GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 5080–5084, doi:10.1002/grl.51005, 2013

A midcrustal ramp-fault structure beneath the Taiwan tectonic wedge illuminated by the 2013 Nantou earthquake series

Ray Y. Chuang,[1] Kaj M. Johnson,[1] Yih-Min Wu,[2] Kuo-En Ching,[3] and Long-Chen Kuo[4]

Received 23 August 2013; revised 24 September 2013; accepted 27 September 2013; published 7 October 2013.

[1] Taiwan's active mountain belt is a spotlight for orogenic studies and was first used to test the critical-taper wedge mechanics. The concept of an orogenic wedge above a shallow detachment surface has been highly influential on current understanding of orogenic processes in Taiwan. However, the recent M_L 6.2 and M_L 6.5 2013 Nantou reverse-faulting earthquakes in central Taiwan have nucleated below the proposed detachment, indicating that active mountain building is occurring below the orogenic wedge. We estimate the coseismic slip distributions and fault geometry using the uniform stress drop slip inversions. The earthquakes occur on essentially the same 30° dipping fault plane ramping up from ~20 km depth near a cluster of 1999 Chi-Chi earthquake aftershocks to the shallow detachment and the Chi-Chi fault plane. The fault could be a deep extension of a mature shallow fault or a newly developed deep ramp fault that is not reflected in the surface geology.
Citation: Chuang, R. Y., K. M. Johnson, Y.-M. Wu, K.-E. Ching, and L.-C. Kuo (2013), A midcrustal ramp-fault structure beneath the Taiwan tectonic wedge illuminated by the 2013 Nantou earthquake series, *Geophys. Res. Lett.*, *40*, 5080–5084, doi:10.1002/grl.51005.

1. Introduction

[2] Critical-taper wedge mechanics was first tested and illustrated with data from the Taiwan mountain belt (Figure 1) [e.g., *Suppe*, 1981; *Davis et al.*, 1983; *Dahlen et al.*, 1984; *Barr and Dahlen*, 1989; *Barr et al.*, 1991; *Suppe*, 2007]. Indeed, wedge mechanics has been highly influential on current understanding of the mountain-building process in Taiwan [e.g., *Wang*, 2001; *Willett and Brandon*, 2002; *Simoes et al.*, 2007; *Upton et al.*, 2009], and numerous studies construct structural cross sections of Taiwan either explicitly or implicitly, assuming critical wedge and thin-skinned tectonics mechanisms [e.g., *Wang et al.*, 2000; *Loevenbruck et al.*, 2001; *Mouthereau et al.*, 2001; *Hsu et al.*, 2003; *Yue et al.*, 2005; *Yang et al.*, 2007; *Yanites et al.*, 2010; *Ching et al.*, 2011a]. However, while the surface geologic structures in Taiwan are compatible with a model of shallow thrusting over a regional detachment surface in the upper crust, the interpretation is nonunique, and a number of geophysical observations suggest that deeper levels of the crust are involved in the mountain-building process. Other studies have noted seismicity in Taiwan extending well below the proposed detachment depth and thick crust underlying high topography and proposed alternative tectonic models for Taiwan, including basement-involved, thick-skinned models [e.g., *Lacombe and Mouthereau*, 2002; *Mouthereau and Lacombe*, 2006], whole lithospheric thickening [*Wu et al.*, 1997], and double suturing and lithospheric duplexing [*Shyu et al.*, 2005a]. In this study we combine geodetic and seismic observations from the 2013 Nantou earthquake series as well as aftershocks from the 1999 Chi-Chi earthquake to demonstrate that ramp faulting below the traditional detachment depth is contributing to present-day mountain building in Taiwan.

[3] Data from the 1999 Chi-Chi earthquake, surface geology measurements, seismic images, and well logs constrain the geometry of shallow (<5 km) subsurface structures in Taiwan's western fold-and-thrust belt [e.g., *Johnson and Segall*, 2004; *Yue et al.*, 2005; *Hung et al.*, 2009; *Yang et al.*, 2007], but it is still debated how this shallow structure is related to the deeper Chi-Chi earthquake main shock and aftershocks and deeper background seismicity and how this shallow structure extends eastward beneath the mountainous Central Range. While studies located the Chi-Chi main shock near the bottom edge of the Chelungpu ramp fault at ~6–10 km depths [*Wu et al.*, 2008; *Chang et al.*, 2000; *Kao et al.*, 2000] near the depth of the proposed Taiwan main detachment (10 km) [*Carena et al.*, 2002], aftershocks of the Chi-Chi earthquake reveal two clusters east of the Chelungpu fault [*Chen et al.*, 2002; *Chang et al.*, 2007]. One high-angle cluster extends between depths of 20 and 30 km (Figure 1), and the other cluster occurs between ~10 and 25 km depths [*Chen et al.*, 2002; *Chi and Dreger*, 2004; *Chang et al.*, 2007]. All of these aftershocks occurred below the shallow detachment inferred from surface geology; however, until the recent Nantou 2013 earthquake sequence, the geometry of active structures below the inferred shallow tectonic wedge has remained unclear.

[4] The 27 March M_L 6.2 and 2 June M_L 6.5 2013 Nantou earthquakes nucleated below the shallow detachment within the deep Chi-Chi aftershock clusters (Figure 1b), and thus, data from these events provide additional insights into the fault geometry connecting the shallow Chi-Chi fault plane to deeper structures. In this study, we use GPS-derived coseismic displacement to estimate the fault geometry and slip distribution. We suggest that these two events ruptured along a ramp fault connecting to the Chi-Chi aftershocks to the shallow Chi-Chi fault plane (Figure 1b), providing

Additional supporting information may be found in the online version of this article.

[1]Department of Geological Sciences, Indiana University, Bloomington, Indiana, USA.
[2]Department of Geosciences, National Taiwan University, Taipei, Taiwan.
[3]Department of Geomatics, National Cheng Kung University, Tainan, Taiwan.
[4]Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan.

Corresponding author: R. Y. Chuang, Department of Geological Sciences, Indiana University, 1001 East 10th St., Bloomington, IN 47405, USA. (chuangyu@indiana.edu)

0094-8276/13/10.1002/grl.51005

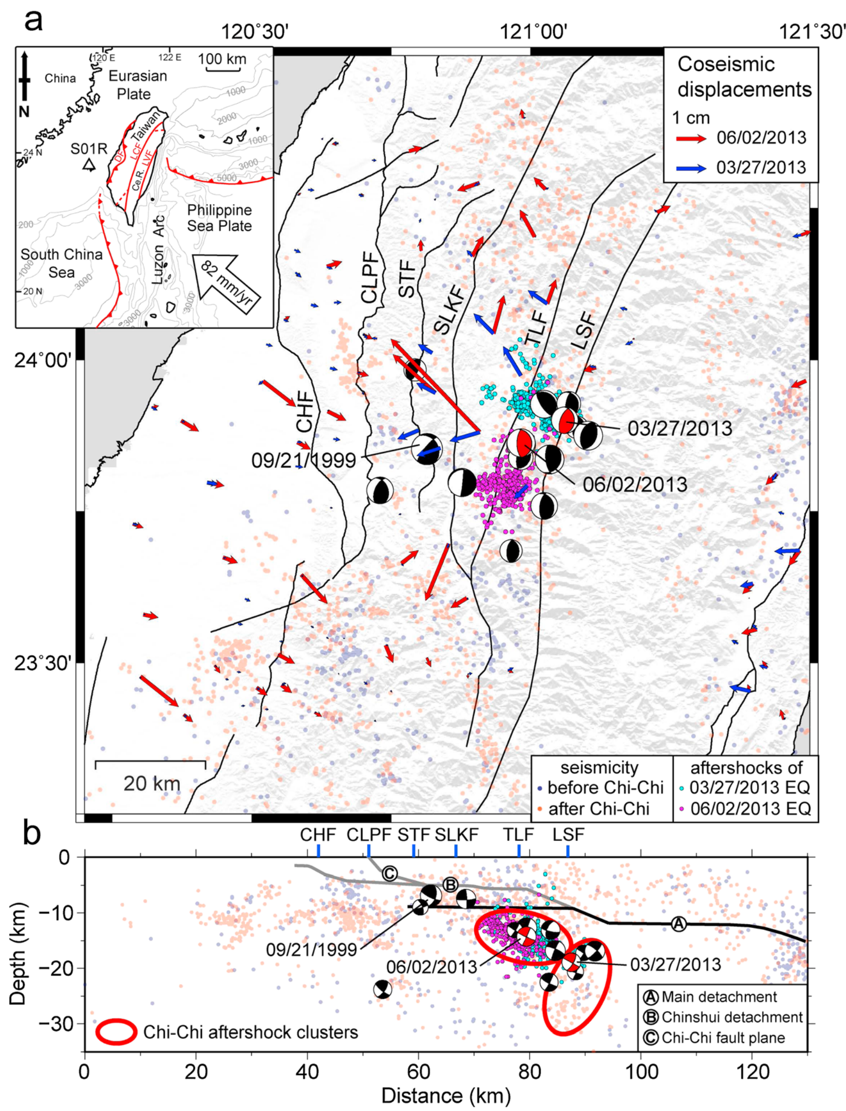

Figure 1. (a) vHorizontal coseismic displacements of the 27 March (blue) and 2 June (red) Nantou earthquakes. Fault traces based on *Shyu et al*. [2005b] and *Brown et al*. [2012]. The red beach balls denote the Nantou main shocks, and the black beach balls denote the Chi-Chi aftershocks and other M_L>5.5 events. Blue and orange dots denote seismicity before and after Chi-Chi earthquake, respectively. Cyan and magenta dots denote the aftershocks of the 27 March and 2 June events, respectively. CHF: Changhua fault; CLPF: Chelungpu fault; STF: Shuangtung fault; SLKF: Shuilikeng fault; TLF: Tili fault; LSF: Lishan fault. Inset shows the tectonic setting modified from *Shyu et al*. [2005b]. S01R (Paisha station) is the reference GPS site. DF: deformation front; LCF: Lishan-Chishan fault; LVF: Longitudinal Valley fault; Ce.R.: Central Range. (b) Cross section of background seismicity and aftershocks of the Nantou earthquakes and main shock focal mechanisms of the Chi-Chi and Nantou earthquakes. Two Chi-Chi aftershock clusters are circled in red. Fault A is the Taiwan main detachment proposed by *Carena et al*. [2002], fault B is the shallow Chinshui detachment from [*Yue et al*., 2005], and fault C is the Chelungpu fault that ruptured during 1999 Chi-Chi earthquake.

evidence of active reverse faulting below the proposed Taiwan detachment [e.g., *Carena et al*., 2002; *Yue et al*., 2005].

2. Data and Modeling

[5] All GPS data were processed by the GPS LAB of Academia Sinica (data source: http://gps.earth.sinica.edu.tw). The coseismic displacements were determined relative to the Paisha station (S01R) at Penghu Island in the Taiwan Strait (Figure 1).

[6] We use the uniform stress drop model of *Sun et al*. [2011], which is also adopted by *Ching et al*. [2011b], with the Markov chain Monte Carlo (MCMC) Metropolis algorithm to solve for the coseismic slip distribution and fault geometry. In these inversions, we fix the size of the fault plane (length and width of 30 km) and solve for all other fault parameters, including position, depth, strike, dip, and two components of stress drop. The fault planes are discretized into 100 patches in total (10 in each direction). We presume no prior information on fault geometry. It is not immediately clear which of the two nodal planes of the focal mechanisms

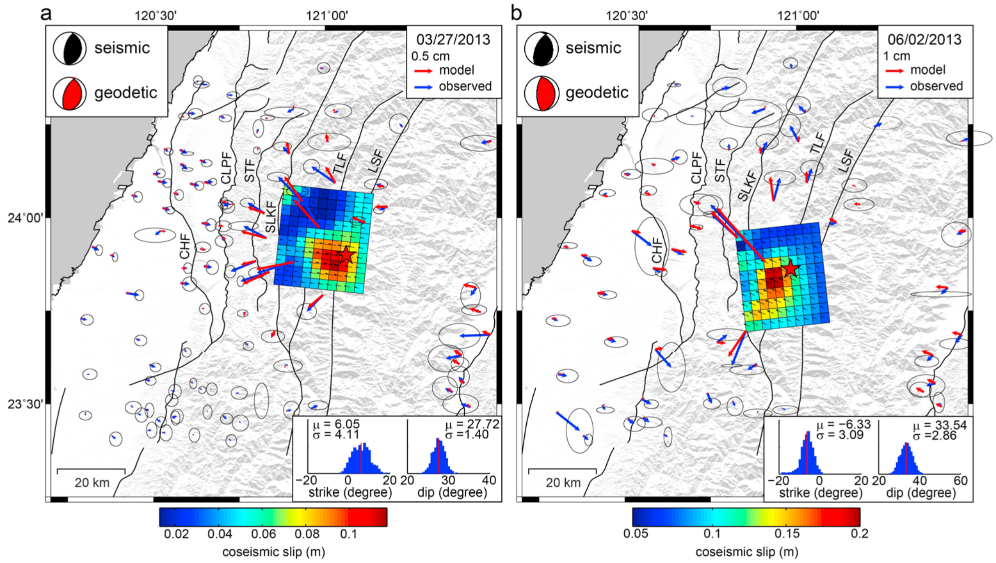

Figure 2. Coseismic slip distribution and model fit for the homogeneous model of the (a) 27 March and (b) 2 June earthquakes. Blue arrows are horizontal observations, and red arrows are model vectors. Error ellipses show 95% confidence level. Upper insets compare geodetic and seismic focal mechanisms. The lower inset shows posterior probability distributions of strike and dip.

is the fault that slipped in these two earthquakes, and it is inherently difficult to design an inversion that will allow both nodal planes to be tested as possible sources. Thus, for both earthquakes, we conduct two different MCMC inversions with initial values for fault dip set equal to the two different nodal planes and compare probabilities to determine the better-fitting fault plane. We examine both uniform elastic half-space models as well as layered half-space models with depth-varying (1-D) elastic properties following *Johnson and Segall* [2004]. Two different sets of layered elastic moduli are derived from a *P* wave velocity profile [*Cheng*, 2000] and a density model [*Yen and Yeh*, 1998].

[7] We compare our fault inversions with relocated main shocks and aftershocks. The relocated earthquakes are calculated using the 3-D location method of *Thurber and Eberhart-Phillips* [1999] and *Wu et al.* [2008] with 3-D tomography data based on *Wu et al.* [2007, 2009]. We processed seismicity from 27 March to 15 June to identify the aftershocks from both events. We also use background seismicity before and after Chi-Chi [*Wu et al.*, 2008] to compare the model results of fault geometry.

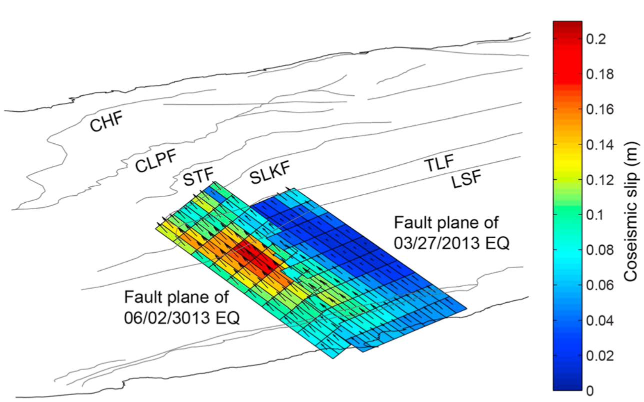

Figure 3. Plot of (mean) model fault planes and slip distributions for the 27 March and 2 June earthquakes using homogeneous models. CHF: Changhua fault; CLPF: Chelungpu fault; STF: Shuangtung fault; SLKF: Shuilikeng fault; TLF: Tili fault; LSF: Lishan fault.

3. Results

[8] All model parameters estimated in the inversion are summarized in Figure S2 and Table S1 in the supporting information, and only the crucial geometric parameters are summarized here in the main text. For both events, the formal probability for the east dipping model is higher (better fitting) than for the west dipping model. This is consistent with the fact that most aftershocks from both events are distributed along the east dipping fault planes (Figure 1b). The average fault geometry and slip distribution for the 27 March event are shown in Figure 2a. The model fault plane strikes roughly N-S with a dip of 25°–32°, consistent with the range of 23°–33° from several different earthquake catalogs (Table S2). The average slip of 0.05 m (maximum 0.12 m) is largely concentrated between depths of 9 and 16 km, updip of the relocated main shock at ~19 km depth (Figure S4). The average rake is 84° (0° means left-lateral movement, and 90° means reverse movement), indicating primarily reverse sense of slip. We estimate a seismic moment of 1.36×10^{18} N m and a moment magnitude of 6.09 assuming a shear modulus of 30 GPa, in agreement with catalog values (Table S2). For the 2 June earthquake, the estimated fault strikes 5° west of north with a dip of 25°–40°, consistent with focal mechanism solutions (22°–37°). The average slip of 0.1 (0.2 m maximum) (Figure 2b) is concentrated between depths of 5 and 14 km (Figure S4). The average rake is 64.5°, almost identical to the rake of the Chi-Chi earthquake [*Chang et al.*, 2000], suggesting more oblique motion than the first event. The estimated seismic moment for the second event is 2.82×10^{18} with a moment

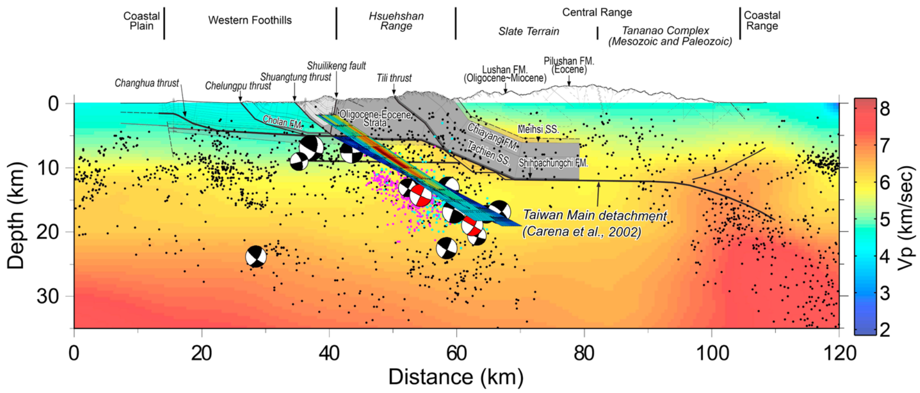

Figure 4. Central Taiwan cross section showing the Nantou fault. The structural profile is modified from *Yue et al.* [2005], and the *P* wave velocity tomography image is from *Kuo-Chen et al.* [2012]. Black dots denote background seismicity from 1991 to 2009. Fault planes are same as those in Figure 3. Other symbols are same as those in Figure 1b.

magnitude of 6.3, both consistent with earthquake catalogs (Table S3). The results of the layered models are similar to the homogeneous models, but the fault plane is shifted downward 1–2 km (Figure S3).

4. Discussion and Conclusions

[9] Our inversion results show that the two earthquakes occur on essentially the same fault plane, hereafter called the Nantou fault, with a dip angle of about 30° (Figure 3). The shallow Chi-Chi aftershock cluster (Figure 1b) might occur on the same fault. The loci of coseismic slip for the two events are also adjacent and essentially connected with the larger slip from the second event occurring updip of slip from the first event. The majority of the combined slip was released between depths of 5 and 20 km. Since the Nantou fault is well constrained by geodetic data and aftershocks, we propose that the Nantou earthquakes as well as the Chi-Chi aftershocks (Figure 1b) illuminate a deep extension of the shallow ramp fault structure into the middle crust (Figure 4). There are at least two structural interpretations of the Nantou ramp fault. First, the Nantou fault could be a deep extension of the Shuilikeng fault, with the Chinshui detachment only present west of the Shuilikeng fault, as proposed by *Brown et al.* [2012]. This view is accordant with the observation of higher-grade rocks exposed east of the Shuilikeng fault in the Hseushan Range [e.g., *Brown et al.*, 2012]. It is not required by these observations, however, that the Nantou fault links directly with any of the shallow ramp faults overlying the detachment. This leads to the second possible interpretation that the Nantou fault is a newly developed subsurface structure that is not directly related to any faults at the surface. Activity on the fault may have commenced rather recently in the development of the Taiwan mountain ranges. More data will be needed to distinguish between these alternative interpretations. The Nantou fault might also link to the shallow detachment that partially ruptured during the Chi-Chi earthquake based on the Chi-Chi aftershock distributions. The bottom of the Nantou fault might link to the deep Chi-Chi aftershock cluster (Figure 1b), which could be a crustal-thickening structure [*Wu et al.*, 2004] or a response to stress concentrating at the eastern edge of the Peikang High [*Byrne et al.*, 2011]. In the latter case, the Nantou fault may develop on the top of this basement high.

[10] It has been recognized that deeper seismicity beneath the proposed Taiwan detachment exists [e.g., *Wu et al.*, 1997, 2004; *Chen et al.*, 2008], including the deep Chi-Chi aftershock cluster at depths between 20 and 30 km. Strong earthquakes exceeding *M*6 beneath Taiwan are fairly uncommon, so the role of deep seismicity in the mountain-building process has remained unclear. One exception is the 2010 *M*6.3 Jiashian earthquake nucleated at ~20 km depth, with most of the slip occurring deeper than the proposed shallow detachment. This earthquake is consistent with motion on a reactivated passive margin structure [*Huang et al.*, 2013] or a lateral ramp of a basal detachment [*Ching et al.*, 2011b]. Triggered tremor and low-frequency earthquakes in southern Taiwan are observed at depths of 15–25 km [e.g. *Chao et al.*, 2011; *Tang et al.*, 2013], and they can be explained by slip along a low-angle detachment at a depth of ~20 km [*Peng and Chao*, 2008; *Chao et al.*, 2011]. Thus, taking all of these observations together with the newly identified Nantou fault, it is becoming clear that a significant portion of the shortening across Taiwan is accommodated by slip on deep fault systems.

[11] The existence of the deep Nantou fault as well as a lack of a clear seismic signature of the detachment beneath the Central Range [e.g., *Wu et al.*, 2004; *Gourley et al.*, 2007; *Wu et al.*, 2008; *Brown et al.*, 2012] implies that the structural architecture across Taiwan cannot be fully explained within the framework of thin-skinned tectonics overlying a main detachment [e.g., *Suppe*, 1981; *Carena et al.*, 2002; *Yue et al.*, 2005], and deep structures play an important role in accommodating regional compressive deformation across the active collisional mountain belt.

[12] **Acknowledgments.** We thank the Central Weather Bureau, Taiwan, for providing seismic data. We thank the GPS LAB of the Institute of Earth Sciences, Academia Sinica, Taiwan (http://gps.earth.sinica.edu.tw), for providing coseismic GPS displacement data. We thank two reviewers, Michael Hamburger, Gary Pavlis, Bruce Douglas, Li-Fan Yue, Te-Cheng Yi, and Hsin-Hua Huang for helpful suggestions.

[13] The Editor thanks Timothy Byrne and an anonymous reviewer for their assistance in evaluating this paper.

References

Barr, T. D., and F. A. Dahlen (1989), Brittle frictional mountain building: 1. Deformation and mechanical energy budget, *J. Geophys. Res.*, *94*, 3906–3922.

Barr, T. D., F. A. Dahlen, and D. C. McPhail (1991), Brittle frictional mountain building: 3. Low-grade metamorphism, *J. Geophys. Res.*, *96*, 10,319–10,338.

Brown, D., J. Alvarez-Marron, M. Schimmel, Y. M. Wu, and G. Camanni (2012), The structure and kinematics of the central Taiwan mountain belt derived from geological and seismicity data, *Tectonics*, *31*, TC5013, doi:10.1029/2012TC003156.

Byrne, T., Y. C. Chan, R. J. Rau, C. Y. Lu, Y. H. Lee, and Y. J. Wang (2011), The arc-continent collision in Taiwan, in *Arc-Continent Collision*, edited by D. Brown and P. D. Ryan, Springer, New York, pp. 213–246.

Carena, S., J. Suppe, and H. Kao (2002), Active detachment of Taiwan illuminated by small earthquakes and its control of first-order topography, *Geology*, *30*, 935–938.

Chang, C. H., Y. M. Wu, T. C. Shin, and C. Y. Wang (2000), Relocation of the 1999 Chi-Chi earthquake in Taiwan, *Terr. Atmos. Oceanic Sci.*, *11*, 581–590.

Chang, C. H., Y. M. Wu, L. Zhao, and F. T. Wu (2007), Aftershocks of the 1999 Chi-Chi, Taiwan, earthquake: The first hour, *Bull. Seismol. Soc. Am.*, *97*, 1245–1258.

Chao, K., Z. Peng, C. Wu, C. C. Tang, and C. H. Lin (2011), Remote triggering of non-volcanic tremor around Taiwan, *Geophys. J. Int.*, *188*, 301–324.

Chen, K. C., B. S. Huang, J. H. Wang, and H. Y. Yen (2002), Conjugate thrust faulting associated with the 1999 Chi-Chi, Taiwan, earthquake sequence, *Geophys. Res. Lett.*, *29*(8), 1277, doi:10.1029/2001GL014250.

Chen, Y. G., Y. T. Kuo, Y. M. Wu, H. L. Chen, C. H. Chang, R. Y. Chen, P. W. Lo, K. E. Ching, and J. C. Lee (2008), New seismogenic source and deep structures revealed by the 1999 Chia-yi earthquake sequence in southwestern Taiwan, *Geophys. J. Int.*, *172*, 1049–1054.

Cheng, W. B. (2000), Three-dimensional crustal structure around the source area of the 1999 Chi-Chi earthquake in Taiwan and its relation to aftershock locations, *Terr. Atmos. Oceanic Sci.*, *11*, 643–660.

Chi, W. C., and D. Dreger (2004), Crustal deformation in Taiwan: Results from finite source inversions of six $Mw > 5.8$ aftershocks, *J. Geophys. Res.*, *109*, B07305, doi:10.1029/2003JB002606.

Ching, K. E., M. L. Hsieh, K. M. Johnson, K. H. Chen, R. J. Rau, and M. Yang (2011a), Modern vertical deformation rates and mountain building in Taiwan from precise leveling and continuous GPS observations, 2000–2008, *J. Geophys. Res.*, *116*, B08406, doi:10.1029/2011JB008242.

Ching, K. E., K. M. Johnson, R. J. Rau, R. Y. Chuang, L. C. Kuo, and P. L. Leu (2011b), Inferred fault geometry and slip distribution of the 2010 Jiashian, Taiwan, earthquake is consistent with a thick-skinned deformation model, *Earth Planet. Sci. Lett.*, *301*, 78–86.

Dahlen, F. A., D. Davis, and J. Suppe (1984), Mechanics of fold-and-thrust belts and accretionary wedges: Cohesive Coulomb theory, *J. Geophys. Res.*, *89*, 10,087–10,101.

Davis, D., J. Suppe, and F. A. Dahlen (1983), Mechanics of fold-and-trust belts and accretionary wedges, *J. Geophys. Res.*, *88*, 1153–1172.

Gourley, J. R., T. Byrne, Y. C. Chan, F. Wu, and R. J. Rau (2007), Fault geometries illuminated from seismicity in central Taiwan: Implications for crustal scale structural boundaries in the northern Central Range, *Tectonophysics*, *445*, 168–185.

Hsu, Y. J., M. Simons, S. B. Yu, L. C. Kuo, and H. Y. Chen (2003), A two-dimensional dislocation model for interseismic deformation of the Taiwan mountain belt, *Earth Planet. Sci. Lett.*, *211*, 287–294.

Huang, M. H., D. Dreger, R. Bürgmann, S. H. Yoo, and M. Hashimoto (2013), Joint inversion of seismic and geodetic data for the source of the 2010 March 4, *Mw* 6.3 Jia-Shian, SW Taiwan, earthquake, *Geophys. J. Int.*, *193*, 1608–1626.

Hung, J. H., K. F. Ma, C. Y. Wang, H. Ito, W. Lin, and E. C. Yen (2009), Subsurface structure, physical properties, fault-zone characteristics and stress state in scientific drill holes of Taiwan Chelungpu fault frilling project, *Tectonophysics*, *466*, 307–321.

Johnson, K. M., and P. Segall (2004), Imaging the ramp-décollement geometry of the Chelungpu fault using coseismic GPS displacements from the 1999 Chi-Chi, Taiwan earthquake, *Tectonophysics*, *378*, 123–139.

Kao, H., R. Y. Chen, and C. H. Chang (2000), Exactly where does the 1999 Chi-Chi earthquake in Taiwan nucleate?—Hypocenter relocation using the master station method, *Terr. Atmos. Oceanic Sci.*, *11*, 567–580.

Kuo-Chen, H., F. T. Wu, and S. W. Roecker (2012), Three-dimensional *P* velocity structures of the lithosphere beneath Taiwan from the analysis of TAIGER and related seismic data sets, *J. Geophys. Res.*, *117*, B06306, doi:10.1029/2011JB009108.

Lacombe, O., and F. Mouthereau (2002), Basement-involved shortening and deep detachment tectonics in forelands of orogens: Insights from recent collision belts (Taiwan, Western Alps, Pyrenees), *Tectonics*, *21*(4), 1030, doi:10.1029/2001TC901018.

Loevenbruck, A., R. Cattin, X. L. Pichon, M. L. Courty, and S. B. Yu (2001), Seismic cycle in Taiwan derived from GPS measurements, *C. R. Acad. Sci., Ser. IIa Sci. Terre Planetes*, *333*, 57–64, doi:10.1016/S1251-8050(01)01567-1.

Mouthereau, F., and O. Lacombe (2006), Inversion of the Paleogene Chinese continental margin and thick-skinned deformation in the western foreland of Taiwan, *J. Struct. Geol.*, *28*, 1977–1993.

Mouthereau, F., J. Angelier, and J. C. Lee (2001), Le séisme du 21 Septembre 1999: Influence de l'héritage structural et implication du socle au front de la chaîne de Taiwan, *C. R. Acad. Sci., Paris*, *333*, 93–103.

Peng, Z., and K. Chao (2008), Non-volcanic tremor beneath the Central Range in Taiwan triggered by the 2001 *Mw* 7.8 Kunlun earthquake, *Geophys. J. Int.*, *175*, 825–829.

Shyu, J. B. H., K. Sieh, and Y. G. Chen (2005a), Tandem suturing and disarticulation of the Taiwan orogen revealed by its neotectonic elements, *Earth Planet. Sci. Lett.*, *233*, 167–177.

Shyu, J. B. H., K. Sieh, Y. G. Chen, and C. S. Liu (2005b), Neotectonic architecture of Taiwan and its implications for future large earthquakes, *J. Geophys. Res.*, *110*, B08402, doi:10.1029/2004JB003251.

Simoes, M., J. P. Avouac, O. Beyssac, B. Goffé, K. A. Farley, and Y. G. Chen (2007), Mountain building in Taiwan: A thermokinematic model, *J. Geophys. Res.*, *112*, B11405, doi:10.1029/2006JB004824.

Sun, J., K. M. Johnson, Z. Cao, Z. Shen, R. Bürgmann, and X. Xu (2011), Mechanical constraints on inversion of coseismic geodetic data for fault slip and geometry: Example from InSAR observation of the 6 October 2008 *Mw* 6.3 Dangxiong-Yangyi (Tibet) earthquake, *J. Geophys. Res.*, *116*, B01406, doi:10.1029/2010JB007849.

Suppe, J. (1981), Mechanics of mountain building and metamorphism in Taiwan, *Mem. Geol. Soc. China*, *4*, 67–89.

Suppe, J. (2007), Absolute fault and crustal strength from wedge tapers, *Geology*, *35*, 1127–1130.

Tang, C. C., Z. Peng, C. H. Lin, K. Chao, and C. H. Chen (2013), Statistical properties of low-frequency earthquakes triggered by large earthquakes in southern Taiwan, *Earth Planet. Sci. Lett.*, *373*, 1–7.

Thurber, C., and D. Eberhart-Phillips (1999), Local earthquake tomography with flexible gridding, *Comput. Geosci.*, *25*, 809–818.

Upton, P., K. Mueller, and Y. G. Chen (2009), Three-dimensional numerical models with varied material properties and erosion rates: Implications for the mechanics and kinematics of compressive wedges, *J. Geophys. Res.*, *114*, B04408, doi:10.1029/2008JB005708.

Wang, W. H. (2001), Lithospheric flexure under a critically tapered mountain belt: A new technique to study the evolution of the Tertiary Taiwan orogeny, *Earth Planet. Sci. Lett.*, *192*, 571–581.

Wang, C. Y., C. H. Chang, and H. Y. Yen (2000), An interpretation of the 1999 Chi-Chi earthquake in Taiwan based on the thin-skinned thrust model, *Terr. Atmos. Oceanic Sci.*, *18*, 609–630.

Willett, S. D., and M. T. Brandon (2002), On steady states in mountain belts, *Geology*, *30*, 175–178.

Wu, F. T., R. J. Rau, and D. Salzberg (1997), Taiwan orogeny: Thin-skinned or lithospheric collision?, *Tectonophysics*, *274*, 191–220.

Wu, F. T., C. S. Chang, and Y. M. Wu (2004), Precisely relocated hypocenters, focal mechanisms and active orogeny in Central Taiwan, in *Aspects of the Tectonic Evolution of China*, Special Publications, vol. *226*, edited by J. Malpas et al., Geol. Soc., London, pp. 333–354.

Wu, Y. M., C. H. Chang, L. Zhao, J. B. H. Shyu, Y. G. Chen, K. Sieh, and J. P. Avouac (2007), Seismic tomography of Taiwan: Improved constraints from a dense network of strong motion stations, *J. Geophys. Res.*, *112*, B08312, doi:10.1029/2007JB004983.

Wu, Y. M., C. H. Chang, L. Zhao, T. L. Teng, and M. Nakamura (2008), A comprehensive relocation of earthquakes in Taiwan from 1991 to 2005, *Bull. Seismol. Soc. Am.*, *98*, 1471–1481.

Wu, Y. M., J. B. H. Shyu, C. H. Chang, L. Zhao, M. Nakamura, and S. K. Hsu (2009), Improved seismic tomography offshore northeastern Taiwan: Implications for subduction and collision processes between Taiwan and the southernmost Ryukyu, *Geophys. J. Int.*, *178*, 1042–1054.

Yang, K. M., S. T. Huang, J. C. Wu, and H. H. Ting (2007), 3D geometry of the Chelungpu thrust system in central Taiwan: Its implications for active tectonics, *Terr. Atmos. Oceanic Sci.*, *18*, 143–181.

Yanites, B. J., G. E. Tucker, K. J. Mueller, Y. G. Chen, T. Wilcox, S. Y. Huang, and K. W. Shi (2010), Incision and channel morphology across active structures along the Peikang River, central Taiwan: Implications for the importance of channel width, *GSA Bull.*, *122*, 1192–1208.

Yen, H. Y., and Y. H. Yeh (1998), Two-dimensional crustal structures of Taiwan from gravity data, *Tectonics*, *17*, 104–111.

Yue, L. F., J. Suppe, and J. H. Hung (2005), Structural geology of a classic thrust belt earthquake: The 00201999 Chi-Chi earthquake Taiwan ($Mw = 7.6$), *J. Struct. Geol.*, *27*, 2058–2083.