A lithospheric profile across northern Taiwan: from arc-continent collision to extension

Harm J.A. Van Avendonk,1 Kirk D. McIntosh,1 Hao Kuo-Chen,2 Luc L. Lavier,1 David A. Okaya,3 Francis T. Wu,3,4 Chien-Ying Wang,2 Chao-Shing Lee5 and Char-Shine Liu 6

1Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, USA. E-mail: harm@ig.utexas.edu
2Institute of Geophysics, National Central University, Jhongli, Taiwan
3Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA
4Department of Geological and Environmental Sciences, State University of New York at Binghamton, Binghamton, NY, USA
5Department of Geophysics, National Taiwan Ocean University, Keelung, Taiwan
6Institute of Oceanography, National Taiwan University, Taipei, Taiwan

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SUMMARY

During arc-continent collision, buoyant sections of sediments and rifted continental crust from a subducting plate will accrete to the forearc of the upper plate as long as this backstop remains intact. Deformation of the oceanic arc and forearc block may ultimately lead to accretion of these mafic rock units to the new orogen. The Taiwan mountain belt, which formed at ∼6.5 Ma by oblique convergence between the Eurasian passive margin and the overriding Luzon arc in northern Taiwan, offers important insight in this process, since the collision is more advanced in the north than in the south. The incipient stage of arc-collision can be studied in southern Taiwan, while the northern portion of the orogen is presently undergoing collapse due to a flip in the subduction polarity between the Eurasian Plate and the Philippine Sea Plate. In this study, we seismically image the structure of the northern section of the mountain belt with a tomographic inversion. We present marine and land-based seismic refraction data, as well as local earthquake data, from transect T6 of the Taiwan Integrated Geodynamic Research (TAIGER) program across the Taiwan mountain belt and the adjacent Ryukyu arc. Our 2-D compressional seismic velocity model for this transect, which is based on a tomographic inversion of 10 213 P-wave arrival times, shows that the Eurasian crystalline continental crust thickens from ∼24 km in the Taiwan Strait to ∼40 km beneath the eastern Central Range of Taiwan. The detailed seismic velocity structure of the Taiwan mountain belt shows vertical continuity in the upper 15 km, which suggests that rocks are exhumed to the surface here from the middle crust in a near-vertical path. The continental crust of the westernmost Ryukyu arc is almost as thick (∼40 km) as in the adjacent northern Central Range of Taiwan, and it appears to override the leading edge of the Philippine Sea Plate offshore northeastern Taiwan. If we assume that the western Ryukyu arc crust also thickened in the collision, then the mountain belt is wider and less thick in northern Taiwan than in central Taiwan (∼50 km), which may be the result of post-collisional extension in the north.

Key words: Seismic tomography; Continental margins: convergent; Crustal structure.

1 INTRODUCTION

Where passive continental margin crust enters a trench and collides with the overriding forearc and island arc, lateral compression will lead to intense shortening and uplift in the incoming plate until the forearc can no longer form a backstop to the growing crustal wedge (Brown et al. 2011). Mechanical failure of the arc/forearc block can lead to a reversal of the polarity of subduction (Draut & Clift 2013), the release of compressive stresses, and collapse of the young orogen (Dewey 1988; Rey et al. 2001). Modern examples of arc-continent collision can be found in the Banda Sea (Bowin et al. 1980; Audley-Charles 2004), in Taiwan (Teng 1990; Byrne et al. 2011), between Venezuela and the southern Caribbean arc (Avé Lallemant 1997; Kroehler et al. 2011), between northern Papua New Guinea and the New Britain arc (Cooper & Taylor 1987; Abers & Roecker 1991), and in Kamchatka (Geist & Scholl 1994;
Konstantinovskaya 2011). One of the major challenges in studies of arc-continent collision is to understand the temporal evolution of these complex plate boundaries.

Continental collision and post-orogenic extension are currently both in progress in different parts of the Taiwan mountain belt (Teng 1996). In central Taiwan, convergence between the Eurasian and Philippine Sea plates (Yu & Kuo 2001) is deforming the continental crust of the Chinese margin into a thick wedge that is compressed against the northern Luzon arc (Brown et al. 2012; Fig. 1). Here the Central Range and Hsuehshan Range are experiencing rapid uplift and exhumation (Fuller et al. 2006; Simoes et al. 2007), but the north end of the Taiwan mountain belt is currently extending and subsiding (Ching et al. 2011b). The extension and collapse of the orogen are caused by the southwestward propagation of the Okinawa trough into northeastern Taiwan (Suppe 1984; Sibuet et al. 1998; Clift et al. 2008; Huang et al. 2012). Receiver function analyses (Kim et al. 2004) and regional seismic velocity models (Kuo-Chen et al. 2012a) show that the crust of Central Taiwan is much thicker (50 km) than to the north (33 km), but more detailed seismic images are needed to characterize how the mountain belt is thinning at the intersection with the Ryukyu subduction system.

In 2008 and 2009, U.S. and Taiwanese scientists acquired several long-offset 2-D seismic transects across the convergent margin between the Eurasian and Philippine Sea plates in the Taiwan Integrated Geodynamic Research (TAIGER) project (Klingelhoefer et al. 2012; Lester et al. 2013; McIntosh et al. 2013; Eakin et al. 2014; Van Avendonk et al. 2014). Due to the oblique angle between the plate boundary and the overriding Luzon arc (Suppe 1981), the TAIGER transects imaged a more mature stage of the arc-continent collision in the north than in the south. In this paper, we present a seismic velocity model based on an analysis of active-source and local earthquake data for TAIGER Transect 6 across northern Taiwan and the adjacent forearc of the Ryukyu subduction system. The dense data coverage along this northernmost TAIGER transect shows structural details in the mountain belt that provide new insight in the formation and subsequent extensional collapse of this well-studied mountain belt.

2 TECTONIC SETTING

The Taiwan orogen developed ~6.5 Ma in northern Taiwan (Lin et al. 2003) when convergence between the Philippine Sea Plate and Eurasian Plate closed up the northern South China Sea. According to McIntosh et al. (2013), the accretion of blocks of the Chinese rifted margin crust to the west-facing prism of the
Arc-continent collision in northern Taiwan

Luzon arc initiated the growth of the Central Range. Over the course of a few million years the collision propagated southward (Liu et al. 2001; Lee et al. 2006), and in central and northern Taiwan the material flux in the orogen subsequently reached a steady state (Willett & Brandon 2002; Simoes & Avouac 2006). In this mature portion of the arc-continent collision, five north-south trending tectonic domains can be recognized in the mountain belt (Ho 1986; Huang et al. 2006): (1) A foreland basin in the coastal plain in the west, (2) a fold-thrust belt in the Western Foothills, (3) an inverted Palaeogene sedimentary basin from the South China Sea passive margin in the Hsiëshshan Range, separated by the Lishan Fault from (4) the Central Range, where metamorphic continental basement is exposed and (5) fragments of Luzon arc basement and intra-arc basins in the Coastal Range in the east (Fig. 2). In central Taiwan, the orogen is accommodating 80 mm yr\(^{-1}\) of NW-SE convergence at present (Hsu et al. 2009; Huang et al. 2010).

Shallow sediments of the foreland basin along the west coast of Taiwan are accreted in the fold-thrust belt, whereas deeper foreland deposits underthrust the Western Foothills along a shallow detachment without significant deformation (Suppe 1981; Yue et al. 2005). However, there is an increasing volume of geological and geophysical evidence that these deeper strata and crystalline basement are engaged in mountain building as well (Mouthereau & Lacombe 2006; Bertrand et al. 2009; Brown et al. 2012; Kuo-Chen et al. 2012a; Van Avendonk et al. 2014). Cooling ages of exhumed rocks from the Eurasian passive margin indicate that deep sediment underplating has driven the Neogene uplift in the Taiwan mountain belt. The Hsüehshan Range and Central Range record strong uplift and exhumation in the last 1 Myr (Lee et al. 2006; Simoes et al. 2007), due to the increasing compression between thick continental crust of the Taiwan Strait and the Luzon arc. In northeastern Taiwan the Coastal Range disappears just north of the intersection with the Ryukyu trench, so the Luzon arc appears to subduct with

Figure 2. Maps of northern Taiwan and transect T6. (a) Topography and major tectonic features. IP, Ilan Plain; LF, Lishan Fault. Land explosive shots (red stars) and OBSs (white circles) illustrate data coverage on transect T6. Marine shot lines used for this study shown as red lines. (b) TAIGER (solid red) and TAICRUST (dashed black) lines offshore northern Taiwan, shown with T6 explosive shots and land seismometer, and local earthquakes (cyan stars) used in the tomography analysis. Data records from labelled earthquakes, explosive shots, land stations and OBS are shown in Figs 4–7.
the Philippine Sea Plate beneath the Ryukyu arc (Fig. 1). As a result of this subduction polarity flip in the convergence between the Eurasian Plate and Philippine Sea Plate, uplift of the Central Range is waning in northern Taiwan (Huang et al. 2012).

The east–west trending western portion of the Ryukyu subduction system consists from north to south of (1) the Okinawa Trough, (2) the nonvolcanic Ryukyu arc, (3) a forearc that includes the Hoping and Nanao basins, (4) an accretionary wedge and (5) incoming oceanic crust and sediments from the Philippine Sea Plate (Sibuet et al. 1998; Lallemand et al. 1999; Klingelhoefer et al. 2012). This segment of the Ryukyu arc is advancing southward over the Philippine Sea Plate with a velocity of 73 mm yr−1 relative to the stable Eurasian Plate (Nakamura 2004), while the Okinawa Trough backarc basin opens rapidly to the north, leading to extension in the Ilan Plain of northeastern Taiwan. Since the Manila trench and Ryukyu trench subduction systems meet at right angles in north-eastern Taiwan, the two deep slabs must interact at depth, which can explain the large amount of local seismicity and surface deformation in this area (Wu et al. 2009). The continental crust overriding this transpressive plate boundary is currently in extension (Hou et al. 2009).

3 TAIGER SEISMIC DATA

3.1 Experiments

The TAIGER experiment was a U.S.–Taiwanese collaborative project to image the Taiwan mountain belt and surrounding areas on a lithospheric scale. Besides the acquisition of long-period magnetotelluric data (Bertrand et al. 2009, 2012), a large effort was made to gather land-based and marine seismic data (McIntosh et al. 2013; Van Avendonk et al. 2014; Wu et al. 2014). In this paper, we present the data from TAIGER transect T6, which lies across northeastern Taiwan between the Taiwan Strait and the Ryukyu accretionary wedge.

In 2008 we conducted an on-land explosion seismic experiment in Taiwan to constrain the crustal structure of the mountain belt. Explosive shots were recorded on linear arrays of vertical component seismic stations that were spaced 200 m apart. In 2009 we used the R/V Marcus Langseth to image offshore areas around Taiwan.
Arc-continent collision in northern Taiwan

335

Figure 4. Wide-angle seismic data from OBS 11 and OBS 07 on transect T6, east of Taiwan. The solid red lines outline the traveltime picks of wide-angle phases used in this study. P1, crustal seismic refraction; P1P, reflection from the base of Eurasian crust; P2, deeper refraction.

The Langseth traversed the main TAIGER transects twice with its 6600 in³ source array to optimize the quality of seismic reflectivity and refraction data. Shots spaced 50 m apart were recorded for 15 s by the Langseth’s 6-km-long streamer for MCS imaging.

TAIGER transect T6 is oriented oblique to the Ryukyu trench east of Taiwan (Fig. 1). Consequently, the MCS line that was shot here by the R/V Marcus Langseth traverses the Hoping and Nanao forearc basins in the northwest, and its southeast end point lies on the Ryukyu accretionary prism 35 km north of the trench (Fig. 3). From several Taiwanese vessels we deployed four-component OBSs at 15 km spacing along these seismic lines to collect wide-angle data, using a shot interval of 150 m to minimize previous shot noise. For the duration of the marine seismic experiment, arrays of 2 Hz land seismometers recorded both the offshore air-gun shots and local earthquakes.

3.2 Seismic phases

Twelve ocean-bottom seismometers from National Taiwan Ocean University (NTOU) recorded seismic refractions from the Langseth air-gun shots east of Taiwan (Figs 1 and 2). To 40 km source–receiver offset we mostly observe waves turning in the Ryukyu forearc crust and prism (P1 in Fig. 4). However, at approximately 50 km or larger source–receiver offsets, a deep wide-angle seismic reflection (P1P in Fig. 4), appears in some of the OBS record sections. As we discuss in the next section, this P1P phase may be a wide-angle reflection from the base of the Eurasian crust. Over a limited range of larger source–receiver offsets (70–100 km) we identify a phase (P2) that must turn at a depth larger than that of the P1P reflection. Due to the shallow water and permitting restrictions we did not gather MCS or OBS seismic refraction data in the Taiwan Strait along line T6.

An array of 45 land-seismic stations from IRIS/PASSCAL (the Program for Array Seismic Studies of the Continental Lithosphere) recorded Langseth air-gun shots from line T6 in the Philippine Sea, and also from marine seismic line 7B, which was oriented parallel to the coast in the Taiwan Strait. In the record sections (Fig. 5) we can recognize the same phases P1, P1P, and P2 that were observed in the OBS data, but in the onshore-offshore data we can see the P1P phases to source-receiver offsets as large as 150 km. P2 phases with a high apparent velocity (>7 km s⁻¹) are observed in the onshore-offshore records at offsets more than 100 km. This suggests that the Eurasian crust is thicker on-land than offshore in the Taiwan Strait. The observation of P1P arrivals also makes the onshore-offshore data from line T6 significantly richer than those of TAIGER transect T5, where these phases were not identified. The wide-angle reflection P1P was also recognized in one of the four explosion seismic refraction shot gathers. Seismic stations on the west coast recorded this deep reflection from Shot 4 at the east coast (Fig. 6). All explosive shot records show a clear P1 seismic refraction, and Shot 4 also registered a mid-crustal wide-angle reflection that we did not use in our analysis.

The TAIGER onshore-offshore seismic stations, which were deployed over three months during the Langseth program around Taiwan, also recorded a large number of local earthquakes (Kuo-Chen et al. 2012a). These earthquakes can provide important constraints
Figure 5. Wide-angle seismic data from land stations N30 (a) and N47 (b) on transect T6, recording air-gun shots east of Taiwan. The solid black lines outline the traveltime picks of wide-angle phases used in this study. Blue boxes indicate details of the data shown in (c) and (d).

Figure 6. Wide-angle seismic refractions from explosive shot 4, near the east coast of Taiwan. The solid red lines outline the traveltime picks of wide-angle phases used in this study.

on the deep lithospheric structure along transect T6, if they occurred within 10–15 km of the vertical profile, and if their origin time and location can be determined accurately. For 52 local earthquakes with a magnitude $M_w \geq 1.5$, we determined compressional and shear wave arrivals on a few different transects of the TAIGER seismic array. As in the case of the tomographic analysis of TAIGER transect T5 (Van Avendonk et al. 2014), we relocated these local earthquakes with regional $P$-wave and $S$-wave velocity models (Kuo-Chen et al. 2012a,b). Many of these events occurred in the Central Range or Hoping basin, but some others were relocated in western Taiwan, or farther east in the Philippine Sea (Fig. 2b). In Fig. 7 we show records of compressional and shear wave arrivals of three such local earthquakes on stations on TAIGER transect T6.

4 SEISMIC DATA ANALYSIS

4.1 Seismic reflection data processing

We stacked and migrated the marine seismic reflection data profile T6, and suppressed seafloor multiples to bring out seismic reflections from the base of the Ryukyu forearc. We used the seismic processing scheme of Lester & McIntosh (2012), which includes bandpass filtering, iterative multiple modelling and subtraction, velocity analysis, normal moveout correction, stacking and Kirchhoff time migration. The resulting image shows relatively recent, flat-lying sediments on tilted older sediments in the Hoping basin (Fig. 3), indicating that the basement 20–30 km east of Taiwan was also deformed in the recent arc-continent collision. The Nanao basin
does not exhibit the same rotation of accumulated sediment. Farther east, the basement of the Ryukyu forearc is uplifted and faulted where the Gagua Ridge subducts beneath the Eurasian Plate. The top of the Philippine Sea Plate can be distinguished in two locations in the seismic reflection image at 10 s two-way traveltime (Fig. 3).

4.2 Traveltime tomography

4.2.1 Ray tracing and inversion

The combined onshore–offshore seismic refraction data set for TAIGER transect T6 provides dense coverage of sources and receivers across the western and eastern shoreline of northern Taiwan, which we use to obtain a 2-D crustal seismic velocity model. For each of the data types, we bandpass filtered the record sections before picking the arrival times. We gathered a total of 10,213 traveltime picks for the $P_1$, $P_{1P}$ and $P_2$ arrivals in the T6 data set (Table 1). Uncertainties between 50 and 250 ms were assigned to these picks.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_{1P}$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBS</td>
<td>3718</td>
<td>50</td>
<td>422</td>
<td>4190</td>
</tr>
<tr>
<td>Sea-land</td>
<td>2628</td>
<td>44</td>
<td>907</td>
<td>3579</td>
</tr>
<tr>
<td>Explosion</td>
<td>1258</td>
<td>0</td>
<td>47</td>
<td>1305</td>
</tr>
<tr>
<td>Earthquake</td>
<td>1139</td>
<td>(P1 and P2)</td>
<td>0</td>
<td>1139</td>
</tr>
</tbody>
</table>

Table 1. The number of picks for each data type used in the tomographic inversion of the TAIGER T6 study. In the earthquake records we did not distinguish between $P_1$ and $P_2$ phases.
traveltime picks based on the signal-to-noise ratio and quality of the observations.

To invert the T6 traveltime data set for seismic velocity structure we adopted the iterative tomography method of Van Avendonk et al. (2004), which was previously used to construct a seismic velocity model for TAIGER transect T5 in central Taiwan (Van Avendonk et al. 2014). We first defined a preliminary seismic velocity model for Taiwan and the Ryukyu arc based on prior work (McIntosh et al. 2005; Kuo-Chen et al. 2012a; Theunissen et al. 2012). Though the choice of the starting model can affect the convergence speed of the iterative inversion, the final seismic velocity image should not depend on the starting model if the regularization in each linear inversion step does not bias the solution to the starting model (Hole 1992; Toomey et al. 1994). The smoothness and flatness constraints employed in our method (Van Avendonk et al. 2004) act on the resulting velocity model, not on the model perturbation, to minimize the effect of the starting model.

We traced rays for the observed refractions (P1, P2) and wide-angle reflections (P1P) in this starting model for profile T6 with the shortest path method (Moser 1991) and ray bending (Moser et al. 1992; Van Avendonk et al. 2001). For the local earthquakes we used 3-D ray tracing to obtain the correct geometry and traveltimes. In addition, unlike in the active-source seismic data of transect T6, we were not able to distinguish between P1 and P2 phases in the earthquake records, so we ray traced these arrivals as first-arriving phases. We iterated between ray tracing and 2-D regularized inversions for seismic velocity structure and Moho depth (Van Avendonk et al. 2004) until the traveltime misfit was reduced to 145 ms, with a normalized χ² of 1.0. The misfit of the earthquake arrivals (280 ms) were relatively large, which is consistent with the larger uncertainty in these traveltime picks.

We examine the ray paths and data fit for different data types after the inversion of transect T6 traveltimes. The ray paths for the four on-land explosions across northern Taiwan mostly sample the upper 5 km, but the P1P phase in our record of Shot 4 is consistent with a reflection from a depth of more than 30 km beneath the Western Foothills (Fig. 8a). The crust of the Ryukyu forearc is reasonably well covered by ray paths from seismic refractions in the OBS data (Fig. 8b), but we obtain little insight in what lies beneath the Ryukyu crust, because relatively few P2 arrivals were observed in the marine seismic refraction data. The onshore-offshore data across the east coast of Taiwan show good coverage of the deep crust with P1P and P2 arrivals (Fig. 8c). The onshore recording of line 7B in the Taiwan Strait gave us similar constraints on the west side of Taiwan (Fig. 1), but this data set was smaller since only one of the Langseth air-gun shots here lies directly on transect T6. Last the local earthquake data greatly complement the ray coverage of the active-source data at larger depth, though the uncertainty and misfits for earthquake traveltimes are larger (Fig. 8d).

4.2.2 Model resolution

The seismic velocity profile of TAIGER transect T6 gives a view of the crust of the northern Taiwan Strait, the northern Taiwan Mountain belt, and the adjacent Ryukyu forearc and prism (Fig. 9). With the help of local earthquake recordings we were able to infer seismic velocity structure to a depth of 70 km in the mantle beneath Taiwan along transect T6. Earthquakes also helped to improve our seismic velocity image of the mountain belt. Although the methodology that we used here closely followed the analysis of TAIGER transect T5 to the south (Van Avendonk et al. 2014), we were able to include P1P reflections from the base of the Eurasian crust in the tomographic inversion, which allowed us to resolve this boundary. Since these wide-angle reflections were only sporadically observed in the T5 data set, Van Avendonk et al. (2014) produced a seismic velocity image for that profile that was based only on first-arriving phases.

We derive an estimate of model resolution from the generalized inverse that produced our final seismic velocity model (Van Avendonk et al. 2004). In Fig. 10 we show how the ray path geometry in our tomographic inversion can constrain model features of two different sizes. Resolution values greater than 0.5 can be considered adequately resolved (Van Avendonk et al. 2004). The resolution tests indicate that seismic structure with a lateral size of 16 km can be resolved in the upper crust, but not in the lower crust. Model features that span 32 km have sufficient resolution in the entire crust and even in parts of the underlying mantle. The Moho is well resolved in the eastern and western flank of the orogen. Straight beneath the Central Range and beneath much of the Ryukyu arc/forearc block (Fig. 1).

5 RESULTS

We here describe the 2-D seismic velocity model for transect T6 that we obtained from the tomographic inversion. The seismic line lies entirely on crust of the Eurasian Plate (Fig. 1), but near the east coast of Taiwan it crosses a major left-lateral shear zone. The shear zone, which is illuminated by frequent seismicity at 135 km in our model (Fig. 9) separates the Taiwan mountain belt from the Ryukyu arc/forearc block (Fig. 1).

5.1 Taiwan mountain belt

On transect T6 the seismic velocity structure of the pre-collision crust in the Taiwan Strait is illuminated only by the onshore recording of air-gun shots from line 7B (Fig. 1). Though the resolution of seismic structure at the far northwest end of our profile is not good (Fig. 10), we think that a thickness of 28 km for the undeformed Chinese margin crust and sediments, with seismic velocity increasing from 4.0 km s⁻¹ at the seafloor to 7.0 km s⁻¹ at the Moho, is a plausible result (Fig. 9). If the 5.0 km s⁻¹ velocity contour lies approximately at the depth of pre-Miocene basement (Camanni et al. 2014; Van Avendonk et al. 2014) then the sediment cover on the incoming Eurasian basement at the west end of our profile may be 4–5 km (Fig. 9), which is consistent with existing marine seismic reflection data (Lacombe et al. 2003). Towards the west coast of Taiwan the basement depth increases to roughly 10 km. The asymmetric shape of this basement low, with a steeper eastern slope beneath the Western Foothills, is typical for the foredeep of the Taiwan mountain belt (Chou & Yu 2002; Simoes & Avouac 2006).

Our model shows distinct seismic velocity anomalies in the upper crust of northern Taiwan that correspond with the major tectonic units of the mountain belt (Fig. 9). The seismic velocity in the Hsiuhshan Range increases rapidly with depth from ~5.0 km s⁻¹ to more than 5.5 km s⁻¹ in the first few kilometres. At 100 km distance in our model, the Lishan fault is characterized by Vp lower than 4.5 km s⁻¹. Farther east, the Central Range has seismic velocities higher than 6 km s⁻¹ in the upper crust. In contrast, the middle crust of northern Taiwan appears more homogeneous with a seismic velocity between 5.5 and 6.0 km s⁻¹, but the smoothed seismic velocity inversion may not represent fine structure at this depth.
Arc-continent collision in northern Taiwan

because the resolution is lower here (Fig. 10). On the other hand, it appears that the seismic velocity in the upper crust of the Hsiiehshan Range and Central Range is not lower than the average $V_p$ of the middle crust.

The Moho beneath northern Taiwan forms a wide crustal root, increasing in depth from 28 km beneath the west coast to a maximum of 38 km just west of the strike-slip zone along the east coast (Fig. 9). The seismic velocity in the lower crust of Taiwan is 6.0–6.5 km s$^{-1}$, which is lower than in the lower crust of the adjacent Taiwan Strait.

In our seismic velocity model, the mantle beneath Taiwan increases with depth from just below 8.0 km s$^{-1}$ at the Moho to more than 8.0 km s$^{-1}$ at 70 km depth. Since the deeper mantle lithosphere is

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**Figure 8.** (a) Bottom: ray paths calculated in the new seismic velocity model for the four explosive shots (red stars) on transect T6. Crustal refractions $P_1$ are shown in green, and reflections $PIP$ in red. White line represents the Eurasian Moho. Top: picked (solid) and calculated (dashed) traveltimes for all wide-angle refractions and reflections in the explosion seismic data. (b) Bottom: ray paths calculated in the new seismic velocity model for selected OBSs (red circles) on transect T6. Crustal refractions $P_1$ are shown in green, wide-angle reflections $PIP$ in red, deeper $P_2$ refractions in blue. Top: picked (solid) and calculated (dashed) traveltimes for all wide-angle refractions and reflections in the OBS seismic data. (c) Bottom: ray paths calculated in the new seismic velocity model for selected land seismic stations (yellow triangles) and air-gun shots on the eastern portion of transect T6. Refractions $P_1$ are shown in green, wide-angle reflections $PIP$ in red, $P_2$ refractions in blue. Top: picked (solid) and calculated (dashed) traveltimes for selected wide-angle refractions in the onshore-offshore seismic data. (d) Bottom: ray paths (in blue) projected on the vertical plane through the new seismic velocity model for selected land earthquakes (light blue stars) recorded by onshore-offshore stations (yellow triangles) on transect T6. Top: picked (solid blue) and calculated (dashed blue) traveltimes for selected earthquake compressional wave arrival times.
only covered by the near-vertical ray paths from local earthquakes (Fig. 8d), we do not have the necessary depth resolution to interpret its seismic velocity.

5.2 Ryukyu forearc and prism

Between 135 and 360 km (Fig. 9) the velocity profile for line T6 obliquely crosses the Ryukyu arc/forearc block and accretory prism. The Eurasian Moho beneath the Hoping Basin varies in depth from 38 km in the northwest to 25 km in the southeast. The crust thins to just ∼12 km beneath the Nanao Basin, though some sections of the southeastern portion of the T6 velocity profile are not well constrained. The Ryukyu arc crust between the Hoping Basin (at 170 km in Fig. 9) and the Eastern Nanao Basin (300 km) has a seismic velocity mostly >6.0 km s⁻¹, but to the southeast the seismic velocities rapidly drop to 3–5 km s⁻¹. Klingelhoefer et al. (2012) interpreted this transition as the boundary between the Ryukyu forearc basement and the prism.

Between the east coast of Taiwan (135 km) and the Nanao Basin (230 km) our tomographic model shows a 5–10 km thick layer beneath the Ryukyu Moho where the seismic velocity is as low as 7.0 km s⁻¹ (Fig. 9). These relatively low seismic velocities are constrained mostly by the onshore-offshore data (Figs 5 and 8c). At larger depth we observe normal mantle seismic velocities (>8.0 km s⁻¹) that we would expect for the mantle of the Philippine Sea Plate. This zone with 7.0 km s⁻¹ seismic velocities could therefore be Philippine Sea Plate ocean crust, or Luzon arc crust, that is underthrusting the Ryukyu arc to the north. This interpretation is consistent with the sparse observations of the top of basement of the Philippine Sea Plate in the MCS image of transect T6 (Fig. 3). Unfortunately, the OBS wide-angle seismic refraction data do not constrain the position of the subducting Philippine Sea Plate ocean crust here or farther to the southeast, because we did not record enough long-offset seismic refractions that turned beneath the Ryukyu arc Moho.

6 DISCUSSION

6.1 Mountain building in Taiwan

It has long been debated whether the internal structure of the Taiwan orogen is more consistent with a thick-skinned or thin-skinned
Arc-continent collision in northern Taiwan

Figure 10. Resolution tests for two different spatial scales, based on the linearized tomographic inversion (Van Avendonk et al. 2004). Dashed lines show the seismic velocity contours at 1.0 km s\(^{-1}\) intervals; light blue stars mark the earthquakes, white circles the OBSs used in the inversion. The row of dark blue triangles along the surface across Taiwan represent land seismic stations. Red stars mark the location of explosive shots. (a) Resolution of 16 km (horizontal) by 6 km (vertical) ellipse in the T6 seismic velocities, and 16 km section of Moho (solid black). (b) Resolution of a 32 km (horizontal) by 12 km (vertical) ellipse and Moho patch.

tectonic evolution (e.g. Suppe 1981; Wu et al. 1997; Brown et al. 2012). Our tomographic inversion shows that the seismic velocity structure in the upper crust along our seismic line across northern Taiwan correlates well with the tectonic provinces of the mountain belt. The seismic velocity anomalies associated with the Hsiuehsan Range, Lishan Fault and Central Range can be traced to approximately 10–15 km depth (Fig. 9), significantly deeper than the ~10 km deep horizontal band of upper crustal earthquakes in the Taiwan mountain belt (Fig. 9b), which may coincide approximately with the brittle-ductile transition (Kidder et al. 2012; Van Avendonk et al. 2014). In various local seismotectonic studies of Taiwan, seismicity outlines sub-vertical shear zones that also bound the major tectonic units to approximately the same depth of ~15 km or deeper (Gourley et al. 2007; Ching et al. 2011a; Brown et al. 2012). It is therefore likely that the arc-continent collision deformed the entire crust, and that deformation in the upper and lower crust are coupled.

The northern Hsiuehsan Range metasediments derive from an inverted Eocene-Oligocene sedimentary basin that formed on the Eurasian shelf (Clark et al. 1993; Tillman & Byrne 1995; Simoes et al. 2007). Seismic velocities 5.0–5.5 km s\(^{-1}\) in the upper few kilometres are consistent with intermediate, upper greenschist facies metamorphic basement (Christensen & Mooney 1995). In the adjacent Lishan fault zone, seismic velocities are as low as 4.0 km s\(^{-1}\). Across the Lishan fault to the east, eastern slate belt rocks are Eocene to Miocene in age, and of prehnite-pumpellylite facies (Lee et al. 1997). Because of the lower metamorphic grade rocks, seismic wave speed of the slate belt rocks could be lower here than in the Hsiuehsan Range. The higher seismic velocities in the Central Range (>6.0 km s\(^{-1}\)) are therefore more easily explained by shallow pre-Miocene basement. The Tananao schist, which outcrops in the eastern central Range, contains igneous intrusive and ultramafic rocks as well as marbles that are consistent with observed > 6.0 km s\(^{-1}\) velocities.

Between 70 and 135 km in our model (Fig. 9) the lower crust of the Taiwan mountain belt forms a broad crustal root with seismic velocities as low as 6.0 km s\(^{-1}\) to a depth of 30 km, and not much higher than 6.5 km s\(^{-1}\) at the Moho at 40 km depth. In comparison, the structure of the crustal root along transect T5 (Van Avendonk et al. 2014) is quite similar to 30 km depth. Possibly, the lower crust along transect T5 has a deeper root (50 km) with seismic velocities exceeding 7.0 km s\(^{-1}\). Unfortunately, the lower crust and Moho along transect T5 is not as well constrained as along T6,
because no Moho reflections were used to obtain the seismic velocity model for T5. Nonetheless, it is possible that the dense lower crust in central to northern Taiwan delaminated, which would also explain why the orogenic crust is thinner on transect T6 than to the south.

6.2 Ryukyu arc crust

The southern Ryukyu arc platform is a ribbon of continental crust that rifted from the Eurasian margin around 2 Ma, when backarc extension formed the Okinawa Trough (Sibuet et al. 1998). Before the backarc opening, this section of the Eurasian margin may have collided with the northernmost section of the Luzon arc, and the continental crust may have thickened in the same manner as we observe in Taiwan at present. During the westward propagation of extension from the Okinawa trough into the Ilan Plain of northeastern Taiwan (Huang et al. 2012), the Ryukyu arc basement rotated clockwise by approximately 90° from a NNE to an ESE trend. The degree to which the Ryukyu arc crust offshore Taiwan was deformed in the aftermath of the collision is not well known.

The crust of the Central Range and Ryukyu arc both reach a maximum thickness of 38–40 km near the coast of northeastern Taiwan in our seismic velocity profile, which is good evidence that the collision between the Luzon arc and the Eurasian margin affected the southwestern Ryukyu arc as well. Beneath the mostly undeformed sediments of the Hoping Basin lie tilted strata of the older Suao basin (Lallemand et al. 1997) that record deformation of the basement in the adjacent arc-continent collision. The crust of the Ryukyu arc beneath the Hoping Basin has seismic velocities between 5.5 and 6.5 km s⁻¹. This is somewhat higher than in the adjacent Taiwan orogen, where the seismic velocity of the upper and middle crust only exceeds 6.0 km s⁻¹ in the eastern Central Range (Fig. 9). High-grade metamorphic rocks may therefore make up a larger proportion of the Ryukyu arc crust (Fabbri & Fournier 1999) than in the Taiwan mountain belt.

The NW-SE oriented TAIGER transect T6 lies obliquely across the Ryukyu arc platform, so we expect that variations in seismic structure can in part be attributed to the general differences between the arc, forearc, and accretionary prism. For example, the Ryukyu crust decreases in thickness from ~38 km near the Taiwan coast (135 km) to ~9 km beneath the Nanao Basin (230 km) in our model. Farther east, the base of the Ryukyu crust is not well resolved in our tomographic inversion. In our interpretation of the TAIGER MCS (Fig. 3) and wide-angle seismic data (Fig. 9b), the Ryukyu arc and forearc crust is relatively constant in thickness (9–10 km) beneath the East Nanao Basin to 320 km. Uplift and brittle deformation of the Ryukyu forearc basement between the Nanao and East Nanao basins (Fig. 3) marks the subduction of the north–south trending Gagua Ridge (Lallemand et al. 1999). Farther south, this ridge of thickened Philippine Sea Plate ocean crust has been imaged with TAIGER marine seismic refraction data, which supports its interpretation as a Miocene-age failed subduction zone (Eakin et al. 2015).

The lateral decrease in seismic velocity in the crust between 300 and 320 km in our seismic velocity profile (Fig. 9) may be representative of the structural variation between the forearc basement and the accretionary prism of the Ryukyu subduction system. This structural boundary has been imaged previously along marine seismic refraction profiles that were oriented perpendicular to the trench system (Wang et al. 2001; Klingelhofer et al. 2012).

6.3 Philippine Sea Plate

The north–south structural continuity of the Taiwan mountain belt (Ho 1986) is strong evidence that the Luzon arc collided with northern Taiwan in the early history of the orogen, but it is not clear what happened to the Luzon arc block and northeast corner of the Philippine Sea Plate in the later stages of the collision. The presence of arc volcanic rocks in the Coastal Range (Barrièr & Angelier 1986) suggests that the Luzon arc is truly accreted to the Eurasian margin. However, the deep seismic velocity structure along TAIGER transect T5 shows that much of the Luzon arc block may have been pushed to mid-crustal depths in central Taiwan (Van Avendonk et al. 2014). Farther north, the Coastal Range terminates south of the intersection with the Ryukyu trench, which may be explained by northward subduction of the Luzon arc along with the Philippine Sea Plate (Wu et al. 2009).

In the active-source seismic data from TAIGER transect T6 we did not find direct evidence for the existence of Philippine Sea Plate crust, such as a deep seismic reflection from its top of basement or from its Moho. On the other hand, the earthquake and onshore-offshore arrivals in our data set require ~7.0 km s⁻¹ velocities beneath the base of Eurasian crust east of Taiwan (Fig. 9), which is constrained by PIP reflections from the onshore-offshore data (Fig. 8c). This 7.0 km s⁻¹ velocity layer is estimated to be just 6 km thick because earthquake and long-offset P2 arrivals in the onshore-offshore data (Fig. 8c) travel with a seismic wave speed of approximately 8.0 km s⁻¹. With the guidance from published seismic velocity models from north-south marine seismic refraction lines across the Ryukyu subduction system (Wang et al. 2001; Klingelhofer et al. 2012), we can reconstruct the location of Philippine Sea Plate crust from the strike-slip zone along the coast of northeastern Taiwan to the Ryukyu accretionary wedge (Fig. 9b). Our seismic velocity model does not have sufficient resolution (Fig. 10) to infer whether the subducting Philippine Sea Plate crust is still attached to the Luzon arc along transect T6, but the arc/forearc block could still reside near the east coast of Taiwan at ~35 km depth.

6.4 Extension of the orogen

The deep mantle seismic velocity structure and the seismicity in Taiwan (Kuo-Chen et al. 2012a,b; Huang et al. 2014) shows that plate convergence changes in Taiwan from eastward subduction of the Eurasian Plate along transect T5 (Fig. 11d) to northwestern subduction of the Philippine Sea Plate along transect T6 (Fig. 11c). After this change in subduction polarity at ~2 Ma, rapid roll-back of the Philippine Sea Plate in the Ryukyu subduction zone (Huang et al. 2012) appears to have been the leading cause of extensional collapse in the northern Taiwan mountain belt, starting in the Okinawa Trough (Fig. 11b). Topographic stresses (Teng 1996) and orogen-parallel extrusion (Angelier et al. 2009) also contributed to the relaxation of the thinned crust. However, the northward subduction of the Luzon arc, which we may now have imaged along transect T6 offshore northeastern Taiwan (Figs 9 and 11c), has removed the backstop that confined the mountain belt. Ryukyu subduction zone backarc extension has since then formed the Ilan Plain (Fig. 2a), a triangular basin that wedges between the Hsüehshan Range and the Central Range (Clift et al. 2008). The northern Taiwan mountain belt is subsiding as well, but the rate here is much more modest than in the Ilan Plain (Ching et al. 2011b).

While the extension in the upper crust is localized in the Ilan Plain, the lower crustal root reaches its maximum thickness of 40 km beneath it (Fig. 11c). The crust of the Taiwan mountain belt is still
thicker to the south. For example, Van Avendonk et al. (2014) found a crustal root to 50 km depth along TAIGER transect T5 in central Taiwan (Fig. 11d). Given the overall difference in crustal thickness between transects T5 and T6, it is quite plausible that the entire crust of the northern Taiwan mountain belt stretched and thinned in the aftermath of arc-continent collision. On the other hand, the arc-continent collision may have also progressed less far in the north, since the subduction of the Coastal Range and the Philippine Sea Plate in northern Taiwan removed the backstop for the Taiwan orogen (Wu et al. 2009). Either way, extensional deformation in the lower crust was not localized beneath the Ilan Plain of northeastern Taiwan, and it was more likely distributed over the width of the mountain belt. The high heat flow in the Taiwan orogen (Lin 2000) implies that the lower crust is relatively hot. It is therefore possible that the crustal root widened and flattened in northern Taiwan (Rey et al. 2001), without significant post-collisional deformation of the stronger upper crust of the Taiwan mountain belt west of the Ilan Plain.

7 Conclusions
From the analysis of wide-angle and local earthquake traveltimes along transect T6 in northern Taiwan we constructed a seismic
velocity model that shows the lithospheric structure of the Taiwan mountain belt and the adjacent Ryukyu arc in unprecedented detail. We summarize the following conclusions:

(1) By combining traveltime data from seismic records of the 2008 and 2009 TAIGER active-source experiments with local earthquakes that were registered by the same instrument arrays, we were able to produce a detailed seismic velocity image of the crustal structure across northern Taiwan. The results from TAIGER transects T5 and T6 illustrate the importance of earthquake traveltimes in tomographic studies of mountain belts with deep crustal roots.

(2) Arc-continent collision in northern Taiwan led to thickening of the Eurasian crust from ~24 km in the Taiwan Strait to ~40 km beneath the eastern Central Range. The Luzon arc block and ocean crust and mantle lithosphere of the Philippine Sea Plate that were engaged in this collision have since then subducted northward into the Ryukyu trench system. Our seismic refraction data provide evidence for a remnant of the Philippine Sea Plate crust beneath the Eurasian crust offshore northeastern Taiwan.

(3) Seismic velocity anomalies associated with the Hsiêshian Range, Lishan Fault and Central Range show that these major elements of the Taiwan mountain belt are continue to at least 15 km depth. Our result suggests that rocks exhumed in the Hsiêshian Range and Central Range are exhumed from middle or perhaps lower crustal levels in a near-vertical path.

(4) Though post-orogenic collapse and extension of the upper continental crust along transect T6 is concentrated in the Ilan Plain of northeastern Taiwan, the orogen still has a 40 km deep lower crustal root in this area. Extension of the mountain belt in northern Taiwan was therefore likely accommodated by ductile, distributed deformation.

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H.J.A. Van Avendonk et al.


