Basin inversion in central Taiwan and its importance for seismic hazard

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ABSTRACT

On 27 March 2013, a 6.2 M_L earthquake occurred at 19 km depth in eastern Nantou, central Taiwan. Over a 2 week period it was followed by more than 680 aftershocks that ranged to 5 M_L. Most events occurred below the ~10-km-deep detachment fault predicted for this part of the mountain belt, coinciding with other precisely located hypocenters that indicate that much of the crust in this area is seismically active. We combine geological data with a three-dimensional (3-D) P-wave velocity model derived from local tomography and earthquake hypocenters to determine a model for the structure of central Taiwan. Much of the surface geology of the area comprises the uplifted Eocene rocks of the Hsuehshan Basin. The 3-D P-wave velocity model shows a shallowing of higher velocities across the Hsuehshan Basin and hypocenter data indicate that its western bounding fault is clearly defined by an eastward-dipping band of events that extends to >20 km depth. The eastern bounding fault is interpreted to coincide at depth with a cluster of events between 20 and 30 km depth. These data suggest that the pre-existing, rift-related extensional faults of the Hsuehshan Basin are currently being reactivated and the basin is being inverted. We present hypocenter data from the Nantou sequence that corroborate this interpretation and show the importance of choosing the correct structural model when assessing seismic risk.

INTRODUCTION

In an arc-continent collision orogeny such as that of Taiwan, the development of a foreland fold-and-thrust belt depends, among other factors, on the thickness profile of the subducting margin crust, the presence and size of the rift basins within it, and the geometry of the platform and slope sedimentary sequences prior to collision (Brown et al., 2011; Harris, 2011). The response of these primary factors to the deformation is determined, to a large degree, by the rheology of the crust, the orientation of the rift basins and their bounding faults relative to the plate convergence vector, and the convergence rate (Sibson, 1995; Poblet and Lisle, 2011).

Many foreland fold-and-thrust belts worldwide (Rodgers, 1990; Poblet and Lisle, 2011) include a deformed sedimentary cover of a rifted continental margin (Fig. 1A) that is detached above the underlying basement (basement is defined here as any pre-rift rocks), often within or at the base of the lowermost postrift sediments, to form what is termed a thin-skinned thrust system (e.g., Poblet and Lisle, 2011) (Fig. 1B). In a thin-skinned thrust system the expected distribution of seismicity would be a narrow, subhorizontal cluster of events around the basal detachment (Ni and Barazangi, 1984; Carena et al., 2002), scattered events along individual faults above it, and rare events below it where rocks are thought to undergo little deformation (Davis et al., 1983; Dahlen et al., 1984). In this scenario, only in the interior part of the mountain belt, where rocks are exhumed along deeply penetrating faults, should any notable increase in the seismic velocities at shallow depths be expected. If, however, the inherited rift-related basin-bounding faults are reactivated, the deformation will penetrate deeper parts of the crust, causing the synrift sediments and the underlying basement to be uplifted and exhumed (Jackson, 1980) in what is termed basin inversion, or thick-skinned deformation (e.g., Poblet and Lisle, 2011) (Fig. 1C). In areas undergoing basin inversion, seismicity can be expected to take place along the reactivating rift-related faults and display steeply inclined hypocenter clusters that possibly extend into the middle and even lower crust (Jackson, 1980; Okada et al., 2007; Sibson, 2009). The uplift of deeply buried sediments and basement will result in increased seismic velocities closer to the surface.

Determining the deformation mode of a foreland fold-and-thrust belt is important for identifying fault source when assessing seismic hazard in an area, and therefore in developing risk models and management protocols for seismic risk within this part of the orogen (Loh et al., 1991; Campbell et al., 2002; Cheng et al., 2007). Furthermore, an accurate structural model also provides information on the expected geometry of faults, which is an important factor in hazard modeling because the dip of a fault can greatly influence the magnitude of an earthquake along it, with steeper dips resulting in higher magnitude events (Cheng et al., 2007).

In this paper we combine geological data with earthquake hypocenters and a three-dimensional (3-D) P-wave velocity model to determine the structure beneath the Hsuehshan Basin in central Taiwan. We find that a model in which preexisting, rift-related extensional faults that bound the basin are being reactivated and inverted better fits the available data than does a structural model in which there is a shallow, through-going basal detachment (e.g., Carena et al., 2002; Yue et al., 2005).

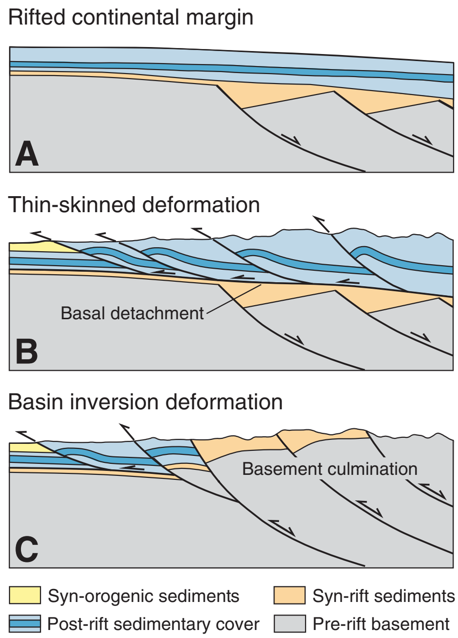

Figure 1. Evolution from rifted continental margin to foreland fold-and-thrust belt. In this figure, plane strain is assumed. A: Idealized rifted continental margin. B: Thin-skinned deformation style: rift-related faults are inactive and only sedimentary cover of A is involved in deformation. C: Basin inversion (or thick-skinned deformation) style: rift-related faults are reactivated and cause deepening in level of deformation.

GEOLOGICAL BACKGROUND

The rifted continental margin of southeast Eurasia has been colliding with the Luzon arc of the Philippine Sea plate since at least the Late Miocene, resulting in the Taiwan orogen (Sibuet and Hsu, 2004). This part of the Eurasian continental margin contains a number of Eocene rift basins (Lin et al., 2003; Teng and Lin, 2004; Yang et al., 2006); the sediments of the Eocene Hsuehshan Basin currently occupy a significant part of the Taiwan orogen (Lin et al., 2003) (Fig. 2A). The basin is bound to the west

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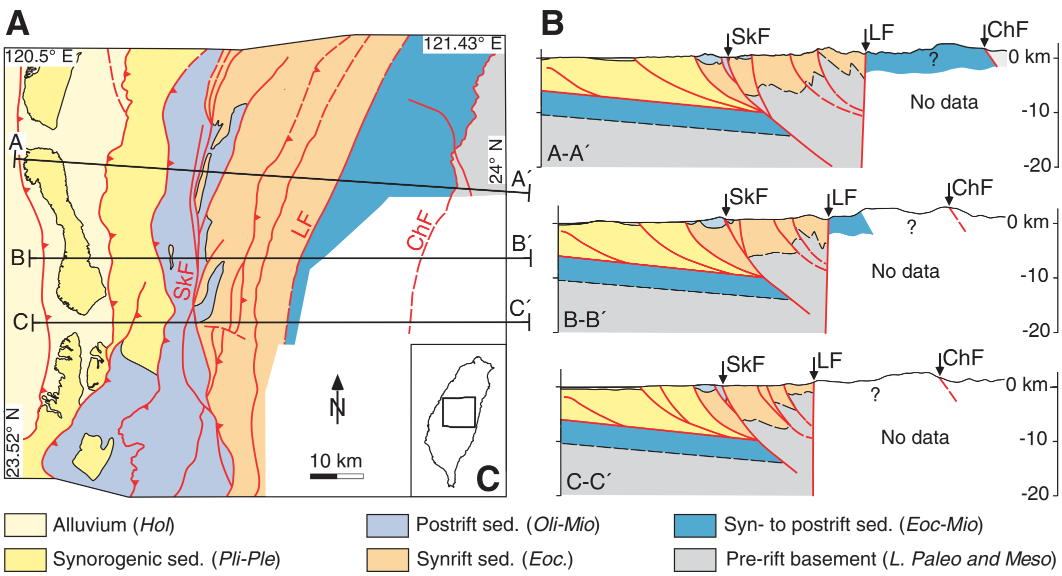

Figure 2. A: Simplified geological map of study area in central Taiwan. B: Geological cross sections through study area (modified after Brown et al., 2012). C: Location of study area. ChF—Chinma fault; LF—Lishan fault; SkF—Shuilikeng fault; Hol—Holocene; Pli—Pliocene; Ple—Pleistocene; Oli—Oligocene; Mio—Miocene; Eoc.—Eocene; L. Paleo—Late Paleocene; Meso—Mesozoic.

by the Shuilikeng fault and to the east by the Lishan fault. The synrift sediments of these basins are overlain by Oligocene to Late Miocene postrift platform and slope sediments that can be as much as several kilometers thick and are variably deformed within the orogen. The onset of synorogenic deposition might have begun as early as the latest Miocene, and continues today. The sedimentary package within the foreland basin can reach 6 km or more in thickness, and the deformation front is within it.

The Eocene synrift rocks of the Hsuehshan Basin now occupy topographically higher ground and structurally overlie Pleistocene rocks of the foreland basin along the Shuilikeng fault (Brown et al., 2012; Camanni et al., 2013) (Fig. 2B). This suggests that inversion of the Hsuehshan Basin is taking place and that the synrift sediments and their underlying basement rocks are being uplifted and exhumed (Clark et al., 1993; Brown et al., 2012).

BASIN INVERSION

To test the hypothesis that inversion of the Hsuehshan Basin is taking place, we use a 3-D P-wave velocity model revised from Wu et al. (2007), and earthquake hypocenters that have been relocated using this model (e.g., Wu et al., 2008), which we collapse using the methodology of Jones and Stewart (1997) (Fig. 3A). We then add the geologically determined fault interpretation (Fig. 3B) in order to evaluate whether ongoing seismic activity is consistent with a shallow detachment or requires inversion of deep-seated rift-related extensional faults that bound the Hsuehshan Basin.

From km 0 to roughly the Shuilikeng fault at km 30, the P-wave velocities in all 3 sections of Figure 3 display an ~8-km-thick low-velocity zone that correlates well with the Miocene and younger postrift and synorogenic sediments. Eastward, this low P-wave velocity zone shallows, and higher velocities appear closer to the surface (with minor complications in section C-C′). The shallowing of higher P-wave velocity material to the east of the Shuilikeng fault (SkF in Fig. 3) is clearly indicated by the 5.5 km s^{-1} isovelocity line, which we interpret to be the top of the low-grade metasedimentary basement clastics intersected in boreholes in western Taiwan (Chiu, 1975; Shaw, 1996). This shallow high-velocity zone is a robust feature that has been recognized in a number of other studies, regardless of the method of tomographic inversion (Rau and Wu, 1995; Kim et al., 2005, 2010; Lin, 2007; Kuo-Chen et al., 2012).

All 3 sections display east-dipping clusters of hypocenters between approximately km 30 and 50, and ~10–20 km depth. Particularly in sections B-B′ and C-C′, this cluster projects to the surface at the mapped location of the Shuilikeng fault (Fig. 3) and, in section B-B′, joins westward with a thin, subhorizontal cluster of hypocenters that marks the location of the basal detachment known to be in this area (Carena et al., 2002; Yue et al., 2005; Brown et al., 2012), forming a linked fault system. In sections B-B′ and C-C′, a cluster of hypocenters at approximately km 50 and between 20 and 30 km depth is interpreted to project to the surface at the location of the Lishan fault (LF in Fig. 3; for a similar interpretation, see Wu et al., 2004; Gourley et al., 2007). Farther east, at approximately km 80, an open to tight cluster of hypocenters appears to be associated with the Chinma fault (ChF in Fig. 3), which places Mesozoic basement on top of Eocene and younger slope-derived sediments.

NANTOU EARTHQUAKE SEQUENCE

Hypocenters from the Nantou earthquake sequence (Fig. 4) have been relocated using the same 3-D velocity model and collapsing methodology as those shown in Figure 3. The majority of the hypocenters plot along the deep trace of the Shuilikeng fault and a number of them, including the main shock, plot within the cluster interpreted to be associated with the Lishan fault. Focal mechanisms that we determined for the four events of $M_L > 4$ have reverse fault-plane solutions (Fig. 4). The coincidence of the Nantou earthquake hypocenters with the interpreted deep locations of the bounding faults of the Hsuehshan Basin determined from the data presented herein further indicates that these faults are important structures contributing to mountain building in central Taiwan.

DISCUSSION AND CONCLUSIONS

The combination of geological, P-wave velocity, and earthquake hypocenter data presented here suggests that the basin inversion model (Fig. 1C) for deformation in central Taiwan is a viable alternative to the previously accepted thin-skinned model (e.g., Davis et al., 1983; Dahlen et al., 1984; Suppe, 1987; Carena et al., 2002; Yue et al., 2005; Malavieille and Trullenque, 2009) (Fig. 1B). Significant seismic activity along the margins of the Hsuehshan Basin and shallowing of higher P-wave velocity material in the area occupied by the Hsuehshan Basin provide strong evidence that the reactivation of its bounding faults and the uplift and exhumation of its synrift sediments and basement rocks compose the dominant deformation style in this part of central Taiwan. The data show that the deformation reaches at least 30 km beneath the Hsuehshan Basin, further suggesting that basement rocks must be involved in the deformation in this region (see also Wu et al., 1997, 2004; Gourley et al., 2007; Brown et al., 2012; Chuang et al., 2013). However, we cannot determine if there is a deep level of detachment at

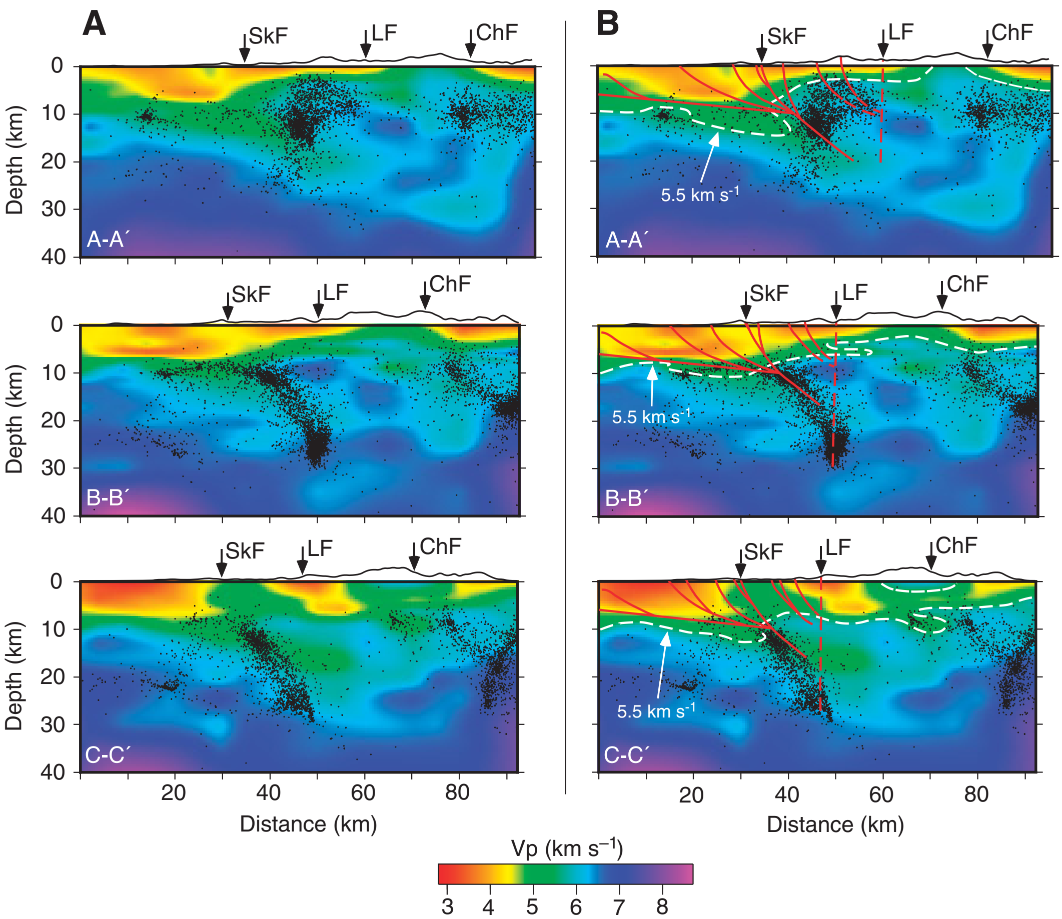

Figure 3. A: Uninterpreted vertical sections through three-dimensional (3-D) P-wave velocity model (Wu et al., 2007) and relocated (Wu et al., 2008) and collapsed seismicity used in this study. ChF—Chinma fault, LF—Lishan fault, SkF—Shuilikeng fault. B: Interpreted vertical sections. Hypocenters are projected from 4.99 km on either side of sections (section locations are in Fig. 2). Spatial uncertainty of hypocenters was determined as horizontal and vertical location errors following Wu et al. (2008), and can be found in hypocenter database (available from authors or at http://seismology.gl.ntu.edu.tw/download_04.htm). Data were collapsed using 3-D spatial uncertainty of 4 standard deviations (methodology of Jones and Stewart, 1997) to truncate confidence ellipsoid and estimated variance in data. Hypocenter movements were compared with χ^2 distribution and repeated until minimum misfit was reached. For comparison, uncollapsed seismicity data are provided in Figure DR1 in the GSA Data Repository[1]. Faults on interpreted sections are derived from surface geological and hypocenter data only. Dashed white line indicates 5.5 km s^{-1} isovelocity line that we use as reference for top of basement.

these depths beneath the Hsuehshan and Central ranges with the current data sets.

The Nantou earthquakes highlight the need for a revised structural model for central Taiwan that provides a more precise framework for seismic risk assessment than the currently used thin-skinned model. We suggest that a model in which preexisting basins that were located on the Eurasian margin are being inverted along deep penetrating faults provides a viable explanation for the Nantou earthquake sequence, and therefore gives a new perspective for identifying fault source when assessing seismic risk in the area. In the light of this new structural model, the Shuilikeng and the Lishan faults are both candidates for future damaging earthquakes such as the Nantou main shock.

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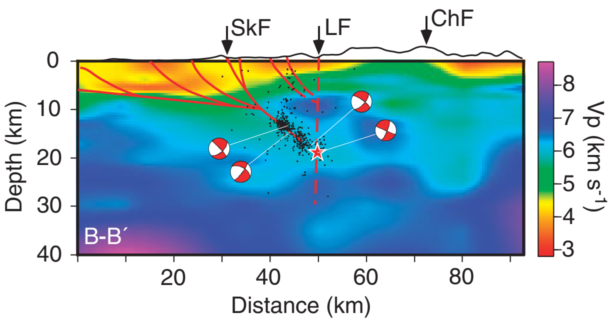

Figure 4. P-wave velocity model B-B′ with geologically determined faults and collapsed 27 March to 15 April 2013 Nantou, central Taiwan, sequence hypocenters. SkF—Shuilikeng fault, LF—Lishan fault, ChF—Chinma fault. Red star indicates location of 6.2 M_L main shock. Hypocenters have been projected from 4.99 km on either side of section, for total of 418 events.

REFERENCES CITED

Brown, D., and 15 others, 2011, Arc-continent collision: The making of an orogen, *in* Brown, D., and Ryan, P.D., eds., Arc-continent collision: Frontiers in Earth Sciences: New York, Springer, p. 477–493, doi:10.1007/978-3-540-88558-0_17.

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

Camanni, G., Brown, D., Alvarez-Marron, J., Wu, Y.-M., and Chen, H.-A., 2013, The Shuilikeng fault in the central Taiwan mountain belt: Geological Society of London Journal, doi:10.1144/jgs2013-014.

Campbell, K.W., Thenhaus, P.C., Barnhard, T.P., and Hampson, D.B., 2002, Seismic hazard model for loss estimation and risk management in Taiwan: Soil Dynamics and Earthquake Engineering, v. 22, p. 743–754, doi:10.1016/S0267-7261(02)00095-7.

[1]GSA Data Repository item 2014039, supplementary geological and geophysical information, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Carena, S., Suppe, J., and Kao, H., 2002, Active detachment of Taiwan illuminated by small earthquakes and its control of first-order topography: Geology, v. 30, p. 935–938, doi:10.1130/0091-7613(2002)030<0935:ADOTIB>2.0.CO;2.

Cheng, C.-T., Chiou, S.-J., Lee, C.-T., and Tsai, Y.-B., 2007, Study on probabilistic seismic hazard maps of Taiwan after Chi-Chi earthquake: Journal of GeoEngineering, v. 2, p. 19–28.

Chiu, H.-T., 1975, Miocene stratigraphy and its relation to the Palaeogene rocks in west-central Taiwan: Petroleum Geology of Taiwan, v. 12, p. 51–80.

Chuang, R.Y., Johnson, K.M., Wu, Y.-M., Ching, K.-E., and Kuo, L.-C., 2013, A midcrustal ramp-fault structure beneath the Taiwan tectonic wedge illuminated by the 2013 Nantou earthquake series: Geophysical Research Letters, v. 40, p. 1–5, doi:10.1002/grl.51005.

Clark, M.B., Fisher, D.M., Lu, C.-Y., and Chen, C.-H., 1993, Kinematic analyses of the Hsuehshan Range, Taiwan: A large-scale pop-up structure: Tectonics, v. 12, p. 205–217, doi:10.1029/92TC01711.

Dahlen, F.A., Suppe, J., and Davis, D., 1984, Mechanics of fold-and-thrust belts and accretionary wedges: Cohesive coulomb theory: Journal of Geophysical Research, v. 89, p. 10087–10101, doi:10.1029/JB089iB12p10087.

Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153–1172, doi:10.1029/JB088iB02p01153.

Gourley, J.R., Byrne, T., Chan, Y.-C., Wu, F., and Rau, R.-J., 2007, Fault geometries illuminated from seismicity in central Taiwan: Implications for crustal scale structural boundaries in the northern Central Range: Tectonophysics, v. 445, p. 168–185, doi:10.1016/j.tecto.2007.08.013.

Harris, R., 2011, The nature of the Banda arc-continent collision in the Timor region, *in* Brown, D., and Ryan, P.D., eds., Arc-continent collision: Frontiers in Earth Sciences: New York, Springer, p. 163–211, doi:10.1007/978-3-540-88558-0_7.

Jackson, J.A., 1980, Reactivation of basement faults and crustal shortening in orogenic belts: Nature, v. 283, p. 343–346, doi:10.1038/283343a0.

Jones, R.H., and Stewart, R.C., 1997, A method for determining significant structures in a cloud of earthquakes: Journal of Geophysical Research, v. 102, p. 8245–8254, doi:10.1029/96JB03739.

Kim, K.-H., Chiu, J.-M., Pujol, J., Chen, K.-C., Huang, B.-S., Yeh, Y.-H., and Shen, P., 2005, Three-dimensional VP and VS structural models associated with the active subduction and collision tectonics in the Taiwan region: Geophysical Journal International, v. 162, p. 204–220, doi:10.1111/j.1365-246X.2005.02657.x.

Kim, K.-H., Chen, K.-C., Wang, J.-H., and Chiu, J.-M., 2010, Seismogenic structures of the 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake and its aftershocks: Tectonophysics, v. 489, p. 119–127, doi:10.1016/j.tecto.2010.04.011.

Kuo-Chen, H., Wu, F.T., and Roecker, S.W., 2012, Three-dimensional P velocity structures of the lithosphere beneath Taiwan from the analysis of TAIGER and related seismic data sets: Journal of Geophysical Research, v. 117, B06306, doi:10.1029/2011JB009108.

Lin, A.T., Watts, A.B., and Hesselbo, S.P., 2003, Cenozoic stratigraphy and subsidence history of the South China Sea margin in the Taiwan region: Basin Research, v. 15, p. 453–478, doi:10.1046/j.1365-2117.2003.00215.x.

Lin, C.-H., 2007, Tomographic image of crustal structures across the Chelungpu fault: Is the seismogenic layer structure- or depth-dependent?: Tectonophysics, v. 443, p. 271–279, doi:10.1016/j.tecto.2007.01.022.

Loh, C.H., Yeh, Y.T., Jean, W.Y., and Yeh, Y.H., 1991, Seismic hazard analysis in the Taiwan area using a bounded fault-rupture model: Seismological Society of America Bulletin, v. 81, p. 265–272.

Malavieille, J., and Trullenque, G., 2009, Consequences of continental subduction on forearc basin and accretionary wedge deformation in SE Taiwan: Insights from analogue modeling: Tectonophysics, v. 466, p. 377–394, doi:10.1016/j.tecto.2007.11.016.

Ni, J., and Barazangi, M., 1984, Seismotectonics of the Himalayan collision zone: Geometry of the underthrusting Indian Plate beneath the Himalaya: Journal of Geophysical Research, v. 89, p. 1147–1163, doi:10.1029/JB089iB02p01147.

Okada, T., Hasegawa, A., Suganomata, J.I., Umino, N., Zhang, H., and Thurber, C.H., 2007, Imaging the heterogeneous source area of the 2003 M6.4 northern Miyagi earthquake, NE Japan, by double-difference tomography: Tectonophysics, v. 430, p. 67–81, doi:10.1016/j.tecto.2006.11.001.

Poblet, J., and Lisle, R.J., 2011, Kinematic evolution and structural styles of fold-and-thrust belts, *in* Poblet, J., and Lisle, R.J., eds., Kinematic evolution and structural styles of fold-and-thrust belts: Geological Society of London Special Publication 349, p. 1–24, doi:10.1144/SP349.1.

Rau, R.-J., and Wu, F.T., 1995, Tomographic imaging of lithospheric structures under Taiwan: Earth and Planetary Science Letters, v. 133, p. 517–532, doi:10.1016/0012-821X(95)00076-O.

Rodgers, J., 1990, Fold-and-thrust belts in sedimentary rocks; Part 1, Typical examples: American Journal of Science, v. 290, p. 321–359, doi:10.2475/ajs.290.4.321.

Shaw, C.-L., 1996, Stratigraphic correlation and isopach maps of the Western Taiwan Basin: Terrestrial, Atmospheric and Oceanic Sciences, v. 7, p. 333–360.

Sibson, R.H., 1995, Selective fault reactivation during basin inversion: Potential for fluid redistribution through fault-valve action, *in* Buchanan, J.G., and Buchanan, P.G., eds., Basin inversion: Geological Society of London Special Publication 88, p. 3–19, doi:10.1144/GSL.SP.1995.088.01.02.

Sibson, R.H., 2009, Rupturing in overpressured crust during compressional inversion—The case from NE Honshu, Japan: Tectonophysics, v. 473, p. 404–416, doi:10.1016/j.tecto.2009.03.016.

Sibuet, J.-C., and Hsu, S.-K., 2004, How was Taiwan created?: Tectonophysics, v. 379, p. 159–181, doi:10.1016/j.tecto.2003.10.022.

Suppe, J., 1987, The active Taiwan mountain belt, *in* Schaer, J.P., and Rodgers, J., eds., The anatomy of mountain ranges: Princeton, New Jersey, Princeton University Press, p. 277–293.

Teng, L.S., and Lin, A.T., 2004, Cenozoic tectonics of the China continental margin: Insights from Taiwan, *in* Malpas, J., et al., eds., Aspects of the tectonic evolution of China: Geological Society of London Special Publication 226, p. 313–332, doi:10.1144/GSL.SP.2004.226.01.17.

Wu, F.T., Rau, R.-J., and Salzberg, D., 1997, Taiwan orogeny: Thin-skinned or lithospheric collision?: Tectonophysics, v. 274, p. 191–220, doi:10.1016/S0040-1951(96)00304-6.

Wu, F.T., Chang, C.-H., and Wu, Y.-M., 2004, Precisely relocated hypocentres, focal mechanisms and active orogeny in central Taiwan, *in* Malpas, J., et al., eds., Aspects of the tectonic evolution of China: Geological Society of London Special Publication 226, p. 333–354, doi:10.1144/GSL.SP.2004.226.01.18.

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

Wu, Y.-M., Chang, C.-H., Zhao, L., Teng, T.L., and Nakamura, M., 2008, A comprehensive relocation of earthquakes in Taiwan from 1991 to 2005: Seismological Society of America Bulletin, v. 98, p. 1471–1481, doi:10.1785/0120070166.

Yang, K.-M., Huang, S.-T., Wu, J.-C., Ting, H.-H., and Mei, W.-W., 2006, Review and new insights on foreland tectonics in western Taiwan: International Geology Review, v. 48, p. 910–941, doi:10.2747/0020-6814.48.10.910.

Yue, L.-F., Suppe, J., and Hung, J.-H., 2005, Structural geology of a classic thrust belt earthquake: The 1999 Chi-Chi earthquake Taiwan (Mw=7.6): Journal of Structural Geology, v. 27, p. 2058–2083, doi:10.1016/j.jsg.2005.05.020.

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