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

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

DOI: 10.3319/TAO.2016.02.26.01(T)

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Running Title: Tectonic Implication of 2005 Ilan Doublet Earthquake, Taiwan

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Key points:

1. 2005 Ilan doublet earthquake displays strike-slip and normal-faulting mechanisms
2. Stress switched from strike-slip faulting to normal faulting of transtension
3. Extension of the Okinawa trough have influenced the stress state in this region

Key words: Ilan Plain, Okinawa Trough, focal mechanism, CLVD, GPS, ductile deformation

Abstract

Focal mechanism of the March 5th, 2005 earthquake doublet 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). The discrepancy causes a debate in the focal mechanism solution, since different focal mechanisms have different tectonic implications. On the basis of dislocation determination from Global Position System (GPS) measurements, we find this event includes both tensile and strike-slip components. Thus, this finding illustrates the reason for the differences in the determined focal mechanisms using two different types of seismic data and analyzing methods. Results of field mapping and microstructure examination indicates that the ductile deformation around the study area was characterized by the evolution from transpression to transtension with predominant strike-slip component, but present-day active structures may be dominated by normal faulting. Thus, the result of active tensile slip determined from dislocation modeling strongly suggests that the backarc extension of the Okinawa trough have influenced the stress state in this region, and switched the major component of transtension from strike-slip faulting to normal faulting.

Introduction

An earthquake doublet (M_L=5.9 or Mw=5.7) occurred within 68 seconds on March 5, 2005 (UT) with focal depths of 6.4 km 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 coastline of the Ilan Plain, according to the report of Central Weather Bureau (CWB) of Taiwan (Figure 1a). The focal mechanism solutions of BATS 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. Focal mechanism of USGS on the first shock of 2002 May is similar to the results of BATS and Harvard but the first shock solution on 2005 March is different from the solutions of BATS and Harvard and moreover there is even no solution for the second shock of 2005 March. The variations of 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 of the second shock in the third quadrant can be identified. 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 May 15, 2002 at the same seismic zone, also has the same phenomenon as this earthquake doublet (Figure 1a). The discrepancies of different focal mechanism solutions are expectable given that the solutions obtained from first-motion polarities reflect the high-frequency behavior of the initial ruptures of the earthquakes, whereas Harvard and BATS solutions are obtained from long-period waveforms and are 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 character.

In the study region, tectonic characteristics have been interpreted to be the result of the interaction of the reversal of the Philippine Sea Plate (PSP) subduction polarity at the corner and the opening of the Okinawa Trough (OT) (Suppe, 1984; Hsu, 2001; Shyu et al., 2005a). Based on the seismological observation, Kao et al. (1998) also 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 Okinawa Trough (e.g., Wang et al., 2000; Shyu et al., 2005b; Wu et al., 2008a). On the other hand, a strike-slip focal mechanism may imply the lateral extrusion at the transition zone between Taiwan mountain range and the OT (Liang et al., 2005).

Wang (2007) had tried 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 became dominated. However, for an event with only Mw5.7, 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?

Thus, it is important to further analyze the focal mechanism of this event and its tectonic implication, with some constraints from data of field mapping 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.

Seismicity and GPS 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 (Figure 1b). The hypocenter distribution of aftershocks may provide us the roughly finite rupture geometry for the doublet. This hypocenter distribution of aftershock does not perfectly fit either the focal mechanisms from moment tensor or first motion. The strike of the aftershock hypocenter distribution (Figure 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 hypocenter distribution of aftershocks is not likely to be north-dipping (Figure 1b), aftershock hypocenter distribution is not consistent with north-dipping moment tensor focal mechanism neither with shallow south-dipping first-motion focal mechanism. On the other hand, the result from the first motion polarities of the 2005 doublet undoubtedly is a normal faulting focal mechanism, but the fault planes from focal mechanism of BATS and Harvard moment tensor are quite different from the results of first-motion polarity (Figure 2). And, results of south dipping fault plane inferred from both aftershock hypocenter distribution and normal faulting focal mechanism determined from the first motion polarity agree with the regional extension resulted from GPS measurements in the period 1995 to 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 (Figure 1a and Table 1) have been installed in the study region by the CWB since 2004. GPS measurements are the finite displacement result due to the doublet event in this study. It should be displacement representative involved both focal mechanisms from moment tensor and first-motion solutions. Thus, GPS measurements offer more information for this event. Figure 3 shows the distance and elevation changes of the closest three GPS stations. No obvious elevation change across the fault in the GPS measurements may support the strike-slip mechanism (Figure 3b). The distance between the closest three GPS stations increased after the 2005 earthquake (Figure 3a), indicating the apparent dilation of normal faulting phenomena. Especially, the station displacement vector is larger when the vector is highly oblique to the fault strike rather than parallel to the strike (Figure 4). Consequently, GPS measurements support both normal faulting and strike-slip focal mechanisms as we expected. In details, when the station displacement vector is not really perpendicular to fault strike, horizontal displacement of GPS measurements should be composed of strike-slip and tensile components. Therefore, we need perform the dislocation fault model to evaluate the amount of strike-slip and tensile components of horizontal displacement in order to compare and integrate with results of focal mechanisms from moment tensor and first motion.

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; 2006b). Table 1 and Figure 4 show the horizontal displacements from GPS measurements. This event did not cause significant displacements in the vertical direction even with relatively poor vertical resolution of GPS measurements (Figure 3b). As a result, we assumed the vertical displacements at the 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. Thus they concluded that the earthquake doublet have the same focal mechanisms with almost the same size of magnitude. Results of BATS and Harvard moment tensor solutions also show the same conclusion. Therefore, we can use the GPS measurements to investigate the dislocation model. The distribution of the aftershocks provides constraints on the fault geometry. Strike, dip and tensile slips are inverted by the dislocation model. Table 2 shows the parameters of fault geometry as well as the inverted slips. Figure 4 shows the observed and best-fitted modeled displacements. Based on dislocation fault model, we confirmed that slip vectors of GPS measurements are composed of two major components of 9.8cm strike-slip and -5.7cm 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 magnitude of dip slip is almost one order smaller than that of second large slip component. Furthermore, slip vectors are not confined to lie on the fault plane of aftershock distribution, suggesting possible existence of tensile deformation. In details, the tensile slip deduced from the fault dislocation model means that how far of two blocks is 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 detected as first-motion polarity focal mechanism for the initial ruptures. Furthermore, strike-slip component determined from dislocation model is consistent with strike-slip faulting of moment tensor focal mechanism as average faulting behavior. Since neither single normal faulting nor single strike-slip faulting from focal mechanism of first-motion and moment tensor can explain the GPS measurements completely, our results can 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 behavior of earthquake source, respectively, their temporal sequence should be able to apply to slip sequence. Therefore, we expect that certain amount of tensile slip and tiny dip slip occurred in the beginning as normal faulting and larger strike-slip took place later as major strike-slip faulting behavior. These results also deliver a possible explanation for the discrepancies of fault geometries inferred from the dislocation fault model and focal mechanisms of first-motion and moment tensor due to complex faulting integrated with tensile faulting and strike-slip faulting.

Field Observations of Ductile Deformation

Field observations of cross-cutting relationship can provide temporal sequence constraints on the tectonic events. Previous results of field mapping of the slate/schist outcrops south of Suao suggested different stages of ductile deformation (Yeh, 1998) as the expectations of previous results (Suppe, 1984, Kao et al., 1998; Shyu et al., 2005b). In details, two ductile deformation stages were clearly identified based on field mapping and microscopic examination in the slate belt of Suao highway (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° (Figure 5a). In the latest stage, the foliation obtains attitude of 063°/33°S and the associated stretching lineation attains the attitude of 21°/103° (Figure 5b). Attitude of foliations in the early stage is more consistent with attitude of regional main foliation in the slate belt of Suao highway as published geological map (Lin and Kao, 1997). The kinematics of the early ductile deformation inferred from chlorite-mica fish, asymmetric folded chlorite-mica aggregates (Figure 5c), and pressure shadows indicated top-to-east shearing with reverse-sense component. It illustrated the transpressional movement, which could be compatible with the explanation of lateral extrusion (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 (Figure5d), suggesting the transtension deformation. Although the exact age of stretching lineation is still unknown, the evidence of evolution of ductile deformations from transpression to transtension in the Late Cenozoic is reliable. Furthermore, no clear evidence of distinctive SE-NW extension structure such as dilation vein or dike intrusion is observed in the field. From such geometry of deformation structures and the sense of shear, we can conclude that the latest ductile deformation in the region involved transtension deformation with predominant strike-slip component. Synthesized with results of earthquake doublet from this study, it illustrated that regional latest deformation has evolved from ductile strike-slip dominated component to brittle extension dominated component.

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 of 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 rupture. Result from dislocation model of this event shows 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 causing the different focal mechanisms from first motion and the moment tensor solutions. Combined these two results, we expect that tensile slip occurred in the beginning as normal faulting and larger strike-slip took place later as entire strike-slip faulting behavior. If removing the tensile component, we expected that an almost pure strike-slip focal mechanism can 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 associated aftershocks are almost located at the same zone as the 2005 events (Figure 1a), Lai et al. (2009) suggest that this reflects dike intrusion. The closest volcano in the region, the offshore Kueishan Island, lastly erupted less than 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 double couple component (Table 2) from dislocation model strongly suggests this active transtension deformation involves a fair amount of extension.

Comparison of 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 2002 and 2005 earthquake doublets in this study area (Figure 1a) are sub-parallel to the coseismic displacement vector of GPS measurements at Suao station (Figure 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), and focal mechanisms (e.g., Wu et al., 2009; Huang et al., 2012; Wu et al., 2014) further showed that the SE-NW orientation in the Ilan Plain resulted from the backarc extension of OT. Given different amount of extension components from the latest ductile deformation to the active faulting events, it evidently indicates that the transtension deformation in the region starts to switch from strike-slip dominated component to extension dominated component. Consequently, our results show that this region has begun to be affected by the backarc extension of OT.

Acknowledgements

We are grateful to the editor Ruey-Juin Rau and Shu-Huei Hung, reviewer Hao Kuo-Chen, and two anonymous reviewers for their kind helps 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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Figure Captions

Figure 1. Earthquakes of 2002/05/15 Mw6.1 and 2005/03/05 Mw5.7 Ilan, Taiwan. (a) Earthquake sequences and their mainshock 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'.

Figure 2. Focal mechanism solutions of the first shock of the Mar 5, 2005 Ilan doublet from USGS, BASTS, Harvard, and first-motion. "Up" and "Down" mean that the first motion is up and down in the seismogram, respectively.

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

Figure 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).

Figure 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 orientation of foliation with measurement number. The contour shows that 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.

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

Station	Lat. (°)	Lon. (°)	Observed North (cm)	Observed East (cm)	Observed Slip (cm)	Modeled North (cm)	Modeled East (cm)	Modeled 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

Table 2. Parameters of the fault geometry and the slips inverted from GPS measurements.

Middle Top Point Lon (°)	Middle Top Point 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

* DC indicates double couple component

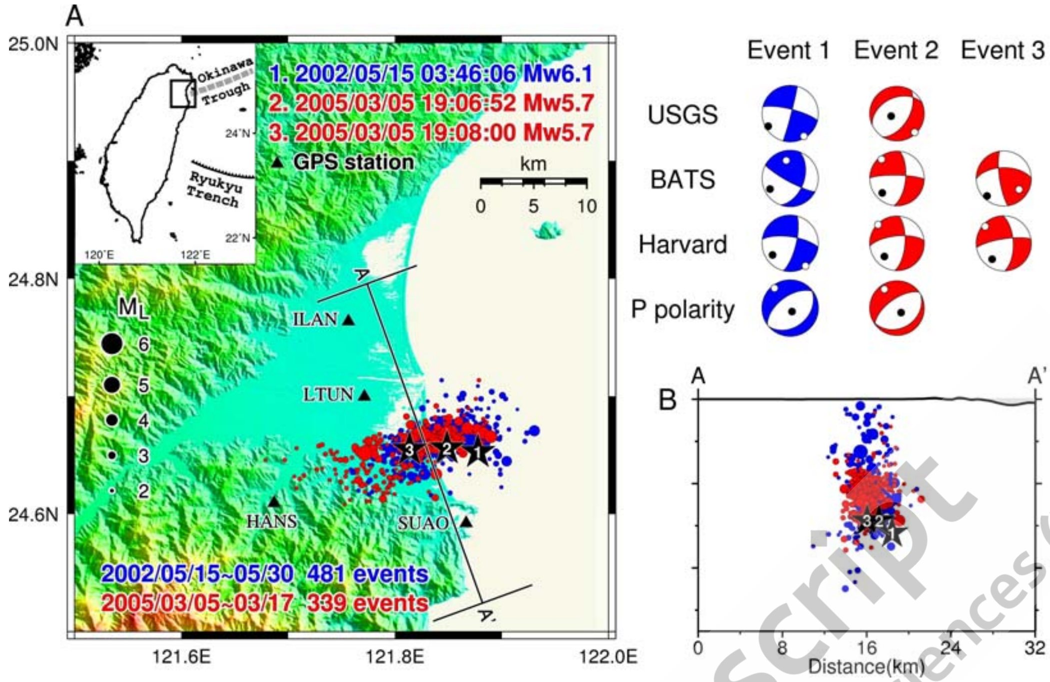


Figure 1.

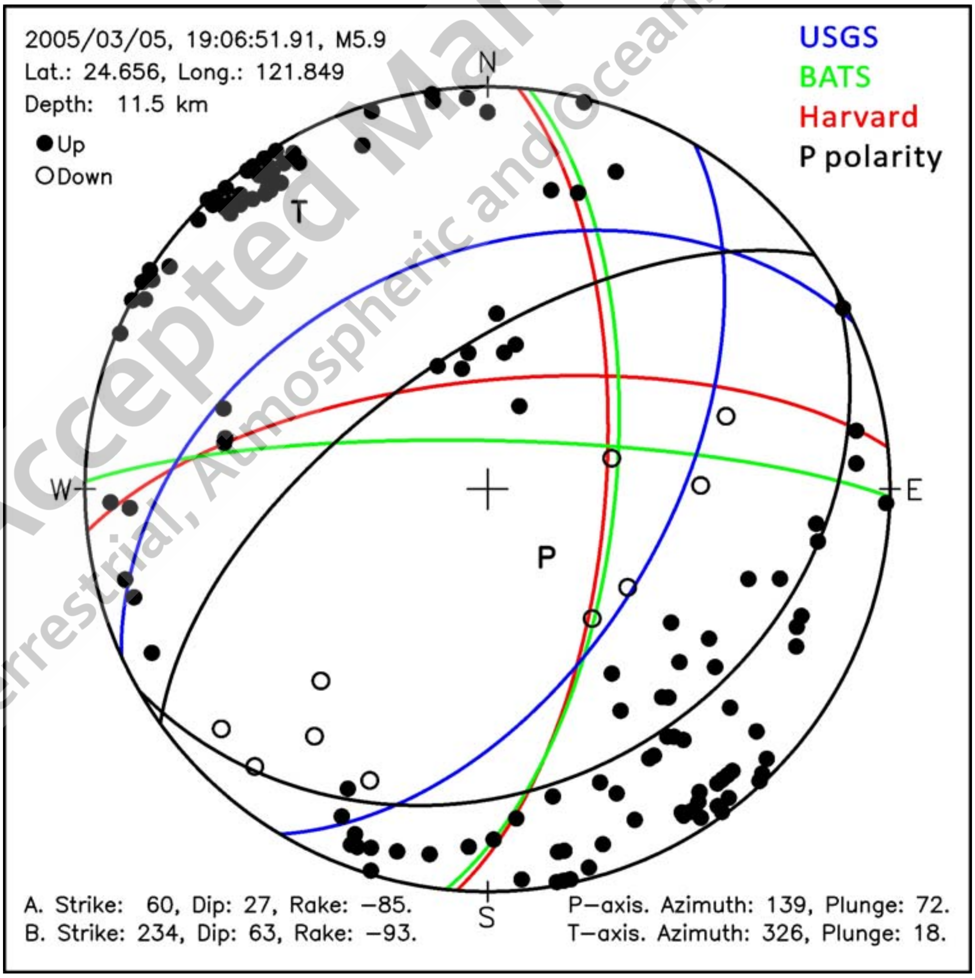
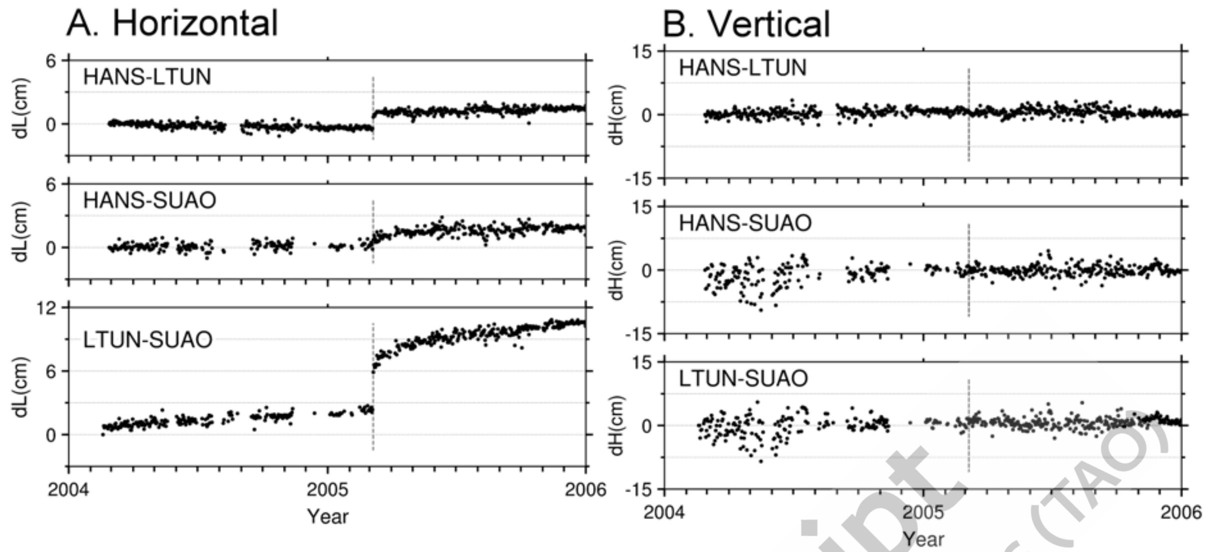


Figure 2.



A. Horizontal
B. Vertical
HANS-LTUN
HANS-SUAO
LTUN-SUAO
dL(cm)
dH(cm)
Year
2004
2005
2006

Figure 3.

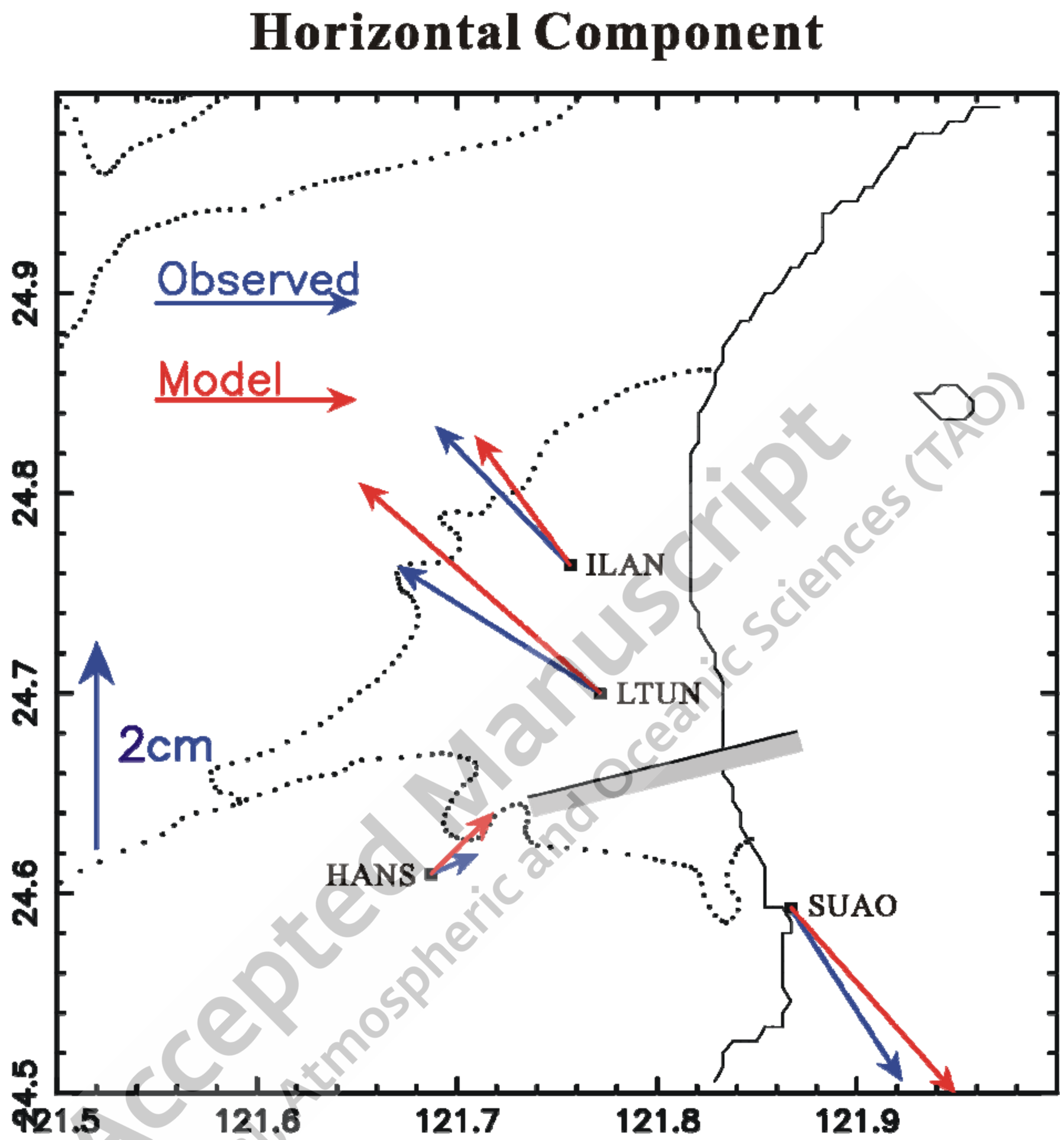

Horizontal Component
Observed
Model
2cm
ILAN
LTUN
HANS
SUAO
24.9
24.8
24.7
24.6
24.5
121.5
121.6
121.7
121.8
121.9

Figure 4.

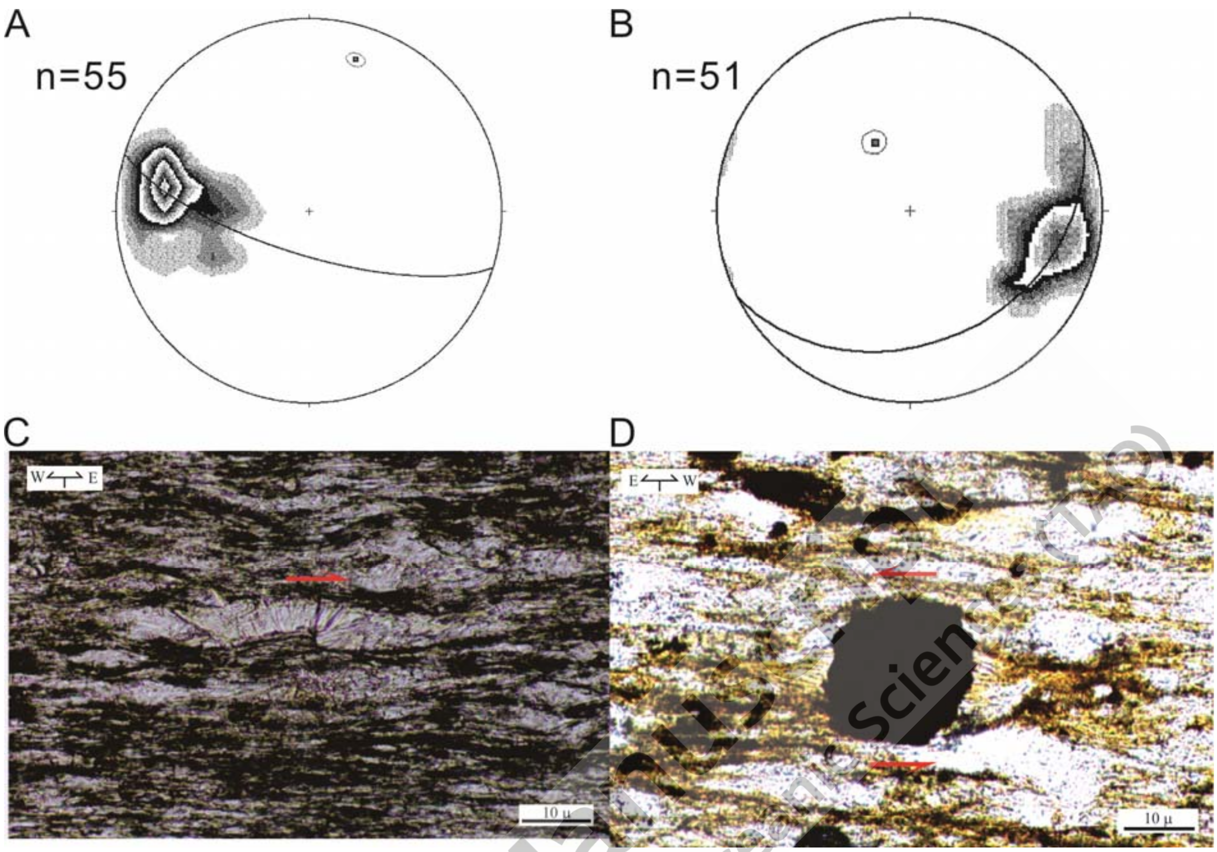


Figure 5.

