Seismotectonics of northeastern Taiwan: Kinematics of the transition from waning collision to subduction and postcollisional extension

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[1] The northeastern region of Taiwan is one of the few places on Earth that experienced a transition from collision to subduction and back-arc opening in a young orogenic belt. This provides us a rare opportunity to study the structural characteristics in such a transition. We attempt to analyze the seismicity and stress patterns in this transitional region using data obtained from a dense and high-quality seismic network. Our results show that from south to north, fault types change from thrust to strike-slip, then to normal faulting. The transitional domain between Ilan and Hualien is dominated by left-lateral strike-slip faulting with a NNW-SSE minimum principal stress axis, consistent with the opening of the Okinawa Trough. To the north, the Ilan Plain is formed by structural activities of a series of normal fault systems. To the south, the spatial distribution of an earthquake cluster north of Taiwan's Coastal Range appears to parallel the subducting interface between the Philippine Sea and Eurasian plates. This implies the northern extension of the Coastal Range has subducted. Consequently, the opening of the Okinawa Trough becomes an important tectonic driving force in northeastern Taiwan. The westernmost Ryukyu arc is pushed by the opening Okinawa Trough, and moves southward. The northern part of Taiwan's Central Range moves with the arc to bend southeastward, and the Ilan Plain forms in the space north of the range. The bending of the Central Range belt results in bedding plane slip with left-lateral strike-slip earthquakes in the transitional domain to accommodate the deformation.

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1. Introduction

[2] The Taiwan orogen is produced by the ongoing oblique collision between the NE-SW trending Chinese continental margin of the Eurasian plate (EP) and the mostly N-S trending Luzon volcanic arc of the Philippine Sea plate (PSP) since about 5 Ma [*Ho*, 1986; *Teng*, 1990; *Shyu et al.*, 2005a]. This oblique collision initiated from northern Taiwan and propagated southward as the Luzon volcanic arc approaches and collides. In this process, the Luzon volcanic arc acts as the backstop and impinges the accretionary wedge, resulting in the deformation of the accretionary wedge and the orogenesis.

[3] Kinematically, two prevailing models have been proposed for the Taiwan orogen, i.e., the thin-skinned model [e.g., *Suppe*, 1980, 1981] and the lithospheric collision model

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[e.g., *Wu et al.*, 1997]. Some of these models were proposed on the basis of seismic and well data in central Taiwan [e.g., *Rau and Wu*, 1995; *Carena et al.*, 2002; *Yue et al.*, 2005], and most of them only provide us a 2-D cross-section view of Taiwan's orogenic mechanism. However, in northeastern Taiwan, structures and earthquakes appear to exhibit a more complicated character.

[4] Offshore northeastern Taiwan, PSP subducts underneath EP, and the Okinawa Trough back-arc basin developed. The opening of the southernmost part of the trough started since around 2 Ma [*Teng*, 1996] and may have extended into northeastern Taiwan [*Tsai et al.*, 1975; *Yeh et al.*, 1989]. As a result, northeastern Taiwan represents a postcollisional environment [*Suppe*, 1984; *Teng*, 1996], and should have been influenced by both the collision and the subsequent subduction and back-arc opening in various phases of tectonic evolution. Thus, this area provides us a rare opportunity to study the structural characteristics of the transition from waning collision to subduction and postcollisional extension. Since the very active northeastern Taiwan is among the few areas on Earth that also experienced a transition from collision to extension, a better

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Figure 1. The tectonic map of northern Taiwan showing tectonic units and seismic station distribution. LV, Longitudinal Valley; IP, Ilan Plain; MT, Meilun Tableland; TV, Tatun volcanoes; CSF, Choshui Fault; CRF, Central Range Fault; MLF, Meilun Fault; LVF, Longitudinal Valley Fault. The stations of Central Weather Bureau Seismic Network and Taiwan Strong Motion Instrumentation Program are denoted by solid and open triangles, respectively. Inset map shows a tectonic overview of Taiwan and adjacent regions. The black rectangle shows our study area bounded by 121.0°E and 123.0°E, and by 23.5°N and 25.5°N. The red lines are the locations of the Chelungpu Fault (in western Taiwan), the Longitudinal Valley Fault (in eastern Taiwan), and the Ryukyu Trench. Current velocity vector of the Philippine Sea plate relative to the Eurasian plate is adapted from *Yu et al.* [1997]. The black stars represent the epicenters of (1) the 1999 Chi-Chi earthquake, (2) the 2003 Chengkung earthquake, (3) the 1994 Nanao earthquake, (4) the 2002 Hualien earthquake, and (5) the 2005 Ilan earthquake doublet.

understanding of this region will undoubtedly enhance our knowledge of transition characteristics of orogenic belts in general.

[5] Previously, detailed geologic and geomorphologic surveys of northeastern Taiwan are limited. This is partly because of the very thick (>1 km) sediments under the Ilan Plain [*Chiang*, 1976] and the adjacent high (>2 km) mountain ranges (Figure 1). However, more geophysical data have been collected since the late 1990s, including global positioning system (GPS) measurements [*Hsu*, 1998; *Rau et al.*,

2008], real time kinematic (RTK) data [Kang, 2007], magnetic surveys [Hsu et al., 2001; Tong et al., 2008], and seismic catalogs [Wu et al., 2008]. In particular, a much denser seismic network with more updated equipment in northeastern Taiwan has made more high-quality seismic data available now. These data became the cornerstone for the recent improvements on tomographic studies [Lin et al., 2004; Wu et al., 2007; Y.-M. Wu et al., 2009; Chou et al., 2009]. [6] Nonetheless, since some earlier studies [e.g., *Tsai* et al., 1975; *Yeh et al.*, 1991; *Cheng*, 1995], there are few detailed analyses of seismogenic structures and stress patterns of northeastern Taiwan using these updated seismic data. Therefore, we aim to combine relocated hypocenters and first motion focal mechanisms of earthquakes to analyze the transitional patterns in stress and seismicity of this area. This enabled us to infer a kinematic model for the tectonic development of northeastern Taiwan.

2. Tectonic Setting

[7] The island of Taiwan is situated at the boundary between EP and PSP (Figure 1), and is very active tectonically and seismically. The PSP moves in the direction of 306° with a 70-80 mm/yr convergence rate relative to EP [e.g., Seno et al., 1993; Yu et al., 1997]. South of Taiwan, the oceanic crust of South China Sea subducts eastward underneath PSP. This produced the Luzon volcanic arc and a submarine accretionary prism. At the latitude of southern Taiwan, the continental margin of the South China Sea has impinged upon the trench. This results in the orogeny that forms the mountainous island of Taiwan. The Longitudinal Valley in eastern Taiwan is generally considered as the onland suture between the two plates [e.g., Shyu et al., 2005a]. On the other hand, the PSP subducts northward under the Eurasian continental lithosphere along the Ryukyu trench offshore northeastern Taiwan, forming the Ryukyu arc and a back-arc basin, the Okinawa Trough, north of the arc. The southwestern Okinawa Trough is characterized by numerous submarine volcanoes and normal faults dipping toward the trough axis with meter-scale vertical offsets [Lee et al., 1980; Sibuet et al., 1987]. From the earthquake distribution patterns and onland normal faults, the Okinawa Trough probably has extended westward into the Ilan Plain [Sibuet et al., 1998].

[8] It has been proposed that the northeastern part of Taiwan consists of two distinct tectonic domains: the Ilan domain and the Hualien domain (Figure 1). The Hualien domain covers the northern half of the Longitudinal Valley, and represents the waning stage of the collision as the orogeny propagates southward [Shyu et al., 2005b]. The waning of the collision is evident from the significant difference of tectonic characteristics between the north and south Longitudinal Valley. For example, the GPS-derived convergence rate across the Longitudinal Valley fault (LVF), the major structure along the valley, shows a significant northward decrease from 30 to 5 mm/yr [Yu et al., 1997; Yu and Kuo, 2001]. The Central Range fault (CRF), the other major active structure in the Longitudinal Valley, is geomorphically and seismically evident, but most prominent in the southern half of valley [Shyu et al., 2005b, 2006; Wu et al., 2006a]. Near the northern end of the valley, the Meilun fault (MLF) runs along the western edge of the Meilun Tableland (MT), and ruptures of the fault produced a M7.3 earthquake in October 1951. Although the MLF is generally considered as a strand of the LVF system, how it extends northward remains unclear. What is the relationship between the northern extension of the LVF and the Ryukyu trench? Has the northern Coastal Range subducted northward beneath the Eurasian continent together with PSP?

[9] The Ilan domain in northeastern Taiwan, by contrast, is regarded as a postcollisional area [Teng, 1996; Shyu et al., 2005b]. Many lines of evidence suggest that this area is under an extensional environment. For instance, the stress pattern in northeastern Taiwan, determined by focal mechanisms, shows a N-S horizontal minimum principal stress axis (σ 3) at shallow depth [Yeh et al., 1991; Cheng, 1995]. GPS data also show a NW-SE extension in the Ilan Plain [Hsu, 1998; Chang et al., 2003; Hsu et al., 2009]. Geomorphic features indicate that several major active normal faults are present bounding both sides of the Ilan Plain [Shyu et al., 2005b]. However, other active faults may also exist, but are not cropping out due to the thick sediments in the plain. Several seismic zones beneath the plain that extends seaward suggest such faults do exist, and seem to be related with the opening of the Okinawa Trough [Chiang, 1976; Ku et al., 2009].

[10] Previously, the Ilan domain and the Hualien domain are mostly studied separately in different analyses. The transitional area between them is even less studied, except for a brief discussion of its structural characteristics, as part of a separate Ryukyu domain in *Shyu et al.* [2005b]. In this study, we analyzed crustal seismogenic characteristics of northeastern Taiwan as three domains: the Ilan domain, the Hualien domain, and the transitional domain between these two, which is roughly between 24.2°N and 24.5°N. From these results, we then attempted to provide a systematic interpretation for the seismotectonics of the entire northeastern Taiwan.

3. Data and Methods

[11] The data used in this study are collected by two seismic networks: the Central Weather Bureau Seismic Network (CWBSN) and the Taiwan Strong Motion Instrumentation Program (TSMIP). CWBSN is responsible for the regional earthquake monitoring in Taiwan [Shin, 1992, 1993], and consists of a central recording system and 71 telemetered stations that are equipped with three component Teledyne/ Geotech S13 seismometers (Figure 1). The instruments of CWBSN were operated in a triggered recording mode until the end of 1993, when they became continuously recording. Therefore, we selected the earthquake catalog since 1994 to ensure the data completeness. In addition, TSMIP consists of about 800 digital accelerographs at free field sites spreading over the Taiwan Island [Shin et al., 2003], and provides excellent spatial coverage in the Ilan and Hualien regions (Figure 1). This provides us a very dense coverage for most earthquakes in northern Taiwan.

[12] The procedures of our analysis are as follows: (1) we first relocate the selected earthquakes from CWBSN catalog; (2) we then determine the first motion focal mechanisms of all relocated events with local magnitudes $(M_L) \ge 4.0$ by including additional P wave first motions from TSMIP; and (3) we invert regional stress patterns using our determined focal mechanisms. For this analysis, we used three criteria to select earthquake records: (1) the earthquakes have arrivals recorded by more than 6 stations; (2) the local magnitudes (M_L) of the earthquakes are larger than 3.0; and (3) the depths of the events are shallower than 30 km. The first

criterion was used to ensure the quality of the data. We used the second and third criteria to focus our analysis on earthquakes occurred on shallow crustal seismogenic structures, rather than the abundant subduction related deeper seismicity. In our study area (121.0°E–123.0°E, 23.5°N–25.5°N), there were 77,340 events recorded by CWBSN from 1994 to 2005. In the end, a total of 29,148 events were selected in this study.

[13] For the earthquake relocation, we adopted the 3DCOR program [*Wu et al.*, 2003], which is modified from the 3-D location method of *Thurber and Eberhart-Phillips* [1999]. In this program, a 3-D pseudo-bending ray tracing method [*Um and Thurber*, 1987] and the 3-D velocity model of Taiwan [*Wu et al.*, 2007; *Y.-M. Wu et al.*, 2009] were used to calculate theoretical travel times. This 3-D velocity model was calculated using a more complete data set that includes records from Japan Meteorological Agency (JMA) stations on Ryukyu Island and S-P times of TSMIP, and is suitable for relocating earthquakes in northeastern Taiwan. It has been shown that after adding the JMA records and S-P times from TSMIP and using the 3-D velocity model in our relocation processes, we are able to get better and more reliable earthquake locations [e.g., *Wu et al.*, 2008].

[14] In addition, we manually determined 169 focal mechanisms of events with $M_L \ge 4.0$ by including the P wave first motions of TSMIP. Based on the relocated hypocenters, we could recalculate the ray paths and take off angles of the earthquakes to obtain the locations of polarities in lower-spherical projection. The relocation helps us get more reliable take off angles and azimuth readings. Abundant polarities from TSMIP have also provided additional constraints to determine the nodal planes of focal mechanisms. The parameters of the events are listed in Table S1 in the auxiliary material.¹ Furthermore, we adopted the stress tensor inversion method implemented as a part of the ZMAP seismological software package [*Wiemer*, 2001] to analyze the regional stress patterns in the study area.

4. Results

4.1. Earthquake Relocations

[15] A total of 26,899 events were relocated. Figure 2 shows the comparison of the root-mean-square (RMS) in travel time residuals, the error in epicenter (ERH), and the error in depth (ERZ) before and after the relocation [*Flinn*, 1965]. The RMS, ERH, and ERZ of CWBSN catalog were initially 0.36 ± 0.09 (sec), 1.14 ± 0.85 (km), and 1.25 ± 1.25 (km), respectively, but were reduced to 0.14 ± 0.06 (sec), 0.09 ± 0.15 (km), and 0.11 ± 0.24 (km) after relocation. This shows that we were able to reduce the errors significantly after the relocation. In Figure 2, we can also see that using the 3-D velocity model from *Wu et al.* [2007] can effectively reduce the RMS, ERH, and ERZ in gap angle $\geq 180^{\circ}$ (which means the earthquakes are located outside the network). This is better than using a 1D velocity model [*Chen*, 1995] as in CWBSN routine locations.

[16] Figure 3 shows the distribution of earthquake epicenters before and after the relocation, as well as the shift of their location by our relocation processes. From the relocated earthquake distribution, several earthquake clusters can be identified, including an ENE-WSW trending cluster extending from southwestern Okinawa Trough into the Ilan Plain, two E-W linear clusters beneath the southern Ilan Plain and the transitional domain, and several NNE-SSW linear clusters along the Longitudinal Valley and under the eastern flank of the Central Range (Figure 3b). In general, seismicity clusters mainly trend E-W in the Ilan and the transitional domain, but trend NNE-SSW in the Hualien domain.

4.2. Focal Mechanisms and Stress Patterns

[17] The distribution of 169 focal mechanisms determined in this study is shown in Figure 4. In general, the Ilan domain is dominated by normal-faulting focal mechanisms, the transitional domain has mostly left-lateral strike-slip focal mechanisms, and thrust-faulting focal mechanisms are predominantly present in the Hualien domain. In comparison with the distribution of relocated earthquakes (Figure 3b), the ENE-WSW trending cluster extending from Okinawa Trough to Ilan Plain is characterized by normal faulting. The two clusters beneath the southern Ilan Plain and the Nanao area have mostly left-lateral strike-slip events. The two NNE-SSW clusters in the Hualien domain, however, have different characteristics. Thrust faulting dominates the cluster along the Longitudinal Valley, but normal faulting events are present beneath the eastern flank of the Central Range.

[18] Figure 5 shows the results of our stress tensor inversion analysis. We divided the 169 focal mechanisms into 6 representative groups based on the tectonic background of their locations, the clusters they belong to, and their fault types. The groups 1 (blue diamond), 4 (red circle), and 5 (red star) have vertical, NW-SE, and N-S maximum principal stress axis (σ 1) that are in good agreement with the opening of the Okinawa Trough, the direction of the arc-continent collision, and the northward subduction of PSP, respectively. The group 3 (green square) represents events in the transitional domain, and shows a distinctive pattern with a NNW-SSE σ 3 and an ENE-WSW σ 1. The σ 3 is consistent with the opening of the Okinawa Trough, but the $\sigma 1$ is horizontal, and is different from the direction of the arccontinent collision. This pattern clearly shows their transitional characteristics. The group 2 (green triangle), between the group 1 and group 3, has transfersion stress pattern, and represents the transition from strike-slip to normal faulting. The group 6 (gray inverted triangle) represents the coseismic activity of the Chi-Chi earthquake under the eastern flank of the Central Range, and shows a transtension stress pattern. These events are probably related to the collapse of the hanging wall of the Chelungpu fault in western Taiwan, on which the Chi-Chi earthquake occurred (Figure 1).

4.3. Integrated Seismic Cross Sections

[19] Figure 6 shows three integrated seismic cross sections combining relocated earthquakes and focal mechanisms determined in this study. The locations of the cross sections are shown in Figure 3. Section A-A' in Figure 6a is a N5°W striking cross section traversing the Ilan Plain. The normal faulting cluster in the northern plain (cluster N1, at distance about 40 km) shows a change of its dipping angle, from steep dipping at its shallow part to gentle dipping at its deeper part, and roughly terminates at a depth of 10–12 km. The strike-slip faulting cluster with two large normal

¹Auxiliary materials are available in the HTML. doi:10.1029/2011JB008852.



Figure 2. The root-mean-square (RMS), error in epicenter (ERH), and error in depth (ERZ) versus gap angle plots (a) before and (b) after the earthquake relocation. Vertical red dotted line represents the 180° gap angle.

faulting events (the 2005 doublet) in the southern plain (cluster S1, at distance about 25 km) dips to the south and also ends at around 13 km deep. In general, seismicity beneath the Ilan Plain occurs in the crust shallower than 15 km. However, south of the plain (in the transitional domain), earthquakes can occur at dramatically deeper crust, down to depths more than 30 km (Figures 6a and 6c).

[20] Figure 6b is a N110°E striking cross section in the Hualien domain. Along this section, there are two clear thrust faulting clusters. One is a steep west-dipping cluster under the eastern flank of Central Range at about 20 km deep (cluster T2). The other is located under the northern end of the Longitudinal Valley and is mostly shallower than 10 km deep (cluster T1). In Figure 6c, the T1 cluster extends farther north and becomes deeper, forming a seismic belt (at distance 5–50 km, depth 5–20 km). The geometry of this

seismic belt appears to parallel to the subducting interface between PSP and EP. Besides, we can clearly observe the significant change of earthquake focal mechanism types along this section, as mentioned in section 4.2.

5. Discussion

5.1. The Ilan Domain

[21] Two linear seismicity clusters are present beneath the northern and southern Ilan Plain (Figure 3b). The northern cluster (cluster N1 in Figure 6a) extends seaward with normal faulting, and is likely related to the westward continuation of the Okinawa Trough (Figure 4). This is consistent with previous studies [e.g., *Tsai et al.*, 1975; *Yeh et al.*, 1989; *Sibuet et al.*, 1998]. This cluster dips to the south and its dipping angle becomes gentler at depth (Figure 6a),



Figure 3. The distribution of earthquake epicenters (a) before and (b) after our relocation, as well as (c) the shift of the earthquake location by the relocation processes (dots indicate relocated points). Line AA', BB', and CC' are the locations of the cross sections shown in Figure 6, and the short lines perpendicular to the cross-section traces represent the projection width of each section. Red lines are active fault traces published by the Central Geological Survey, Taiwan.

exhibiting a listric fault geometry. The location of this cluster is near some old thrust faults identified in seismic profiles beneath the plain [*Chiang*, 1976]. This suggests the normal faulting activities are related to the reactivation of these old structures.

[22] The other cluster, which is beneath the southern Ilan Plain, has mostly left-lateral strike-slip events (cluster S1 in Figure 6a). Its location and orientation are consistent with the Choshui fault (CSF in Figure 1) [*Chiang*, 1976; *Kang*, 2007], on which the 5 March 2005 Ilan earthquake doublet



Figure 4. The distribution of determined focal mechanisms. Thrust, strike-slip, and normal fault types are categorized by the rake (thrust, 45° to 135° ; normal, -45° to -135° ; strike-slip, others) and denoted by red, green, and blue, respectively. Red lines are active fault traces published by the Central Geological Survey, Taiwan.

occurred. According to recent offshore seismic investigations, this fault may extend further seaward [*Ku et al.*, 2009].

[23] Two loci of abrupt changes in geodetic patterns in the Ilan Plain have been identified previously: in the northern part of the plain, the GPS-calculated dilatation rate is higher than other parts of the plain [Hsu, 1998], and in the southern plain, there is a change of GPS-derived rotation direction, from counterclockwise rotation in the north to clockwise rotation in the south [Chiu, 2007]. These two loci of deformation are similar to the locations of the two abovementioned earthquake clusters. The focal mechanism types of those earthquakes are also consistent with the geodetic characteristics. This indicates the Ilan Plain is formed by structural activities of south-dipping normal fault systems near the northern side of the plain (Figure 6a). The strike-slip faulting cluster, on the other hand, may be related to structures near the southern boundary of the plain against the Central Range basements. These southern strike-slip structures are likely to accommodate the deformations north and/ or within the Central Range block.

5.2. The Hualien Domain

[24] In the Hualien domain, the distribution of seismicity is more complex. Based on the aftershock distributions and focal mechanisms of the 10 December 2003 Chengkung earthquake sequence (its epicenter is shown in the inset map of Figure 1), the LVF along the southern Longitudinal Valley is interpreted as a reverse fault that dips 60° to the east [Wu et al., 2006b]. However, we did not find any earthquake cluster of such characteristics along the northern part of the valley (Figure 6b). Instead, a west-dipping earthquake cluster at 15-25 km deep is present beneath the eastern foot of the Central Range (cluster T2 in Figure 6b). Kim et al. [2006] interpreted this feature as the result of a polarity reversal of the LVF. Alternatively, this west-dipping cluster may also be related to the seismic activities of the CRF [e.g., Shyu et al., 2006; Wu et al., 2006a], whose existence along the northern Longitudinal Valley is still under debate. If so, the northern part of the LVF either is much less active than its southern part, or is locked.

[25] On the other hand, we found another earthquake cluster under the western edge of the Coastal Range at about



Figure 5. Regional stress tensor map derived from grouped focal mechanisms. Six groups are denoted by different symbols in the map. S1, S2, and S3 are the maximum (σ 1), secondary (σ 2), and minimum (σ 3) principal stress axes, and are denoted by black square, red triangle, and blue circle, respectively.

10 km deep (cluster T1 in Figure 6b). It exists only locally around the northern tip of the Coastal Range and extends seaward (Figure 3). In the cross section of Figure 6c, this cluster displays an apparent parallel geometry with the subduction interface of PSP. This implies that the northern extension of the Coastal Range has already subducted with PSP, as suspected by *Shyu et al.* [2005a].

[26] On the basis of seismicity relocated using a different data sets and a different 3-D velocity structures, *F. T. Wu* et al. [2009] proposed a model for the tectonic development of northern Coastal Range. In their model, the Coastal Range north of about 23.7° N overlies the shallow dipping

subduction zone, and, instead of being part of the Philippine Sea plate, lies on the Eurasian plate. This would imply that the crust of northern Coastal Range needs to detach into two layers. The upper crustal materials attached to the Eurasian plate and are left above the surface, whereas the middle to lower crust needs to subduct northward along with the Philippine Sea plate. Therefore, the north-dipping seismic cluster in our analysis may alternatively correlate with the subduction of the middle to lower crustal materials of the Coastal Range, as proposed by *F. T. Wu et al.* [2009]. However, in this case, we would need to find a major active



Figure 6. Three seismic cross sections combining our relocated earthquakes and determined focal mechanisms. (a) Cross section A-A'; (b) cross section B-B'; and (c) cross section C-C'. The locations of these cross sections are shown in Figure 3. Red, green, and blue colors represent thrust, strike-slip, and normal fault types of focal mechanisms, respectively. N1, S1, S2, T1, and T2 are earthquake clusters or groups discussed in the text.

E-W reverse fault that separates the northern Coastal Range from the other parts of the range at the surface.

5.3. Stress Transition and Tectonic Driving Forces

[27] Based on a two-dimensional plane stress finite element model, *Hu et al.* [2002] predicted that a regime of stress transition should exist between the arc-continent collision and the Okinawa Trough opening. In our analysis, we in fact observed the spatial variation of fault types in focal mechanisms in northeastern Taiwan, from thrust to strikeslip, then to normal faulting from south to north (Figure 4). The transitional domain we observed is characterized by a



Figure 7. A proposed kinematic model of northeastern Taiwan. These figures represent tectonic evolution (a) before the beginning of the southern Okinawa Trough opening (5–2 Ma), (b) after the beginning of the southern Okinawa Trough opening (2–0 Ma), and (c) at present. (d) The current situation (same as c) with plotted GPS vectors [*Yu et al.*, 1999]. Red, green, and blue shadow areas represent the compression (regime A), postcollision (regime B), and extension (regime C) stress regimes (see detailed discussion in section 5.4). HR, Hsuehshan Range; CeR, Central Range; CoR, Coastal Range; IP, Ilan Plain; PSP, Philippine Sea Plate; HB, Hoping Basin; NB, Nanao Basin; ENB, East Nanao Basin.

remarkably consistent left-lateral shearing (earthquake group S2 in Figure 6c).

[28] The stress tensor of earthquakes in the transitional domain displays a NNW-SSE σ 3, which agrees well with the opening direction of the Okinawa Trough (Figure 5). Its ENE-WSW σ 1 is different from PSP motion, but seems to correspond to the lateral compression of the subducting slab [*Kao et al.*, 1998; *Chou et al.*, 2006; *Y.-M. Wu et al.*, 2009]. This indicates that the subduction and the back-arc opening

have more dominant influences in the transitional domain than the arc-continent collision. Based on geodetic and geomorphologic analyses, it has been shown that deformation and uplift rates, which are direct products of plate convergence, are much lower in the northern Longitudinal Valley than in the southern valley at present [*Yu et al.*, 1997; *Yu and Kuo*, 2001; *Shyu et al.*, 2005a]. Therefore, we believe that other than the northwestward motion of PSP and the convergence between EP and PSP, the back-arc opening of the Okinawa Trough is another crucial tectonic driving force in northeastern Taiwan.

5.4. Kinematic Model of Northeastern Taiwan

[29] Based on our analysis and observations, we attempt to propose a new kinematic scenario for northeastern Taiwan (Figure 7). North of the northern part of the Longitudinal Valley, the collision between EP and PSP becomes waning, possibly due to the northward subduction of the northern Coastal Range with PSP. As a result, the southward opening of the Okinawa Trough becomes a dominant driving force in the regional stress regime (Figures 7a and 7b). As the trough opens, the westernmost part of the Ryukyu arc moves southward at a rate of 40 mm/yr [Lallemand and Liu, 1998; Nakamura, 2004]. The northernmost part of the Central Range appears to move southward along with this southward motion of the western Ryukyu arc. Topographically, there is a prominent southeastward bending of the northern Central Range. Such a southward motion created a space north of the range for the formation of the subsiding Ilan Plain. The bending of the northern Central Range produced bedding plane slip within the belt, which shows as left-lateral strikeslip shearing with related earthquakes (Figure 7c). The Ilan Plain is bounded in the north by a major listric normal fault system. Together with the left-lateral strike-slip fault zone, these two seismic zones represent the two major seismogenic zones in northeastern Taiwan.

[30] Our model also shows a good agreement with GPS measurements [Yu et al., 1999] (Figure 7d). We can therefore divide northeastern Taiwan into three different regimes. These three regimes can represent different regimes of stress in space, or different stages of orogeny in time. In regime A, despite the fact that the collision is waning, the surface deformation patterns are still consistent with the motion of PSP. In regime B, the GPS-derived crustal movements are almost zero, which means that this area is a postcollisional environment after the collision ended [Teng, 1996]. Seismicity in this area is also rare, except for some volcanic events related with the Tatun volcanoes in northern Taiwan (TV in Figure 1). The regime C to the east is also a postcollisional environment, but shows different characteristics from regime B. GPS-derived movements in this regime are much faster, and show a clear clockwise rotation. This reflects a predominant influence of the opening of the Okinawa Trough. This spatial change of stress regime can also be viewed as the temporal evolution of the Taiwan orogen, which experienced a transition from collision, postcollision, to back-arc opening. As the arc-continent collision migrates southward, the postcollisional regime is also likely to expand southward, and the Okinawa Trough may extend further into northeastern Taiwan.

6. Conclusions

[31] Northeastern Taiwan is a complex tectonic transitional area that is influenced by collision, subduction, and back-arc opening. It therefore provides us a good opportunity to study the transitional tectonics. Using data obtained from two major earthquake networks in Taiwan, we were able to relocate more than 16,000 earthquakes in northeastern Taiwan, and determine the focal mechanisms for 169 events. Most of the relocated earthquakes are clustered. One of the clusters is located near the northern edge of the Ilan Plain, and may represent a listric normal fault system bounding the northern plain. Another major cluster is located near the northern end of the Central Range, and has mostly left-lateral earthquakes. These two areas may represent two major seismogenic zones in northeastern Taiwan.

[32] Our determined focal mechanisms enabled us to analyze the stress tensor of this area. The results show a clear transitional pattern, from the arc-continent collision in the south (the Hualien domain), to a combination of influences of collision and extension in the middle (the transitional domain), to the extension related with the opening of the Okinawa Trough in the north (the Ilan domain).

[33] Based on these results, we propose a kinematic model for the structural characteristics in northeastern Taiwan. In the Hualien domain, the collision has become waning, possibly due to the northward subduction of the northern Coastal Range. As a result, the southward opening of the Okinawa Trough becomes a major tectonic driving force in northeastern Taiwan. The opening of the trough pushes the westernmost Ryukyu arc southward, and the northern part of the Central Range moves with the arc to bend southeastward. This southward motion created the space north of the range where the Ilan Plain forms. The plain is produced by a series of south-dipping normal fault systems, and the southward bending of the Central Range belt produced bedding plane slip with related left-lateral strike-slip earthquakes we observed in the transitional domain.

[34] Although the complicated northeastern Taiwan has attracted many tectonic investigations in the past, our attempt is the first to analyze the seismic characteristics in the entire transitional area. We hope our observations in the young and active Taiwan orogen would further our understanding in the transitional characteristics of orogenic belts in the world.

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