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Re-Examining Source Parameters of the 2012 Wutai, Taiwan Earthquake

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ABSTRACT

On 26 February 2012, an inland M_L 6.4 earthquake occurred near Wutai Township in Pingtung County, Taiwan and caused massive shaking in southern Taiwan. After the 2010 M_L 6.4 Jiasian earthquake caused extensive damage in southern Taiwan, deep, complicated structures were revealed. This earthquake provided us an opportunity to further investigate related tectonic issues and hazard mitigation. Although the focal mechanisms of the Wutai earthquake from various institutes's readings were quite consistent, a large uncertainty was present with regard to focal depth. The relocated source parameters suggest a deeper depth of 32.3 km and a focal mechanism of a 326° strike, a 35° dip, and a 57° rake. Based on the tectonic seismic profile in southern Taiwan, the hypocenter of the Wutai earthquake is therefore likely located in the lower crust and implied that the deep blind fault system under the southwestern Central Range could even go deeper southward, revealing complicated thick-skinned tectonics. In addition, due to the abundance records of the *P*-wave first-motion polarities collected, we also tested the feasibility of searching the source depth by a polarity fitting for which we demonstrated several synthetic tests and showed its strength. In applying the polarity fitting method to the real case of Wutai earthquake, the results indicated that this approach may be affected by the uncertainty of the epicenter sensitively. However, the application showed the potential that a large number of polarity data existing in earthquake catalog does not only dedicate to determine the focal mechanisms conventionally but may also contribute to the source location in the future.

Key words: Wutai Earthquake, Earthquake relocation, Focal mechanism, First-motion polarity

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1. INTRODUCTION

Following the 2010 M_L 6.4 Jiasian earthquake, the M_L 6.4 Wutai earthquake occurred on 26 February 2012 was a moderate inland earthquake ($M_L > 6$) which further rattled southern Taiwan. The epicenter at 22.75°N and 120.75°E, and a focal depth of 26.3 km were reported by the Central Weather Bureau (CWB). The largest peak ground acceleration value reached 160 cm s^{-2}, corresponding to a CWB intensity scale of V (80 - 250 cm s^{-2}) in Taiwan (Wu et al. 2003a). The Taiwan High Speed Rail and the Kaohsiung Metro system were temporally suspended during the occurrence of the Wutai earthquake, which was approximately 50 km away from Kaohsiung City. The earthquakes occurring in southern Taiwan, due to considerable site effects along the southwest coastal plain (Wu et al. 2001; Huang 2009), can generally cause amplified ground shaking in cities, resulting in large amounts of damage and loss. Furthermore, Chan and Wu (2012) also pointed out an increase in the seismicity rate in southern Taiwan, induced by the Coulomb stress increasing after the 2010 Jiasian earthquake. Therefore, a better understanding of the earthquakes in this region has become a crucial issue for seismic hazard mitigation as well as related tectonic issues.

The Centroid Moment Tensor (CMT) focal mechanisms for the Wutai earthquake have been reported by the Broadband Array in Taiwan for Seismology (BATS), the National Research Institute for Earth Science and Disaster (NIED), the CWB, and the Global CMT project (GCMT). All suggested a thrust mechanism with two nodal planes striking very sharply NW-SE and nearly in a N-S directions,

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respectively (Fig. 1). However, the focal depths from published source mechanisms are quite different, ranging from 15 - 34 km. (BATS: 15.0 km; CWB CMT: 24.0 km; NIED: 32.0 km; and GCMT: 34.0 km) (Fig. 1). In order to distinguish between the depth of the CWB report by the 1D travel-time location (26.3 km) and of the CWB CMT solution (24.0 km), we refer them as CWB1D and CCMT hereafter in this study. Although this depth deviation may be attributed to different selections of stations, epicenter location, velocity model, and parameter setting (e.g., the allowance of the isotropic component) from differing institutes, the accurate focal depth is important for tectonic interpretations in southern Taiwan. For example, study of the Jiasian earthquakedeep focal depth uncovered a blind fault system (Huang et al. 2011) and implied a thick-skinned deformation (Ching et al. 2011). In this scenario, the following earthquakes such as the Wutai earthquake can provide us an opportunity to further investigate the structural environment of southern Taiwan. Thus, we combined a large dataset of *S-P* times from the Taiwan Strong-Motion Instrumentation Program (TSMIP) records and *P*- and *S*-wave arrivals from the CWB Seismic Network (CWBSN) to relocate the hypocenter of the Wutai earthquake by a 3D relocation algorithm (3DCOR, Wu et al. 2003b) with a 3D velocity model (Wu

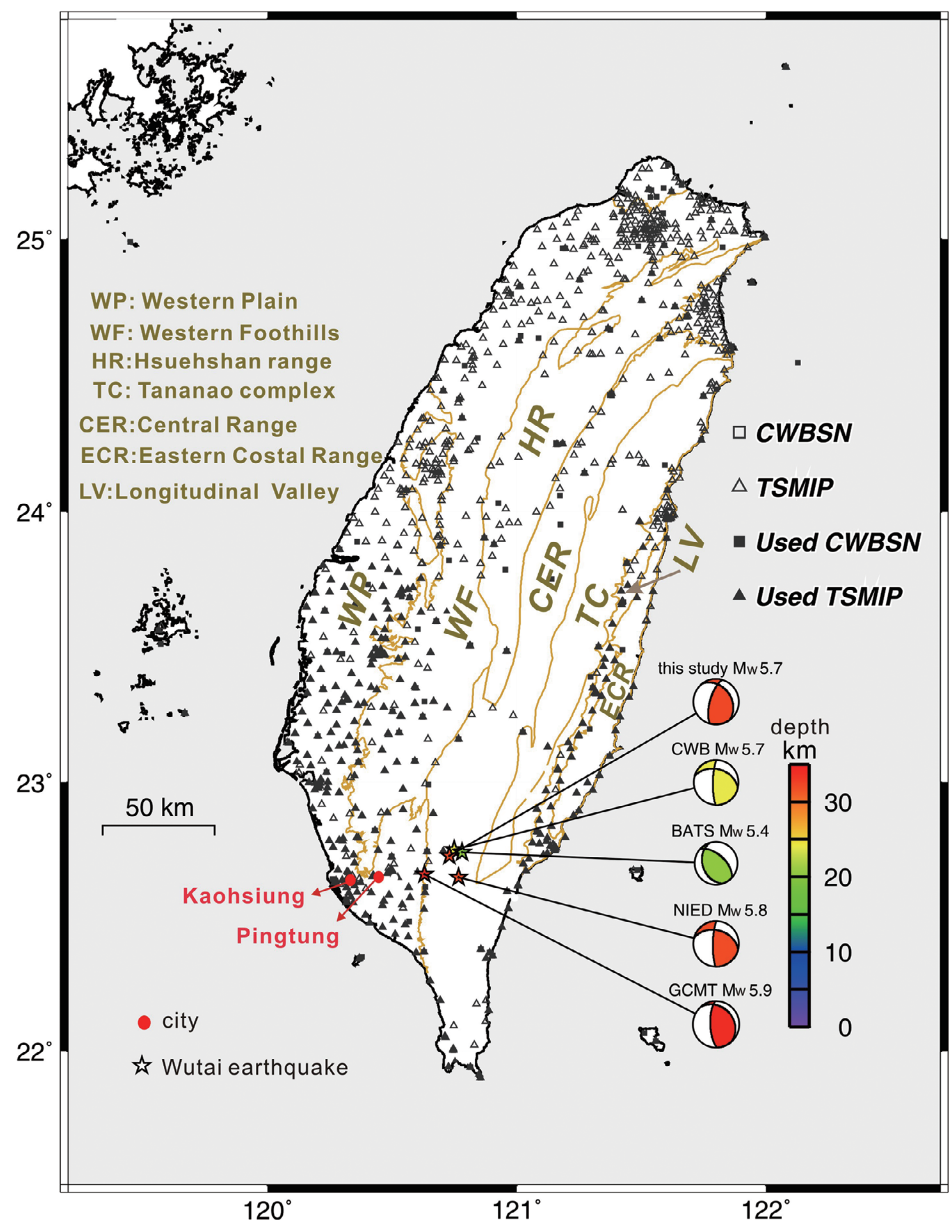

Fig. 1. The CWBSN and the TSMIP stations are denoted by squares and triangles, respectively. Solid symbols represent the stations used in our study. The red circles are the locations of nearby cities. The stars represent possible epicenters and focal mechanisms of the Wutai earthquake as derived from the CWB, BATS, GCMT, NIED, and this study. Yellow lines delineate the geological units (Ho 1975).

et al. 2007, 2009). Based on the relocated location, the focal mechanism of first-motion determination (Wu et al. 2008; Huang et al. 2011) was then derived.

In addition, because of the abundant polarities of first-motion *P*-waves we gained good station coverage of the Wutai epicenter, and were also able to test the possibility of searching the source depth by a first-motion polarity fitting (FMPF). The determination of first-motion solutions relies heavily on the location of earthquakes that directly influences the azimuths and take-off angles of seismic waves (i.e., the distribution of polarity points on a focal sphere). This characteristic therefore enables the determination of focal depths using the first-motion *P*-wave polarity. A series of synthetic tests were conducted for validating the approach, and ultimately the application of FMPF was carried out with the real case of the Wutai earthquake in this study.

2. DATA AND METHODS

2.1 Data

Since the beginning of 2012, just prior to the occurrence of the Wutai earthquake, the new generation of the CWBSN was thoroughly upgraded with the resolution of the recorder (24-bit) and with an increased station number of ca. 140 which included the original short period S13 network, broadband stations, and newly deployed borehole stations, as well as one Marine Cable Hosted Observatory (MACHO) station. In addition to the records of this new CWBSN, now routinely used for earthquake bulletins, we also collected *P*- and *S*-wave arrivals and *S-P* times from the TSMIP which encompassed approximately 800 free-field stations densely distributed over the Taiwan region with an inter-station spacing of ca. 5 km with the exception of dense mountainous areas (Shin et al. 2003). The high density of the TSMIP stations and the inland epicenter of the Wutai earthquake offered an abundant dataset and fairly good station coverage improved the hypocenter relocation, as well as the feasibility of our FMPF. In the end, readings from the Wutai earthquake indicated 513 *P*-wave arrivals, 128 *S*-wave arrivals, and 208 *S-P* times for earthquake relocation, and 276 decidable first-motion polarities of the *P*-wave for focal mechanism determinations (Fig. 1).

2.2 Relocation Scheme

We adopted a three-dimensional location program, 3DCOR, proposed by Wu et al. (2003b), for earthquake relocation. The program was modified from a previous 3D location algorithm (Thurber and Eberhart-Phillips 1999) using a station correction term in which the hypocenter locations and the station corrections were iteratively implemented to optimization. The synthetic travel times of the *P*- and *S*-waves were calculated theoretically using 3D ray-tracing (Thurber 1993). In order to take the subsurface heterogeneity into account, a three-dimensional velocity model (Wu et al. 2007, 2009) was used instead of the layer model in the CWBSN routine location (Chen 1995).

2.3 Focal Mechanism Determination and FMPF

Wu et al. (2008) proposed a method named FPsearch in which they used a genetic algorithm (GA) for the optimal determination of first-motion focal mechanism. The GA involves the three operators of natural selection, namely reproduction, crossover, and mutation. In each operation the optimal parameters need to be set through extensive testing. Accordingly, the GA parameters in Wu et al. (2008) are designed for determining the focal mechanisms in Taiwan region, and we can directly apply their tested parameters to our study. The operators are a population of 800, a reproduction rate of 3.6%, a mutation rate of 72%, and a pure crossover rate of 24.4%. In FPsearch, a comprehensive quality index (Q_{fp}), including factors of gaps, the number of readings, and the fitness of polarities, was also provided for the solution evaluation. To demonstrate how the first motion distribution varies, three examples of the Wutai earthquake at different depths with different levels of Q_{fp} and polarity misfits are shown in Figs. 2a - c.

In the additional attempt of the depth search by FMPF, we only use the GA-misfit term, a percentage of the polarity misfit, of Q_{fp} as our cost function and then determine the global minimum of misfits as the optimal depth and solution (i.e., focal mechanism). Except for the GA-misfit, the other factors (e.g., number of readings, gap, etc.) of Q_{fp} would not change during the 1D depth searching. Therefore, the GA-misfit at a certain predefined focal plane can be individually extracted to evaluate the fitting level at different depths. A series of synthetic experiments using the FMPF was carried out to display how the polarity points are redistributed in take-off angle and azimuth as source depth and noise level varies.

3. SYNTHETIC TESTS ON FMPF

To test the idea of FMPF, we conducted two synthetic tests. First, we used the relocated hypocenter and recording stations of the Wutai earthquake to simulate the synthetic focal mechanism (i.e., synthetic first-motion polarity distribution in a focal sphere) and then randomly inverted polarities in a different percentage for depth searching. To compare the fitting level between different misfit ranges, Fig. 3a shows the normalized misfit for different cases with mis-polarities ranging from 0 to 30% and demonstrates that even with 25% of random mis-polarities the relocated depth of 32 km can still be recovered which proves the stability and the robustness of our method, although several misfit local minima at shallow depth are present. The second experiment tests the recovery capability at a different focal depth containing the same 5% mis-polarities at depths of 13.0, 24.0, 32.0, and 38.0 km, respectively. Different depths of the source were all well resolved in either depth (Fig. 3b) or focal mechanism (Fig. 3c) which also assures the depth sensitivity of the polarity fitting method.

4. RESULTS AND DISCUSSION

4.1 The Relocated Hypocenter and the Re-determined Focal Mechanism

The Wutai earthquake was relocated to a longitude of 22.728°N and latitude of 120.729°E with a focal depth of 32.3 km which was significantly deeper than the CWB 26.3 km of CWB1D. Using the relocated hypocenter, the focal mechanism from the first-motion determination was also derived in two sets of nodal planes of (184°, 61°, 111°) and (326°, 35°, 57°) in strike, dip, and rake, respectively (Fig. 2c). As compared with the CMT solutions from different institutes (e.g., BATS, CCMT, NIED, GCMT), in general, the patterns of the focal mechanisms are rather similar. However, the focal depths exhibited considerable discrepancies. Surprisingly, our derived depth was closer to the results of global/remote networks which generally have poorer depth constraints than local networks. For this reason, we examined our relocation scheme and found that the addition of the *S-P* times used in the 3D relocation was the main factor influencing the focal depth determination (26.0 km without *S-P* times). However, in principle, the relative times between the *P* and *S* arrivals which cancel out the potential errors from the time clock (i.e., the clock drift at the station) and the original time estimation (i.e., the trade-off impact with focal depth) should provide us with better constraints on earthquake locations.

4.2 Depth Searching of Wutai Earthquake by FMPF

Following the synthetic tests for FMPF, we then applied it to the real case of the Wutai earthquake. We used a grid-based search in depth to determine the optimal solution of the Wutai earthquake with a fix on the relocated epicenter

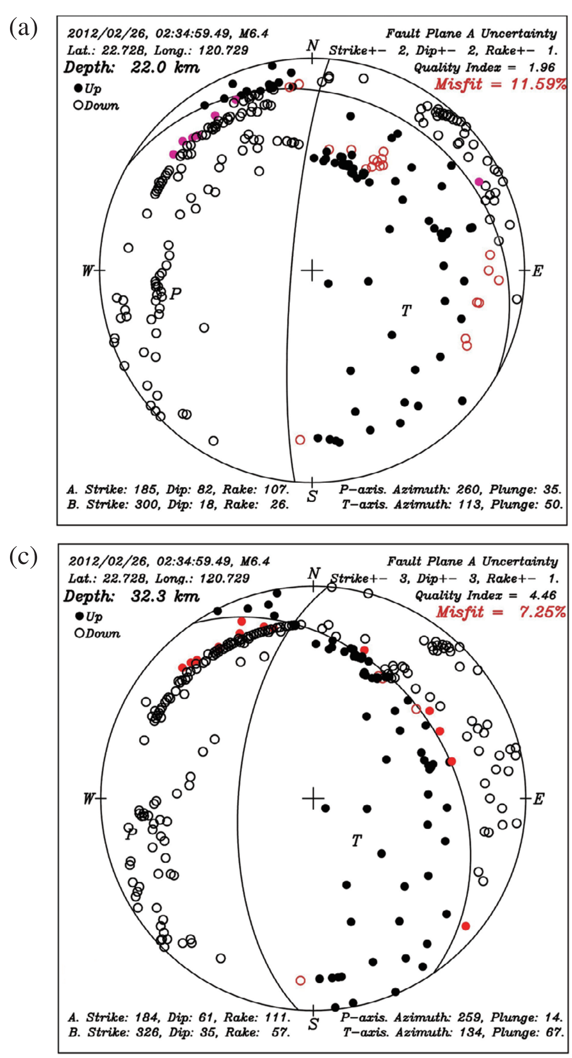

Fig. 2. The lower-hemisphere projection of the first-motion polarities for the Wutai earthquake. A total number of 276 polarities are projected to determine the focal solution. (a) through (c) represent the cases with misfits from high to low at 22.0, 26.0, and 32.3 km depths, respectively. Mis-polarities are highlighted in red. (c) is the result of the relocated depth.

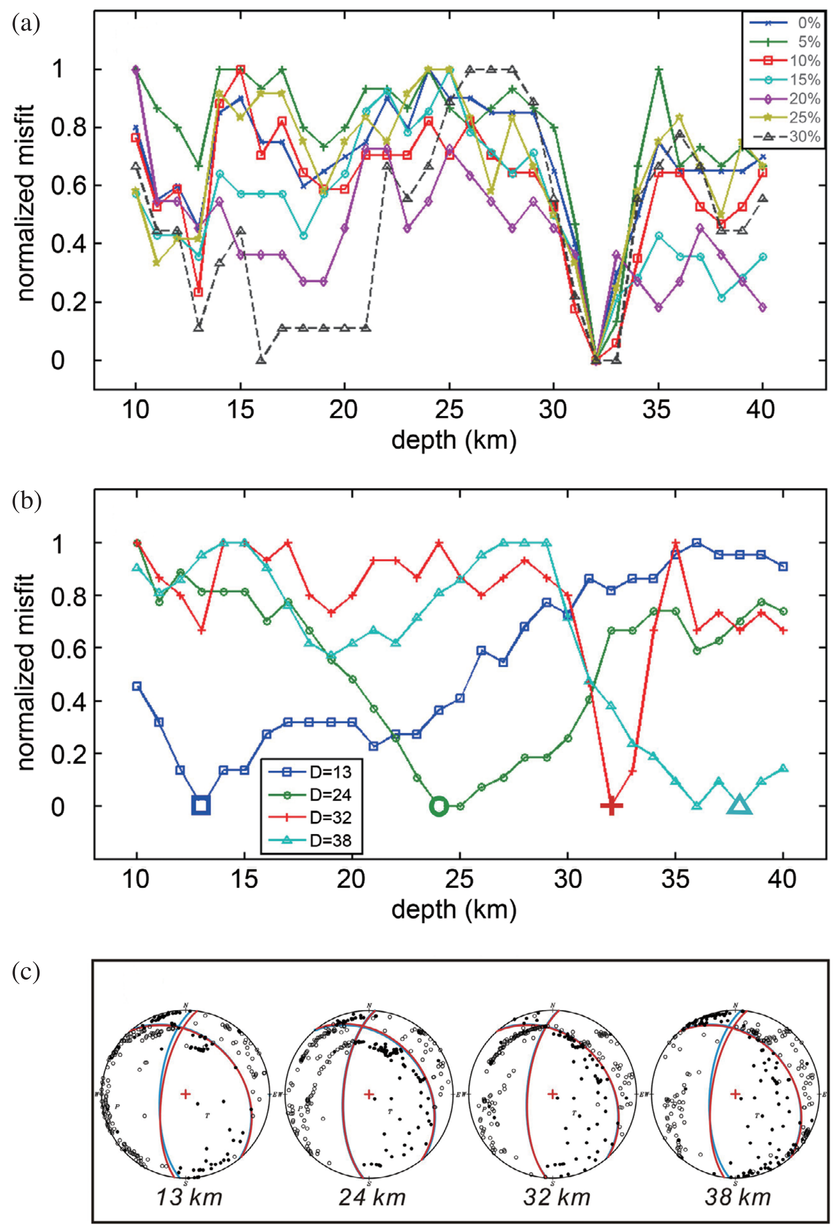

Fig. 3. (a) Synthetic tests with different percents of mis-polarities using the relocated epicenter and recording stations of the Wutai earthquake. The normalized misfits show a distinguishable soulution recovered at a 32-km depth within 25% of mis-polarities. (b) Synthetic tests for the synthetic focal mechanisms at a different depth with a 5% polarity misfit; and, the respective misfit curves of inversion are drawn in different colors. (c) The corresponding recovery focal mechanism of (b). The synthetic focal planes and the recovered focal planes are highlighted in blue and red lines, respectively. Different depths of sources are all well recovered.

which similar to the common process for a waveform fitting approach (Dzeiwonski et al. 1981; Kao et al. 1998; Chao et al. 2011). Although this method only takes information concerning *P*-wave polarities into account, it also has a strong dependence on spatial locations because the corresponding take-off angles and the azimuths of polarities relative to the stations will vary with the moving source. Theoretically, the method can be extended into a 3D spatial grid search to find the optimal hypocenter and focal mechanism at the same time. However, in this study we first tested and focused on a 1D depth searching for the Wutai earthquake.

By fixing the relocated epicenter, a grid search in depth with a 1-km interval was performed, see Fig. 4a. The results exhibited a double-peak pattern. Rather than perfectly inverted results as found in a synthetic test, the global minimum appeared at a shallow depth of 13 km in the real case of the Wutai earthquake. From the lesson of synthetic tests, we knew that unless the random mis-polarities exceed 25%, the global minimum should hold. This is a rather large error percentage and cannot match our data as we rechecked the

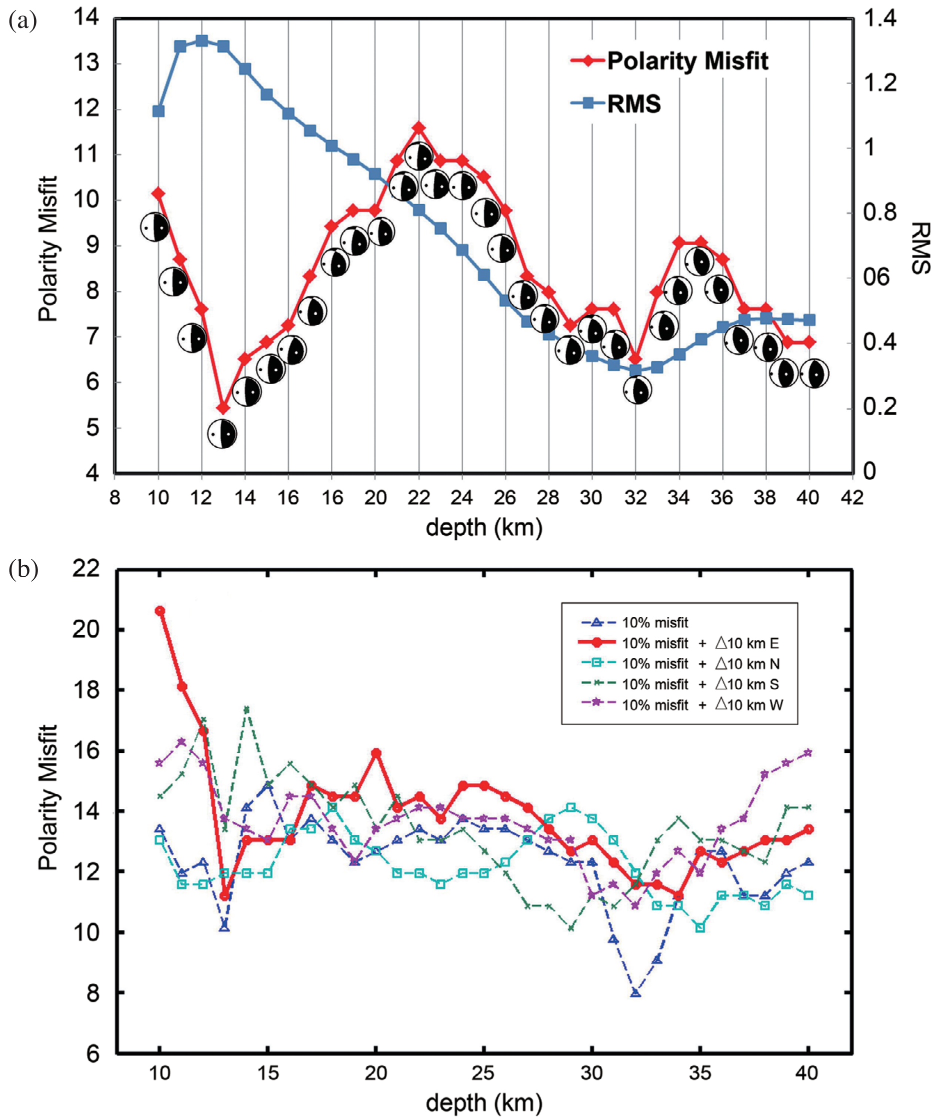

Fig. 4. (a) Polarity misfit and RMS of travel-time residuals against the focal depth. A double-peak pattern is exhibited in the Wutai earthquake by usng the FMPF. The focal mechanisms are optimal solutions at each depth. (b) Synthetic tests with 10% mis-polarities and a 10 km epicenter shift in four directions. The global minimum becomes a more shallow depth of 13 km as the epicenter shifts 10 km to the east which is similar with the real case of the Wutai earthquake in (a). A detailed discussion can be found in section 4.2.

first-motion polarities. Therefore, the mis-polarities should not be the reason dominating the shallower global minimum of the Wutai earthquake. Another possibility which might have caused the discrepancy between the results of FMPF and 3D relocation is the error concerning the epicenter which was not considered in former synthetic tests. Thus, we conducted another test to shift the synthetic epicenter 10 km in four directions with 10% mis-polarities for depth searching, respectively. The results showed that the global minimum is present at 13 km depth with a 10 km shift of epicenter to the east (Fig. 4b) which is very similar to the observation of the real case (Fig. 4a). This indicated that FMPF is very likely sensitive to the epicenter uncertainty (and as mentioned earlier, it should have a 3D sensitivity for earthquake location). Hence, the relocated epicenter (from 3D relocation using additional *S-P* times) may not be the best epicenter for the FMPF in terms of the 3D point of view and cause an anomalous peak at 13 km. But note that the second minimum is quite consistent with the relocated depth and persists in epicenter-shifting tests. Even though the epicenter uncertainty may need further analyses in a 3D FMPF, in this study we focused primarily on addressing and demonstrating the potential of the FMPF which can offer auxiliary information for either the 1D focal depth search or the 3D hypocenter location with travel time data in the future.

4.3 Tectonic Implication of the Focal Depth of Wuati Earthquake

We also collected the *S-P* times and relocated the 2010 M_L 5.7 Taoyuan earthquake in this study. Combining the source parameters of the Jiasian earthquake (Huang et al. 2011), we aimed at exploring the spatial distribution and the tectonic implications for these relatively large earthquakes in southern Taiwan.

The relocated depth of 32.3 km of the Wutai earthquake, deeper than the 26.3 km recorded by the CWB1D is likely within the lower crust according to the 35 - 40 km Moho surface (Tang et al. 2011; Ustaszewski et al. 2012) and indicates that the deep blind thrust system, revealed by the Jiasian earthquake, is probably going deeper and involves the lower crust in this region. Figure 5a shows the distribution of earthquakes of a magnitude larger than 5.0 and partly resolved focal mechanisms (Wu et al. 2008). It is clear that the focal mechanisms deeper than 20 km in depth

(a)

(b)

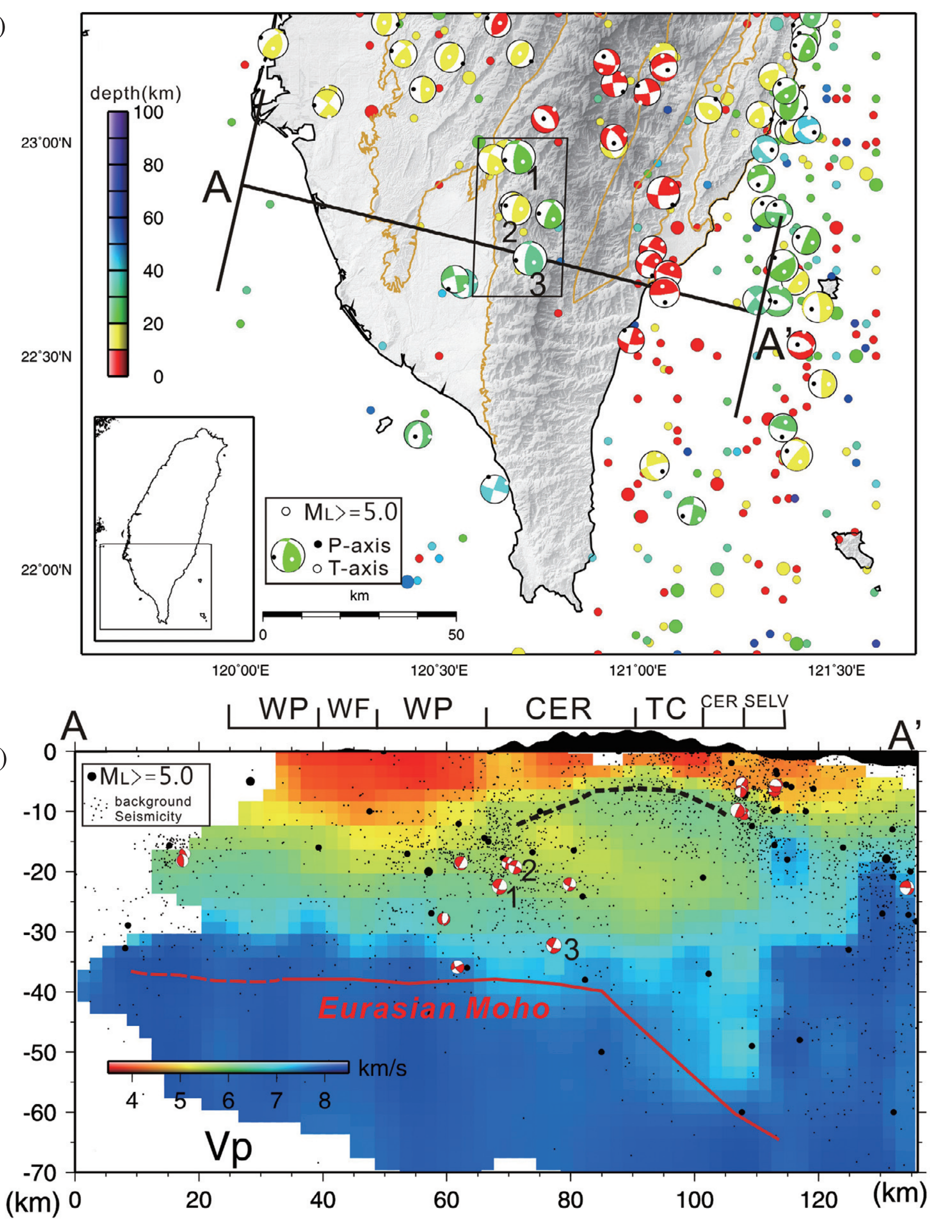

Fig. 5. (a) Map view of the relative epicenter of $M_L \geq 5.0$ in Southern Taiwan from 1900 to 2010. Focal mechanisms ($M_L \geq 5.0$) are from Wu et al. (2008), Huang et al. (2011) and this study. The numbers represent: 1. The Jiasian earthquake, 2. Taoyuan earthquake, and 3. Wutai earthquake. A discussion concerning the boxed area can be found in section 4.3. (b) *P*-wave velocity (Vp) imaging in southern Taiwan along the profile AA' in (a). The background seismicity of $M_L \geq 3.0$ (Cheng et al. 2010) and focal mechanisms are projected within a 30 km width with black dots and red beach balls, respectively. The black solid circles are earthquakes with $M_L \geq 5.0$. The uplift of high Vp velocity structures (Wu et al. 2009), and the Eurasian Moho surface (Tang et al. 2011) are drawn as a black dashed line and red line, respectively. The abbreviation of geological units can be seen in Fig. 1. (SELV: Southern extension of LV). The black stars with corresponding numbers are the same earthquakes described in (a).

in the southwestern Central Range (CER) (Box in Fig. 5a) behave distinctly under the ENE-WSW compression unlike the NW-SE compression/extension of the general tectonic trend. Moreover, due to the similarity of the focal mechanism of the Jiasian earthquake (depth 23.2 km), the Wutai earthquake (depth 32.3 km) may reveal an even deeper blind fault system under a similar local tectonic environment. However, the principle compressive axis of the Taoyuan earthquake seems to slightly deviate.

Figure 5b further shows the profile with the *P*-wave tomographic imaging (Wu et al. 2009) and the background seismicity of $M_L \geq 3.0$ from 1900 ~ 2010. The earthquake catalog is originally collected by the CWB and revised by Cheng et al. (2010) afterward. The earthquake distribution shows strong lateral variations and is difficult to delineate a basal decollement under the Western Plain (WP) and Western Foothills (WF). The seismicity is concentrated primarily around the boundary between WP and CER and steeply extended into the middle and even lower crust right above the subduction zone. Under the central of CER and Tananao Complex (TC), the sparsity of seismicity occurring ≥ 20 km and the up-arching of high velocity structures may indicate the uplift of the basement with a relatively high temperature in the mid-lower crust. This similar pattern was also found in central Taiwan. According to thermo-rheological modeling (Lin 2000; Zhou et al. 2003), a high-temperature core appears beneath the CER and the TC, and was interpreted as the heat carried up by the crustal exhumation (Lin 2000). It may also be applicable in southern Taiwan. Further to the east, the southern extension of the Longitudinal valley, the majority of earthquakes located within 25 km in depth should result from the oblique collision of the plate boundary (Kuochen et al. 2004, 2007; Wu et al. 2006a, b).

5. CONCLUSIONS

This study aims at clarifying the discrepancy of focal depth and reexamining the source parameters of the 2012 Wutai earthquake. By combining the abundant *S-P* times from the TSMIP, the hypocenter is relocated to 22.728°N, 120.729°E and at a depth of 32.3 km. The focal mechanism based on the relocated hypocenter is determined in the 326° strike, the 35° dip, and the 57° rake. Together with recent relative large earthquakes (e.g., 2010 Jiasian and 2010 Taoyuan earthquakes) in southern Taiwan, we also delineated a picture of their tectonic environment. The more deeply relocated Wutai earthquake implied the involvement of the lower crust and that the blind thrust system in this region could go deeper (Huang et al. 2011). A complicated thick-skinned deformation is taking place in southwestern CER. This could be crucial for our tectonic understanding and the future seismic hazards assessments.

In the meantime, we also demonstrated the potential of depth searching by the FMPF once a sufficient number of polarity data and good station coverage became available. We obtained a consistent depth result with the relocated depth although the pattern of the shallow peak seems to be affected by the uncertainty of the epicenter. This experiment is encouraging because of the large polarity dataset extant within the earthquake catalogs of different institutes which can be used not only for focal mechanism determination but also for refining the location of the earthquake using travel time data.

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