along profile C–C′, we can see that the P-wave velocity is slightly lower beneath the western edge of the Luzon arc (at distance between 70 and 80 km). Deeper, there is a large low Vp body (A in Fig. 3b). This body may represent the shallow asthenosphere of the Philippine Sea plate or, alternatively, the upwelling magma beneath the Luzon arc, since the Vp/Vs ratio directly above it is very high. This is similar to a recent observation in western Ryukyu subduction zone (Wu et al., 2009b). Therefore, breaking-off of the forearc lithosphere likely occurs at the boundary between the hotter and weaker magmatic arc and the colder and stronger oceanic forearc.

Along the northernmost profile A–A′, the Luzon forearc lithosphere (FL) is clearly underthrusting beneath the accreted arc along the listric Longitudinal Valley fault (L; Fig. 5). The Central Range fault system (C) shows much fewer earthquakes than in the south. This is consistent with the current observation that the Longitudinal Valley fault has a much higher slip rate than that of the Central Range fault (Shyu et al., 2006a,b). This suggests that, at this latitude, whereas the west-dipping Central Range fault is still seismically active, the Longitudinal Valley fault system has replaced it to become the major structure between the accreted Luzon arc and the mainland of Taiwan.

5. Discussion and conclusions

Throughout Earth's geologic history, the collision and accretion of volcanic arcs onto continental margins is one of the most common phenomena in the geologic record (e.g., Saleeby, 1983). In many of those accreted arcs, the forearc regions are largely or even completely missing (e.g., Clift et al., 2005; Cloos et al., 2005). However, once the forearc has been removed, it is difficult to investigate the processes and mechanisms that are responsible for the transportation of the forearc materials from rock records of old orogens. The young and ongoing collision between the Luzon volcanic arc and the Eurasian continental margin that forms the island of Taiwan thus provides a rare opportunity to examine these processes and mechanisms as they occur.

On the basis of physical and numerical modeling (e.g., Chemenda et al., 1997, 2001), it has been suggested that the Luzon forearc materials are continuously subducting along an east-dipping thrust fault once the collision began (e.g., Malavieille et al., 2002; Malavieille and Trullenque, 2009). A similar geometry has been proposed recently based upon another tomographic analysis (Cheng, 2009). However, the 2006 Taitung earthquake series illustrated the significance of the east-vergent Central Range fault system in the tectonic evolution of Taiwan, which would be difficult to incorporate into a single eastward underthrusting geometry. Nor does this geometry sufficiently explain the observation of the widespread east-vergent backfolding and backthrust records observed in the basement rocks of Taiwan's eastern Central Range (e.g., Stanley et al., 1981; Lu et al., 2001; Chang et al., 2009). Moreover, no major east-dipping structure has been observed offshore southeastern Taiwan. Instead, a major west-dipping fault is clearly present west of the closing forearc basin southeast of Taiwan (Malavieille et al., 2002; Shyu et al., 2005b; Fig. 6). Thus the history of the removal of Luzon forearc materials may be more complicated than a continuous eastward subduction.

The observations based upon our new tomography results and the 2003 and 2006 earthquake sequences thus provide a slightly different alternative model. Although it is clear that the final removal of the Luzon forearc materials is through eastward subduction, possibly related to the Longitudinal Valley fault system, westward underthrusting may play important roles during the early stages of the collision. Along profile C–C′, it is clear that the east-dipping Longitudinal Valley fault system has not developed yet, and the forearc lithosphere, or at least the western tip of it, appears to underthrust westward beneath southern Taiwan (Fig. 3). This lithospheric relationship indicates that basement rocks in the Central Range of Taiwan would be overthrusting eastward. This would produce the east-vergent backfolding and backthrust observed in eastern Central Range, and may also be responsible for the recorded rapid (up to $\sim$6 mm/yr) exhumation of eastern Central Range rocks (e.g., Jahn et al., 1986; Liu et al., 2001; Willett et al., 2003). Thus the westward underthrusting is likely an important process during the collision (Yamato et al., 2009).

Between profile C–C′ and B–B′, the Longitudinal Valley fault system begins to appear, and the forearc lithosphere begins to subduct eastward instead. Judging from the intensity of the seismicity, the east-dipping structure is equally important as the steeply west-dipping structure that forms the western boundary of the forearc lithosphere at the latitude of profile B–B′ (Fig. 4). Slightly farther north along profile A–A′, however, the east-dipping Longitudinal Valley fault system clearly has become more seismically active (Fig. 5). According to tomography results and seismicity in northern Longitudinal Valley (Kim et al., 2005) and crustal strain rate analysis (Mouthereau et al., 2009; Yamato et al., 2009), the Central Range fault system may be still active along the entire Longitudinal Valley. However, geomorphic and structural observations indicate that its slip rate has become much slower than that of the Longitudinal Valley fault in the latest Quaternary (Shyu et al., 2006a,b). As a result, more recent uplift and exhumation of the northern Central Range rocks (e.g., Dadson et al., 2003; Willett et al., 2003) may be the product of some pervasive crustal thickening at depth, rather than brittle deformation of the west-dipping Central Range fault system (Shyu et al., 2006b).

In conclusion, our results, on the basis of the new tomography results and two recent earthquake sequences, provide a detailed subsurface observation for the removal processes of the Luzon forearc as the arc collides with the metamorphic basement of Taiwan. The forearc lithosphere appears to be removed by the process of tectonic erosion and is being transported eastward into the mantle. One major complexity of this process in Taiwan is that during the early stage of the collision, the forearc lithosphere may initially underthrust westward beneath southern Taiwan, and produced the rapid exhumation of the basement rocks in Taiwan's eastern Central Range. Our observations will provide important insights for interpreting the collision and accreting processes of many arc-continent collisional belts in the world.

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