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Large variations of crustal thickness across the Taiwan orogeny constrained by Moho-refraction recorded by the Formosa Array

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Abstract

The Taiwan orogenic belt is formed by the strong convergence between the Philippine Sea Plate and the Eurasian Plate. The detailed mountain building process is still under debated largely due to the poor constraint of deep crustal structures, particularly the geometry at the Moho-depth. Here the Moho-refracted P waves are identified from the seismic data recorded by a dense seismic array (Formosa Array) in northern Taiwan. Although the refracted seismic energy is often weak at each individual station, the waveform similarity recorded at the nearby stations provides a reliable constraint for estimating the apparent velocity recorded by the dense seismic array. The forward modeling of the observed Moho-refracted P waves shows a larger crustal thickness (~ 52 km) beneath the Backbone Ranges than beneath the adjacent Hsuehshan Ranges (~ 36 km). Such a result is not only confirming the Moho variations along a few of the NW-SE profiles from the previous studies, but also showing the strong Moho variation is well extended along the NE-SW direction. The large change in the crustal thickness across the Taiwan orogeny strongly indicate that the orogenic deformation in Taiwan might extend beyond the shallow crust, possibly involving in the deep crust and upper mantle. The Taiwan orogeny may not be reaching to the isostatic equilibrium yet.

Keywords Crustal thickness, Taiwan orogeny, Dense seismic array, Refracted waves

1 Introduction

The general characteristics of plate tectonics are strongly reflected in the variation of crustal thickness. It is well known that the typical crustal thickness in the continental plate (~ 35 km) is significantly larger than that in the oceanic plate (5–12 km). However, the crustal thickness in the orogenic belts such as Tibet (Holt and Wallace 1990; Chen and Yang 2004) and the Alps (Hetenyi et al. 2018) could be up to 70 km, which is almost double that of the standard continent plates. The significant increase of the crustal thickness in an orogenic belt results from the complicated deformation in the crust and even the uppermost mantle due to the plate convergence. Thus, the determination of the crustal thickness is a fundamental issue in plate tectonics, particularly orogenic belts.

The Taiwan orogenic belt is one of the most active collision zones on the earth (Fig. 1). To improve the understanding of orogenic mechanisms in Taiwan, different tectonic models have been proposed in the past decades (i.e., Suppe 1981; Wu et al. 1997; Chemenda et al. 1997; Teng et al. 2000; Lallemand et al. 2001; Lin 2002, Malaveille et al. 2002). Among them, the arc-continental collision has been often considered to explain the Taiwan

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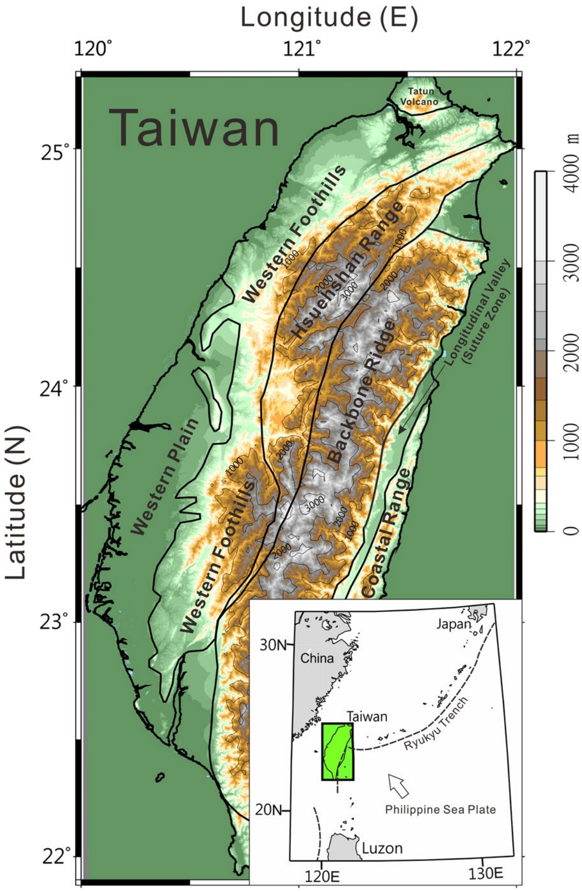


Fig. 1 Geologic provinces and topographic reliefs in Taiwan. The insert map shows general tectonics in and around Taiwan

orogeny mainly because Taiwan is located at the plate boundary between the continental margin of the Eurasian Plate and the Luzon Volcanic Arc of the Philippine Sea Plate. The crustal deformation in the Taiwan area has been caused by the strong indenter of the volcanic arc, and thus the major deformation is limited to the shallow crust above the decollement (Suppe 1981). In contrast, other tectonic models suggest that the deep crustal deformation might be involved in the Taiwan orogeny such as a lithosphere deformation (Wu et al. 1997), the continental subduction (Chemenda et al. 1997) and the continental subduction and crustal exhumation (Lin 2002). The major debate among all of the proposed tectonic models might be largely attributed to poor constraint of the deep crustal structures, particularly the geometry at the Moho-depth.

Although the Moho-depth in the Taiwan orogenic belt has been investigated by various geophysical observations such as seismic data and gravity survey, the results are quite diverse. The crustal thickness in Taiwan ranges from approximately 30 to 70 km. Initially, a typical 1-D model obtained from the early earthquake data suggested a Moho-depth of approximately 36 km (Yeh and Tsai 1981). This is roughly consistent with the result from the gravity surveys (Yen et al. 1995, 1998) and the first seismic tomographic images in Taiwan (Roecker et al. 1987). However, two of the wide-angle seismic reflection and refraction experiments across the central and southern Taiwan, respectively, show that the Moho-depth might be up to approximately 45 km beneath the Central Range (Shih et al. 1998; Yeh et al. 1998a). A similar result giving a thick crust (> 50 km) was also obtained from another seismic profile across the southern Taiwan area (Lin 2005) as well as the seismic tomographic results (Kuo-Chen et al. 2012). Another wide-angle seismic reflection and refraction experiment further shows that the crustal thickness reaches approximately 46 km (Van Avendonk et al. 2014). However, crustal thickness obtained from the receiver function also shows some strong variations between approximately 30 and 50 km (Wang et al. 2010). The locations of the deepest Moho-depths for some typical results are marked at Fig. 2. The Pn study indicates that Moho-depths only range from 31 to 43 km (Ma and Song 1997). Some high-resolution tomographic images indicate the Moho depths of around 35 km in the Taiwan area, while the depth might be up to 40–70 km beneath the Central Range (Rau and Wu 1995; Wu et al. 2007; Kuo-Chen et al. 2012; Ustaszewski et al. 2012; Huang et al. 2014). A joint inversion of seismic and gravity data shows a Moho-depth of 56 km beneath the Central Range (Li et al. 2014). The latest result obtained from the receiver function (Goyal and Hung 2021) indicates the deepest Moho-depth of ~ 47 km beneath the Central Range. The significant diversity of the Moho-depths in the Taiwan area might be a result of uncertainty in both the data collected and the methods employed. Therefore, the crustal thickness is still under strong debate.

In this study, the seismic data generated by several strong earthquakes in the central and southern Taiwan area and recorded by the broadband seismic arrays in the Taiwan area are employed to obtain the Moho-depth beneath the major orogenic belts. In addition to the Broadband Array in Taiwan for Seismology (BATS), which is the first broadband seismic array covering Taiwan and comprises approximately 45 stations (Kao et al. 1998), seismic data recorded by the Formosa Array is examined. The array consists of 146 broadband seismic stations that cover an area of approximately 60 × 40 km in the northern part of Taiwan (Lin et al. 1998, 2000, 2020; Huang et al. 2021). Since the station spacing is approximately 5 km on average, the array provides an unambiguously seismic data for identifying the P-waves refracted from the Moho-discontinuity (Pn). The detection of Pn arrival times from a dense seismic array is

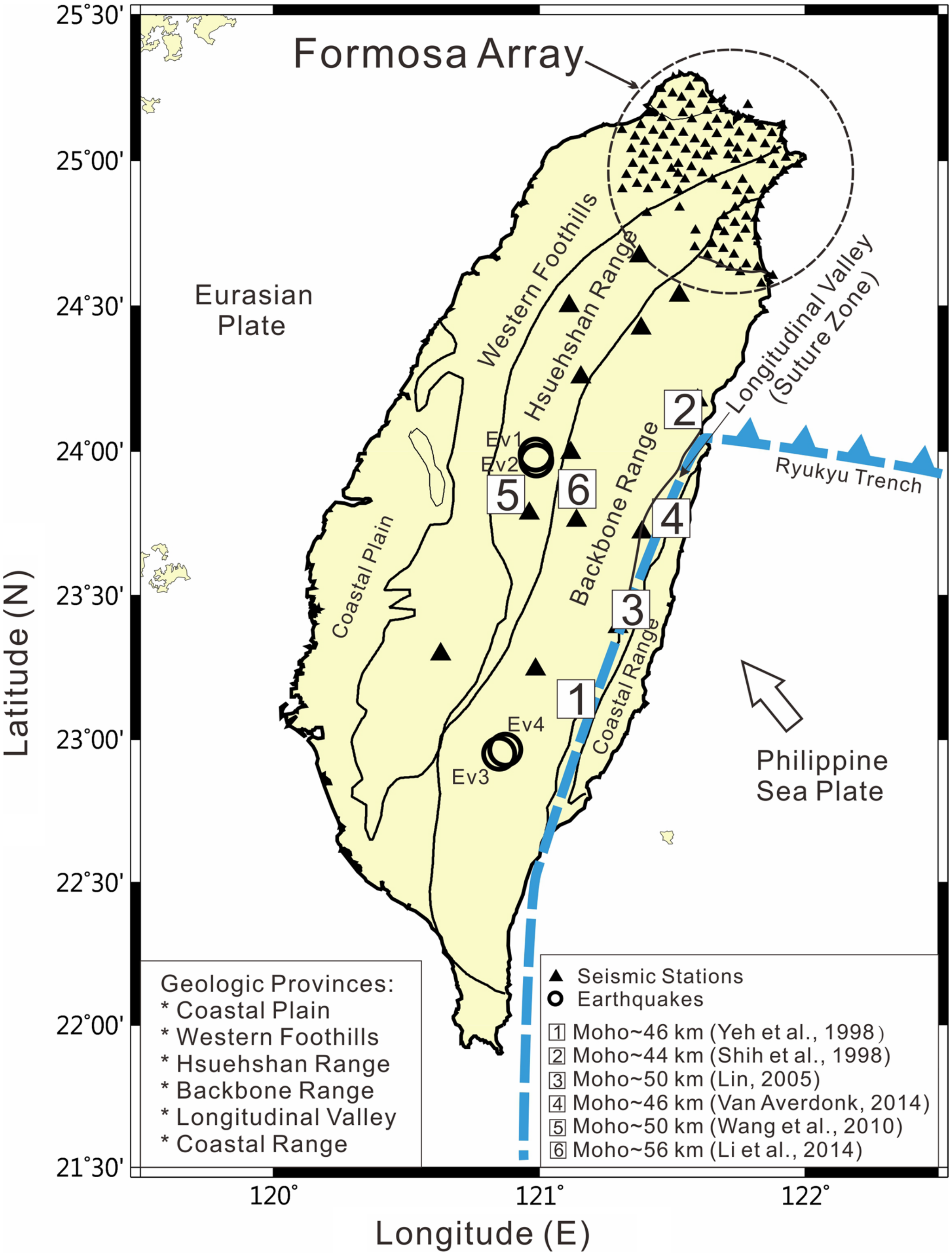


Fig. 2 Geologic provinces and locations of both the Formosa Array and some Broadband Array in Taiwan for Seismology (BATS) seismic stations in the mountainous area of Taiwan. Locations of the deepest crustal thickness are marked by Number 1–6 within squares, which were obtained from some previous studies

dramatically better than that from a single seismic station or a sparse seismic network. Since the seismic amplitude refracted from the Moho-discontinuity is small, it is often extremely difficult to distinguish the Pn signals from the background noise based on the seismograms recorded by a single seismic station alone or distant stations. Thus, the apparent velocity calculated from the observed Pn arrival times often has much uncertainty. However, the seismic data recorded at a dense seismic array will dramatically improve the detection of the Pn arrivals, as the correlated Pn signals are easily identified from the nearby seismic stations. As a result, the apparent velocity can be observed to distinguish the refracted waves from the direct waves. The observed Pn arrivals are compared with the 2-D ray-tracing modeling to estimate the difference of crust thickness between the Hsuehshan Range and the adjacent Backbone Range.

2 Tectonic settings and geological background

The island of Taiwan is located at a small section of the convergent zone between the Eurasian Plate (EUP) and Philippine Sea Plate (PSP), however, it is very interesting that a significant orogenic belt has been created due to the complicated plate convergence. The PSP is subducting beneath the EUP along the Ryukyu Trench in the northeastern Taiwan area, while the EUP in underthrusting the PSP along the Manila trench in the southern Taiwan area (Tsai et al. 1977). A significant collision orogeny occurred in the island of Taiwan due to the strong convergence (~ 8 cm/y) between two plates since the late Miocene (Seno 1977; Yu et al. 1997). The suture zone between the two plates is marked along the Longitudinal Valley (Fig. 1). East of the suture zone, the Coastal Range is the part of the Luzon volcanic arc in the PSP. West of the suture, the major geological units from west to east including the Coastal Plain, Western Foothills, Hsuehshan Range, Backbone Range and Eastern Central Range are belonged to the continental margin of the EUP (Ho 1988). Both of the topographic relief and metamorphic rate at the geological units in the EUP gradually increase eastward. The major mountain building process occurs across most of the geological units, and then the significantly topographic relief (up to 3,940 m) is created due to strong horizontal shortening and vertical exhumation. Meanwhile, the major crustal deformation is shown by many active faults and frequent earthquakes in the Taiwan area (Bonilla 1975; Tsai et al. 1977; Tsai 1986; Ho 1988; Wang and Shin 1998; Ota et al. 2005).

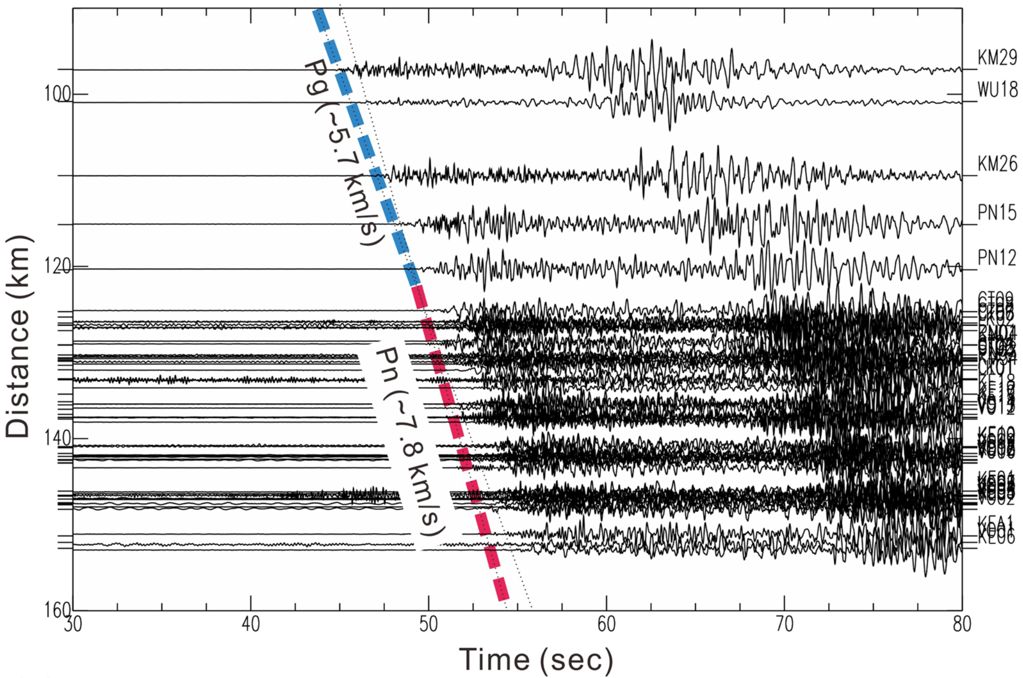
3 Formosa array and earthquake data

The Formosa Array (Fig. 2), a dense broadband seismic array, has been deployed in the northern Taiwan area for improving the seismic detection of magma reservoirs as well as other major subsurface structures (e.g., Lin 2016; Lin et al. 1998, 2000, 2020; Huang et al. 2021). The Formosa Array consists of 146 broadband seismic stations that cover an area of approximately 60 × 40 km. The station spacing is around 5 km on average. The installation of the seismic stations started in 2017, and then seismic data were successfully recorded at more than 100 stations by the end of 2018, (Fig. 2). The entire array was completely installed in 2019. Each seismic station is equipped with a broadband seismometer (Meridian compact PH by Nanometrics), whose instrument response curve ranges from 0.01 to 100 Hz. Seismic data are recorded with a sampling rate of 100 Hz. Most of the seismometers are installed within a bore-hole at a depth of approximately 2 m. All the seismic data are transmitted to the Taiwan Volcano Observatory at Tatun (TVO) as well as Institute of Earth Sciences (IES), Academia Sinica at Taipei in real-time by wireless radio or telephone systems. Thus, the seismic data can be obtained immediately and all seismic stations (instruments and transmission systems) can be ensured to be functioning well.

For examining the crustal thickness beneath the Hsuehshan Range, seismic data recorded by the Formosa Array from two strong earthquakes ($M_L = 4.8$ and 4.4) in central Taiwan in 2018 (Events 1 and 2 in Table 1) was collected. Since both earthquakes occurred near the center of the island of Taiwan, their locations were well captured by the dense seismic stations in the Taiwan area (Shin et al. 2000). The estimated location errors in longitude, latitude and depth were approximately 3.1 km, 1.3 and 4.6 km, respectively (Wu et al. 2013). Based on the earthquake catalog provided by the Central Weather Bureau (CWB) of Taiwan, both earthquakes were close to each other at the mid-crust (approximately 17 km in depth). To remove low-frequency ocean noises and other high-frequency ambient noises, the seismic data were filtered by a band-pass between 2 and 5 Hz. The P-wave arrivals have been picked manually by considering the seismic waveforms at each station and its vicinity stations. Thus, an apparent velocity of approximately 5.7 km/s was consistently obtained from P-waves recorded at the seismic stations less than 120 km away (Fig. 3). Since such an apparent velocity is generally consistent with the true velocity in the upper crust in the Taiwan area (Yeh and Tsai 1981; Chen 1995; Chen and Shin 1998), the P-wave arrivals are likely propagating through the crust directly (Pg). In contrast, the first P-wave arrivals recorded at seismic stations at the epicentral distances between 120 and 160 km give that an apparent velocity is approximately 7.8 km/s (Fig. 3). Although the first arrivals at some stations might not be real clear with a possible uncertainty of ~ 0.1 s (e.g., Fig. 4), the general trend of the seismic energy roughly follows the arrivals propagated with the apparent velocity (~ 7.8 km/s). Obviously, such a velocity is the typical P-waves propagation through the uppermost mantle, indicating that those arrivals are likely refracted from the Moho-discontinuity (Pn). Thus, the cross-over distance, which is the offset where the refracted wave overtakes the direct wave to become the first arrival on the seismogram, between the Pg and Pn is around 120 km.

For comparing the crustal thickness beneath the Hsuehshan Range with the Backbone Ridge, the seismic data

(a) Event 1



(b) Event 2

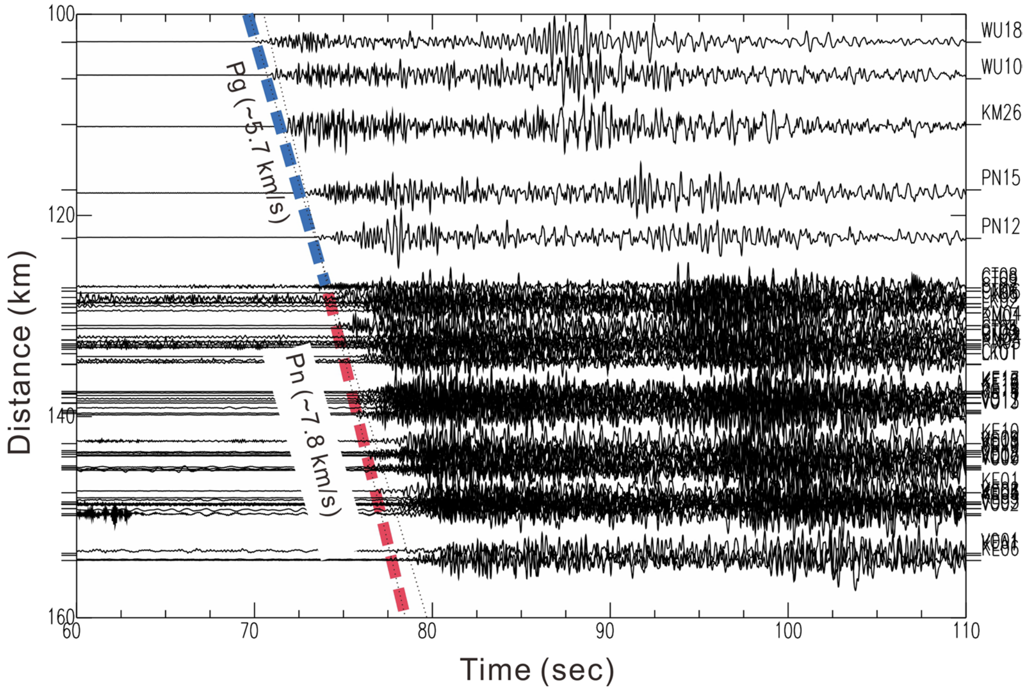


Fig. 3 The vertical velocity seismograms generated by **a** Event 1 and **b** Event 2 and recorded by the Formosa Array. The color dashed lines mark the general trend of the first arrivals plotted with the epicentral distances

recorded by the Formosa Array from another two strong earthquakes ($M_L = 5.6$ and 5.2) in the southern Taiwan area on April 3 and 4, 2019, respectively (Events 3 and 4 at Table 1), are examined. Again, both earthquakes were well located with uncertainties of less than a few kilometers since they occurred within the seismic network (Wu et al. 2013). Based on the CWB earthquake catalog, both earthquakes were located nearby each other at the depths

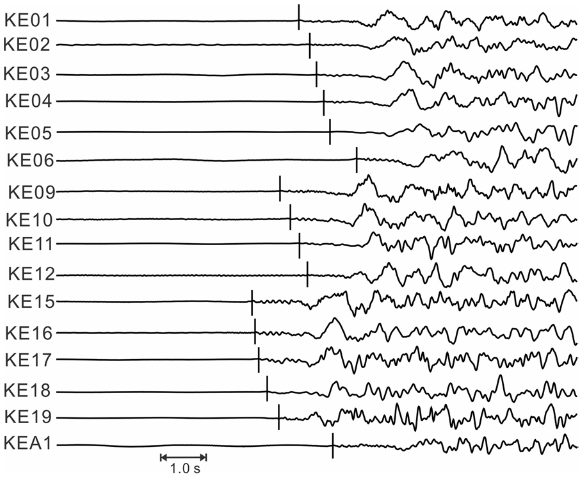


Fig. 4 The 1st arrivals picked on seismograms (verticals bars) recorded at Stations KE01-19 from Event 1

of approximately 10 km. In addition to the CWB seismic stations, certainly, both earthquakes were well recorded by the broadband seismic arrays in Taiwan, including BATS and the Formosa Array. Since both seismic arrays are recording seismic data at different epicentral distances, they may provide a good method for examining the possible ray-paths propagating through the crust.

As we expected, at first, the broadband seismograms recorded at the BATS in the Backbone Range at the distances ranging from 30 to 220 km show the first P-wave arrivals are the direct waves (Pg). The apparent velocity of approximately 5.7 km/s fits well with the arrivals of the unambiguously P waves recorded at the seismic stations in the Backbone Ridge (Fig. 5). Since such an apparent velocity is generally consistent with the true velocity in the upper crust in the Taiwan area (Yeh and Tsai 1981; Chen 1995; Chen and Shin 1998), the P wave arrivals are propagating through the crust directly. In contrast, the first P-wave arrivals recorded by the Formosa Array in the northern Taiwan around the distances between 220 and 270 km demonstrate that they are the Moho-refracted waves (Pn) given the apparent velocity is approximately 7.7 km/s (Figs. 6 and 7). The seismograms plotted with the reduced arrival times confirm the apparent velocity of approximately 7.7 km km/s (Figs. 6b and 7b). Again, such an apparent velocity is a typical P wave velocity in the uppermost mantle, indicating that the seismic energy is propagating through the upper portion of the uppermost mantle. As a result, the crossover distance might be more than 220 km based on the seismograms recorded at the BATS and Formosa Array.

In addition to the apparent velocity, in fact, the waveforms between the direct waves (Pg) and the refracted waves (Pn) are distinguishable (i.e., Fig. 8). For the direct waves (Pg), the waveforms usually begin with a large, sharp amplitude. By contrast, for the refracted waves (Pn), the waveforms usually begin with a smaller amplitude. It is well known that the amplitude of the refracted wave is only a small portion of that of the direct wave (Wolf 1936; Berg and Long 1966; Sharma et al. 1990). The refracted wave with a smaller amplitude was confirmed by both of the observational data and waveform simulation (i.e., Lin et al. 1999). Although the refracted seismic energy is often small at each individual station, the waveform similarity recorded at the nearby stations provides a reliable method for estimating the apparent velocity recorded by the dense seismic array.

4 Ray-tracing

To further examine the possible geometry of the subsurface structures that will generate the different seismic ray-paths detected by the Formosa Array, a two-dimensional ray-tracing method was employed for calculating the ray-paths and their travel-time arrivals (Luetgert 1992). Although the real velocity structures might be more complicated such as a dipping Moho-discontinuity or strong lateral variations along the NE-SW direction, a simplified 1-D velocity model of the mantle and overlaying crust was assumed for estimating the crustal thickness beneath the Taiwan area. Based on the apparent velocities observed in the seismic arrays in Figs. 3, 4, 5, 6 and 7, it is assumed that the crustal velocity is gradually increasing from 5.7 km/s in the uppermost crust to 6.7 km/s in the bottom of the crust, and jumping to 7.7 km/s in the uppermost mantle. This 1-D velocity model is not only consistent with the observations in Figs. 3, 4 and 5, but also generally agree with the previous results (e.g., Yeh and Tsai 1981; Chen 1995; Chen and Shin 1998).

Table 1 Earthquake parameters (Provided by Central Weather Bureau)

Earthquake	Longitude (Deg.)	Latitude (Deg.)	Depth (km)	Magnitude (M_L)	Year/Mo/Dy
Event 1	121.01E	24.00 N	16.8	4.8	2018/08/17
Event 2	121.01E	24.02 N	18.4	4.4	2018/09/17
Event 3	120.85E	22.95 N	10.0	5.6	2019/04/03
Event 4	120.88E	22.97 N	10.0	5.2	2019/04/04

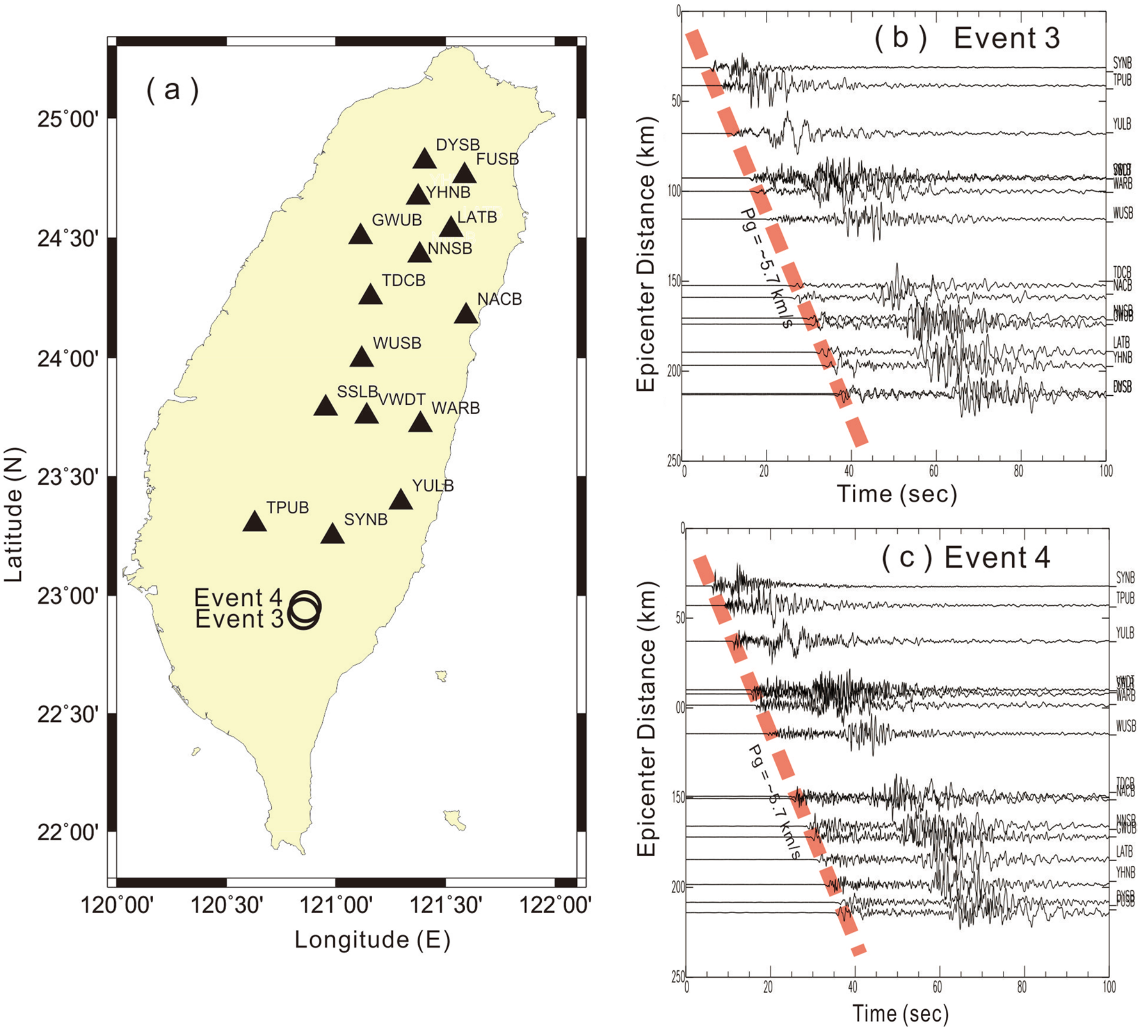


Fig. 5 **a** Locations of Events 3, 4 and the BATS seismic stations in mountainous area. **b**, **c** The observed seismograms plotted with epicentral distances generated by Events 3 and 4, respectively

For the first set of two earthquakes in central Taiwan (Events 1 and 2), assuming that the focal depth is 17 km, the observed Pn arrivals fit the calculated results well for the typical crustal depth of approximately 36 km (Fig. 9). The assumed velocity model is a typical 1-D structure obtained by some previous investigations in the Taiwan area (e.g., Yeh and Tsai 1981; Chen and Shin 1998). The cross-over distance from the directed Pg to the Moho-refraction Pn is approximately 120 km for Event 1 (Fig. 3a). The calculated arrival times for Moho-refractions at the depth of 36 km fit with the observations (Fig. 9). However, the velocity model with a Moho depth of approximately 36 km is poorly fits the Pn arrivals observed in Events 3 or 4. For example, the observed Pn arrivals (squares in Fig. 10) are significantly delayed by several seconds after the calculated arrivals for the stations at epicentral distances greater than ~ 220 km. Instead, the observations of Pn arrivals (squares in Fig. 10c) are better explained by the crustal model with an extremely thick crust of approximately 52 km (Fig. 10d). The cross-over distance obtained from Events 3 and 4 in the southern Taiwan area is over 220 km, which is significantly larger than that obtained from Events 1 and 2 in the central Taiwan area.

5 Discussion

A thick crust of approximately 52 km with an estimated uncertainty of approximately 1 km is desired for fitting the large cross-over distance obtained from the seismic data along the Backbone Range of the Taiwan orogeny, even though there remain some possible uncertainties in the earthquake locations, the simplified velocity model, and the apparent velocities. At first, the uncertainty in the earthquake locations is less than a few of kilometers

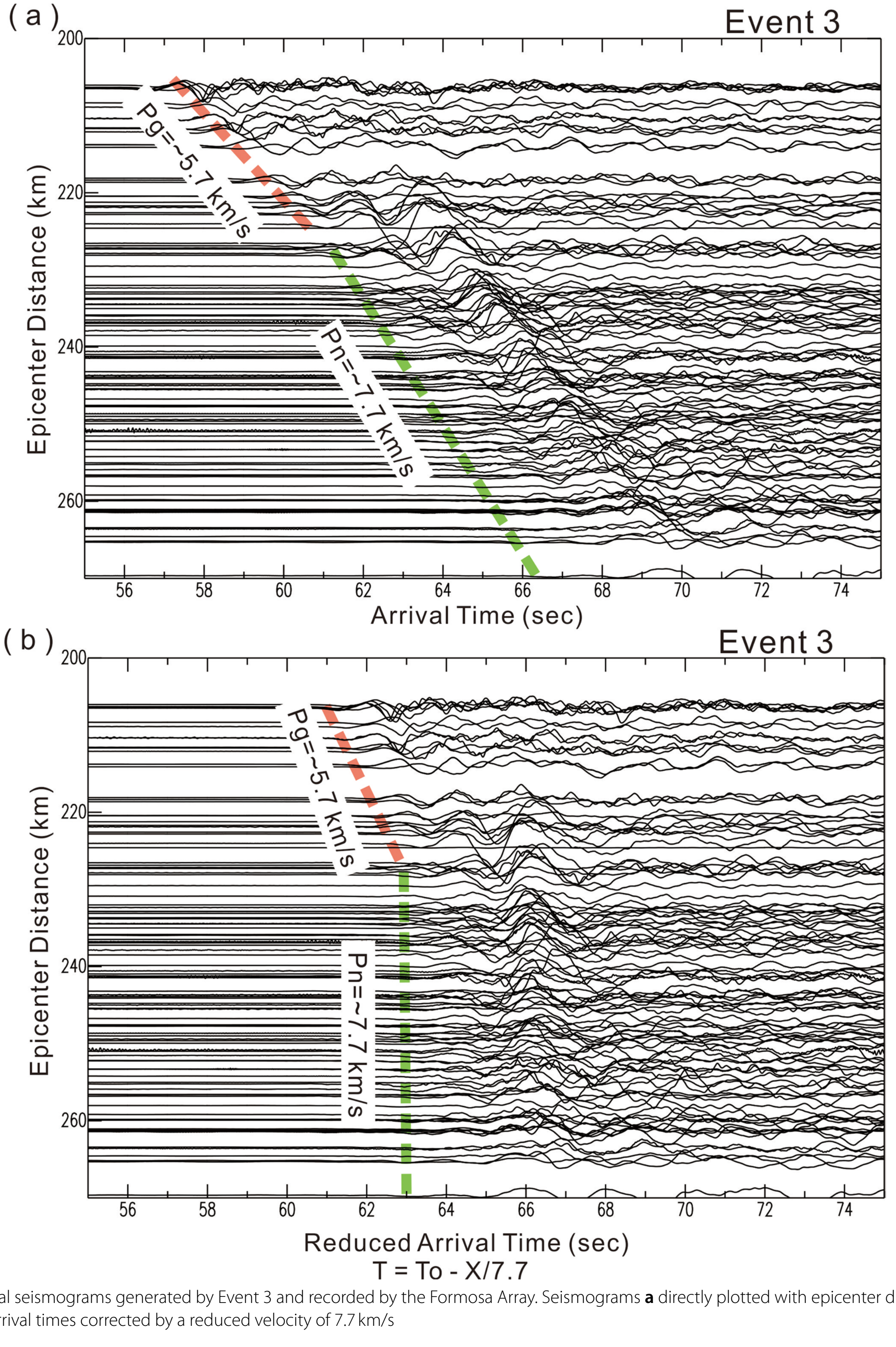


Fig. 6 Vertical seismograms generated by Event 3 and recorded by the Formosa Array. Seismograms **a** directly plotted with epicenter distances, and **b** with arrival times corrected by a reduced velocity of 7.7 km/s

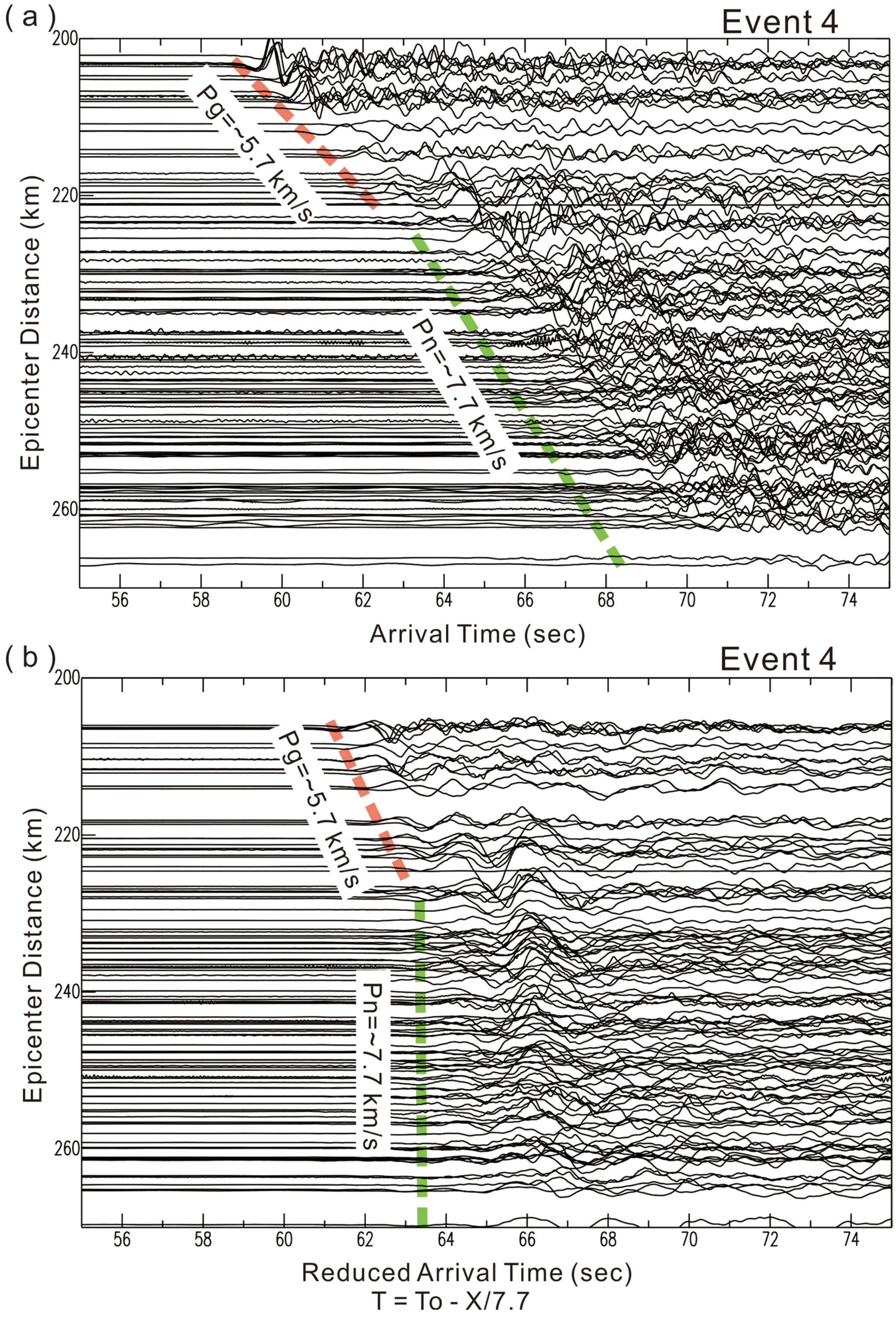


Fig. 7 Vertical seismograms generated by Event 4 and recorded by the Formosa Array. Seismograms **a** directly plotted with epicenter distances, and **b** with arrival times corrected by a reduced velocity of 7.7 km/s

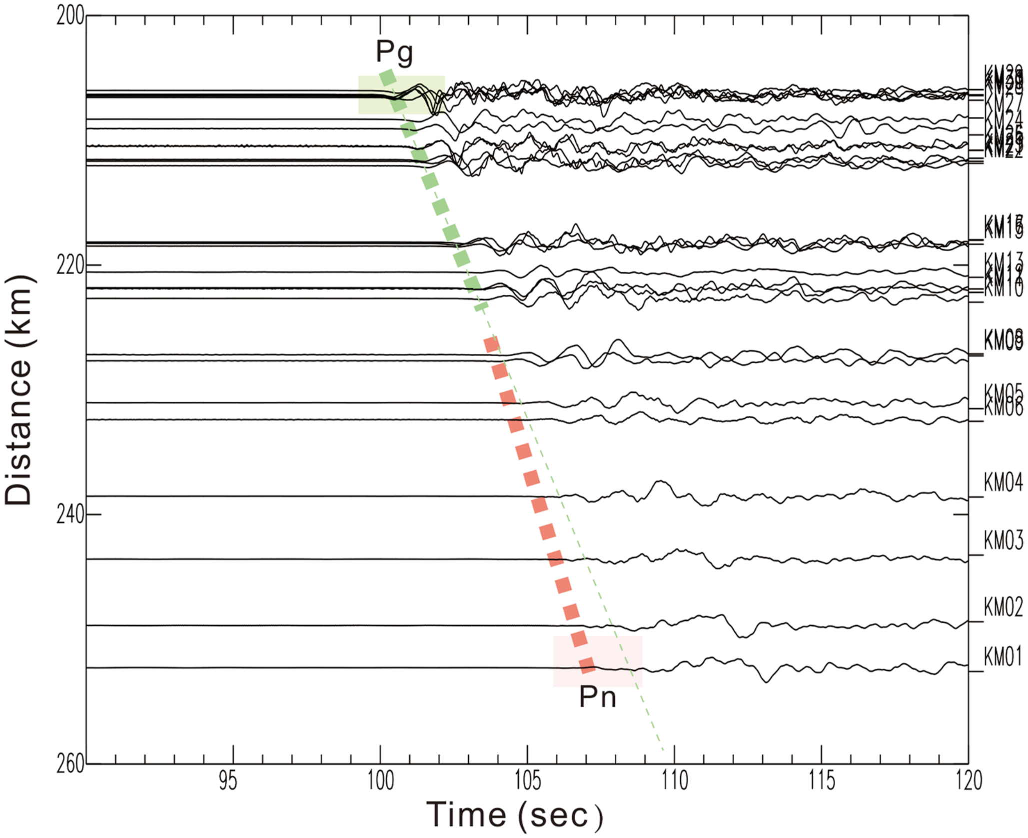


Fig. 8 Waveform comparison between Pg and Pn as generated by Event 3. The seismic amplitudes of Pg (green) are significantly larger than those of Pn (pink)

in that those earthquakes are located within the dense seismic arrays in the Taiwan area (Wu et al. 2013). Such a location uncertainty might not cause any considerable change of the estimated crustal thickness. Although a simplified 1-D model, instead of 3-D subsurface structures, was employed to calculate the cross-over distance, this might be representative of the real velocity model because the velocities (Pg and Pn) are not only directly observed by the dense seismic stations in the Taiwan area, but also consistent with the majority of the previous results (e.g., Yeh and Tsai 1981; Chen 1995; Chen and Shin 1998). That is because the apparent velocities of both Pg and Pn estimated from the dense seismic arrays are quite acceptable. Therefore, the thick crust of approximately 52 km beneath the Backbone Range of Taiwan is well constrained by the Pn arrivals as well as the large cross-over distances of approximately 220 km with some limited uncertainties.

As compared with the previous observational data, which demonstrate a large variation in the crustal thickness ranging from 30 to 70 km in the Taiwan area, a thick crust of approximately 52 km beneath the Backbone Range of the Taiwan orogeny might be more reliable as it was straightforwardly obtained here without excessively complicated data processing and too much uncertainties (Fig. 11). For the Backbone Range, a thick crust of approximately 52 km is roughly similar to the results from seismic experiments (Shih et al. 1998; Yeh et al. 1998b; Lin 2005; Kuo-Chen et al. 2012; Van Avendonk et al. 2014) and the joint inversion of seismic and gravity data (Li et al. 2014) (Fig. 2). In particular, the seismic profiles obtained by Shih et al. (1998) and Yeh et al. (1998a), that show the Moho-depths significantly increase beneath the Backbone Range (Fig. 11b and c), are very similar to the results in this study. A major improvement in this study is the significant thick crust beneath Backbone Range is not only shown by the previous results along the NW-SE profiles, but also found along the NE-SW profiles. Although a similar thick crust was also obtained by some tomographic images (i.e., Rau and Wu 1995; Wu et al. 2007; Kuo-Chen et al. 2012, Ustaszewski et al. 2012; Huang et al. 2014; Goyal and Hung, 2021), for a crustal thickness ranging from ~40 km to ~70 km, the Moho-discontinuity might not be well imaged due to the relatively limited ray-paths at the deep crust and upper mantle in the Taiwan area. The large increase in crustal thickness

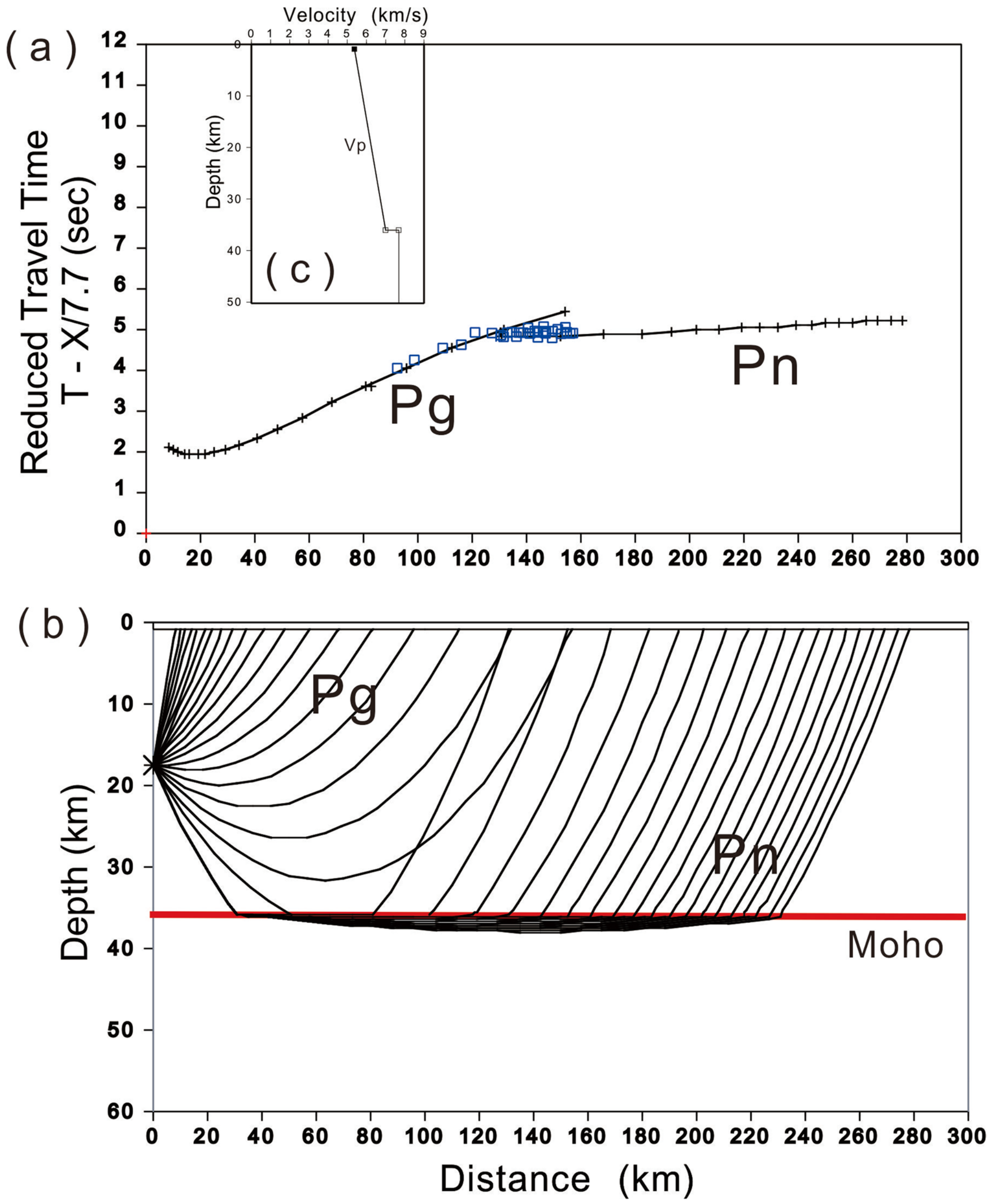


Fig. 9 **a** Comparison of observed (small squares) and calculated (lines with pluses) P wave arrivals for Events 1 or 2. **b** The ray paths of the direct (Pg) and refracted (Pn) P-waves from the Moho-discontinuity. **c** The one-dimensional velocity model for calculating P wave travel times

beneath the Backbone ridge indicates the crustal deformation at both upper and lower crusts are strong. For the Hsuehshan Range, on the other hand, a typical continental crust with a thickness of approximately 36 km is similar to the early 1-D model obtained by Yeh and Tsai (1981) and Yen et al. (1995; 1998) and the 3-D seismic images by Kuo-Chen et al. (2012). This result indicates the lower crust beneath Hsuehshan Range might not be strongly deformed, even the topographic relief is significant. Therefore, the crust thickness constrained by the cross-over distance of the Pg and Pn arrivals provides an independent result of a thick crust beneath the backbone Range of the Taiwan orogeny. Further comparing the large variation of the crustal thickness between Hsuehshan Range and Backbone Range, whose topographic relief are similar, it indicates the Taiwan orogeny might not be reaching to the isostatic equilibrium yet.

A thick crust of approximately 52 km beneath the Backbone Range of the Taiwan orogeny may play an important role in the discussion of previously proposed, possible

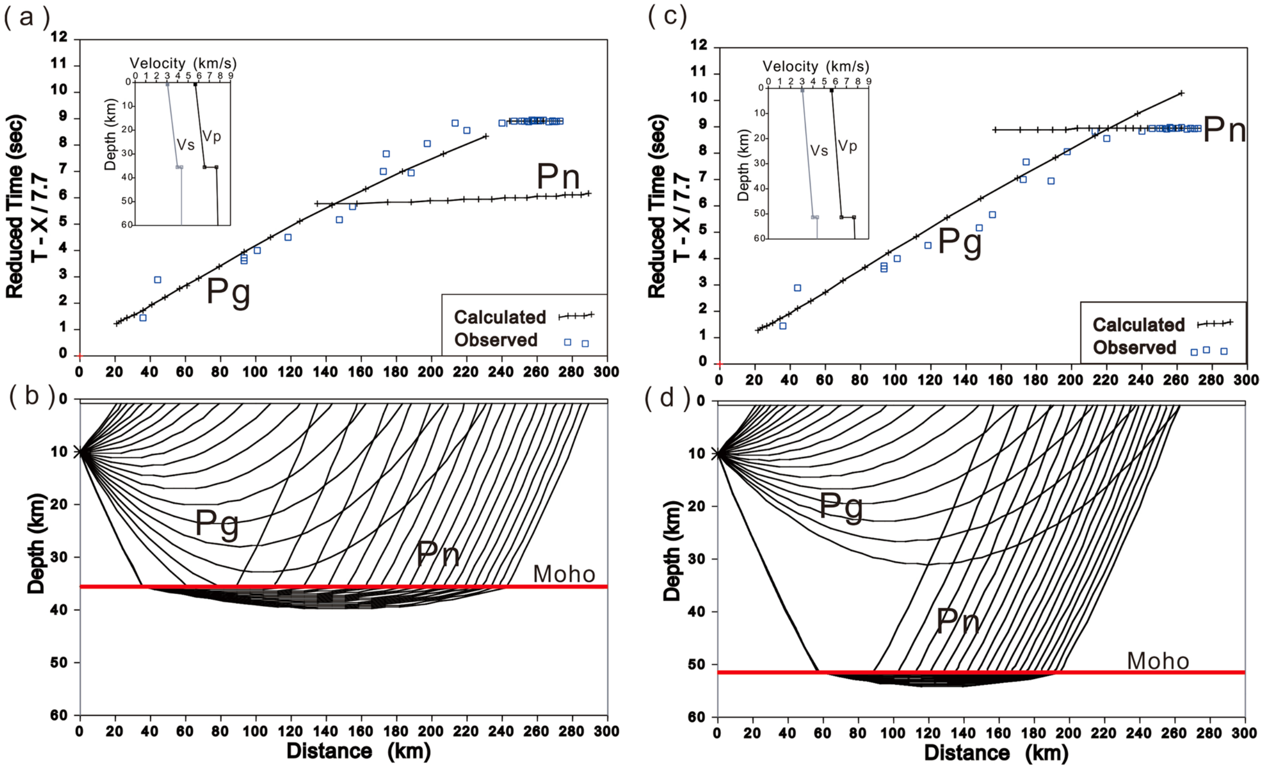


Fig. 10 Comparison of observed and calculated P waves for Event 3. Pg are the direct P-waves and Pn are refracted from the Moho-discontinuity. Calculated results of **a**, **c** the reduced travel-times of **b**, **d** two groups of ray-paths by given the Moho-depth of 36 and 52 km, respectively

tectonic models. One of the most popular models for explaining the mountain building in the Taiwan area is considering the thin-skin model (Suppe 1981), which suggests that the crustal deformation is largely limited at the upper crust and there is no significant deformation below the decollement. A thick crust beneath the Backbone Range does not fully support the thin-skinned model. By contrast, the thick crust is more consistent with those models that suggest the lithospheric deformation occurred during the plate convergence in the Taiwan area (e.g., Lin and Roecker 1993; Wu et al. 1997; Chemenda et al. 1997; Lin 2002; Ustaszewski et al. 2012; Kuo-Chen et al. 2012). However, more detailed subsurface structures are still necessary for improving the understanding of the tectonic model of the Taiwan orogeny in the future.

6 Conclusion

Careful examination of the seismic data recorded at a dense seismic array (Formosa Array) in the northern Taiwan area shows the Moho-refracted P waves (Pn) as well as the directed P-waves (Pg) generated by four strong earthquakes located at central and southern Taiwan were well identified. Although the refracted seismic energy is often small at each individual station, the waveform similarity recorded at the nearby stations provides a reliable method for estimating the apparent velocity recorded by the dense seismic array. The forward modeling of the Pn and Pg gives a larger crustal thickness beneath the Backbone Ranges (~52 km) than beneath the adjacent Hsuehshan Ranges (~36 km). Such a result is not only confirming the Moho variations along a few of the NW-SE profiles from the previous studies, but also showing a large Moho-depth variation is well extended along the NE-SW directions. It indicates the lower crust beneath the Hsuehshan Range may not be strongly deformed, even the topographic relief is significant. But the thick crust beneath the Backbone ridge shows both the upper and lower crusts are significantly deformed. Such a large change in the crustal thickness across the Taiwan orogeny strongly indicate that the orogenic deformation in Taiwan might be not only limited with the shallow crust, but also the deep crust and upper mantle. Also, the Taiwan orogeny might not be reaching to the isostatic equilibrium yet.

7 Data and resources

The seismic data used in this study were collected by the Institute of Earth Sciences, Academia Sinica. Some plots were made using the Generic Mapping Tools

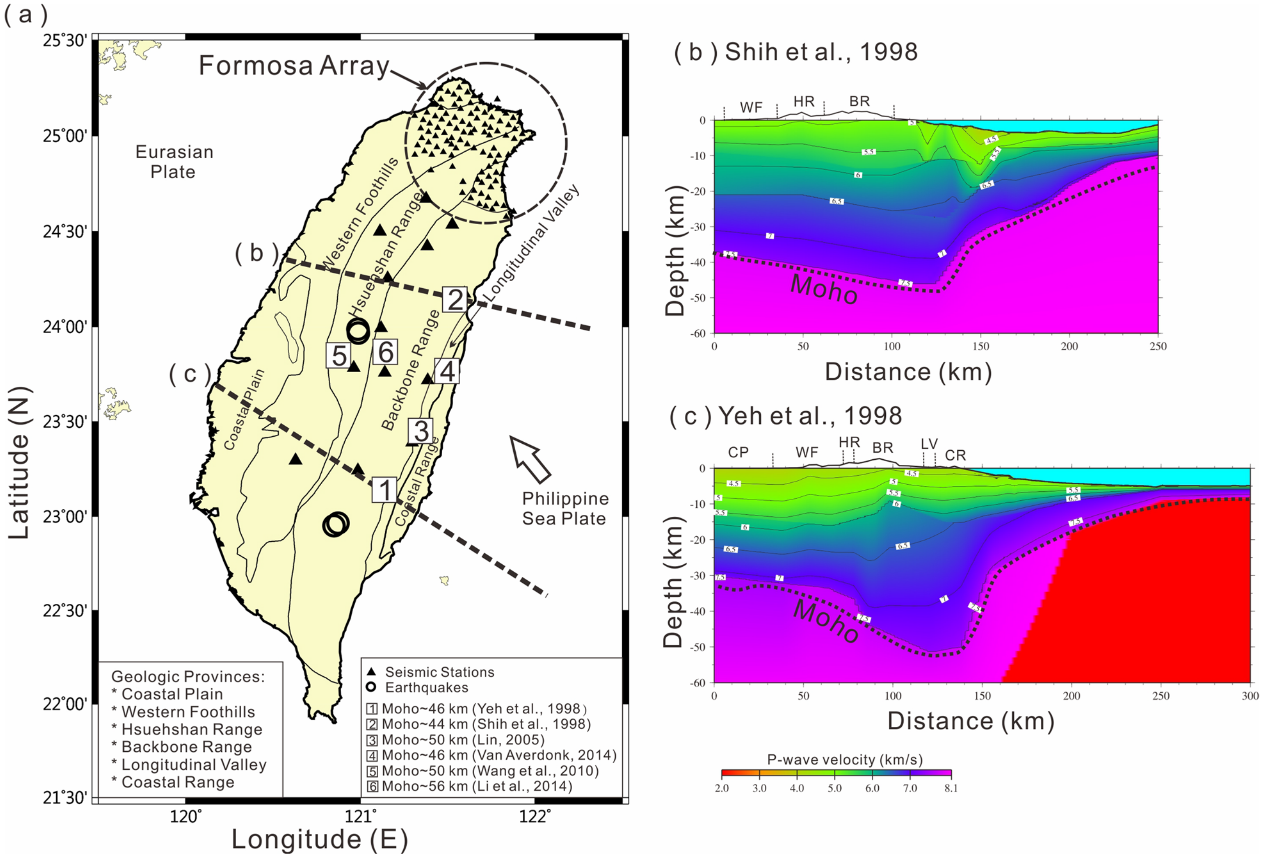


Fig. 11 Comparison of Moho-depths between this study and some previous results. **a** Geological provinces and locations of both the Formosa Array and some BATS seismic stations in Taiwan. Locations of the deepest crustal thickness were obtained from previous studies (Number 1–6). Dashed lines with arrows show the crustal thickness obtained in this study along the representative paths of Moho-refractions beneath the Backbone Range and Hsuehshan Range. **b**, **c** are velocity profiles obtained from Shih et al. (1998) and Yeh et al. (1998b), respectively

(version 4.5.18; https://www.generic-mapping-tools.org/download) and the SAC software (version 101.5; URL:ds.iris.edu).

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Author contributions
MHS and YCL collected the data and participated in the discussion; CHL analyzed the data and wrote the paper. All authors read and approved the final manuscript.

Declarations

Competing interests
The authors declare that they have no competing interests (including both financial and non-financial interests).

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References

Berg JW, Long LT (1966) Characteristics of refracted arrivals of seismic waves. J Geophy Res 71:2583–2589

Bonilla MG (1975) A review of recent active faults in Taiwan, United States Geological Survey Open File Report, 75–41, 58 pp

Chemenda AI, Yang RK, Hsieh CH, Groholsky AL (1997) Evolutionary model for the Taiwan collision based on physical modelling. Tectonophysics 274:253–274. https://doi.org/10.1016/S0040-1951(97)00025-5

Chen YL (1995). Three-dimensional velocity structure and kinematic analysis in the Taiwan area, PhD thesis, National Central University, Jungli, Taiwan

Chen YL, Shin TC (1998) Study on the earthquake location of 3-D velocity structure in the Taiwan area. Meteorol Bull 42:135–169

Chen WP, Yang Z (2004) Earthquakes beneath the Himalayas and Tibet: evidence for strong lithospheric mantle. Science 304:1949–1952. https://doi.org/10.1126/science.1097324

Goyal A, Hung SH (2021) Lateral variations of Moho depth and average crustal properties across the Taiwan orogen from H-V stacking of P and S receiver functions. Geochem Geophys Geosyst 22:e2020GC009527

Hetenyi G, Plomerova I, Bianchi HK, Enerova G, Bokelmann MR (2018) V. Handy and AlpArray-EASI working group, : From mountain summits to roots: Crustal structure of the Eastern Alps and Bohemian Massif along longitude 13.3 E. Tectonophysics 744:239–255. https://doi.org/10.1016/j.tecto.2018.07.001

Ho CS (1988) An introduction to the geology of Taiwan—explanatory text of the geologic map of Taiwan, 2nd edn. Taipei, Ministry of Economic Affairs, p 192

Holt WE, Wallace TC (1990) Crustal thickness and upper mantle velocities in the tibetan Plateau Region from the inversion of regional pnl waveforms: evidence for a thick upper mantle lid beneath southern Tibet. J Geophy Res 95:12499. https://doi.org/10.1029/JB095iB08p12499

Huang HH, Wu YM, Song XD, Chang CH, Lee SJ, Chang TM, Hsieh HH (2014) Joint vp and vs tomography of Taiwan: implications for subduction-collision orogeny. Earth Planet Sci Lett 392:177–191. https://doi.org/10.1016/j.epsl.2014.02.026

Huang HH, Wu ES, Lin CH, Ko YT, Shih MH, Koulakov I (2021) Unveiling Tatun volcanic plumbing structure induced by post-collisional extension of Taiwan mountain belt. Sci Rep 11:5286. https://doi.org/10.1038/s41598-021-84763-z)

Kao H, Jian PR, Ma KF, Huang BS, Liu CC (1998) Moment-tensor inversion for offshore earthquakes east of Taiwan and their implications to regional collision. Geophy Res Lett 25:3619–3622. https://doi.org/10.1029/98GL02803

Kuo-Chen H, Wu FT, Roecker SW (2012) Three-dimensional P velocity structures of the lithosphere beneath Taiwan from the analysis of TAIGER and related seismic data sets. J Geophys Res 117:B06306. https://doi.org/10.1029/2011JB009108

Lallemand S, Font Y, Bijwaard H, Kao H (2001) New insights on 3-D plates interaction near Taiwan from tomography and tectonic implications. Tectonophysics 335:229–253. https://doi.org/10.1016/S0040-1951(01)00071-3

Li ZW, Roecker S, Kim KH, Xu Y, Hao T (2014) Moho depth variations in the Taiwan orogeny from join inversion of seismic arrival time and bouguer gravity data. Tectonophysics 632:151–159. https://doi.org/10.1016/j.tecto.2014.06.009

Lin CH (2002) Active continental subduction and crustal exhumation: the Taiwan orogeny. Terr Nova 14:281–287. https://doi.org/10.1046/j.1365-3121.2002.00421.x

Lin CH (2005) Identification of mantle reflections from a dense linear seismic array: tectonic implications to the Taiwan orogeny. Geophy Res Lett 32:L06315. https://doi.org/10.1029/2004GL021814

Lin CH (2016) Evidence for a magma reservoir beneath the Taipei metropolis of Taiwan from both S-wave shadows and P-wave delays. Sci Rep 6:39500. https://doi.org/10.1038/srep39500

Lin CH, Roecker SW (1993) Deep earthquakes beneath central Taiwan: Mantle shearing in an acr-continent collision. Tectonics 12:745–755. https://doi.org/10.1029/92TC02812

Lin CH, Yeh YH, Yen HY, Chen KC, Huang BS, Roecker SW, Chiu JM (1998) Three-dimensional elastic wave velocity structure of the Hualien region of Taiwan: evidence of active crustal exhumation. Tectonics 17:89–103. https://doi.org/10.1029/97TC02510

Lin CH, Huang BS, Rau RJ (1999) Seismological evidence for a low-velocity layer within the subducted slab of southern Taiwan. Earth Planet Sci Lett 174:231–240. https://doi.org/10.1016/S0012-821X(99)00255-1

Lin CW, Chan HC, Lu ST et al (2000) An introduction to the active faults of Taiwan, vol 13, 2nd edn. Spec. Publ. Cent. Geol. Survey 13, 1–122

Lin CH, Shih MH, Lai YC (2020) Mantle wedge diapirs detected by a dense seismic array in northern Taiwan. Sci Rep 11:1561. https://doi.org/10.1007/s00024-019-02396-w

Luetgert JH (1992) Interactive two-dimensional seismic raytracing for the Macintosh. USGS open-file report 92–356, 43 pp

Ma KF, Song DR (1997) Pn velocity and moho depth in Taiwan. J Geol Soc China 40:167–183

Malavieille J, Lallemand SE, Dominguez S et al (2002) Arc-continent collision in Taiwan: New marine observations and tectonic evolution. Spec Pap Geol Soc Am 358:189–213

Ota Y, Chen YG, Chen WS (2005) Review of paleoseismological and active fault studies in Taiwan in the light of the Chichi earthquake of September 21, 1999. Tectonophysics 409:63–77. https://doi.org/10.1016/j.tecto.2005.05.040

Rau RJ, Wu FT (1995) Tomographic imaging of lithospheric structures under Taiwan. Earth Planet Sci Lett 133:517–532. https://doi.org/10.1016/0012-821X(95)00076-O

Roecker SWYH, Yeh, Tsai YB (1987) Three-dimensional P and S wave velocity structures beneath Taiwan – deep structure beneath an arc-continent collision. J Geophys Res 92:547–10570. https://doi.org/10.1029/JB092iB10p10547

Seno T (1977) The instantaneous rotation vector of the Philippine Sea plate relative to the eurasian plate. Tectonophysics 42:209–226. https://doi.org/10.1016/0040-1951(77)90168-8

Sharma MD, Kaushik VP, Gogna ML (1990) Reflection and refraction of plane waves at an interface between liquid-saturated porous solid and viscoelastic solid. Quart J Mech Appl Math 43:427–448. https://doi.org/10.1093/qjmam/43.4.427

Shih RC, Lin CH, Lai HL, Yeh YH, Huang BS, Yen HY (1998) Preliminary crustal structures across Central Taiwan from modeling of the onshore-offshore wide-angle seismic data. Terr Atmos Ocean Sci 9:317–328

Shin TC, Kuo KW, Lee WHK, Teng TL, Tsai YB (2000) A preliminary report on the 1999 Chi-Chi (Taiwan) earthquake. Seis Res Lett 71:24–30. https://doi.org/10.1785/gssrl.71.1.24

Suppe J (1981) Mechanics of mountain building in Taiwan. Mem Geol Soc of China 4:67–89

Teng LS, Lee CT, Tsai YB, Hsiao LY (2000) Slab breakoff as a mechanism for the flipping of subduction polarity in Taiwan. Geology 28:155–158. https://doi.org/10.1130/0091-7613(2000)28

Tsai YB (1986) Seismotectonics of Taiwan. Tectonophysics 125:17–37. https://doi.org/10.1016/0040-1951(86)90005-3

Tsai YB, Ten TL, Chiu JM, Liu HL (1977) Tectonic implications of the seismicity in the Taiwan region. Mem Geol Soc of China 2:13–41

Ustaszewski K, Wu YM, Suppe J, Huang HH, Chang CH, Carena S (2012) Crust-mantle boundaries in the Taiwan-Luzon arc-continent collision system determined from local earthquake tomography and 1D models: implications for the mode of subduction polarity reversal. Tectonophysics 578:31–49. https://doi.org/10.1016/j.tecto.2011.12.029

Van Averdonk HJA, Kuo-Chen H, Mcintosh KD, Lavier LL, Okaya DA, Wu FT, Wang CY, Lee CS, Liu CS (2014) Deep crustal structure of an arc-continent collision: constraints from seismic traveltimes in central Taiwan and the Philippine Sea. J Geophys Res 119:8397–8416. https://doi.org/10.1002/2014JB011327

Wang CY, Shin TC (1998) Illustrating 100 years of Taiwan seismicity. Terr Atm Ocean 9:589–614

Wang HL, Zhu L, Chen HW (2010) Moho depth variation in Taiwan from teleseismic receiver functions. J Asian Earth Sci 37:286–291. https://doi.org/10.1016/j.jseaes.2009.08.015

Wolf A (1936) The amplitude and character of refraction waves. Geophysics 1:319–326

Wu FT, Rau RJ, Salzberg D (1997) Taiwan orogeny: thin-skinned or lithospheric collision? Tectonophysics 274:191–220. https://doi.org/10.1016/S0040-1951(96)00304-6

Wu YM, Chang CH, Zhao L, Shyu JBH, Chen YG, Sieh K, Avouac JP (2007) Seismic tomography of Taiwan: improved constraints from a dense network of strong motion stations. J Geophys Res 112:B08312. https://doi.org/10.1029/2007JB004983

Wu YM, Chang CH, Kuo-Chen K, Huang HH, Wang CY (2013) On the use of explosion records for examining earthquake location uncertainty in Taiwan. Terr Atmos Ocean Sci 24:685–684. https://doi.org/10.3319/TAO.2013.01.31.01(T

Yeh YH, Tsai YB (1981) Crustal structures of central Taiwan from inversion of P-wave arrival times. Bull Inst Earth Sci Acad Sin 1:83–102

Yeh YH, Shih RC, Lin CH, Liu CC, Yen HY, Huang BS, Liu CS, Chen PZ, Huang CS, Wu CJ, Wu FT (1998a) Onshore/offshore wide-angle seismic profiling in Taiwan. Terr Atmos Ocean Sci 9:301–316

Yeh YH, Shih RC, Lin CH, Liu CC, Yen HY, Huang BS, Liu CS, Wu FT (1998b) Onshore/offshore wide-angle deep seismic profiling in Taiwan. Terr Atmos Ocean Sci 9:301–316

Yen HY, Yeh YH, Lin CH, Chen KJ, Tsai YB (1995) Gravity survey of Taiwan. J Phys Earth 43:685–696

Yen HY, Yeh YH, Wu FT (1998) Two-dimensional crustal structures of Taiwan from gravity data. Tectonics 17:104–111. https://doi.org/10.1029/97TC02697

Yu SB, Chen HY, Kuo LC (1997) Velocity field of GPS stations in the Taiwan area. Tectonophysics 274:41–59. https://doi.org/10.1016/S0040-1951(96)00297-1

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