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Significant contribution of the shallow crust to seismic PKP travel-time residuals and implications: An example from Taiwan and nearby islands

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ABSTRACT

Array observations indicate that the relative PKP travel-time residuals in the Taiwan region vary from −2.5 to +2.0 s, a range greater than the largest known teleseismic travel-time residuals from deep Earth. PKP waves are generally employed to probe structures of the deep Earth; however, the contribution of shallow geological structures to PKP waves is generally undefined and the implications of such a contribution have rarely been discussed. Current travel-time tomographic models of Taiwan are able to predict less than 40% of the observed PKP residuals, and the PKP residuals are consistent with the pattern of station corrections used in determining local earthquakes. Detailed island-wide gravity measurements indicate that the distribution of Bouguer anomalies, which were previously proposed to be induced by thick sedimentary deposits in large tectonic basins, is consistent with the pattern of PKP travel-time residuals. In conclusion, the observed PKP residuals are strongly affected by shallow sediments. Therefore, the contribution of residuals from shallow crustal structures should be carefully considered when employing PKP observations for imaging structures of the deep Earth or the deep crust and upper mantle.

1. Introduction

Seismic travel-time residuals are commonly employed to infer crustal structures in complex tectonic regions and to quantify spatial variations in the Moho depth and upper mantle structures (Iyer, 1975; Hadley and Kanamori, 1977; Kohler and Davis, 1997). Making use of local, regional, and teleseismic observations, seismic tomography methods enable researchers to determine the 3-D Earth structure based on the minimization of the travel time residuals of seismic waves (Dziewonski, 1984; Humphreys and Clayton, 1990; Zhao and Hasegawa, 1994; Rau and Wu, 1995; Ma et al., 1996; Kim et al., 2005; Wu et al., 2007). Limited by spatial resolution of observations, the effect of the shallow crust, one of the most heterogeneous layers of the Earth, on the seismic tomography results, remains poorly understood.

Teleseismic P-waves that penetrate the Earth's core and arrive at a given station onto the surface with a near-vertical incident angle are referred to as PKP waves, of which three types are recognized: PKP(AB), which bottom in the outermost part of the inner core, PKP(DF), which pass through the inner core and PKP(BC), which pass through the base of the outer core and becomes as a diffraction wave with epicentral distance greater than 156° (Huang, 1996). The approaching waves of PKP(DF) phase (Fig. 1a) have essentially a planar wavefront from the deep mantle to the surface within a typical regional seismic array. Relative travel time residuals of PKP phases within seismic array are generally regarded as invaluable when probing deep structures within the Earth (Green and Meyer, 1992). In direct contrast to ray paths from local and regional events, PKP waves provide deep paths with which to sample the Earth. In addition, near-vertical incident PKP(DF) waves are less affected by lateral variations in the surrounding seismic structure, except for seismic velocity structure beneath the seismic array station. Thus, PKP(DF) phase allows for the clear identification of lateral variations in deep Earth structure beneath an array and has been selected for future analysis by this study.

PKP(DF) waves yield integrated travel-time residuals beneath each station, from the deep Earth to the surface, meaning that PKP(DF) observations provide an independent data set with which to examine the travel time residuals of 3-D Earth models determined from tomography inversions using local or regional seismic data. Ideally, such observations would provide an opportunity to independently examine either seismic velocity models from different approaches or regional tectonic models based on a variety of

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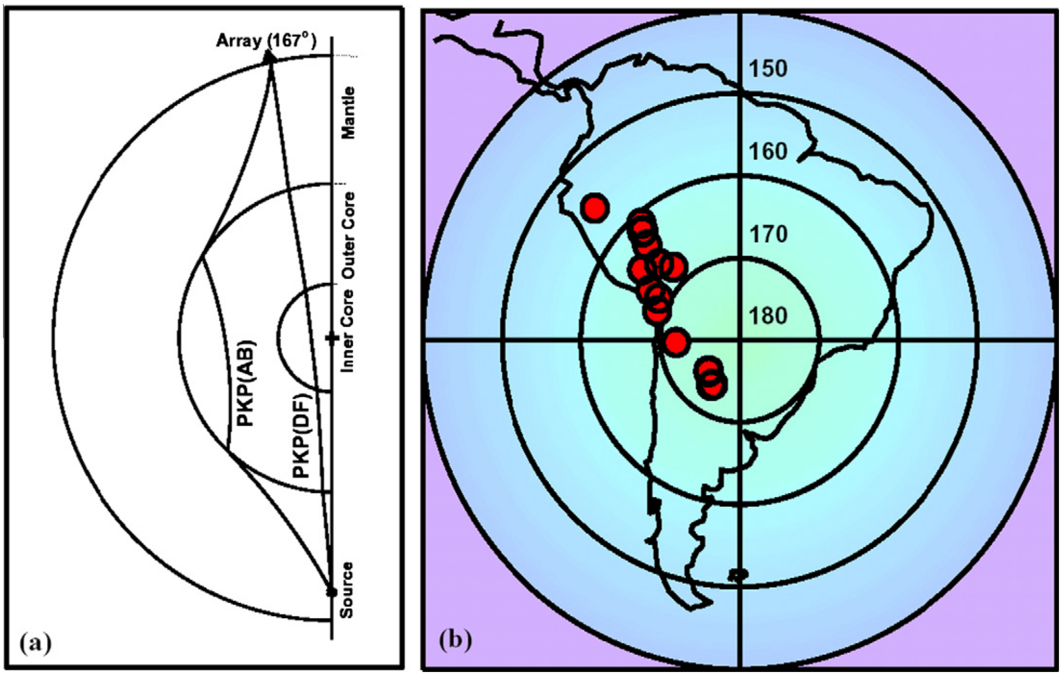

Fig. 1. (a) Schematic diagram showing the ray paths of PKP(DF) and PKP(AB) within the Earth, from a deep event in South America to the seismic array in Taiwan. (b) Azimuthal distribution of the 16 events (red circles) analyzed in the present study (Table 1). The numbers within circles represent epicentral distances from the center of the seismic array in Taiwan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

geodynamic hypotheses; however, PKP(DF) travel-time residuals are influenced not only by deep structures beneath seismic array, but by the low-velocity sedimentary layer beneath each station. This means that in employing PKP(DF) residuals to determine deep structures, errors will automatically be mapped as a deep anomalous structure if the contribution of shallow structures is not carefully corrected.

Because the crust of Taiwan Island is characterized by heterogeneous surface geology (Ho, 1988), the stations in an island-wide seismic network are located in contrasting geological settings, with many stations located in the Western Plain area, which is covered by Quaternary sediments of variable thickness and soil properties. It was anticipated that the observed PKP(DF) travel-time residuals obtained from the stations located in the Western Plain would be affected by the great thickness of underlying low-velocity sediments. As a general rule, low-velocity sedimentary layers have an influence on seismic array observations; however, the significance of travel time residuals from shallow structures, and their seismological implications, has received little attention in the literature (Mori and Frankel, 1992).

The aim of this study is to identify the origin of PKP(DF) residuals observed in Taiwan. We investigate the relationship between the PKP(DF) residuals and local gravity anomalies, network station corrections, and synthetic residuals from updated seismic tomography models. Our findings indicate that PKP(DF) residuals are strongly affected by shallow structures near the station of interest. A detailed analysis of these residuals may provide significant background information for further studies concerning seismic structures, estimates of hypocenter locations and predictions of strong motions.

2. Data

The Central Weather Bureau Seismic Network (CWBSN) is a regional network of 75 digitally telemetered seismic stations covering Taiwan and offshore islands in their entirety, designed to monitor local earthquakes. Each station is equipped with a set of three-component short-period velocity sensors (Teledyne S-13) with a peak amplitude response near 1 Hz and is operated in trigger mode at a sampling rate of 100 Hz. The location of Taiwan means that CWBSN is an excellent array for core phase observations, particularly for deep events that occur in subduction zones within South America. Furthermore, the small spacing between CWBSN stations (about 25 km) allows for teleseismic short-period array waveform studies. Teleseismic events are poorly recorded by the CWBSN trigger-mode detection; however, network data are continuously recorded at the Institute of Earth Sciences, Academia Sinica (IESAS), Taiwan. The recording is set in continuous mode to observe major teleseismic events (Huang et al., 1996). Large deep events at a distance greater than 140° from South America are well recorded on the IESAS continuous data string. These seismic core phases have been employed to study the structure of the Earth's core (Tseng et al., 2001) and the rupture mechanisms of deep earthquakes (Huang, 2002).

In the present study, we selected 16 events that occurred in South America, with epicentral distances greater than 155°, with which to analyze the PKP travel-time residuals around the Taiwan area (Table 1). Fig. 1b shows the epicentral distribution of these events based on the Preliminary Determination of Epicenters (PDE) of the United States Geological Survey (USGS), and Fig. 2 shows the array seismograms from one of the selected deep events with a distance close to 166°. The two branches of PKP waves [i.e., PKP(DF) and PKP(AB)] are commonly recorded in the same seismogram, and both the PKP(DF) and PKP(AB) phases sample the crust and mantle nearly identically (Fig. 1a). However, the PKP(AB) branch has a near-grazing incidence to the Earth's outer core (Fig. 1a) and because its travel times and waveforms are sensitive to lateral heterogeneity at the base of the mantle, while PKP(DF) with its near-normal incidence is less sensitive to the core–mantle structure. In this study, we only analyze relative travel times from PKP(DF), for which the ray paths penetrate the inner core and arrive at the Earth's surface as first arrivals. No absolute timing of

Table 1
Selected events analyzed in the present study.

No.	Date time	Lat.	Long.	Dist	Baz	Dep	Mb	Location
1	870808154856.7	19.022S	69.991W	168.8	68.6	70	6.4	Northern Chile
2	890505182839.4	8.281S	71.381W	160.8	40.1	593	6.4	Western Brazil
3	901017143013.1	10.970S	70.776W	163.2	44.0	599	6.7	Peru–Brazil Border Reg
4	910405041949.5	5.982S	77.094W	155.4	47.8	20	6.5	Northern Peru
5	910524205055.4	16.483S	70.718W	167.0	59.8	125	6.3	Southern Peru
6	910623212230.7	26.820S	63.403W	174.8	130.6	581	6.4	Santiago Delestero Prov
7	910706121900.0	13.900S	71.600W	164.7	53.5	120	6.4	Peru Iris
8	940110155349.6	13.310S	69.387W	165.9	46.0	589	6.4	Peru–Bolivia Border Reg
9	940609003316.4	13.834S	67.563W	167.4	41.6	637	6.9	North Bolivia
10	940524235119.0	23.000S	67.700W	172.0	88.2	200	6.6	Jujuy Province, Argentina
11	940429071129.0	28.400S	62.800W	174.0	145.8	571	5.8	Santiago Del Estero Prov
12	940510063628.7	28.498S	63.060W	173.8	144.6	605	6.4	Santiago Del Estero Prov
13	940819100251.8	26.653S	63.378W	174.9	129.2	565	6.4	Santiago Del Estero Prov
14	941104011320.0	9.200S	71.200W	161.6	41.4	595	5.7	Peru–Brazil Border Reg
15	941105120528.9	9.304S	71.324W	161.6	41.9	597	5.6	Peru–Brazil Border Reg
16	941212074155.4	17.504S	69.650W	168.4	61.1	151	5.8	Peru–Bolivia Border Reg

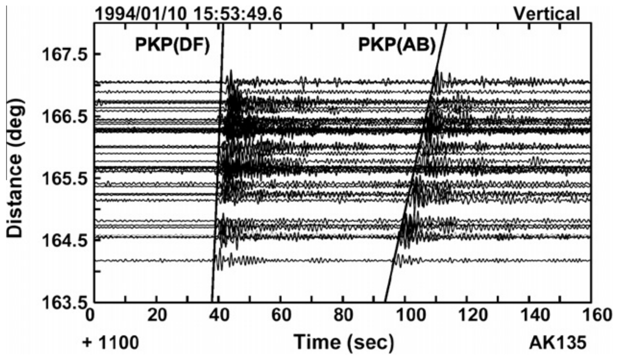

Fig. 2. Array seismograms of a selected event analyzed in the present study (location = 10.970°S, 70.776°W; depth = 599 km, $M_b = 6.7$ after PDE). Solid lines represent the theoretical travel times of PKP phases, as predicted by the AK135 model (Kennett et al., 1995). The corresponding ray paths of this event are shown in Fig. 1a. The seismograms were filtered with a signal band (0.5–2.0 Hz) and normalized individually.

PKP(DF) arrivals were analyzed, thus our results are sensitive to structure of the receiver site only.

3. Analysis and results

To determine the travel times of the PKP waves, the seismograms were filtered between 0.5 and 2.0 Hz, and phase pickings were performed using the multi-channel cross-correlation method (Van Decar and Crosson, 1990). The relative picking errors were minimized by least squares fitting. Although the precision of manual or single-trace automated picking allows the same gross features in the data to be observed, however, the increased accuracy of cross-correlation derived arrival times allows subtler details to be resolved. Based on trials using different subsets of array seismograms, we have found that for reasonably high-quality events, the root mean square uncertainty in arrival time estimates is on the order of 0.05 s. The travel time residual, in this study, is defined as observed time minus predicted time. Positive residuals indicate that seismic velocities of the real Earth are slower than those in the reference model. The predicted times were computed using the AK135 model (Kennett et al., 1995). Then, for each event, the relative residuals with respect to the mean of all stations were computed to eliminate errors induced by source mislocation, absolute time uncertainty, and differences between the real Earth and the standard model outside the target area. Furthermore, the travel time residuals were adjusted to sea level using 5.8 km/s as an

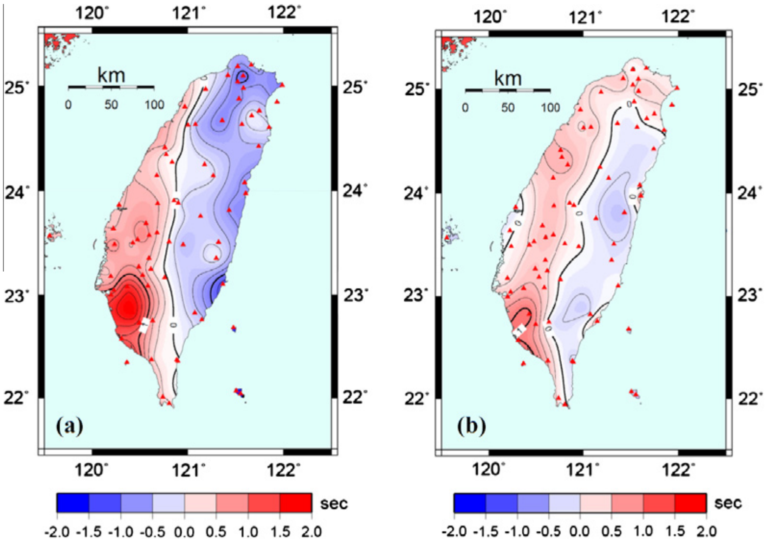

Fig. 3. (a) Contour map of stacked PKP travel-time residuals for all recording stations. (b) Contour map of network station corrections for all recording stations. Contour interval is 0.25 s. Triangles represent seismic stations. Positive residuals indicate that seismic velocities of the real Earth are slower than those in the reference model.

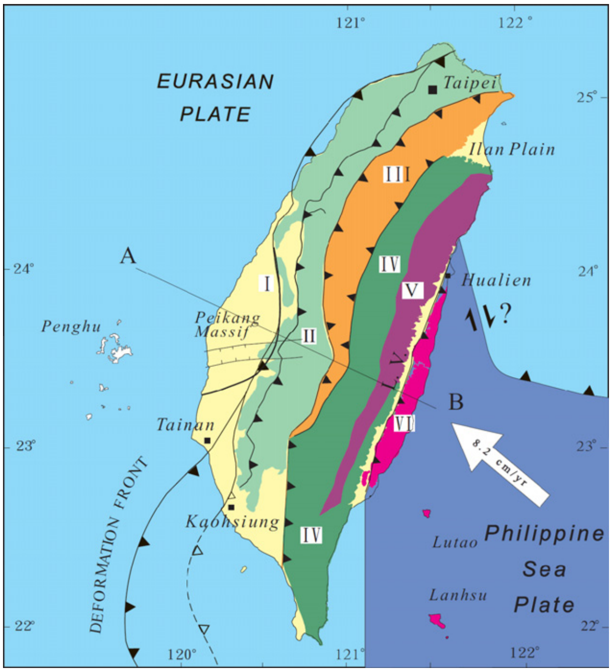

Fig. 4. The Tectonic framework with a general geological map of Taiwan (modified from Teng (1990) and Lee et al. (2002)). Rock units I to V belong to the Euroasia plate. I: the Western plain, II: Foothills, III: the Hsuehshang Range, IV: the Backborn Range, V: the Tananao metamorphic basement; and Rock unit VI: the Coastal Range belongs to the Philippine Sea plate.

upper crustal velocity (Kennett et al., 1995). The largest elevation correction was 0.6 s for station YUS of CWBSN located at central range of Taiwan. A station with a high signal-to-noise ratio was selected as a reference (station TWK1 of CWBSN). The residuals of other stations were then reduced by the value of this reference station. Following these corrections, the relative PKP(DF) travel-time residuals for each event possessed a common time base. All of the estimations from the different events showed a similar pattern. In the final stage, the travel time residuals were stacked to reduce measurement errors (see Fig. 3a). The values of the travel time residuals range from −2.0 to +1.6 s for Taiwan Island and from −2.5 to +2.0 s when nearby islands are included.

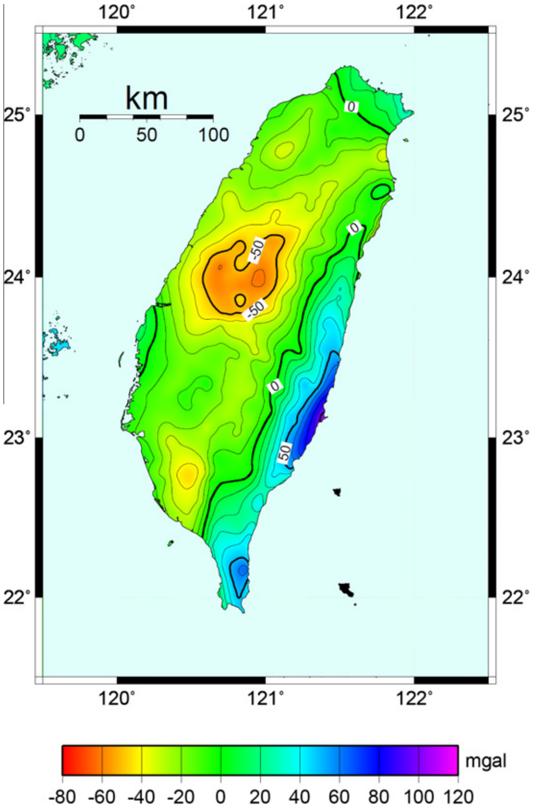

Fig. 6. The Bouguer gravity anomaly map of Taiwan (Yen et al., 1995). Contour interval is 10 mgal.

The most significant finding of this analysis is that relative PKP(DF) travel-time variations are related to the surface geology of Taiwan (Fig. 4). The data show a high degree of consistency, positive travel-time residuals are related to unconsolidated shallow-level deposits, such as alluvium and soil. Large residuals are usually obtained for deep sedimentary basins, such as those in northeastern and southwestern Taiwan. Negative travel-time residuals, on the other hand, are associated with bedrock sites, as in central Taiwan.

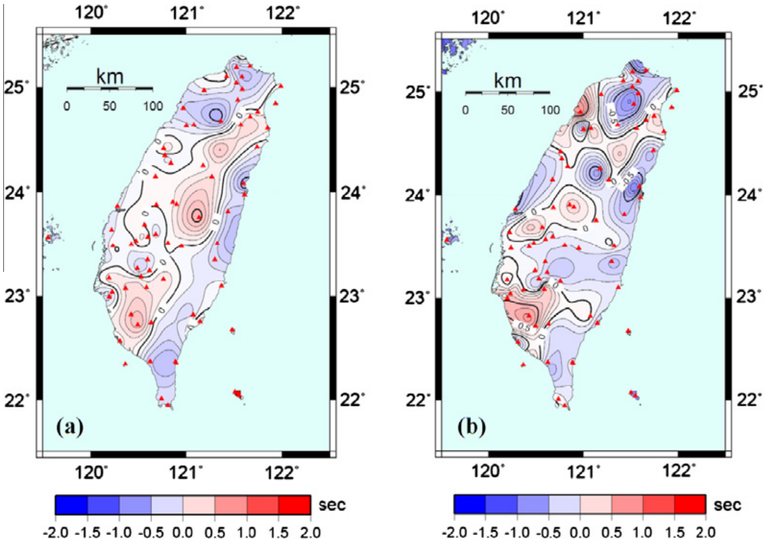

Fig. 5. Contour maps of synthetic travel-time residuals from the 3-D crustal models proposed by Kim et al. (2005) (a) and Wu et al. (2007) (b). Contour interval is 0.1 s.

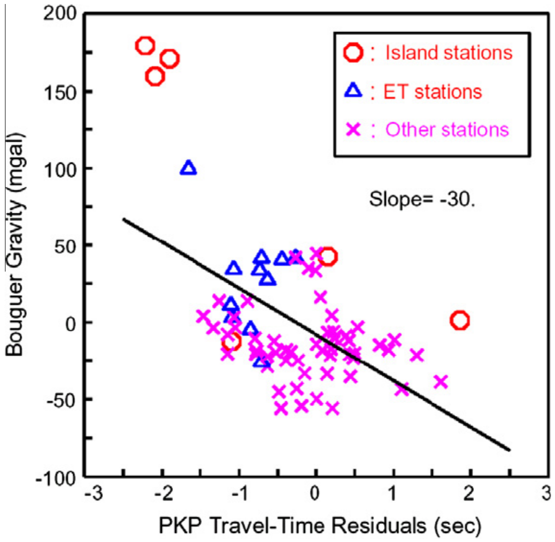

Fig. 7. Relationship between PKP residuals and Bouguer gravity data extracted at the locations of seismic station. Open circles represent data observed at island stations. Open triangles represent data observed in eastern Taiwan; crosses indicate data observed in other areas of Taiwan. The solid line is the least-squares fitting of the data.

The observed PKP(DF) travel-time residuals were compared with those from station corrections that had previously been used by CWBSN to determine earthquake locations using a 1-D Earth model (Ho, 1994). The pattern of these station corrections is shown in Fig. 3b, comprising travel-time residuals ranging from −0.43 to +1.57 s that were induced near seismic stations. Similarly to the data in Fig. 3a, these variations are related to the surface geology, although a major difference between the two data sets is that some regional negative variations in the PKP travel-time residuals in northern and eastern Taiwan are apparently unrelated to the regional surface geology (Fig. 4). Therefore, these anomalies may be attributed to the effects of the deep crust and/or upper mantle. Recently, using dense seismic linear array observations, Chen et al. (2011) identified a east-dipping fast anomaly beneath the upper mantle of the southern Taiwan. It indicates seismic wave propagation in the upper mantle beneath southeastern Taiwan should be faster than that in the western part of Taiwan. This result consists with our observation of negative relative PKP travel-time residuals in eastern Taiwan.

To estimate the possible PKP travel-time residuals from the Earth's crust, we employed two recent 3-D crustal models from tomographic inversion studies (Kim et al., 2005; Wu et al., 2007). Both models determined P- and S-wave velocity structures of crust and uppermost mantle beneath Taiwan using seismic observations based on local events determined by CWBSN. No events within teleseismic distance ranges (30–90°) or events with core phases were employed to invert both 3-D crustal models. In each selected location within the models, the synthetic PKP travel-time residuals contributed by the crust were considered as the integrated travel times from the base of the crust to the free surface, assuming a vertically incident seismic wave. Each residual computed in this way was considered to have been induced by seismic velocity variations beneath the station but was considered to have been unaffected by the surrounding seismic velocity structure.

Fig. 5 shows the travel time residuals determined from both 3-D crustal models. It is found that the overall patterns are not consistent with the PKP travel-time residuals (Fig. 3a), although both models reflect a similar pattern of residuals from deep sedimentary basins in northeastern and southwestern Taiwan. Furthermore, the residuals from both models are less than ±0.8 s, which is approximately 40% of the observed PKP travel-time residuals (Fig. 3a).

The observed PKP residuals (Fig. 3a) are greater than those in many other regions. For example, teleseismic relative travel-time residuals from Japan and southern California range from −0.8 to +0.8 s and from −0.68 to +0.65 s, respectively (Humphreys and Clayton, 1990; Zhao and Hasegawa, 1994). The travel time residuals in these areas are less than 36% of the values determined in the Taiwan area. One of reasons for this discrepancy is that observed seismic residuals in Taiwan region which included many measurements from deep sedimentary plain and basins. In a similar case of Taiwan, some observations showed that a single basin can contribute up to 0.5 s in teleseismic travel time residuals (Tkalcic et al., 2008). Controversially, if we assume no influence from shallow sediment, more than half observed PKP travel-time residuals (Fig. 3a) should be considered to be induced by lateral variations in mantle structures.

The observed PKP travel-time residuals (Fig. 3a) show mainly opposite in sign pattern to the Bouguer gravity anomaly over Taiwan (Fig. 6); thus, it can be assumed that a more strongly negative Bouguer anomaly corresponds to a larger travel-time residual. The extracted gravity data at seismic stations were regressed against the PKP travel-time residuals (Fig. 7), yielding an apparent linear relationship with a least-squares slope of −30.0 mgal/s, although some observations on offshore islands plot away from this trend. A linear relationship was expected because the Bouguer anomaly is strongly affected by near-surface sediments (Yen et al., 1995). The scatter in Fig. 7 may reflect, at least in part, uncertainties in the data sets; however, it seems unlikely that the high Bouguer gravity values with negative PKP travel-time residuals in eastern Taiwan can be fully explained by near-surface features. Alternatively, the scatter may indicate lateral heterogeneity in deep-level structure.

4. Discussion and conclusions

The present results provide a clear image of the relative PKP travel-time residuals in Taiwan. It is reasonable to conclude that PKP travel-time residuals are strongly affected by travel time residuals within shallow sediments. Mori and Frankel (1992) reported similar observations for southern California and discussed the correlation between travel time residuals and the seismic amplification of teleseismic waves, proposing that many of the travel time anomalies recorded at non-bedrock sites can be well explained in terms of a near-surface layer with heterogeneous velocity. Hence, based on array observations of core phase travel-time residuals, it is possible to obtain additional information on the lateral heterogeneity of the uppermost crust. This information on the near-surface low-velocity layer can be used to correct station residuals and, in the process, an earthquake hypocenter located in an area of thick sediments can be accurately determined, because routine local earthquake determination in Taiwan assumes a laterally homogeneous (1-D layered crust) structure. Of course, some observations in Taiwan and surrounding islands cannot be accounted for by near-surface features and should be considered to reflect lateral heterogeneity of deep Earth structures, such as slab subduction beneath northern Taiwan and arc–continent collision located east of Taiwan. Furthermore, the relative travel-time residuals determined from two islands located east and west of southern Taiwan (within 150 km of Taiwan) are greater than 4 s (Fig. 7). Although the surface geology differs among these offshore islands, it is difficult to explain the travel time residuals solely in terms of the shallow structure. It is likely that lateral variations in the structure of the deep crust and upper mantle make a significant contribution to these PKP travel-time residuals.

The PKP travel-time residuals were underestimated by both of the 3-D crustal models of Taiwan (Kim et al., 2005; Wu et al., 2007), although these models have been successful in explaining the deep crustal structure and in constructing tectonic models. This underestimate may reflect the fact that the models were constructed from tomographic inversions using local earthquake events. Moreover, given the limited number of available stations, to construct optimal models it is necessary to include coarse grids and station corrections in order to obtain stable results.

The inverted 3-D crustal models do not include shallow low-velocity layers of sediments: they only represent lateral variations within the deep crust. Hence, while these models may be deemed successful with regard to tectonic interpretations, they are unsuitable for use in modeling the propagation of strong ground motions because near-surface low-velocity layers, which were not included in the tomographic models, make a significant contribution to the amplification of strong ground motions during large, shallow earthquakes, such as the 1999 Chi–Chi, Taiwan earthquake. Thus, predictions of strong motion based on numerical modeling for 3-D wave propagation require detailed information on shallow-level sedimentary layers. The PKP waves travel time residuals obtained in this study, which showed strongly correlated to shallow layer structures, may provide extra constrain to the ground motion prediction for seismic hazard evaluation.

The Taiwan region, which is situated in an area of active arc–continent collision in the west Pacific, is characterized by oblique subduction, regional collision, and back-arc opening (Lallemand et al., 2001). The portion of Taiwan Island experiencing orogenesis is not only the entire crust but also the upper mantle. Teleseismic observations are crucial in terms of understanding the deep structure of Taiwan. The present results show that travel time residuals of PKP(DF) phases from thick sediments should be carefully determined before analyzing teleseismic travel-time residuals as a means of interpreting deep Earth structures. Limited teleseismic P-wave observations from Taiwan region to analyze the deep mantle structure have shown the significance of shallow structure with a low velocity anomaly to affect interpretations (Chen et al., 2004, 2011). However, those teleseismic P-wave residuals shows more complex pattern than PKP(DF) phases for the reason of their dipping incidences which incident waves sample different regions of upper mantle. Till now, both observed PKP and teleseismic P-wave residuals in Taiwan region do not analyze systematically for shallow structure yet. To understand the deep structures beneath Taiwan, it is necessary to perform further investigations that seek to integrate gravity data, deep seismic reflection data, and earthquake information from local and regional events. Furthermore, ambient noise and receiver function analyses (Huang et al., 2010; Wang et al., 2010) may be useful to verify the contribution of shallow layer structure. In Taiwan region, limited shear-wave splitting analyses from SKS waves have been reported for the lateral variation of the upper mantle structure (Huang et al., 2006), however, not any travel time residuals from ScS, SKS or teleseismic S waves are reported for seismic velocity structure analysis. It would be interesting to compare them to teleseismic P wave and PKP residuals to reveal important physical parameters, thus S-wave structure and Vp/Vs ratio in the crust, in the near future.

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