Terr. Atmos. Ocean. Sci., Vol. 27, No. 3, 311-323, June 2016 doi: 10.3319/TAO.2015.11.27.02(TEM)

A New On-Land Seismogenic Structure Source Database from the Taiwan Earthquake Model (TEM) Project for Seismic Hazard Analysis of Taiwan

J. Bruce H. Shyu[1,*], Yi-Rung Chuang[1,2], Ya-Lin Chen[1], Yi-Rui Lee[2], and Chin-Tung Cheng[2]

[1] *Department of Geosciences, National Taiwan University, Taipei, Taiwan, R.O.C.*
[2] *Disaster Prevention Technology Research Center, Sinotech Engineering Consultants, Inc., Taipei, Taiwan, R.O.C.*

Received 10 August 2015, revised 6 November 2015, accepted 27 November 2015

ABSTRACT

Taiwan is located at an active plate boundary and prone to earthquake hazards. To evaluate the island's seismic risk, the Taiwan Earthquake Model (TEM) project, supported by the Ministry of Sciences and Technology, evaluates earthquake hazard, risk, and related social and economic impact models for Taiwan through multidisciplinary collaboration. One of the major tasks of TEM is to construct a complete and updated seismogenic structure database for Taiwan to assess future seismic hazards. Toward this end, we have combined information from pre-existing databases and data obtained from new analyses to build an updated and digitized three-dimensional seismogenic structure map for Taiwan. Thirty-eight on-land active seismogenic structures are identified. For detailed information of individual structures such as their long-term slip rates and potential recurrence intervals, we collected data from existing publications, as well as calculated from results of our own field surveys and investigations. We hope this updated database would become a significant constraint for seismic hazard assessment calculations in Taiwan, and would provide important information for engineers and hazard mitigation agencies.

Key words: Taiwan Earthquake Model (TEM), Seismic hazard analysis, Seismogenic structure, Database, Slip rates, Recurrence intervals

Citation: Shyu, J. B. H., Y. R. Chuang, Y. L. Chen, Y. R. Lee, and C. T. Cheng, 2016: A new on-land seismogenic structure source database from the Taiwan Earthquake Model (TEM) project for seismic hazard analysis of Taiwan. Terr. Atmos. Ocean. Sci., 27, 311-323, doi: 10.3319/TAO.2015.11.27.02(TEM)

1. INTRODUCTION

The island of Taiwan is the result of the ongoing collision between the Eurasian and Philippine Sea plates (Fig. 1). Rapid rates of both horizontal and vertical deformation and an abundance of seismic activity amply demonstrate the current vigor of the orogeny. The 1999 Chi-Chi earthquake, with its unanticipated disastrous effects on population and infrastructure, focused much scientific and public attention on Taiwan and demonstrated the urgent need for a better understanding of the island's numerous other seismogenic structures and future earthquake hazards (e.g., Cheng et al. 2007, 2010). In order to obtain more information toward fulfilling this need, the integrated Taiwan Earthquake Model (TEM) project was carried out with the goal to assemble information for seismic hazard assessment and risk management for the island. One of the most fundamental tasks of TEM is to construct an up-to-date seismogenic structure database for Taiwan.

Several previous efforts have been attempted to construct an active structure database for Taiwan (e.g., Shyu et al. 2005; Central Geological Survey 2010). However, some of these databases include only active faults that produce observable offset at the surface, without structures that only produced tectonic geomorphic features but have not yet ruptured the surface. Moreover, a seismogenic structure database for seismic hazard calculation needs many structural parameters. These parameters include physical characteristics of the structures such as their types and geometries, those obtained by geological investigations such as their slip rates, as well as calculated parameters related to the earthquakes they may produce, such as the earthquake magnitudes and average recurrence intervals. Since some of these parameters are difficult to obtain, a dataset with all structural parameters is still lacking.

Toward this end, we reviewed the pre-existing active structure databases and related reports in order to construct a more complete seismogenic structure database for Taiwan. For example, the Central Geological Survey (CGS) of

* *Corresponding author*
E-mail: jbhs@ntu.edu.tw

Taiwan has investigated many active faults in Taiwan using a wide variety of methods, including outcrop mapping, trenches, seismic investigations, and the integration of historical documents. They have assembled these data to publish several versions of active fault maps for Taiwan (e.g., Chang et al. 1998; Lin et al. 2000; Central Geological Survey 2010). These maps focus especially on faults that crop out at the surface, such as the Chelungpu fault that ruptured in 1999 and produced the Chi-Chi earthquake. The 1999 rupture, in fact, followed a pre-existing topographic scarp that could have been identified even before the earthquake (e.g., Chen et al. 2002; Chang and Yang 2004). Such phenomenon inspired Shyu et al. (2005) to review all geomorphic features in detail and to produce a neotectonic map of Taiwan with additional aid from geodetic and seismologic data. This dataset not only includes faults that crop out at the surface, but also considers structures that are blind but expressed geomorphically.

Several structural parameters were also reported in Shyu et al. (2005). For example, geometries of the structures are constrained by either seismic data or the depth of an assumed brittle-ductile transition. These parameters can be further used to estimate the possible magnitude of earthquakes produced by these structures using empirical equations (e.g., Wells and Coppersmith 1994). However, in order to calculate seismic hazard for TEM, more information is needed. The average recurrence interval of earthquakes produced by the structure, for instance, is a key parameter for calculating seismic hazards. Such information may be obtained by paleoseismological investigations (e.g., Chen et al. 2007), but not all structures in Taiwan have been trenched. Alternatively, for structures with constrained long-term slip rates, the recurrence interval can be calculated from the slip rates and the average slip amount, which can be estimated from the earthquake magnitude or from empirical equations (e.g., Wells and Coppersmith 1994).

Therefore, in this study, we constructed a new seismogenic structure database by integrating and re-interpreting previous databases and combining previously published information for the structural parameters. For those without previous information, we provide our new estimations. Since the long-term slip rates for most of the structures were previously not well constrained, we focused especially on the slip rate estimation of structures from geomorphic and field investigations. It is noteworthy that this result represents only an updated version of such dataset based on the most current knowledge. As pointed out by Shyu et al. (2005) in one of the earlier versions of such database, we by no means suggest that all seismogenic structures or related information are constrained and described in this dataset. Decades of additional work and regular updates would be necessary to accomplish such goals as new information becomes available. With these caveats in mind, we present in this study a first version of such database and hope our results not only can provide important constraints for the seismic hazard calculations of TEM, but can also assist in future land-use and other planning programs in Taiwan.

2. FIELD INVESTIGATIONS

As the long-term slip rates of many structures were not previously constrained, we conducted intensive field investigations to obtain the structures' long-term slip rates. Such information can be applied further to calculate potential earthquake recurrence intervals produced by each seismogenic structure. In fact, more than half of the structures included in this new database do not have any published slip rate or recurrence interval information. As a result, we utilize the topographic features of these structures to estimate reasonable long-term slip rates for them.

Many of the structures included in this database have produced distinctive deformation of young geomorphic

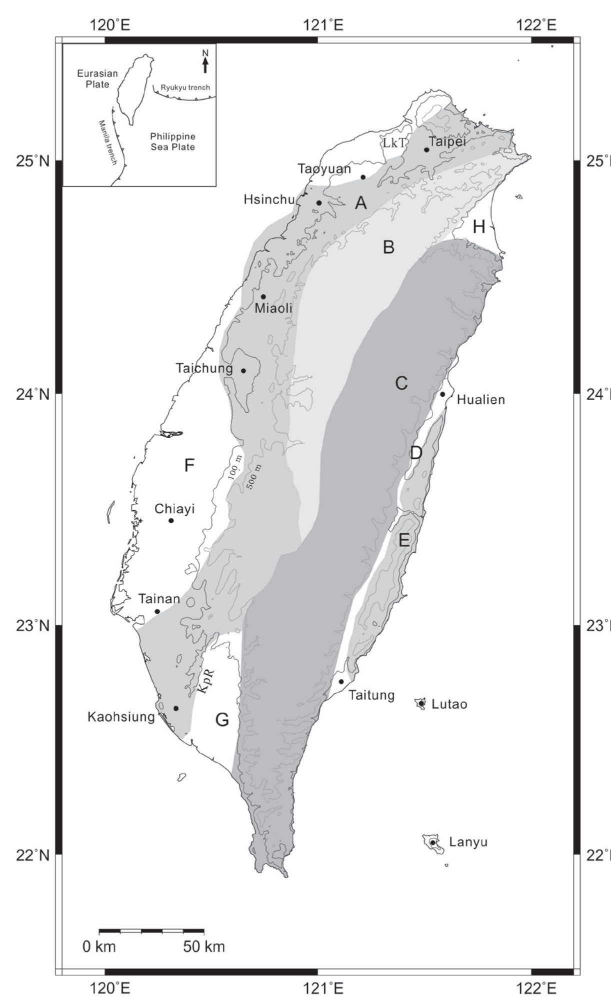

Fig. 1. Major tectonic elements of the island of Taiwan. A: Western Foothills; B: Hsueshan Range; C: Central Range and Hengchun Peninsula; D: Longitudinal Valley; E: Coastal Range; F: western Taiwan coastal plains; G: Pingtung Plain; H: Ilan Plain; LkT: Linkou Tableland; KpR: Kaoping River.

surfaces, such as fluvial or marine terraces. Indeed, scarps that cut across widespread fluvial terraces are one of the fundamental features for the identification of active structures in Taiwan (e.g., Shih et al. 1984, 1986; Yang 1986; Shyu et al. 2005). Such structural scarps can be distinguished from erosional terrace risers since the latter would generally follow the flow direction of the rivers, whereas scarps produced by active deformation can trend at an angle with the rivers and are generally parallel to the mountain front (Fig. 2). Once we obtain the amount of total deformation and age of the deformed surface, we will be able to calculate a long-term deformation rate for the structure.

The amount of deformation is generally determined by the height of the structural scarp. This is based on the hypothesis that the two surfaces on both sides of the scarp have the same age. Therefore, we need to pay additional attention to exclude the possibility of later erosion of the upthrown side or deposition on the downthrown side. In cases such possibility cannot be excluded, the amount of deformation determined will just be the minimum. For the height of the scarps we measured them both in the field using a laser range finder and from the Digital Elevation Model (DEM) with 5-m resolution. Both results were compared with each other and we found that generally the measurements from DEM were higher than those obtained in the field. This is likely due to the fact that our measured length in the field was not long enough to cover the entire deformation zone. As a result, we used the data from DEM measurements for most of the structures to obtain a more complete structural deformation amount.

The ages of the deformed surfaces are, however, much more difficult to determine. Ideally, one would like to date all of those deformed terrace sediments to obtain their ages. However, in reality datable materials are difficult to come across in the field. More importantly, many of the older terraces in Taiwan are older than the upper limit of the radiocarbon dating method (e.g., Chen 1988; Lee et al. 1999; Ota et al. 2002; Shyu et al. 2006a), which is the most reliable and well-developed dating method.

It has been reported that in Taiwan, terraces with initial development of reddish, or lateritic, soil at their surface generally have ages of about 30 - 40 ka, near the upper limit of the radiocarbon dating method (e.g., Chen 1988; Ota et al. 2002). The degree of lateritic development will increase as the terraces become older due to a longer period of weathering (e.g., Tsai et al. 2007). On the other hand, the best developed lateritic soil in Taiwan is present at the top surface of the Linkou Tableland (e.g., Lee et al. 1999; Fig. 1). This tableland is preserved on the upthrown side of a normal fault, and the oldest sediment on the downthrown side has been determined to be at least 400 kyr old (Wei et al. 1998). Based on the above information we decided to categorize all fluvial terrace surfaces in Taiwan to provide a reasonable estimation of their ages. For lateritic terraces there are two categories. Those with less developed lateritic soil are assigned an age of 30 - 150 ka and those with well-developed lateritic soil are assigned an age of 100 - 500 ka. For non-lateritic terraces there are also two categories. For those very young terraces without any soil development, an age of 1 - 5 ka is assigned. If there is some soil development at the surface but the color of the soil has not yet turned red, we assigned an age of 5 - 25 ka for such terraces (Fig. 3). We intentionally set a large error bar for these estimations, at 5 times of the youngest ages. This is a conservative approach based on current understandings and will of course be improved as more information becomes available. Moreover, this would be the first systematic estimation for all terrace ages in Taiwan. Without such estimation it would be impossible to reasonably calculate the seismic hazards of Taiwan, since sometimes unrealistic extreme values were also considered in some previous models.

3. SEISMOGENIC STRUCTURES OF TAIWAN AND THEIR PARAMETERS

After determining the slip rates of all structures we are able to construct a new on-land seismogenic structure

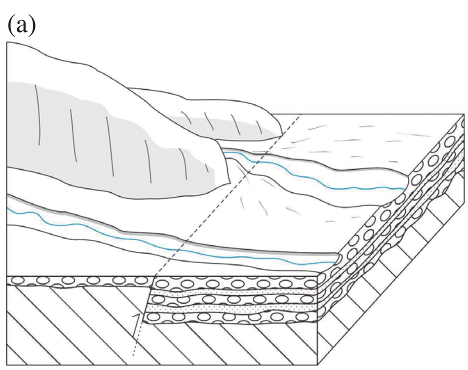

Fig. 2. The formation of a fault scarp. (a) If a fault has not moved for an extended period of time, erosional and sedimentary processes may have eliminated all previous topographic features of the fault. (b) However, if a fault has moved recently, a fault scarp will be present next to the uplifted flood plain. (Color online only)

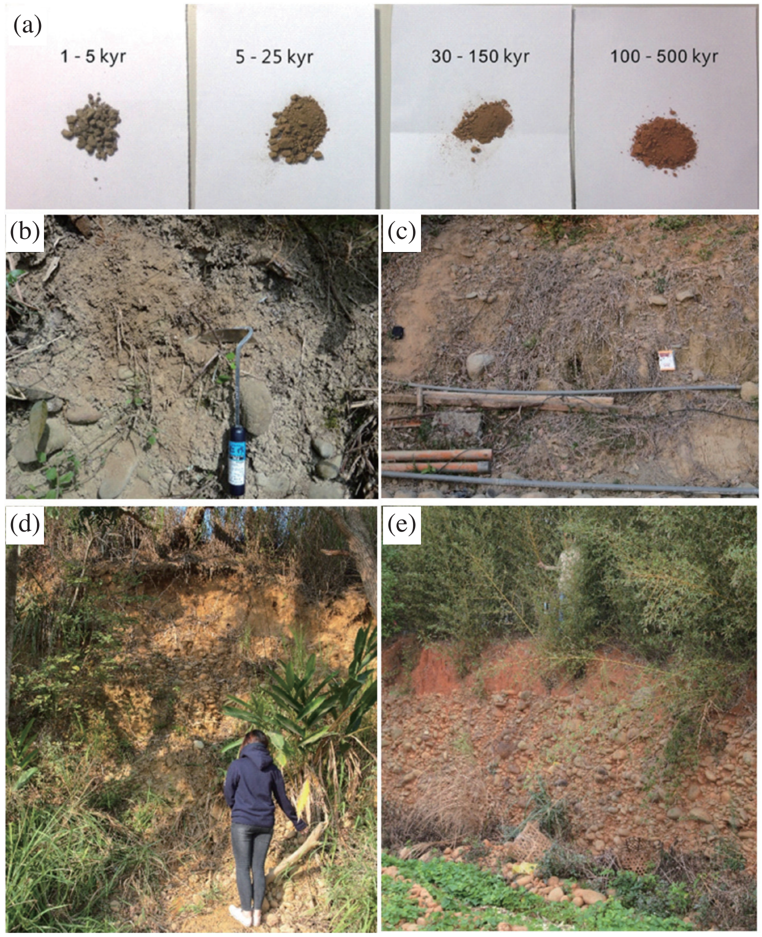

Fig. 3. Our classification of soils on the terraces. (a) The degree of lateritic development will increase as the terraces become older due to a longer period of weathering. (b) An outcrop of a typical 1 - 5 kyr old terrace. (c) An outcrop of a typical 5 - 25 kyr old terrace. (d) An outcrop of a typical 30 - 150 kyr old terrace. (e) An outcrop of a typical 100 - 500 kyr old terrace. See text for more discussion.

database for Taiwan with all important structural parameters (Fig. 4 and Table 1). A more detailed structural parameter table and the ArcGIS shapefiles of all the structures are included in the supplementary files of this paper.

For the structural geometries one of the fundamental parameters is the down-dip limit of each structure. In this study, we started by following the approach of Shyu et al. (2005) to estimate the depth of the brittle-ductile transition. As pointed out by Shyu et al. (2005), most of the rocks in the upper crust of Taiwan are quartz- and feldspar-rich sedimentary rocks. Since the brittle-plastic transition of quartz occurs at approximately 300°C (e.g., Kerrich et al. 1977; Tullis and Yund 1977), and that of feldspar occurs at approximately 500°C (e.g., White 1975; Tullis and Yund 1977), Shyu et al. (2005) used a conservative depth of 15 km (~450°C) for the down-dip limit of most structures in Taiwan.

Some of the seismogenic structures in western Taiwan, however, do not seem to cut the crust to the depth of the brittle-ductile transition. Instead, many of them appear to stop at, or merge with a shallow detachment (e.g., Suppe 1976, 1987; Carena et al. 2002). Therefore, for those structures whose seismogenic depths have been well illuminated either by published seismic investigation data or seismicity distribution patterns, we used such better constrained information.

For other structures that may indeed extend to the brittle-ductile transition, we followed the temperature proposed by Shyu et al. (2005), but used new geothermal gradient data of Taiwan to calculate the actual depth of such temperature. Several new geothermal gradient datasets for Taiwan have become available in recent years, including one using the Curie point depth from magnetic data in Taiwan (Hsieh et al. 2014) and one using silica heat flow geothermometry from hot springs (Liu et al. 2015). The geothermal gradients proposed by Hsieh et al. (2014) appear to be higher, especially for the south and southeastern parts of Taiwan. As a result, the brittle-ductile transition depths calculated using this dataset are shallower than 10 km for almost all structures in Taiwan. This appears to be inconsistent with the observation of numerous seismicity in Taiwan below the depths of 10 km (e.g., Wu et al. 1997; Rau and Wu 1998). Therefore, we decided to calculate the depths of the brittle-ductile transition in Taiwan using the dataset proposed by Liu et al. (2015), which yielded results generally between 10 - 15 km (see the detailed structural parameter table in the supplementary files). Since the geothermal gradient contours shown in Liu et al. (2015) have an interval of 3.75°C and most of the structures are located in areas with geothermal gradients between 30 - 45°C km^{-1}, the seismogenic depth calculated in this study would have error bars in the range of ~1 to 1.5 km.

After the seismogenic depth of each structure is obtained we then construct the general structural geometry. These geometries were further checked for any possible conflicts using our three-dimensional (3-D) structural model described below.

The moment magnitudes (M_w) of earthquakes likely produced by these structures were calculated using published regression results from Wells and Coppersmith (1994). We can further use this information to obtain the average slip per earthquake event through the seismic moment calculation. The average recurrence intervals for such earthquakes were then calculated from the average slip per event and the slip rates of the structures.

Thirty-eight structures are identified in this new seismogenic structure database. The following is the general information for each structure:

(1) The Shanchiao fault is located near Taipei City with a length of 53.4 km. It is a listric fault with a dip of 60° between 0 - 7 km deep and 45° from 7 - 10 km deep. Then it dips at 30° to a depth of 13.8 km. The vertical deformation rate is 2.25 mm yr^{-1} from Huang et al. (2007). We calculated a slip rate of 1.85 ± 0.76 mm yr^{-1} in this study based on the estimated age of the Linkou Tableland on its upthrown side.

(2) The Shuanglienpo structure is near Taoyuan with a length of 9.0 km. Its dip is 45° until 3 km deep and then becomes 15° to a depth of 5 km. Its slip rate is estimated at 0.25 ± 0.17 mm yr^{-1} in this study.

(3) The Yangmei structure is southeast of the Shuanlienpo structure and its length is 21.7 km. It dips 60° and extends to a depth of 3 km. We estimated its slip rate at 0.38 ± 0.26 mm yr^{-1}.

(4) The Hukou fault is parallel to the Yangmei structure. This fault is 25.8 km in length, dips at 30°, and extends to 10 km deep. In previous studies the slip rate was estimated at 1.65 ± 0.15 mm yr^{-1} based on a 50 m scarp height and an age of 60.9 ± 5.5 ka of the deformed terrace (Shen et al. 2005; Chen et al. 2006). We estimated a slip rate of 1.16 ± 0.84 mm yr^{-1} in this study.

(5) The Fengshan river strike-slip structure is a structure that appears to cut the Hukou fault. The length of this structure is 30.4 km, and we propose a dip of 80° for the structure, with a depth of 13.9 km. We estimated its slip rate at 3.61 ± 2.41 mm yr^{-1}.

(6) The Hsinchu fault is located near downtown Hsinchu. The depth of the fault is 10 km with a 45° dip, and its length is 12.6 km. A slip rate of 0.45 mm yr^{-1} is reported previously (Chen et al. 2004), and we estimated at 0.70 ± 0.46 mm yr^{-1} in this study.

(7) The Hsincheng fault is another important structure in the Hsinchu area. It is 13.0 km in length, dips at 30°, and extends to 12.9 km. Previous reported slip rates of the fault include 0.7 - 1.6 mm yr^{-1} (Shih et al. 2003) or 1.075 ± 0.025 mm yr^{-1} based on optically stimulated luminescence (OSL) ages of deformed terraces (Chen et al. 2003a). We estimated a slip rate of 1.08 ± 0.72 mm yr^{-1} for the fault.

(8) The Hsinchu frontal structure is near the coastline of the Hsinchu area. Its length is 10.4 km, dip is 30°, and it extends to 10.0 km deep. We obtained a slip rate of 2.80 ± 1.86 mm yr^{-1}.

(9) The Touhuanping structure is in the Miaoli area and its length is 24.8 km. It dips at 85° and extends to a depth of 12.0 km. We calculated a slip rate of 0.13 mm yr^{-1} based

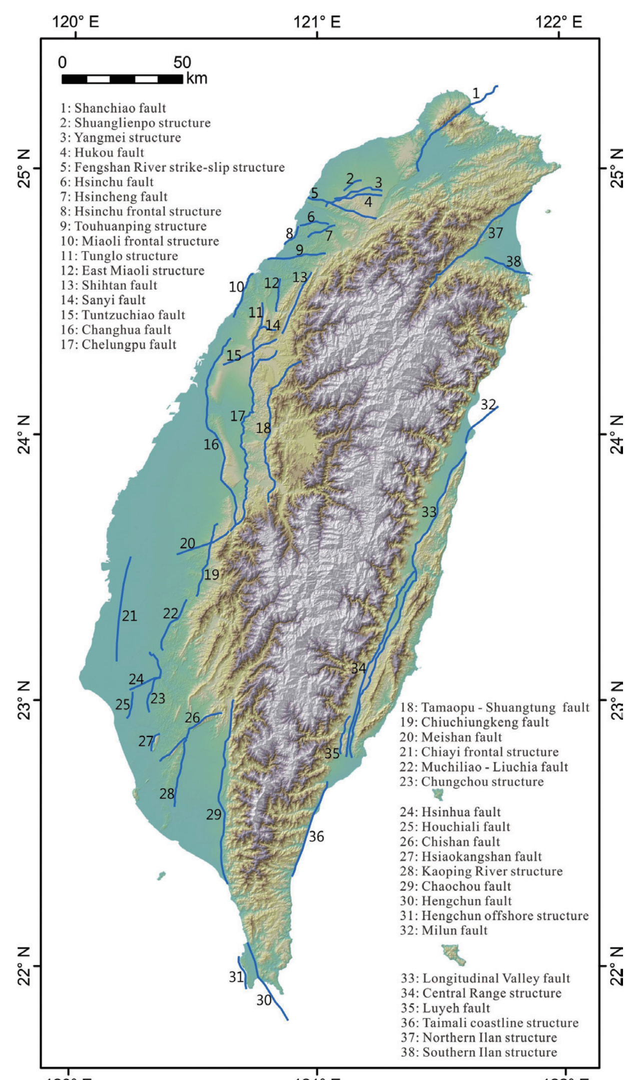

Fig. 4. Map of major seismogenic structures of Taiwan. The blue lines show the 38 structures in Taiwan.

Table 1. The structural parameters of all seismogenic structures.

No.	Fault Name	Type[#a]	Length (km)	Width[#b] (km)	Area[#c] (km^2)	M_w[#d]	Displacement[#e] (m)	Slip rate[#f] (mm yr^{-1})	Recurrence Interval[#g] (yr)
1	Shanchiao fault	N	53.40	19.84	1059.46	7.02	1.33	1.85 ± 0.76	510 - 1220
2	Shuanglienpo structure	R	9.00	11.97	107.73	6.16	0.67	0.25 ± 0.17	1600 - 8380
3	Yangmei structure	R	21.70	3.46	75.08	6.02	0.59	0.38 ± 0.26	920 - 4540
4	Hukou fault	R	25.80	20.00	516.00	6.77	1.15	1.16 ± 0.84	580 - 3600
5	Fengshan River strike-slip structure	SS	30.40	13.90	422.56	6.66	0.96	3.61 ± 2.41	160 - 800
6	Hsinchu fault	R	12.60	14.14	178.16	6.36	0.81	0.70 ± 0.46	690 - 3380
7	Hsincheng fault	R	13.00	25.71	334.23	6.60	0.99	1.80 ± 1.20	330 - 1650
8	Hsinchu frontal structure	R	10.40	20.00	208.00	6.42	0.85	2.80 ± 1.86	180 - 900
9	Touhuanping structure	SS	24.80	12.05	298.84	6.50	0.78	0.14	5570
10	Miaoli frontal structure	R	20.80	20.00	416.00	6.69	1.08	3.60 ± 2.40	180 - 900
11	Tunglo structure	R	11.10	7.00	77.70	6.03	0.59	1.08 ± 0.72	330 - 1640
12	East Miaoli structure	R	14.10	8.00	112.80	6.18	0.69	1.60 ± 1.06	260 - 1280
13	Shihtan fault	R	28.60	11.18	319.75	6.58	0.96	1.86 ± 1.24	310 - 1550
14	Sanyi fault	R	27.20	34.77	945.74	7.01	1.44	1.86 ± 1.23	470 - 2320
15	Tuntzuchiao fault	SS	25.10	14.85	372.74	6.60	0.88	1.00 ± 0.68	520 - 2670
16	Changhua fault	R	86.10	48.55	4180.15	7.59	2.41	3.40 ± 2.26	430 - 2130
17	Chelungpu fault	R	92.00	46.36	4265.12	7.60	2.44	6.94	350
18	Tamaopu-Shuangtung fault	R	68.70	12.00	824.40	6.95	1.34	2.00 ± 1.34	400 - 2030
19	Chiuchiungkeng fault	R	32.90	24.00	789.60	6.94	1.35	7.20 ± 4.80	110 - 560
20	Meishan fault	SS	24.00	14.75	354.00	6.58	0.87	2.51	350
21	Chiayi frontal structure	R	44.30	46.36	2053.75	7.31	1.86	6.49 ± 4.33	170 - 860
22	Muchiliao-Liuchia fault	R	24.90	24.00	597.60	6.83	1.22	5.75 ± 1.35	170 - 280
23	Chungchou structure	R	29.70	24.00	712.80	6.90	1.30	12.20 ± 0.60	100 - 110
24	Hsinhua fault	SS	14.10	15.06	212.35	6.35	0.65	2.65 ± 1.85	140 - 810
25	Houchiali fault	R	11.50	7.07	81.31	6.05	0.61	7.07	86
26	Chishan fault	SS/R	34.80	11.18	389.06	6.62	0.91	1.10 ± 0.36	620 - 1250
27	Hsiaokangshan fault	R	9.00	14.00	126.00	6.22	0.70	3.30 ± 2.20	130 - 640
28	Kaoping River structure	SS/R	29.20	12.71	371.13	6.60	0.89	0.61 ± 0.41	870 - 4450
29	Chaochou fault	SS/R	79.60	11.50	915.40	7.00	1.43	1.76 ± 1.17	490 - 2420
30	Hengchun fault	SS/R	37.20	15.53	577.72	6.80	1.14	6.15 ± 0.29	180 - 200
31	Hengchun offshore structure	R	14.50	8.00	116.00	6.19	0.69	3.65 ± 1.11	140 - 270
32	Milun fault	SS/R	21.30	10.35	220.46	6.37	0.68	10.15 ± 0.04	70
33	Longitudinal Valley fault	R/SS	143.10	23.79	3404.35	7.51	2.24	11.35 ± 5.75	130 - 400
34	Central Range structure	R	85.50	28.28	2417.94	7.38	2.02	7.28 ± 1.77	220 - 370
35	Luyeh fault	R	17.50	6.83	119.52	6.20	0.69	6.34 ± 0.17	110
36	Taimali coastline structure	R/SS	42.60	10.93	465.62	6.73	1.11	7.32 ± 1.46	130 - 190
37	Northern Ilan structure	N	60.50	10.87	657.64	6.80	1.00	3.29 ± 2.25	180 - 960
38	Southern Ilan structure	N	20.60	12.99	267.59	6.41	0.64	5.48 ± 0.64	100 - 130

Note: #a: R: reverse fault; SS: strike-slip fault; N: normal fault; SS/R: strike-slip dominated fault with minor reverse motion; R/SS: reverse dominated fault with minor strike-slip motion.

#b: Width equals to down-dip limit divided by the sine value of fault dip.

#c: Area of fault rupture equals to the Length times the Width.

#d: The moment magnitudes were calculated using the following equations: for reverse faults and reverse dominated faults, $M_w = 4.33 + 0.90 \times \log$ Area; for strike-slip faults and strike-slip dominated fault, $M_w = 3.98 + 1.02 \times \log A$; for normal faults, $M_w = 3.93 + 1.02 \times \log A$ (Wells and Coppersmith 1994).

#e: The average displacement (D) per event was calculated using the equation $M_o = \mu AD$, where μ equals 3×10^{11} dyne cm^{-2}, A is the rupture area in #c, M_o was calculated from M_w by equation: $M_w = 2/3 \log M_o - 10.73$.

#f: Slip rate is obtained from field investigations or previous studies. We measured the age and the vertical deformation amount of terraces to calculate the vertical deformation rate, and then calculated the slip rate (along the dip direction) by dividing the vertical deformation rate by the sine value of fault dip. For structures with multiple dip angles such as Shanchiao, Shuanglienpo, Changhua, Longitudinal Valley, and Luyeh, the slip rates were calculated using the dip angle closest to the surface. For SS/R and R/SS structures, we assumed a 45° rake, thus the net slip rate would be $\sqrt{2}$ times of the rate along the dip direction. For the Longitudinal Valley fault, we assume that the aseismic creeping rate is up to 3/4 of its total slip rate, thus we only used 1/4 - 3/4 of its total slip rate in the calculation.

#g: Recurrence interval equals Displacement divided by Slip rate.

on a published age constraint of the deformed terraces (Ota et al. 2009).

(10) The Miaoli frontal structure is near the coastline of the Miaoli area. Its length is 20.8 km, dip is 30°, and it extends to a depth of 10.0 km. We obtained a slip rate of 3.60 ± 2.40 mm yr^{-1}.

(11) The Tunglo structure is a north-south striking structure in the Miaoli area. The depth of the down-dip limit of this structure is 3.5 km, with the dip of the structure at 30° and the length at 11.1 km. The slip rate is estimated at 1.08 ± 0.72 mm yr^{-1} in this study.

(12) The East Miaoli structure is another north-south striking structure in the Miaoli area. It dips at 30° with a length of 14.1 km. We calculated a slip rate of 1.60 ± 1.06 mm yr^{-1} for this structure.

(13) The Shihtan fault is the seismogenic fault of the M 7.1 Hsinchu-Taichung earthquake in 1935 (Hayasaka 1935; Otuka 1936). The length of the fault is 28.6 km. The fault dips at 75° to a depth of 10.8 km. According to our estimation, the fault slip rate is 1.86 ± 1.24 mm yr^{-1}.

(14) The Sanyi fault is also in the Miaoli area. The geometry of this fault includes a length of 27.2 km, a dip of 15°, and a down-dip limit at 9.0 km deep. The slip rate is estimated at 1.86 ± 1.23 mm yr^{-1}.

(15) The Tuntzuchiao fault is also related with the Hsinchu-Taichung earthquake in 1935 (Otuka 1936). It has a length of 25.1 km. We speculated an 85° dipping of the fault that extend to a depth of 14.8 km. From these data we estimated its slip rate at 1.00 ± 0.68 mm yr^{-1}.

(16) The Changhua fault is located along the front of a series of tablelands in central Taiwan. It is also a listric fault with a dip of 45° from 0 - 3 km deep, 30° from 3 - 5 km deep, and finally 10° from 5 - 12.00 km deep. Previous estimated slip rates of this fault include 6.18 ± 0.10 mm yr^{-1} constrained by uplifted terraces (Ota et al. 2002) and 1.7 - 10.3 mm yr^{-1} from borehole data (Chen et al. 2008a). Its slip rate is estimated at 3.40 ± 2.26 mm yr^{-1}.

(17) The Chelungpu fault is one of the best known faults in Taiwan, since it is the seismogenic fault of the 1999 Chi-Chi earthquake. We used information obtained from many previous studies on the fault in this database.

(18) The Tamaopu-Shuangtung fault is sub-parallel to the Chelungpu fault and to its east. The length of the fault is 68.7 km. It dips at 30° and extends to a depth of 6.0 km. We estimated its slip rate at 2.00 ± 1.34 mm yr^{-1}.

(19) The Chiuchiungkeng fault is at the boundary between the hills and the coastal plain in the Chiayi area. The slip rates were reported between 0.28 - 13.7 mm yr^{-1} in previous studies (Chen et al. 2006; Lin et al. 2007). Its length is 32.9 km and it dips at 30° to a depth of 12.0 km. The slip rate is estimated at 7.20 ± 4.80 mm yr^{-1} in this study.

(20) The length of the Meishan fault is 24.0 km. Rupture of this fault produced a M 7.1 earthquake in 1906 (Omori 1907). Its dip is 85° to a depth of 14.7 km. We estimated a slip rate of 2.51 mm yr^{-1} in this study.

(21) The Chiayi frontal structure is a blind fault beneath the coastal plain of the Chiayi and Tainan areas. The length of this structure is 44.3 km, with a dipping angle of 15° to a depth of 12.0 km. The slip rate of this structure is estimated at 6.49 ± 4.33 mm yr^{-1}.

(22) The Muchiliao-Liuchia fault is also at the front of the hills in the Chiayi and Tainan areas. The length of the fault is 24.9 km, and the dip is 30°. The previous reported slip rate of the fault is between 4.7 - 12.78 mm yr^{-1} (Yang et al. 2005; Chen 2006; Du 2013). We calculated its slip rate at 5.75 ± 1.35 mm yr^{-1}.

(23) The Chungchou structure is east of Tainan City. Its length is 29.7 km, its dip is 30°, and the structure extends to a depth of 12.0 km. Chen and Liu (2000) and Chen (2010) used borehole data to calculate the uplift rate of the upthrown side of this structure, and their results are between 5 - 8 mm yr^{-1}. We calculated its slip rate at 12.20 ± 0.60 mm yr^{-1}.

(24) The Hsinhua fault is near the Chungchou structure, and rupture of this fault produced the M 6.3 earthquake in 1946 (Chang et al. 1946; Bonilla 1977). Its length is 14.1 km, and it dips at 85° to a depth of 15 km. The uplift rate of the upthrown side has been reported at 0.8 - 4.5 mm yr^{-1} (Chen et al. 2011), and we estimated a slip rate of 2.65 ± 1.85 mm yr^{-1} for this fault in this study.

(25) The Houchiali fault is in the Tainan City proper with a length of 11.5 km. It dips at 45° and extends to 5.0 km deep. Based on borehole data, Chen and Liu (2000) obtained an uplift rate of its upthrown side at 6 mm yr^{-1}. Thus we estimated a slip rate of 8.49 mm yr^{-1} for this fault in this study.

(26) The Chishan fault is southeast of Tainan. This fault is 34.8 km in length, dips at 75°, and extends to a depth of 10.8 km. Whereas Chen et al. (2012) estimated a slip rate of 0.75 ± 0.25 mm yr^{-1} for this fault, we calculated its slip rate at 1.10 ± 0.36 mm yr^{-1}.

(27) The Hisaokangshan fault is west of the Chishan fault. It is likely dipping at 30° to a depth of 7.0 km. Chen et al. (2008b) reported that this fault has a slip rate of 6.2 ± 0.8 mm yr^{-1}. In this study, its slip rate is estimated at 3.30 ± 2.20 mm yr^{-1}.

(28) The Kaoping River structure is identified by a linear scarp at the western side of the Kaoping River. Its length is 29.2 km and it dips at 75° to a depth of 12.3 km. We calculated the slip rate as 0.61 ± 0.41 mm yr^{-1}.

(29) The Chaochou fault at the eastern side of the Pingtung Plain forms the boundary between the southern Central Range and the plain. The length of this fault is 79.6 km. It dips at 75° and extends to a depth of 11.1 km. The fault slip rate is estimated at 1.76 ± 1.17 in this study.

(30) The Hengchun fault is one of the southernmost structures in Taiwan. The length of this fault is 37.2 km and the fault dips at 75° and extends to a depth of 15.0 km. Based on the dating result of marine terraces, Chen et al. (2010) calculated an uplift rate of 4.2 ± 0.2 mm yr^{-1} for the upthrown side of the fault. Thus we estimated its slip rate at 6.15 ± 0.29 mm yr^{-1}.

(31) The Hengchun offshore structure is to the west of the Hengchun fault. It dips at 30° and extends to a depth of 4.0 km. The length of this structure is 14.5 km and the slip rate is estimated at 3.65 ± 1.11 mm yr^{-1}.

(32) The Milun fault in eastern Taiwan is near Hualien City. Rupture of this fault produced the M 7.3 earthquake in October 1951 (Yang 1953; Hsu 1962). This fault has a length of 21.3 km, and it dips at 75° to 10.0 km deep. Chen (2013) calculated an uplift rate of 6.93 ± 0.03 mm yr^{-1} of its upthrown side based on U-Th dating results of corals found in uplifted marine terraces. Thus we estimated a slip rate of 10.15 ± 0.04 mm yr^{-1} for this fault.

(33) The Longitudinal Valley fault is an important structure in eastern Taiwan, and forms the eastern boundary of the Longitudinal Valley. This fault is related to several historical earthquakes in eastern Taiwan, including the M 7.0 earthquake series in November 1951 (Hsu 1962; Cheng et al. 1996; Shyu et al. 2007). The seismicity of this fault also illuminated that it has a listric shape, dipping at 75° to a depth of 5.0 km, 60° between 5.0 - 15.0 km deep, and finally 45° to a depth of 20.0 km. Several previous studies reported that the slip rate of this fault is between 20.5 - 32 mm yr^{-1} (Chen 2006, 2010; Shyu et al. 2006b, 2008). However, this fault is also known for its aseismic creeping (e.g., Angelier et al. 1997; Lee et al. 2001). After considering its creeping rate, we estimated a slip rate of 11.35 ± 5.75 mm yr^{-1} for this fault.

(34) The Central Range structure is located at the western edge of the Longitudinal Valley. It is 85.5 km long, dips at 45° to a depth of 20 km. We estimated a slip rate of 7.28 ± 1.77 mm yr^{-1} based on published uplift rate estimations of its upthrown side (Shyu et al. 2006a).

(35) The Luyeh Fault is located near the southern end of the Longitudinal Valley. With a length of 17.5 km, the fault dips at 45° to a depth of 2.0 km, then dips at 30° to a depth of 4.0 km. Based on the ages of deformed terraces, it has been reported that the upthrown side of the fault has an uplift rate of 4.5 mm yr^{-1} (Shyu et al. 2008), and the fault has a slip rate of 5.4 mm yr^{-1} (Chen 2010). We estimated a slip rate of 6.34 ± 0.17 mm yr^{-1} for this fault.

(36) The Taimali coastline structure is along the coastline in southeastern Taiwan. Its length is 42.6 km and the structure dips at 75° to a depth of 10.6 km. The slip rate of this structure is estimated at 7.32 ± 1.46 mm yr^{-1}.

(37) We propose two structures bounding both sides of the Ilan Plain in northeastern Taiwan. The structure in the north is the Northern Ilan structure with a length of 60.5 km. It dips at 60° to a depth of 9.4 km. Based on borehole data, Su (2011) reported the vertical separation rate of this structure is 0.90 - 4.80 mm yr^{-1}. We used this information to obtain a slip rate of 3.29 ± 2.25 mm yr^{-1} for this structure.

(38) South of the Ilan Plain is the Southern Ilan structure with a length of 20.6 km. It dips at 60° to a depth of 11.3 km. We estimated its slip rate at 5.48 ± 0.64 mm yr^{-1} based on the borehole data reported in Su (2011).

4. THREE-DIMENSIONAL (3-D) SUBSURFACE MODEL OF THE STRUCTURES

In order to check for geometrical conflicts and to visualize the subsurface geometry of the seismogenic structures, we also constructed a 3-D subsurface model for these structures (Fig. 5). Furthermore, for structures that lack good depth constraints, the 3-D model also enabled us to estimate their proper down-dip limit. For example, some structures are proposed to originate from a single décollement, either as branches or as a thrust-backthrust system. The 3-D model would help us verify if such systems indeed merge at depth. For structures that are listric and have dipping angles changing at depth, the 3-D model is also helpful for visualizing such changes, as shown by the Changhua fault in Fig. 6. A similar characteristic is also found in the Shanchiao fault and the Longitudinal Valley fault.

This 3-D structural model is useful for seismic hazard calculations, since the distance-to-fault-plane data would be better constrained using such a model. The detailed datasets of this 3-D seismogenic structural model for Taiwan are included in a supplementary file of this paper.

5. DISCUSSION

As the first attempt to construct a complete seismogenic structure database by the TEM project, we combined most of the previously published structural parameters in the database. However, many of the parameters, especially the slip rates of the structures, have not yet been well constrained. As a result, we have also estimated the slip rates of structures based on our field investigations. Since many of the ages of deformed surfaces are unknown, we used a conservative approach to estimate those ages. This can be improved significantly as new information becomes available. For example, other dating methods such as OSL and cosmogenic nuclides (e.g., Chen et al. 2003b; Siame et al. 2012) can be applied to determine the ages of older terraces. Such new data will lower the error bar of the age estimates, and will improve the precision of structural slip rates and average earthquake recurrence intervals.

Another issue for the structural slip rates is related to strike-slip structures. Most of the long-term slip rates were determined by vertical offset observed either in bore-hole data (e.g., Chen et al. 2008a) or by the deformation of surfaces (e.g., Shyu et al. 2008). However, the horizontal offsets by strike-slip structures are difficult to observe. A strike-slip offset of terrace risers helped us constrain the long-term slip rate of the Touhuanping structure (Ota et al. 2009), but many other pure strike-slip structures, such as

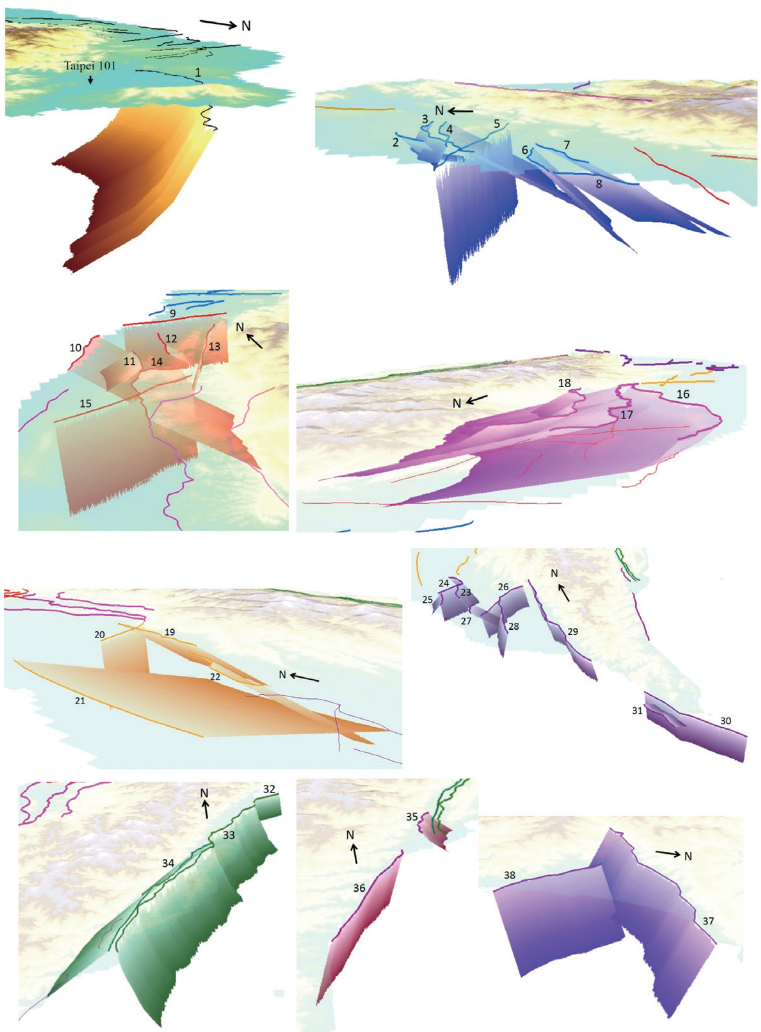

Fig. 5. Figures showing three-dimensional structural geometries below the surface. The geometries of the 38 structures are shown as colored polygons in the 3-D model and the background is the topography of Taiwan. The structural geometries are constrained mostly by seismic data from the Chinese Petroleum Corporation (CPC), Taiwan, as well as the geothermal gradient data from Liu et al. (2015). Numbers correspond to the structure number in Fig. 4 and Table 1, and colors of the patches represent structures in different areas of Taiwan.

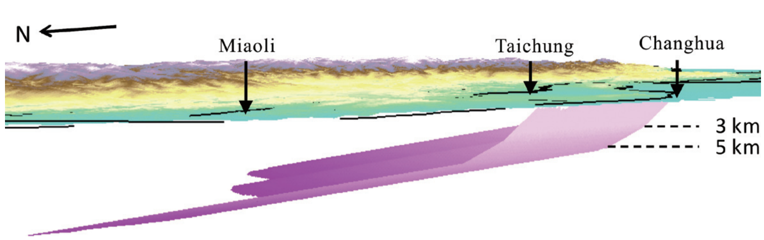

Fig. 6. The geometry of the listric Changhua fault. The Changhua fault is listric based on previous studies, thus it is constructed using 3 segments of surfaces (between 0 - 3, 3 - 5, and 5 - 12 km deep) to show the varied dipping angle at different depths. This approach was also applied to several other structures, such as the Shanchiao fault.

the Meishan fault and the Hsinhua fault (Chen et al. 2011, 2013), lack such piercing points. More detailed investigations are needed to solve this issue in the future.

This seismogenic structure database is constructed on the basis of the structures' geomorphic manifestations. Therefore, for structures that do not have any topographic features, we were unable to identify and include them in this database. During the past several years, however, several moderate earthquakes occurred on previously unidentified blind faults. A well-known example is the M_w 6.3 Jiasian earthquake that occurred on 4 March 2010, whose seismogenic structure appears to extend below 10 km deep and does not extend to the surface (Huang et al. 2011). A challenge for future versions of seismogenic structure databases would be how to identify and consider such blind structures.

We mostly followed the results of Shyu et al. (2005) in this study in identifying active seismogenic structures. Although several other studies have proposed a few additional structures as active seismogenic structures, most of these structures do not show obvious geomorphic features. However, this may also indicate that these structures are slipping at lower rates than the rates of erosion or sedimentation, thus the deformation features have been obliterated or covered. Any ongoing or future efforts to update the seismogenic structure databases would need to focus on such structures to further understand their current activities.

With all of these caveats in mind, we constructed the first version of a complete seismogenic structure database with all structural parameters for Taiwan. This information has already been utilized as the seismogenic source model to calculate a first version of probabilistic seismic hazard analysis for Taiwan (Wang et al. 2016). As more data become available, either through the ongoing TEM and other scientific research projects or as regular updating efforts by the government agencies, we hope this database will continue to improve and provide better constraints for future seismic hazard assessments for Taiwan.

6. CONCLUSIONS

As part of the team effort of the TEM project, we combined previously published information and our field investigation results to construct a first complete on-land seismogenic structure database with all structural parameters for Taiwan. Thirty-eight structures were identified in this study. We also constructed a 3-D subsurface structural model for the visualization of these structures. Such information will be useful for seismic hazards calculations for Taiwan. As more data become available, we hope this database will continue to improve and provide better constraints for future seismic hazard assessments for Taiwan.

Acknowledgements We are grateful for the valuable comments from and discussion with C. H. Chan, S. N. Cheng, K. E. Ching, Y. T. Lee, K. F. Ma, R. J. Rau, Y. J. Wang, and K. L. Wen. Numerous previous efforts organized and supported by the Central Geological Survey (CGS) of Taiwan provided valuable input datasets for this research. The comments and suggestions from three anonymous reviewers greatly helped us to improve this manuscript. This research is supported by the Ministry of Science and Technology (MOST) of Taiwan (Project 101-2119-M-008-023, 102-2119-M-006-010, and 104-2119-M-006-007 as the TEM project, and 102-2628-M-002-007-MY3 to J.B.H.S.).

REFERENCES

Angelier, J., H. T. Chu, and J. C. Lee, 1997: Shear concentration in a collision zone: Kinematics of the Chihshang Fault as revealed by outcrop-scale quantification of active faulting, Longitudinal Valley, eastern Taiwan. *Tectonophysics*, **274**, 117-143, doi: 10.1016/S0040-1951(96)00301-0. [Link]

Bonilla, M. G., 1977: Summary of Quaternary faulting and elevation changes in Taiwan. *Mem. Geol. Soc. China*, **2**, 43-55.

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, doi: 10.1130/0091-7613(2002)030<0935:ADOTIB>2.0.CO;2. [Link]

Central Geological Survey, 2010: Active fault map of Taiwan. Available at http://fault.moeacgs.gov.tw/UploadFiles/images/500K/C_activefault(A4)_E.jpg.

Chang, H. C., C. W. Lin, M. M. Chen, and S. T. Lu, 1998: An introduction to the active faults of Taiwan: Explanatory text of the active fault map of Taiwan scale 1:500,000. *Spec. Publ. Cent. Geol. Surv.*, **10**, 1-103. (in Chinese)

Chang, J. and G. Yang, 2004: Deformation and occurrence of the Che-lung-pu Fault from geomorphic evidence. *Quat. Int.*, **115-116**, 177-188, doi: 10.1016/S1040-6182(03)00106-X. [Link]

Chang, L. S., M. C. Chow, and P. Y. Chen, 1946: The Tainan earthquake of December 5, 1946. *Bull. Geol. Surv. Taiwan*, **1**, 11-20. (in Chinese)

Chen, C. F., 2013: Seismotectonic characteristics of the northernmost part of the Longitudinal Valley suture, eastern Taiwan. Master Thesis, National Taiwan University, Taipei, Taiwan, 112 pp. (in Chinese)

Chen, W. S., 2006: Neotectonic, paleoseismology and trenching research, trenching and paleoseismologic research projects (overall report), earthquake geology investigation and the construction of the active faults database projects. Cent. Geol. Surv. Rep. 95-08, Taipei, 133 pp. (in Chinese)

Chen, W. S., 2010: Research of long-term slip rates and recurrence intervals of faults (overall report), earthquake geology and potential deformation analysis projects. Cent. Geol. Surv. Rep. 99-09, Taipei, 141 pp. (in Chinese)

Chen, W. S., L. H. Liu, Y. C. Yen, H. C. Yang, L. S. Lee, N. T. Yu, and H. C. Chang, 2003a: Paleoseismologic study of the Hsincheng fault. *Spec. Publ. Cent. Geol. Surv.*, **14**, 11-23. (in Chinese)

Chen, W. S., C. C. Yang, I. C. Yen, L. S. Lee, K. J. Lee, H. C. Yang, H. C. Chang, Y. Ota, C. W. Lin, W. H. Lin, T. S. Shih, and S. T. Lu, 2007: Late Holocene paleoseismicity of the southern part of the Chelungpu fault in central Taiwan: Evidence from the Chushan excavation site. *Bull. Seismol. Soc. Am.*, **97**, 1-13, doi: 10.1785/0120050161. [Link]

Chen, W. S., N. T. Yu, N. Matsuta, and H. C. Yang, 2008a: Research of long-term slip rates and recurrence intervals of faults (1/4), earthquake geology, and potential deformation analysis projects. Cent. Geol. Surv. Rep. 96-10, Taipei, 86 pp. (in Chinese)

Chen, W. S., N. T. Yu, N. Matsuta, and H. C. Yang, 2008b: Research of long-term slip rates and recurrence intervals of faults (2/4), earthquake geology, and potential deformation analysis projects. Cent. Geol. Surv. Rep. 97-9, Taipei, 75 pp. (in Chinese)

Chen, W. S., N. T. Yu, N. Matsuta, and H. C. Yang, 2010: Research of long-term slip rates and recurrence intervals of faults (4/4), earthquake geology, and potential deformation analysis projects. Cent. Geol. Surv. Rep. 99-09, Taipei, 76 pp. (in Chinese)

Chen, W. S., N. T. Yu, and H. C. Yang, 2011: Active characteristics analysis and assessment of faults (1/4), structural characteristics investigation of important active faults research projects. Cent. Geol. Surv. Rep. 100-11, Taipei, 118 pp. (in Chinese)

Chen, W. S., N. T. Yu, and H. C. Yang, 2012: Active characteristics analysis and assessment of faults (2/4), structural characteristics investigation of important active faults research projects. Cent. Geol. Surv. Rep. 101-9, Taipei, 130 pp. (in Chinese)

Chen, W. S., N. T. Yu, and H. C. Yang, 2013: Active characteristics analysis and assessment of faults (3/4), structural characteristics investigation of important active faults research projects. Cent. Geol. Surv. Rep. 102-9, Taipei, 90 pp. (in Chinese)

Chen, Y. G., 1988: C-14 dating and correlation of river terraces along the lower reach of the Tahan-chi, northern Taiwan. Master Thesis, National Taiwan University, Taipei, Taiwan, 88 pp. (in Chinese)

Chen, Y. G. and T. K. Liu, 2000: Holocene uplift and subsidence along an active tectonic margin southwestern Taiwan. *Quat. Sci. Rev.*, **19**, 923-930, doi: 10.1016/S0277-3791(99)00076-1. [Link]

Chen, Y. G., W. S. Chen, Y. Wang, P. W. Lo, T. K. Liu, and J. C. Lee, 2002: Geomorphic evidence for prior earthquakes: Lessons from the 1999 Chichi earthquake in central Taiwan. *Geology*, **30**, 171-174, doi: 10.1130/0091-7613(2002)030<0171:GEFPEL>2.0.CO;2. [Link]

Chen, Y. G., Y. W. Chen, W. S. Chen, J. F. Zhang, H. Zhao, L. P. Zhou, and S. H. Li, 2003b: Preliminary results of long-term slip rates of 1999 earthquake fault by luminescence and radiocarbon dating. *Quat. Sci. Rev.*, **22**, 1213-1221, doi: 10.1016/S0277-3791(03)00037-4. [Link]

Chen, Y. G., J. B. H. Shyu, Y. Ota, W. S. Chen, J. C. Hu, B. W. Tsai, and Y. Wang, 2004: Active structures as deduced from geomorphic features: A case in Hsinchu Area, northwestern Taiwan. *Quat. Int.*, **115-116**, 189-199, doi: 10.1016/S1040-6182(03)00107-1. [Link]

Chen, Y. G., W. S. Chen, T. Watanuki, Y. W. Chen, T. S. Wu, Y. N. N. Lin, and Y. Wang, 2006: Thermoluminescence and optically stimulated luminescence dating, trenching and paleoseismologic research projects (overall report), earthquake geology investigation and the construction of the active faults database projects. Cent. Geol. Surv. Rep. 95-8, Taipei, 56 pp. (in Chinese)

Cheng, C. T., S. J. Chiou, C. T. Lee, and Y. B. Tsai, 2007: Study on probabilistic seismic hazard maps of Taiwan after Chi-Chi earthquake. *J. GeoEngineering*, **2**, 19-28, doi: 10.6310/jog.2007.2(1).3. [Link]

Cheng, C. T., C. T. Lee, P. S. Lin, B. S. Lin, Y. B. Tsai, and S. J. Chiou, 2010: Probabilistic earthquake hazard in metropolitan Taipei and its surrounding regions. *Terr. Atmos. Ocean. Sci.*, **21**, 429-446, doi: 10.3319/TAO.2009.11.11.01(TH). [Link]

Cheng, S. N., Y. T. Yeh, and M. S. Yu, 1996: The 1951 Taitung earthquake in Taiwan. *J. Geol. Soc. China*, **39**, 267-285.

Du, K. Y., 2013: Neotectonic characteristics of Liuchia fault, southwestern Taiwan, from the analysis of fluvial channel morphology. Master Thesis, National Taiwan University, Taipei, Taiwan, 109 pp. (in Chinese)

Hayasaka, I., 1935: On the earthquake of April, 21, 1935 in Sintiku and Taityû Prefectures. *Taiwan Tigaku Kizi*, **6**, 58-78. (in Japanese)

Hsieh, H. H., C. H. Chen, P. Y. Lin, and H. Y. Yen, 2014: Curie point depth from spectral analysis of magnetic data in Taiwan. *J. Asian Earth Sci.*, **90**, 26-33, doi: 10.1016/j.jseaes.2014.04.007. [Link]

Hsu, T. L., 1962: Recent faulting in the Longitudinal Valley of eastern Taiwan. *Mem. Geol. Soc. China*, **1**, 95-102.

Huang, H. H., Y. M. Wu, T. L. Lin, W. A. Chao, J. B. H. Shyu, C. H. Chan, and C. H. Chang, 2011: The preliminary study of the 4 March 2010 M_w 6.3 Jiasian, Taiwan earthquake sequence. *Terr. Atmos. Ocean. Sci.*, **22**, 283-290, doi: 10.3319/TAO.2010.12.13.01(T). [Link]

Huang, S. Y., C. M. Rubin, Y. G. Chen, and H. C. Liu, 2007: Prehistoric earthquakes along the Shanchiao fault, Taipei Basin, northern Taiwan. *J. Asian Earth Sci.*, **31**, 265-276, doi: 10.1016/j.jseaes.2006.07.025. [Link]

Kerrich, R., R. D. Beckinsale, and J. J. Durham, 1977: The transition between deformation regimes dominated by intercrystalline diffusion and intracrystalline creep evaluated by oxygen isotope thermometry. *Tectonophysics*, **38**, 241-257, doi: 10.1016/0040-1951(77)90213-X. [Link]

Lee, J. C., J. Angelier, H. T. Chu, J. C. Hu, and F. S. Jeng, 2001: Continuous monitoring of an active fault in a plate suture zone: A creepmeter study of the Chihshang Fault, eastern Taiwan. *Tectonophysics*, **333**, 219-240, doi: 10.1016/S0040-1951(00)00276-6. [Link]

Lee, T. Q., S. F. Lin, and H. C. Chou, 1999: Preliminary magnetic study of the Quaternary red-soil bed on Linkou Terrace, northern Taiwan. *Terr. Atmos. Ocean. Sci.*, **10**, 763-776.

Lin, C. W., H. C. Chang, S. T. Lu, T. S. Shih, and W. J. Huang, 2000: An introduction to the active faults of Taiwan: Explanatory text of the active fault map of Taiwan scale 1:500,000. *Spec. Publ. Cent. Geol. Surv.*, **13**, 1-122. (in Chinese)

Lin, C. W., C. Y. Hsu, and T. D. Yu, 2007: The Chiuhsiungken fault: A candidate to trigger a hazardous earthquake in western Taiwan. *J. Asian Earth Sci.*, **30**, 390-402, doi: 10.1016/j.jseaes.2006.07.021. [Link]

Liu, C. M., S. R. Song, and C. H. Kuo, 2015: Silica geothermometry applications in the Taiwan orogenic belt. *Terr. Atmos. Ocean. Sci.*, **26**, 387-396, doi: 10.3319/TAO.2015.02.09.01(TT). [Link]

Omori, F., 1907: Preliminary note on the Formosa earthquake of March 17, 1906. *Bull. Imp. Earthquake Invest. Comm.*, **1**, 53-69.

Ota, Y., J. B. H. Shyu, Y. G. Chen, and M. L. Hsieh, 2002: Deformation and age of fluvial terraces south of the Choushui River, central Taiwan, and their tectonic implications. *Western Pacific Earth Sci.*, **2**, 251-260.

Ota, Y., Y. N. N. Lin, Y. G. Chen, N. Matsuta, T. Watanuki, and Y. W. Chen, 2009: Touhuanping Fault, an active wrench fault within fold-and-thrust belt in northwestern Taiwan, documented by spatial analysis of fluvial terraces. *Tectonophysics*, **474**, 559-570, doi: 10.1016/j.tecto.2009.04.034. [Link]

Otuka, Y., 1936: The earthquake of central Taiwan (Formosa), April 21, 1935, and earthquake faults. *Bull. Earthq. Res. Inst. Tokyo Imperial Univ.*, **3**, 22-74. (in Japanese)

Rau, R. J. and F. T. Wu, 1998: Active tectonics of Taiwan orogeny from focal mechanisms of small-to-moderate-sized earthquakes. *Terr. Atmos. Ocean. Sci.*, **9**, 755-778.

Shen, S. M., J. C. Chang, G. S. Yang, H. M. Lin, Z. Y. Lin, J. M. Lin, H. J. Su, I. H. Yeh, and Y. S. Weng, 2005: Active structure geomorphology interpretation and database construction and analysis (1/2), earthquake geology investigation and the construction of the active faults database projects. Cent. Geol. Surv. Rep. 94-13, Taipei, 127 pp. (in Chinese)

Shih, T. S., S. T. Lu, W. H. Lin, and Y. H. Lee, 2003: A study on the location and activity of the Hsincheng fault. *Spec. Publ. Cent. Geol. Surv.*, **14**, 37-52. (in Chinese)

Shih, T. T., J. C. Chang, K. H. Teng, C. D. Shih, G. S. Yang, and M. Y. Hsu, 1984: A geomorphological study of active fault in western and southern Taiwan. *Geogr. Res.*, **10**, 49-94. (in Chinese)

Shih, T. T., K. H. Teng, J. C. Chang, C. D. Shih, and G. S. Yang, 1986: A geomorphological study of active fault in Taiwan. *Geogr. Res.*, **12**, 1-44. (in Chinese)

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

Shyu, J. B. H., K. Sieh, Y. G. Chen, and L. H. Chung, 2006a: Geomorphic analysis of the Central Range fault, the second major active structure of the Longitudinal Valley suture, eastern Taiwan. *Geol. Soc. Am. Bull.*, **118**, 1447-1462, doi: 10.1130/B25905.1. [Link]

Shyu, J. B. H., K. Sieh, J. P. Avouac, W. S. Chen, and Y. G. Chen, 2006b: Millennial slip rate of the Longitudinal Valley fault from river terraces: Implications for convergence across the active suture of eastern Taiwan. *J. Geophys. Res.*, **111**, B08403, doi: 10.1029/2005JB003971. [Link]

Shyu, J. B. H., L. H. Chung, Y. G. Chen, J. C. Lee, and K. Sieh, 2007: Re-evaluation of the surface ruptures of the November 1951 earthquake series in eastern Taiwan, and its neotectonic implications. *J. Asian Earth Sci.*, **31**, 317-331, doi: 10.1016/j.jseaes.2006.07.018. [Link]

Shyu, J. B. H., K. Sieh, Y. G. Chen, R. Y. Chuang, Y. Wang, and L. H. Chung, 2008: Geomorphology of the southernmost Longitudinal Valley fault: Implications for evolution of the active suture of eastern Taiwan. *Tectonics*, **27**, TC1019, doi: 10.1029/2006TC002060. [Link]

Siame, L. L., R. F. Chen, F. Derrieux, J. C. Lee, K. J. Chang, D. L. Bourlès, R. Braucher, L. Léanni, C. C. Kang, C. P. Chang, and H. T. Chu, 2012: Pleistocene alluvial deposits dating along frontal thrust of Changhua Fault in western Taiwan: The cosmic ray exposure point of view. *J. Asian Earth Sci.*, **51**, 1-20, doi: 10.1016/j.jseaes.2012.02.002. [Link]

Su, C. C., 2011: The last interglacial depositional environment and tectonic characteristics of the Ilan Plain, northeastern Taiwan. Master Thesis, National Taiwan University, Taipei, Taiwan, 129 pp. (in Chinese)

Suppe, J., 1976: Decollement folding in southwestern Taiwan. *Petrol. Geol. Taiwan*, **13**, 25-35.

Suppe, J., 1987: The active Taiwan mountain belt. In: Schaer, J. P. and J. Rodgers (Eds.), Anatomy of Mountain Ranges, Princeton University Press, Princeton, N.J, 277-293.

Tsai, H., Z. Y. Hseu, W. S. Huang, and Z. S. Chen, 2007: Pedogenic approach to resolving the geomorphic evolution of the Pakua river terraces in central Taiwan. *Geomorphology*, **83**, 14-28, doi: 10.1016/j.geomorph.2006.06.006. [Link]

Tullis, J. and R. A. Yund, 1977: Experimental deformation of dry westerly granite. *J. Geophys. Res.*, **82**, 5705-5718, doi: 10.1029/JB082i036p05705. [Link]

Wang, Y. J., C. H. Chan, Y. T. Lee, K. F. Ma, J. B. H. Shyu, R. J. Rau, and C. T. Cheng, 2016: Probabilistic seismic hazard assessment for Taiwan. *Terr. Atmos. Ocean. Sci.*, **27**, 325-340, doi: 10.3319/TAO.2016.05.03.01(TEM). [Link]

Wei, K., Y. G. Chen, and T. K. Liu, 1998: Sedimentary history of the Taipei Basin with constraints from thermoluminescence dates. *J. Geol. Soc. China*, **41**, 109-125.

Wells, D. L. and K. J. Coppersmith, 1994: New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seismol. Soc. Am.*, **84**, 974-1002.

White, S., 1975: Tectonic deformation and recrystallisation of oligoclase. *Contrib. Mineral. Petrol.*, **50**, 287-304, doi: 10.1007/BF00394854. [Link]

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

Yang, C. C. B., Y. C. Yen, S. H. Sung, N. W. Huang, Y. C. Chen, W. S. Chen, Y. G. Chen, L. C. Wu, H. C. Chang, C. S. Hou, and C. W. Lin, 2005: Study on the slip rate of the Liuchia fault in the Holocene, southwestern Taiwan. *Spec. Publ. Cent. Geol. Surv.*, **16**, 1-16. (in Chinese)

Yang, G. S., 1986: A geomorphological study of active faults in Taiwan – especially on the relation between active faults and geomorphic surfaces. Ph.D. Thesis, Chinese Culture University, Taipei, Taiwan, 178 pp. (in Chinese)

Yang, Y. C., 1953: Earthquakes in Hualien in the latest 41 years. *Hualien Literatures*, **1**, 67-71. (in Chinese)