Terr. Atmos. Ocean. Sci., Vol. 27, No. 6, 799-805, December 2016 doi: 10.3319/TAO.2016.02.26.01(T)

Tectonic Implication of the 5th March 2005, Doublet Earthquake in Ilan, Taiwan

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Received 26 August 2015, revised 22 February 2016, accepted 26 February 2016

ABSTRACT

The 5th March 2005 earthquake doublet focal mechanism was determined as strike-slip faulting from Harvard and BATS moment tensor inversion. However, based on first motion polarities, the first shock has a normal focal mechanism (Wu et al. 2008a). This discrepancy has caused a debate over the focal mechanism solution because different focal mechanisms have different tectonic implications. Based on the dislocation determination from Global Position System (GPS) measurements, we find this event includes both tensile and strike-slip components. This finding illustrates the reason for the differences in the determined focal mechanisms using two different types of seismic data and analyzing methods. Field mapping and microstructure examination results indicate that the ductile deformation around the study area was characterized by the evolution from transpression to transtension with a predominant strike-slip component, but present-day active structures may be dominated by normal faulting. Thus, the active tensile slip result determined from dislocation modeling strongly suggests that the back arc extension of the Okinawa trough influences the stress state in this region, and changes the major transtension from strike-slip faulting to normal faulting.

Key words: Ilan Plain, Okinawa Trough, Focal mechanism, CLVD, GPS, Ductile deformation

Citation: Yeh, E. C., Y. M. Wu, J. B. H. Shyu, and C. H. Chang, 2016: Tectonic implication of the 5th March 2005, doublet earthquake in Ilan, Taiwan. Terr. Atmos. Ocean. Sci., 27, 799-805, doi: 10.3319/TAO.2016.02.26.01(T)

1. INTRODUCTION

An earthquake doublet (M_L = 5.9 or Mw = 5.7) occurred within 68 sec on 5 March 2005 (UT) with focal depths of 6.4 and 7.0 km. The epicenters were located on-land at 24.65°N, 121.84°E and 24.65°N, 121.80°E, close to the Ilan Plain coastline, according to the Central Weather Bureau (CWB) of Taiwan (Fig. 1a). The focal mechanism solutions of BATS (Broadband Array in Taiwan for Seismology) and Harvard moment tensor database indicate strike-slip dominated events for the double shocks on 2005 March and also for the first shock on 2002 May. The USGS focal mechanism on the first shock of 2002 May is similar to the BATS and Harvard results but the first shock solution on 2005 March is different from the BATS and Harvard solutions and moreover there is even no solution for the second shock of 2005 March. These variations in moment tensor focal mechanisms might result from different input parameters, such as velocity structure, amplitude-ratio, and period, under different algorithms (e.g., Helffrich 1997). On the other hand, a pure normal faulting is determined for the first shock of 2005 March (Wu et al. 2008a) based on first P-wave polarities from CWB Seismic Network (CWBSN) and Taiwan Strong Motion Instrumentation Program (TSMIP). Unfortunately, since the first motion polarities of the second shock were strongly influenced by the first shock in the southwest quadrant, no clear first-motion polarity can be identified for the second shock in the third quadrant. The first motion focal mechanism of the second shock could not be determined. However, other than this event, an earlier earthquake (Mw = 6.1), which occurred on 15 May 2002 at the same seismic zone, also has the same phenomenon as this earthquake doublet (Fig. 1a). The discrepancies of different focal mechanism solutions are expected given that the solutions obtained from first-motion polarities reflect the high-frequency behavior of the initial

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earthquake ruptures, whereas the Harvard and BATS solutions are obtained from long-period waveforms and more representative of the average behavior of the entire sources. However, in Taiwan area, only earthquakes occurred in this region have such phenomenon (Wu et al. 2008a). Thus, this phenomenon may reflect a tectonic-related characteristics.

The tectonic characteristics in the study region have been interpreted as the result of the interaction of the reversal of the Philippine Sea Plate (PSP) subduction polarity at the corner and opening of the Okinawa Trough (OT) (Suppe 1984; Hsu 2001; Shyu et al. 2005a). Based on seismological observations, Kao et al. (1998) suggests that this region is located where an interaction exists between the extension of the opening of OT and the compression of the PSP oblique collision. Generally, normal faulting in this region would be consistent with the opening and extension of the OT (e.g., Wang et al. 2000; Shyu et al. 2005b; Wu et al. 2008a). A strike-slip focal mechanism may imply the lateral extrusion at the transition zone between the Taiwan mountain range and the OT (Liang et al. 2005).

Wang (2007) attempted to analyze the focal mechanism of this event using near-field waveform modeling. She obtained an oblique solution between normal and strike-slip. She suggested that the first motion solution may represent the initial rupture motion of an event, which could be different from the subsequent major slip motion. She concluded the initial motion of this event was normal and later strike-slip motion dominated. However, for an event with only Mw 5.7, we suspect that it could have such a complicated rupture process. In her result, there was a 27% compensated linear vector dipole (CLVD) component for the moment tensor solution. This motivated us to elucidate the difference between moment tensor and fist motion focal mechanisms. Could the non-double couple component cause the differences?

It is important to further analyze the focal mechanism of this event and its tectonic implication, with some constraints from field mapping data and microstructure examination. Based on integrated data we emphasize the recent tectonic change with the major component of transtension from strike-slip faulting to normal faulting in this region.

2. SEISMICITY AND GLOBAL POSITION SYSTEM MEASUREMENTS

Based on the distribution of relocated hypocenters using 3D velocity model (Wu et al. 2003, 2007, 2008b), two earthquake sequences of the 2005 doublet event are identified in the same zone with an almost 90 degree dip angle (Fig. 1b). The hypocenter distribution of aftershocks may provide us the roughly finite rupture geometry for the doublet. This aftershock hypocenter distribution does not perfectly fit either the focal mechanisms from the moment tensor or first motion. The strike of the aftershock hypocenter distribution (Fig. 1a) is closer to that of the moment tensor strike-slip focal mechanism than normal faulting focal mechanism from first motion polarities for this event. Because the aftershock hypocenter distribution is not likely to be north-dipping (Fig. 1b), the aftershock hypocenter distribution is not consistent with north-dipping moment tensor focal mechanism neither with shallow

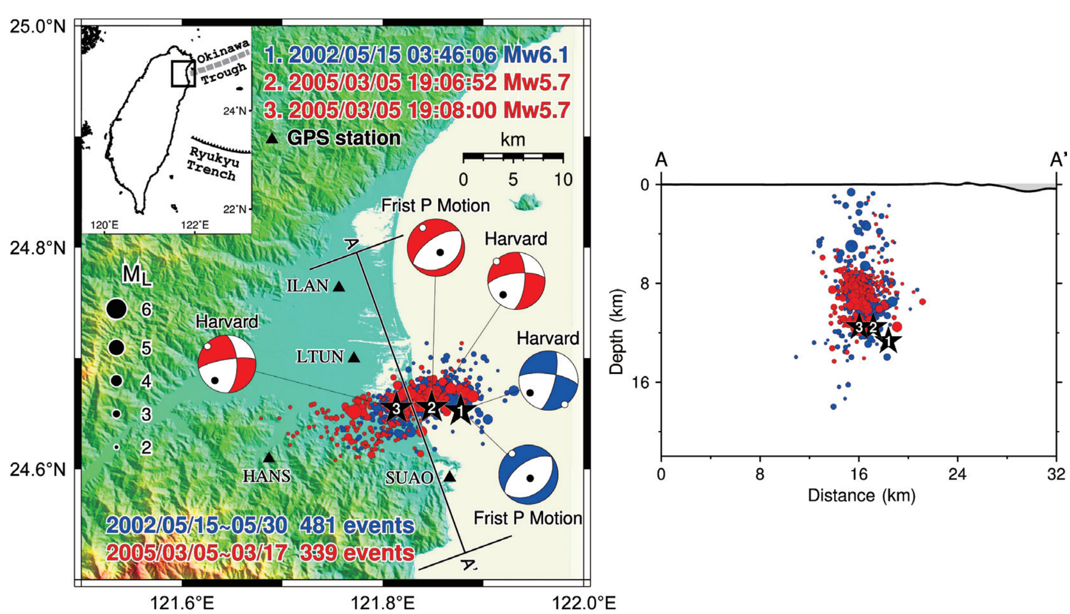

Fig. 1. Earthquakes of 2002/05/15 Mw6.1 and 2005/03/05 Mw5.7 Ilan, Taiwan. (a) Earthquake sequences and their main shock focal mechanisms are shown in map view. The focal mechanisms determined from USGS, BATS, Harvard, and P-wave polarities are shown. Solid triangles show the location of GPS stations maintained by the Central Weather Bureau used in this study. (b) The hypocenter distribution of doublet earthquakes and their aftershocks in cross-section AA'. (Color online only)

south-dipping first-motion focal mechanism. The result from the first motion polarities of the 2005 doublet undoubtedly is a normal faulting focal mechanism, but the fault planes from the BATS and Harvard moment tensor focal mechanism are quite different from the first-motion polarity results (Fig. 2). The south dipping fault plane results inferred from both the aftershock hypocenter distribution and normal faulting focal mechanism determined from the first motion polarity agree with the regional extension resulted from Global Position System (GPS) measurements in the period 1995 - 2005 (Rau et al. 2008). Consequently, GPS measurements involve deformation induced by normal faulting deformation determined by first-motion focal mechanism solution.

Four continuously recording GPS stations (Fig. 1a and Table 1) were installed in the study region by the CWB in 2004. GPS measurements are the finite displacement result due to the doublet event in this study. GPS measurements are the displacement representative involved in both focal mechanisms from the moment tensor and first-motion solutions. Thus, GPS measurements offer more information for this event. Figure 3 shows the distance and elevation changes in the closest three GPS stations. No obvious elevation change across the fault in the GPS measurements will support the strike-slip mechanism (Fig. 3b). The distance between the closest three GPS stations increased after the 2005 earthquake (Fig. 3a), indicating the apparent dilation of normal faulting phenomena. The station displacement vector is especially larger when the vector is highly oblique to the fault strike rather than parallel to the strike (Fig. 4). Consequently, GPS measurements support both normal faulting and strike-slip focal mechanisms as we expected. When the station displacement vector is not really perpendicular to the fault strike, horizontal GPS measurement displacement should be composed of strike-slip and tensile components. Therefore, we need to perform the dislocation fault model to evaluate the amount of strike-slip and tensile components in horizontal displacement in order to compare and integrate with the focal mechanism results from the moment tensor and first motion.

3. DISLOCATION FAULT MODEL

In order to understand the focal mechanism of this event, four horizontal ground displacement records from GPS are used to invert the rupture dislocation model. The method is modified mainly after the previous study of Okada (1992) and is described in Wu et al. (2006a, b). Table 1 and Fig. 4 show the horizontal displacements from GPS measurements. This event did not cause significant displacements in the vertical direction even with relatively poor GPS measurement vertical resolution (Fig. 3b). As a result, we assumed the vertical displacements at all stations to be zero in this study. Since this is a doublet event, the GPS measurements include two earthquake coseismic deformations. Lai et al. (2009) compared the GPS coseismic deformation from the two earthquakes and coseismic deformation from strong motion records (Wu and Wu 2007) of the first earthquake of the doublet. The GPS measurements are just twice the amount of displacements measured from strong motion records. They concluded that the earthquake doublet has the same focal mechanisms with almost the same size of magnitude. BATS and Harvard moment tensor solution results also show the same conclusion. Therefore, we can use the GPS measurements to investigate the dislocation model. The aftershock distribution provides constraints on the fault geometry. Strike, dip, and tensile slips are inverted by the dislocation model. Table 2 shows the fault geometry parameters as well as the inverted slips. Figure 4 shows the observed and best-fitted modeled displacements. Based on dislocation fault model we confirmed that GPS slip vectors are composed of two major components of 9.8 cm strike-slip and -5.7 cm tensile slip, without distinctive dip slip. Even no vertical displacement as input parameter, because of simplified fault geometry and overdetermined conditions, the dip slip component will come out. Even so, the dip slip magnitude is almost one order smaller than that of the second large slip component. Furthermore, slip vectors are not confined to lie on the fault plane of aftershock distribution, suggesting the possible existence of tensile deformation. The tensile slip deduced from the fault dislocation model means how far the two blocks are moved away from each other during coseismic deformation. Certain CLVD component in this study is due to large tensile slip inverted from dislocation model. Thus, we expect that this tensile slip can generate normal faulting

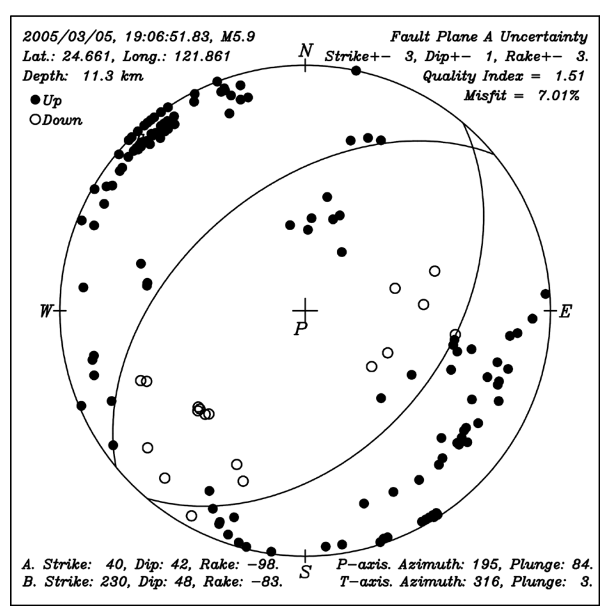

Fig. 2. Focal mechanism solutions for the first shock of the 5th March 2005 Ilan doublet from USGS, BASTS, Harvard, and first-motion. "Up" and "Down" means that the first motion is up and down in the seismogram, respectively.

Table 1. Coseismic displacements determined from GPS observation and modeled values from this study.

Station	Lat. (°)	Lon. (°)	Observed			Modeled		
			North (cm)	East (cm)	Slip (cm)	North (cm)	East (cm)	Slip (cm)
ILAN	24.7640	121.7566	1.39 ± 0.05	-1.34 ± 0.05	1.94 ± 0.07	1.30	-0.95	1.61
LTUN	24.7000	121.7716	1.27 ± 0.03	-2.03 ± 0.03	2.39 ± 0.04	2.11	-2.41	3.20
SUAO	24.5924	121.8671	-1.73 ± 0.07	1.11 ± 0.10	2.06 ± 0.12	-1.87	1.66	2.50
HANS	24.6095	121.6871	0.21 ± 0.03	0.48 ± 0.03	0.52 ± 0.04	0.62	0.63	0.88

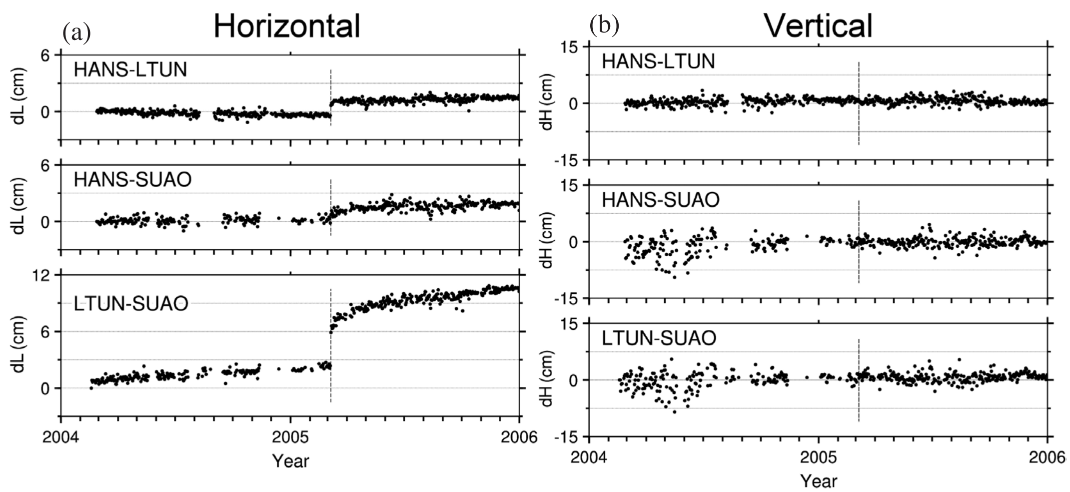

Fig. 3. Horizontal distance change (a) and vertical elevation change (b) before and after the 5th March 2005 Ilan doublet earthquake between the GPS stations Hans, Ltun, and Suao. The locations of these three GPS stations show in Fig. 1 and they are on two sides of the fault.

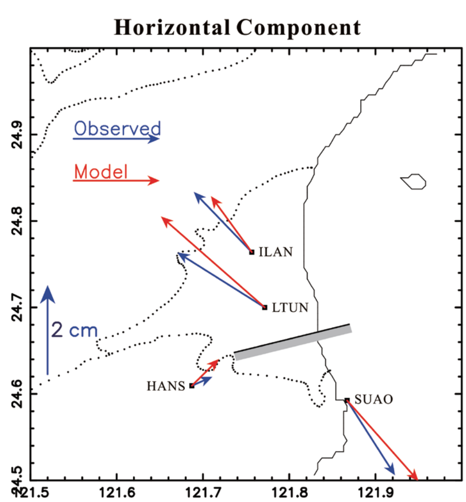

Fig. 4. Maps showing the coseismic displacements from the GPS measurements and modeled values. The gray rectangle is the projections of the modeled fault-plane and the thick black line is the top of it (see details in text and Table 2). Arrows show the displacements, including the modeled (red) and observed (blue). (Color online only)

Table 2. Fault geometry parameters and the slips inverted from GPS measurements.

Middle Top Point											
Lon. (°)	Lat. (°)	Depth (km)	Strike (°)	Dip. (°)	Length (km)	Width (km)	Strike Slip (cm)	Dip Slip (cm)	Tensile Slip (cm)	Mw (DC*)	Mw (nonDC)
121.803	24.664	1	75	85	14	12	9.8	-0.6	-5.7	5.73	5.68

*Note: *: DC indicates double couple component.*

detected as first-motion polarity focal mechanism for the initial ruptures. Furthermore, the strike-slip component determined from the dislocation model is consistent with strike-slip faulting of moment tensor focal mechanisms as the average faulting behavior. Since neither single normal faulting nor single strike-slip faulting from the first-motion and moment tensor focal mechanism can explain the GPS measurements completely, our results illustrate that GPS measurement is the finite combination outcome of first-motion and moment tensor focal mechanisms as expected. Because normal faulting and strike-slip faulting are representatives of first-motion and average earthquake source behavior, respectively, their temporal sequence should be applied to the slip sequence. We expect that a certain amount of tensile slip and tiny dip slip occurred at the beginning as normal faulting and larger strike-slip took place later as the major strike-slip faulting behavior. These results also deliver a possible explanation for the discrepancies in fault geometries inferred from the dislocation fault model and first-motion and moment tensor focal mechanisms due to complex faulting integrated with tensile faulting and strike-slip faulting.

4. FIELD OBSERVATIONS OF DUCTILE DEFORMATION

Field observations of cross-cutting relationship can provide temporal sequence constraints on the tectonic events. Previous field mapping results of slate/schist outcrop results south of Suao suggested different ductile deformation stages (Yeh 1998) as the expectations of previous results (Suppe 1984; Kao et al. 1998; Shyu et al. 2005b). Two ductile deformation stages were clearly identified based on field mapping and microscopic examination in the Suao highway slate belt (Yeh 1998). In the early stage the foliation strikes 107° and dips 71° towards the south and the associated stretching lineation has the attitude of 30°/276° (Fig. 5a). In the latest stage, the foliation obtains an attitude of 063°/33°S and the associated stretching lineation attains the attitude of 21°/103° (Fig. 5b). The foliation attitude in the early stage is more consistent with the regional main foliation attitude in the Suao highway slate belt as published in the geological map (Lin and Kao 1997). The kinematics of the early ductile deformation inferred from chlorite-mica fish, asymmetric folded chlorite-mica aggregates (Fig. 5c), and pressure shadows indicated top-to-east shearing with a reverse-sense component. It illustrated the transpressional movement, which could be compatible with the lateral extrusion explanation (Liang et al. 2005). The kinematics of the latest ductile deformation deduced from the overgrowth of quartz fibers over pyrite showed the top-to-southeast shearing with normal-sense component (Fig. 5d), suggesting the transtension deformation. Although the exact stretching lineation age is still unknown, the evidence of ductile deformation evolution from transpression to transtension in the Late Cenozoic is reliable. Furthermore, no clear evidence of distinctive SE-NW extension structure, such as a dilation

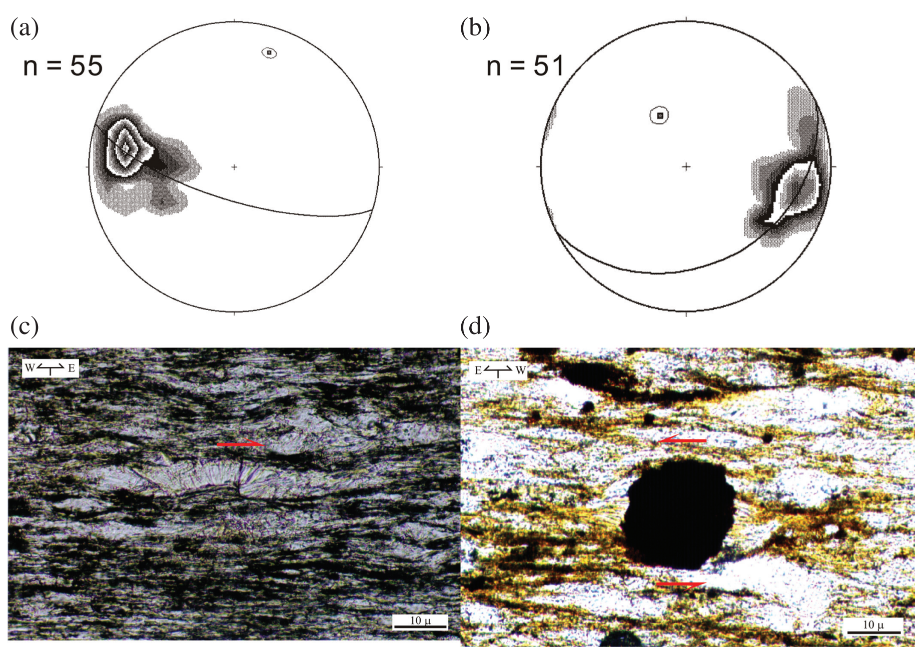

Fig. 5. Characteristics of ductile deformations in the slate belt of Suao highway. Attitudes of foliation and associated stretching lineation are projected on the lower-hemisphere equal-area stereonet for the early stage (a) and the latest stage (b). The great circle is the representative foliation orientation with measurement number. The contour shows the statistic density of stretching lineation. (c) The open-nicole micrograph of asymmetric folded chlorite-mica aggregates shows clearly top-to-east shear sense. (d) The micrograph of syntectonic pressure shadow under open-nicole indicates top-to-east shear sense. The thin section is cut parallel the stretching lineation and perpendicular to the foliation. (Color online only)

vein or dike intrusion is observed in the field. From such deformation structural geometry and the sense of shear, we can conclude that the latest ductile deformation in the region involved transtension deformation with a predominant strike-slip component. Synthesized with the earthquake doublet results from this study, regional latest deformation has evolved from a ductile strike-slip dominated component to a brittle extension dominated component.

5. DISCUSSION AND CONCLUSIONS

The Ilan Plain is a large, triangular basin that reflects the current foundering of the western tip of the westward propagating OT (Wang et al. 2000). The plain is bounded on its northwestern and southern sides by two of the major mountain ranges of Taiwan. Along both of these mountain fronts, there appear to be geomorphically and geodetically expressed normal fault systems (e.g., Shyu et al. 2005b; Kang et al. 2015). The northwestern mountain front is likely to consist of a zone of normal faults several km wide. Geomorphically, there is a family of short, discontinuous faults, marked by triangular facets. Geodetic results further support the active subsidence in the southern part of Ilan Plain (Kang et al. 2015). Therefore, normal faulting may be the dominant active structural characteristics of the Ilan Plain at present.

First-motion and moment tensor solutions from a 2005 earthquake doublet in the southern Ilan Plain illustrate that temporal sequence of current earthquake behavior changes from normal faulting in the beginning to strike-slip faulting as the entire fault ruptures. Results from dislocation model of this event show that most of the slips are strike-slip with tensile components, which is consistent with the involvement of both focal mechanisms. We suggest that this is the reason for the different focal mechanisms from first motion and the moment tensor solutions. Combining these two sets of results, we expect that tensile slip occurred in the beginning as normal faulting and larger strike-slip took place later as the entire strike-slip faulting behavior. If the tensile component is removed, we expected that an almost pure strike-slip focal mechanism would be determined. This is the reason that moment tensor solution shows a strike-slip solution with large CLVD component (Wang 2007). We suggest this phenomenon is the characteristic of this event and the structure.

Since a similar event in 2002 and the associated aftershocks are located nearly at the same zone as the 2005 event (Fig. 1a), Lai et al. (2009) suggested that this reflects dike intrusion. The closest volcano in the region is offshore Kueishan Island, which experienced its' last eruption about 7 ka ago (Chen et al. 2001). Thus, there may be some active magmatic sources in this region. However, without further observations, it is difficult to clarify this hypothesis. Even without knowing the actual mechanism for extension, the same amount of non-double couple component as the double couple component (Table 2) from the dislocation model strongly suggests this active transtension deformation involves a fair amount of extension.

Comparison of the active focal mechanism solution with the latest ductile deformation in the region provides a constraint for the temporal deformation sequence and the tectonic implications. The latest ductile deformation displayed that top-to-ESE strike-slip movement with normal-sense component during the development of stretching lineation and foliation. Conversely, the T-axes of the 2002 and 2005 earthquake doublets in this study area (Fig. 1a) are sub-parallel to the coseismic displacement vector of GPS measurements at Suao station (Fig. 4), indicating the active extensional orientation in the southeastern Ilan plain is SE-NW. Previous results such as GPS measurements (e.g., Rau et al. 2008; Hou et al. 2009), active tectonic studies (e.g., Shyu et al. 2005b; Kang et al. 2015), and focal mechanisms (e.g., Wu et al. 2009, 2014; Huang et al. 2012) further showed that the SE-NW orientation in the Ilan Plain resulted from the back arc extension of OT. Given the different amount of extension from the latest ductile deformation to the active faulting events, this evidently indicates that the transtension deformation in the region starts to switch from a strike-slip dominated component to an extension-dominated component. Consequently, our results show that this region has begun to be affected by the back arc extension of OT.

Acknowledgements We are grateful to the Editors Ruey-Juin Rau and Shu-Huei Hung, Reviewer Hao Kuo-Chen, and Two Anonymous Reviewers for their kind help and constructive comments. This research was supported by the Central Weather Bureau and the Ministry of Science and Technology of the Republic of China (MOST 104-3113-M-002-001).

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