Terr. Atmos. Ocean. Sci., Vol. 22, No. 5, 463-473, October 2011 doi: 10.3319/TAO.2011.04.22.01(TT)

Faulting and Mud Volcano Eruptions Inside of the Coastal Range During the 2003 M_w = 6.8 Chengkung Earthquake in Eastern Taiwan

Guo-Jang Jiang[1], Jacques Angelier[2], Jian-Cheng Lee[3,*], Hao-Tsu Chu[4], Jyr-Ching Hu[5], and Chung-Hsiang Mu[2,6]

[1] Eastern Taiwan Study Association, Taitung, Taiwan
[2] Géosciences Azur, Observatoire de la Côte d'Azur and Observatoire Océanologique de Villefranche, Villefranche-sur-Mer, France
[3] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
[4] Central Geological Survey, Taipei, Taiwan
[5] Department of Geosciences, National Taiwan University, Taipei, Taiwan
[6] Graduate Institute of Applied Geology, National Central University, Jhongli, Taiwan

Received 19 February 2011, accepted 22 April 2011

ABSTRACT

Field investigations following the 2003 M_w = 6.8 Chengkung earthquake in eastern Taiwan revealed some interesting observations of surface geological processes closely related to the co-seismic deformation. We discovered that the Tama Fault, which is about 15 km east of the causative Chihshang Fault, underwent shortening of about 15.5 mm locally in 2001 - 2006, particularly during the 2003 earthquake. This shows that ESE-WNW compression affects the upper crust of the Coastal Range and produces significant shortening in addition to that of the major Chihshang Fault. On the hanging wall of the Chihshang Fault, we also found vigorous activities of the two major mud volcanoes during the main shock, lasting several days. To the north, the Luoshan Mud Volcano, a large mud basin, erupted noisily with water and gases during the earthquake. To the south, in the Leikunghuo Mud Volcano, two sets of fractures, one aligned with the N16°E right-lateral fault and the other with the N80°E left-lateral fault, occurred during the earthquake. This conjugate system revealed a strike-slip stress regime with NE-SW compression and NW-SE extension. We interpret it to be the result of local stress permutation rather than regional tectonic stress. We conclude that deformation did occur inside of the Coastal Range, especially during the co-seismic event. Therefore, a better understanding of the internal deformation of the Coastal Range is an important target for future studies, particularly across three mapped faults: the Yungfeng, Tuluanshan and Tama faults. We also want to draw attention to the stress analysis in the mud volcanoes area, where the local stress perturbation plays an important role.

Key words: Mud volcano, LVF, Coastal Range, Chengkung earthquake, Taiwan

Citation: Jiang, G. J., J. Angelier, J. C. Lee, H. T. Chu, J. C. Hu, and C. H. Mu, 2011: Faulting and mud volcano eruptions inside of the Coastal Range during the 2003 M_w = 6.8 Chengkung earthquake in eastern Taiwan. Terr. Atmos. Ocean. Sci., 22, 463-473, doi: 10.3319/TAO.2011.04.22.01(TT)

1. INTRODUCTION

Taiwan's active collision and orogeny has occurred since the Late Pliocene to the present, at the contact borders between the NW-moving Philippine Sea plate and the relatively stable Eurasian plate (e.g., Ho 1986), as revealed in Fig. 1a. The Coastal Range of eastern Taiwan is located at the northwestern corner of the Philippine Sea plate, representing the Luzon Arc units which were thrust over the Quaternary infill of the Longitudinal Valley and the metamorphic rocks of the eastern Central Range (Hsu 1956; Teng and Wang 1981; Angelier 1986; Barrier and Angelier 1986; Ho 1988). As the major plate suture, the Longitudinal Valley of eastern Taiwan shows a straight, narrow morphological feature separating the high mountains of the Central Range to the west and the Coastal Range to the east (Fig. 1b).

The Longitudinal Valley Fault (LVF), located mainly along the foot of the Coastal Range adjacent to the Longitudinal Valley, is an active high-angle oblique thrust fault with a left-lateral strike slip component (Barrier et al. 1982; Yu and Liu 1989; Yu et al. 1990; Lee and Angelier 1993;

* *Corresponding author*
E-mail: jclee@earth.sinica.edu.tw

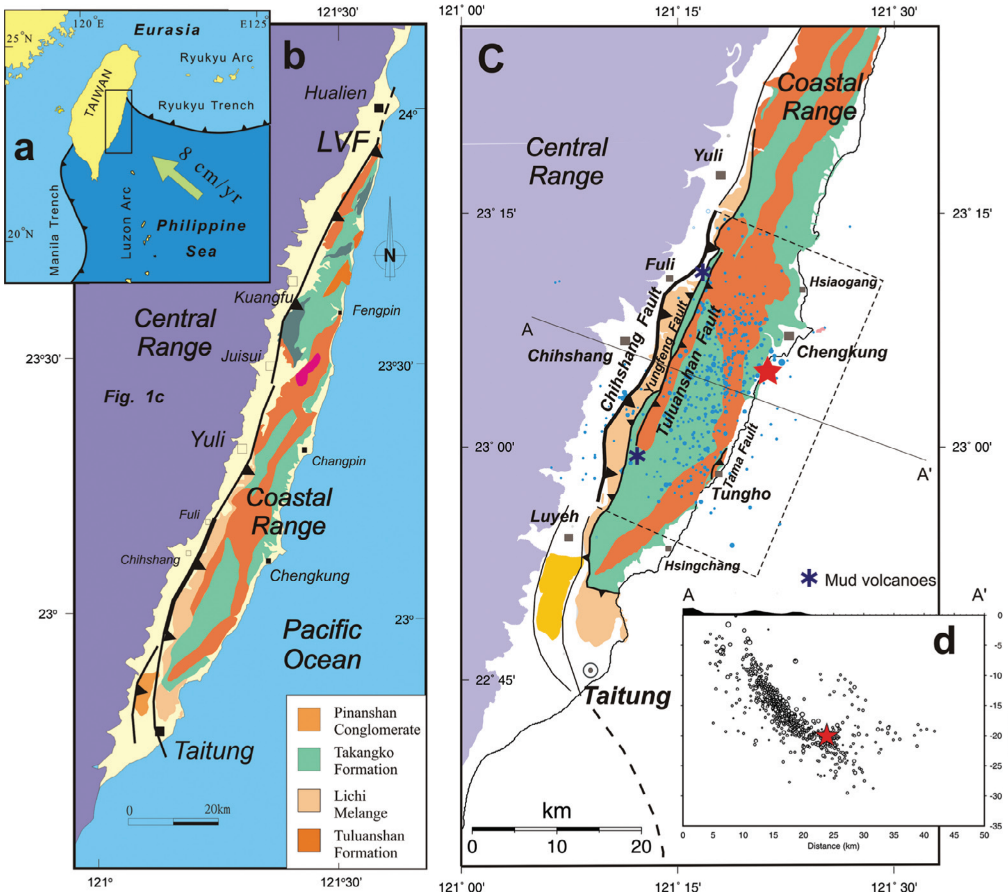

Fig. 1. (a) Plate tectonic setting of Taiwan. (b) General geology of the Coastal Range. The Coastal Range is thrusted onto Longitudinal Valley and Central Range along the Longitudinal Valley Fault (LVF). Thrust faults are indicated by the thick line with triangles on up thrust side. (c) Location of the main shock and aftershock of the 2003 M_w = 6.8 Chengkung earthquake and the Chihshang Fault. Three mapped geological faults inside the Coastal Range, the Yungfeng Fault, the Tuluanshan Fault and the Tama Fault are shown in the map. Two mud volcanoes, the Luoshan and Leikunghuo Mud Volcanoes, are located in the hanging wall of the Chihshang Fault (modified from Lee et al. 2006). (d) Cross-section of the distribution of the 2003 earthquake sequence (Lee et al. 2006). The distribution of the main shock and aftershocks, which formed a listric-shaped in 2-D profile, corresponds to the geometry of the Chihshang Fault.

Angelier et al. 1997, 2000), along which continuously rapid creep (Lee et al. 2003) and major earthquakes occur alternately. The largest seismically documented earthquake was the 1951 M = 7.1 Yuli earthquake (Hsu 1962; Bonilla 1975; Cheng et al. 1996). However, much better geophysical and geological information is available from the 2003 M_w = 6.8 Chengkung earthquake (Chen et al. 2006; Lee et al. 2006; Wu et al. 2006; Hu et al. 2007; Kuochen et al. 2007; Cheng et al. 2009; Hsu et al. 2009) (Figs. 1c and d). The Luzon Arc's collision against Taiwan resulted in the deformed Coastal Range. In the mountain belt of Taiwan, rapid plate convergence occurs along a SE-NW direction between the Philippine Sea plate (including the Coastal Range) and the South China portion of Eurasia (Seno 1977, 1987; Yu et al. 1997). This arc-continent collision (e.g., Suppe 1981; Teng and Wang 1981) induced the rapid emergence of the Taiwan Island in Plio-Pleistocene.

The rock sequences of the Coastal Range are, from bottom to top, composed of the Miocene volcanic Tuluanshan Formation uncomformably overlain by the Plio-Pliestocene deep-sea turbidites of the Takangkou Formation. Along the western flank of the southern Coastal Range, the Lichi Mélange is a distinct unit composed of chaotic mudstones intermixed with exotic blocks of various sizes and lithology (Hsu 1956; Suppe and Liou 1979; Chang et al. 2000). The Wuhe Conglomerate and Pinanshan Conglomerate, in the middle and southern segments of the Coastal Range respectively, are the youngest units, which are composed mainly of fluvial gravels derived from the metamorphic terrain of the Central Range. These conglomerate units of probable middle-late Pleistocene age (Chi et al. 1983) have been folded during the continuing collision of the Luzon arc. For instance, the eastern limb of the Pinanshan Conglomerate shows dips of about 90° against the Lichi Fault (Barrier and Angelier 1986; Ho 1988; Lee et al. 1998).

Although the LVF represents the major fault expressing that the Coastal Range thrusts over the Longitudinal Valley, a few geological faults also exist and have been mapped in the hanging wall of the LVF within the Coastal Range. For instance, the Yungfeng Fault, which is located 3 - 5 km east of the LVF, can be considered a backthrust of the LVF (Chang et al. 2000); and the Tama Fault, a short segment of about 5 km long, has been mapped near the coastline (Lo et al. 1993). However, the active deformation, including active faulting and folding, remains little known inside of the Coastal Range. In this paper, we intend to present an outcrop near the Tama Fault, where we observed possible co-seismic deformation inside the Coastal Range as related to the 2003 Chengkung earthquake, although it was of a relatively smaller magnitude.

Within this tectonic framework dominated by active collision, we also address the characteristics of mud volcano behavior as it relates to active shortening and earthquake activity inside the Coastal Range. Two groups of mud volcanoes are both located in the Lichi Mélange of the Coastal Range (Fig. 1c). To the south, the Leikunghuo Mud Volcano, about 15 km northeast of the town of Luyeh, appears as a mud shield with dozens of big and small craters (Shih 1967; Hsieh et al. 1993). This mud volcano essentially developed in the hanging wall of the Yungfeng Fault, a major backthrust of the LVF in the Lichi Mélange. Farther north, the Luoshan Mud Volcano (previously also named Yencheng Mud Volcano by Shih 1967), 8 km northeast of the town of Fuli, is also located in the same type of backthrust system. This mud volcano is comprised of more than 100 mud ponds scattered over a line for a distance of about 1 km along the hanging wall of the Yungfeng Fault (Shih 1967; Hsieh et al. 1994). Isotopic chemical analysis from the gas of the mud volcanoes (Hsieh 2000; Chao 2003) indicated that the gas of the Leikunghuo Mud Volcano derived mainly from the turbiditic sediments of the Coastal Range. By contrast, the gas of the Luoshan volcano showed mantle-derived signal. Nevertheless, it appears that the two mud volcanoes in the Lichi Mélange are strongly associated with the Yungfeng Fault, a major backthrust of the LVF.

In this paper, we highlight the close relationships in space and time between the active shortening of an earthquake event that affects the Coastal Range, the Longitudinal Valley, and the erupting events of the mud volcanoes, taking into special consideration the major seismic event of the 2003 Chengkung earthquake.

2. THE 2003 CHENGKUNG EARTHQUAKE

The Chengkung earthquake of magnitude $M_w = 6.8$ occurred in eastern Taiwan on 10 December 2003. This major earthquake ruptured the Chihshang Fault, one of the most active segments of the LVF. The surface trace of the Chihshang Fault is located at the boundary between the Longitudinal Valley and the western edge of the Coastal Range, roughly from Yuli to the north to Luyeh to the south (Fig. 1c) (Lee et al. 2006). The hypocenter depth of the Chengkung earthquake was 20 - 22 km (Wu et al. 2006; Kouchen et al. 2007). Because of the eastward dip of the Chihshang Fault, along which this earthquake occurred, the epicenter of the main shock was located near the shoreline of the Coastal Range, at a distance of about 20 km from the surface trace of the fault, as the seismic cross-section of Fig. 1d shows. The earthquake sequence, including the main shock and numerous aftershocks, was mainly distributed along the NNE striking and east dipping Chihshang Fault (Figs. 1c and d), forming a patch approximately 35 km long (along strike) and 25 km wide (in the downdip direction) (Lee et al. 2006; Ching et al. 2007). The focal mechanism solution of the main shock showed a nearly pure thrust event with minor left-lateral component (strike 37°, dip 50° and rake 94°) (Wu et al. 2006; Hu et al. 2007; Kuochen et al. 2007).

No human lives were lost during the Chengkung event and the damage was generally moderate. Typical examples of damage on man-made structures around the epicenter area are shown in Fig. 2, including a harbor dyke fracturing (Fig. 2a), fissuring in pillars of a school building (Fig. 2b), and rupturing of walls in occupied houses (Fig. 2c). In addition, a few landslides and large numbers of surface cracks developed, not only near the epicenter but also along the surface trace of the Chihshang Fault at a distance of about 20 km west of the epicenter.

From the seismotectonic point of view, the focal mechanisms of the Chengkung earthquake sequence, including the main shock and a few larger aftershocks, are clearly compatible with the general SE-NW direction of compression (Hu et al. 2007; Kuochen et al. 2007) that prevails across the whole Coastal Range and the Longitudinal Valley of eastern Taiwan during the interseismic period (Barrier and Angelier 1986).

3. INTERSEISMIC AND COSEISMIC SHORTENING WITHIN THE COASTAL RANGE AND ACROSS THE CHIHSHANG FAULT

Before the 2003 Chengkung earthquake, the most damaging activity of the Chihshang Fault occurred during the M = 7.1 Yuli earthquake sequence (with apparently a pre-shock of M = 6.2 earthquake near Chihshang) in 1951 (Cheng et al. 1996). Since then the Chihshang Fault has been undergoing a rapid continuous creep, which caused abundant cracks in man-made constructions such as buildings, bridges, retaining walls and concrete water channels along the surface trace of the fault (Barrier and Chu 1984; Lee 1994; Angelier et al. 1997, 2000).

The pattern of surface interseismic displacement velocity across the Chihshang Fault that resulted from geodetic GPS surveying (mostly from 1992 - 1999) is shown in Fig. 3a. The surface deformation was compatible with the general shortening rate of about 31 mm yr^{-1} in direction 312 - 323° across the LVF (Yu et al. 1997; Yu and Kuo 2001),

Fig. 2. Damage of human structure resulting from Chengkung earthquake in December 2003 near the epicenter area: (a) Fractures of cemented ground in a small harbor of Hsiao-Gang, about 8 km north of Chengkung. (b) Conjugate fractures in a concrete pillar of the Taiyuan junior high school. (c) Conjugate fractures in the wall of a house in Hsingchang village about 29 km south of Chengkung. See locations in Fig. 1c. These fractures of the concrete structures are interpreted to be mostly resulted from severe ground shaking near the epicenter during the main shock.

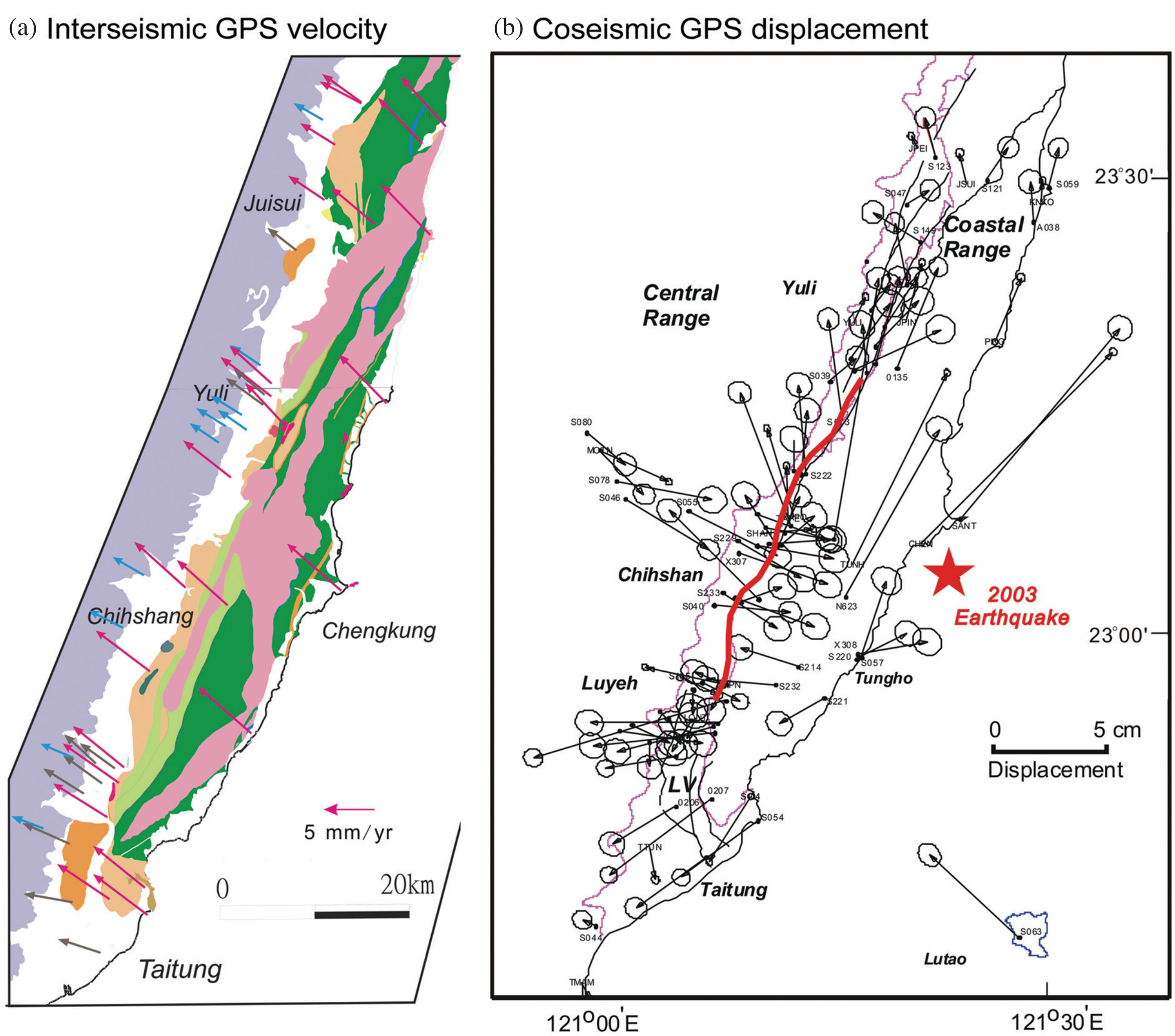

Fig. 3. Interseismic (a) and coseismic (b) GPS horizontal displacements in the southern Longitudinal Valley and Coastal Range (after Yu and Kuo 2001 and Chen et al. 2006). The surface trace of the Chihshang fault is marked in red heavy lines in Fig. 3b.

which accounted for about 38% of total plate convergence, as compared to 82 mm yr^{-1} in direction 317 - 330° across the whole mountain belt. In addition to shortening across the LVF, the GPS velocity indicates that horizontal shortening of approximately 8 - 10 mm yr^{-1} occurred inside of the Coastal Range. As a result, the Coastal Range is seemingly undergoing deformation during the interseismic period.

The 2003 Chengkung earthquake revealed significant surface deformation with two opposite fan-shaped horizontal displacements on both sides of the 35-km-long Chihshang Fault according to the coseismic GPS measurements (Chen et al. 2006; Ching et al. 2007) (Fig. 3b). The maximal co-seismic horizontal displacements of about 20 - 25 cm occurred around the epicentral area. However, the co-seismic displacement decreased dramatically near the surface trace of the Chihshang Fault. Close to the fault and near the surface level, the Chengkung earthquake produced a relatively small co-seismic slip and a relatively larger post-seismic slip along the Chihshang Fault (Lee et al. 2006; Chang et al. 2009; Cheng et al. 2009; Hsu et al. 2009). For instance, the creep meters at the Chinyuan site exhibited less than 1 cm of co-seismic shortening during the main shock (Lee et al. 2006). The total displacements, including co-seismic and 4-month post-seismic displacements, obtained from measurements of the geodetic networks across the Chihshang Fault zone were 7 - 12 and 6 - 11 cm, for horizontal shortening and vertical offset respectively (Lee et al. 2006). Lee et al. (2006) and Chang et al. (2009) interpreted that the fault had undergone strongly elastic coupling or partial locking at shallow depths according to velocity-strengthening friction behavior, which impeded dynamic rupturing of the Chengkung earthquake from propagating up to the surface.

The deformation across the Longitudinal Valley and the Coastal Range, especially regarding its inter-seismic versus co-seismic components, was accommodated in a complex way (Fig. 3). Most of the accommodated shortening runs across the LVF with a small though non-negligible portion in the Coastal Range, the upthrust block of the LVF.

As a typical illustration, we found field evidence of active shortening near Tungho village (location in Fig. 1), close to the eastern coastline of the Coastal Range. We observed fractures that offset concrete retaining walls (Fig. 4) along the Cross Coastal Range Highway (No. 23). These fractures certainly existed before the Chengkung earthquake, having been observed for the first time in October 2001. They form small conjugate systems of reverse-fault type, clearly indicating compression approximately parallel to the road that trends N121°E. Geologically, these fractures are located in the hanging wall of the Tama fault (location in Fig. 1c), a 5-km-long thrust fault within the Coastal Range (Hsu 1956; Lo et al. 1993).

We have installed local networks of bolts on the side of the fractured wall in the site. Two WNW-trending networks (Networks A and B in Fig. 5) separated by a distance of a few tens of meters were established in 2001 to monitor the displacement of fractures. Three repeated measurements have been conducted since then: October 2001, February 2004 and September 2006. They showed that most of the displacements affecting the conjugate-like systems of fractures occurred between 2001 and 2004. The Tungho networks revealed a total shortening of at least about 15.5 mm from 2001 to 2006 (Table 1). The shortening recorded between 2004 and 2006 involved only a single fracture; and it was minor, approximately 2 mm. A larger total shortening, about 13.5 mm, occurred between October 2001 and February 2004.

In the absence of other major earthquakes between October 2001 and September 2006 save that of the Chengkung earthquake in December 2003, it is reasonable to say that most of the shortening must have been caused by the latter when it struck. The absence of strike-slip displacements on fractures indicates that the direction of shortening is close to

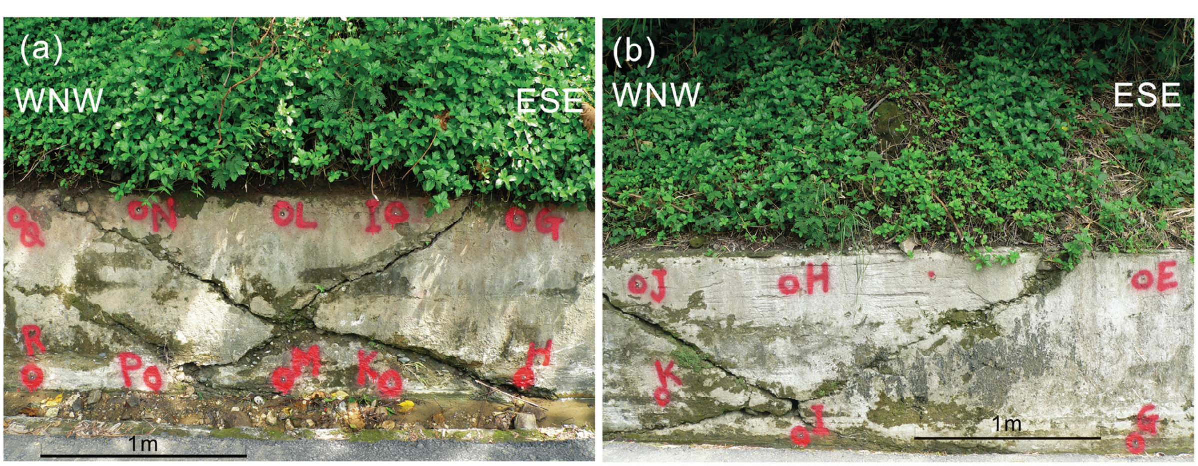

Fig. 4. Side view of the fractures of the Tungho network: (a) network A. (b) network B. Fractures show a conjugated type of faults on the retaining wall along the Road No. 23.

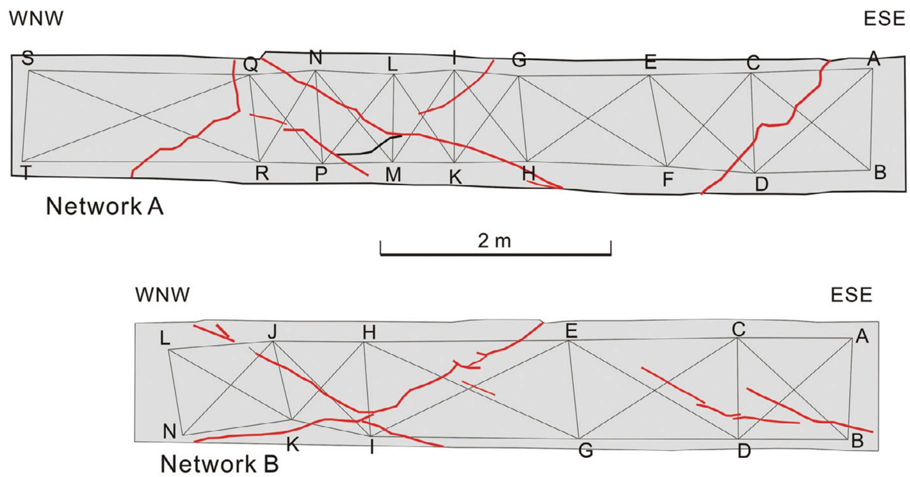

Fig. 5. Side view of the Tungho networks of nails. We have installed a network of bolts on the retaining wall in order to monitor the deformation and shortening on the wall. See results of measurements in the main text and Table 1.

Table 1. Shortening across fractures on the retaining wall recorded by the Tungho networks.

Date of measurement	Length of network A	Length of network B
October 2001	7364.5 mm	5919 mm
February 2004	7355 mm	5915 mm
Shortening	9.5 mm	4 mm
Date of measurement	**Length of network A**	**Length of network B**
February 2004	7355 mm	5915 mm
September 2006	7355 mm	5913 mm
Shortening	0 mm	2 mm

that of the trending of the networks, approximately N121°E. This direction agrees with the general trend of compression as indicated by the focal mechanisms of the Chengkung earthquake sequence.

The results above demonstrate that active shortening (inter-seismic or co-seismic) does not merely affect the Longitudinal Valley Fault, but also some pre-existing faults inside the Coastal Range (e.g., the Tama Fault for the Tungho case). Viewed from this perspective, the shortening of more than 1 cm recorded by the Tungho network, presumably caused mostly by the Chengkung earthquake, should be considered as significant.

4. ERUPTIONS AND FAULTING AT MUD VOLCANOES DURING THE CHENGKUNG EARTHQUAKE

A major aim of the study was to investigate the possible relationships between earthquakes and eruptions of mud volcanoes. In addition to our geological investigation in the two mud volcanoes in the vicinity of the Chihshang Fault, Luoshan and Leikunghuo, we conducted a systematic oral enquiry with local villagers soon after the Chengkung earthquake to identify the location, time and amplitude of eruptions with special reference to the earthquake. According to observations by nearby inhabitants, a large mud basin of the Luoshan Mud Volcano near the house numbered 52, Luoshan village (Fig. 6), erupted with water, gases and strong noise, accompanied by the main shock of Chengkung earthquake on 10 December 2003. The erupting muddy water, which reached more than 2 m in height, continued to spew out intermittently thereafter for about two days. Eventually, the flow stopped and the water drained. The quake also opened up a few cracks in a nearby countryside road.

The case of the Leikunghuo Mud Volcano differs. Because of the absence of inhabitants within a distance of 5 km, nobody witnessed the eruption, if any, at the time of the Chengkung earthquake. When we carried out field investigation two months later, in early February 2004, the surface of Leikunghuo Mud Volcano was dried out for over 90% of the area. Although no direct evidence of mud or water eruption could be identified, large fresh strike-slip faults, including right- and left-lateral ones, were observed, cutting through the mud shield (Fig. 7).

Later, on 19 June 2004, while visiting again this mud volcano, by happenstance, a large aftershock of magnitude $M_w = 4.5$ occurred at 10:53 am. We felt like standing on a water bed, wherein it contents we sloshing around when the shock struck; however, no water or mud spewed out immediately. According to the later seismic report of the Central Weather Bureau, the epicenter was located at the foot of the Central Range near Kuanshan, about 10 km west of the Leikunghuo Mud Volcano. This observation suggests that a likely liquefaction occurred at Leikunghuo during the earthquake, although the water beneath the mud volcano did not reach the surface to erupt. It is worth noting that the Leikunghuo Mud Volcano was relatively more quiescent for the last 15 years than before, without significant water or mud eruption. In contrast, about twenty years ago, one could observe frequent water eruptions at Leikunghuo, commonly reaching heights of one metre or more.

The Leikunghuo Mud Volcano area is about 150 m long and 50 m wide. A series of mud volcano shields, with about 80 erupting holes, align approximately in the direction of N165°E (NNW-SSE), sub-parallel to the local trend of the LVF. Fresh fractures, which probably developed during the Chengkung earthquake, revealed a seemingly conjugate system of strike-slip faults. We found a typical set of fractures with a N16°E-trending right-lateral fault (Fig. 8a) and another set of fractures revealing a N75 - 95°E trending left-lateral fault (Fig. 8b). This conjugate system is consistent with a transtensional stress regime indicating a NE-SW compression and NW-SE extension (Figs. 8c and d). The stress orientation does not reflect the usual seismotectonic orientation recorded in the Coastal Range and Longitudinal Valley, typically dominated by a WNW-ESE compression, and hence should be interpreted as a result of a local stress concentration rather than an expression of regional tectonic stress.

5. DISCUSSION AND CONCLUSION

Previously in eastern Taiwan, the ongoing shortening/compression in terms of active tectonics across the

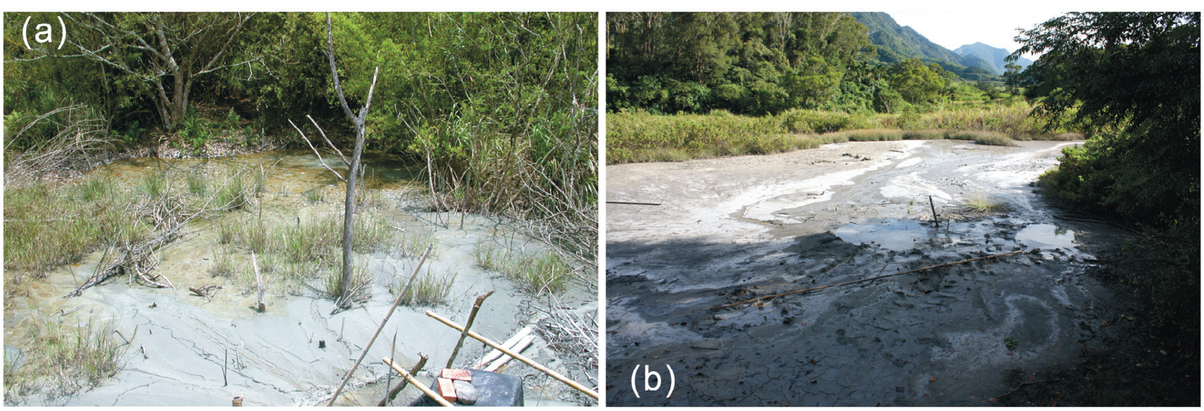

Fig. 6. Mud basin of Luoshan Mud Volcano near the house of Luoshan No. 52, Luoshan village. Waters and gases erupted with strong noise during the main shock of the Chengkung earthquake on 10 December 2003.

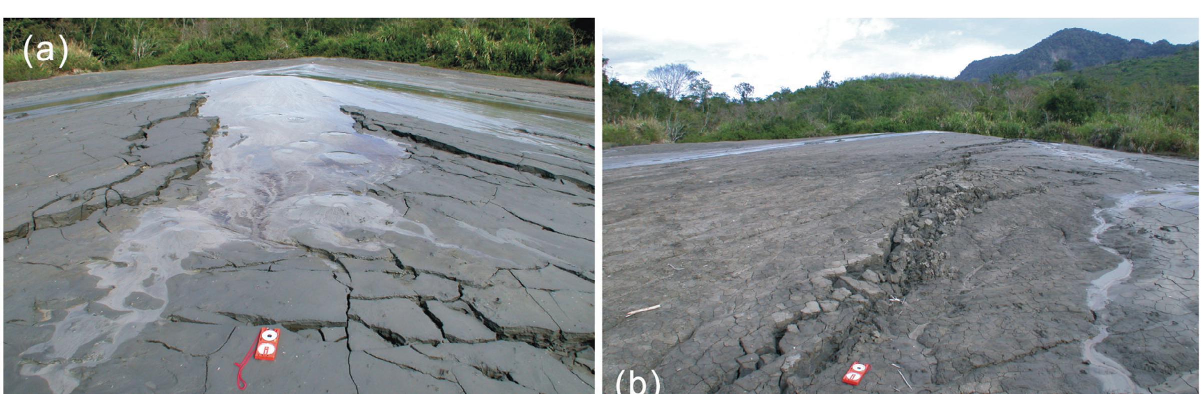

Fig. 7. (a) Mud shield in the Leikunghuo Mud Volcano area, where water erupted during the Chengkung earthquake, with a large number of fractures. (b) Obvious strike-slip faults cutting through the mud shield of the Leikunghuo mud volcano produced by the Chengkung earthquake.

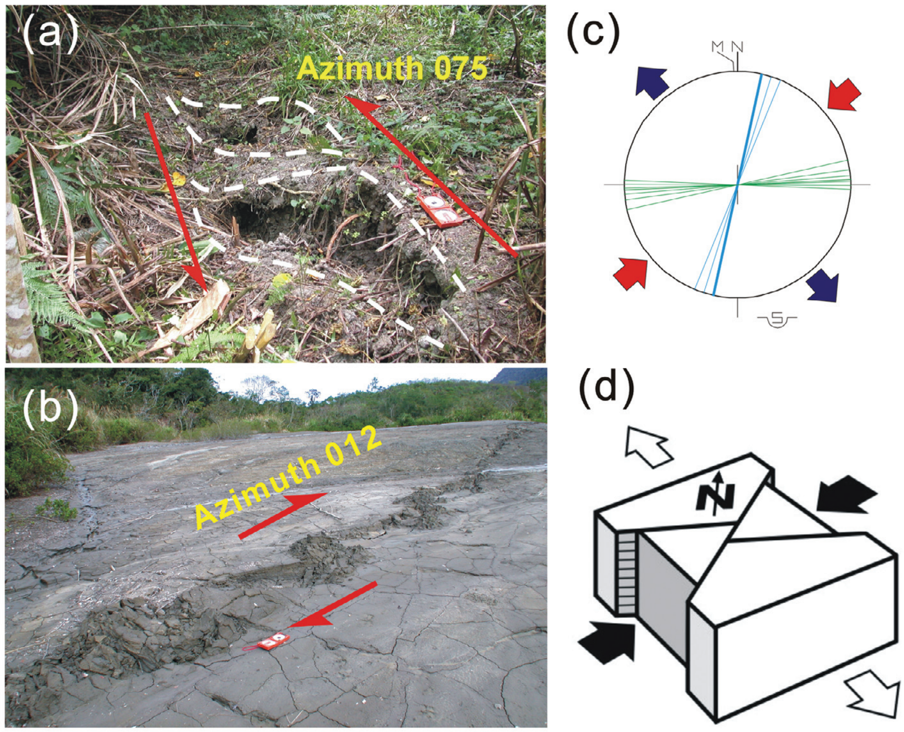

Fig. 8. Fracture analysis on the Leikunghuo Mud Volcano. (a) Left-lateral strike-slip fractures developing on Leikunghuo Mud Volcano during the Chengkung earthquake, December 2003, as shown by en-échelon open cracks. (b) Right-lateral strike-slip fractures, also shown by en-échelon cracks. (c) Fracture analysis in Stereonet. Two conjugated sets of fractures indicate a NE-trending compression and NW-trending extension. (d) Mechanical interpretation of strike-slip fractures that developed at Leikunghuo, December 2003. Right-lateral fractures strike N16°E, left-lateral over strike N75 - 95°E, indicating a NE-SW compressive stress (convergent arrows) and NW-SE minimum extensive stress (divergent arrows).

Longitudinal Valley and the Coastal Range has been well documented. A variety of geodetic and seismological studies supports the dominance of active ESE-WNW compression in the upper crust (Barrier and Angelier 1986; Yu et al. 1990; Yeh et al. 1991; Kao and Angelier 2001; Yu and Kuo 2001). Not only did the Chengkung earthquake sequence directly illustrate this aspect (Lee et al. 2006; Wu et al. 2006; Hu et al. 2007), it also revealed some complexity in block movement and lateral escape (Angelier et al. 1997; Chung et al. 2008).

Local studies of the Chihshang Fault revealed a rather stable shortening rate of 22 - 27 mm yr^{-1} during the period 1986 - 1999 (e.g., Angelier et al. 2000) followed by a decreasing creep rate from 22 to 14 mm yr^{-1} during the period 2000 - 2003 (Lee et al. 2005). After the 2003 Chengkung earthquake, which caused a small co-seismic slip and a larger post-seismic slip around the surface trace of the fault, the total co- and post-seismic displacements came to be 12 and 11 cm for the horizontal shortening and the vertical offset respectively, about four months later. To summarize, all available data indicated a strong concentration of convergence motion along the Chihshang Fault.

This general picture of the tectonic framework, however, needs some adjustment. Minor but significant shortening seemingly took place inside the Coastal Range. Observations near the Tama Fault revealed that active shortening of about 15.5 mm locally occurred near the eastern coast of the Coastal Range within five years, between October 2001 and September 2006 (section 3 and Fig. 5). This shows that ESE-WNW compression affects the upper crust of the Coastal Range of the Philippine Sea plate and produces significant shortening in addition to that of the major thrust, the Chihshang Fault. Therefore, despite the primary importance of shortening across the Longitudinal Valley a better understanding of the internal deformation of the Coastal Range is an important target for future studies, especially across three mapped geological faults: the Yungfeng Fault, Tuluanshan Fault and Tama Fault (Fig. 1).

Our investigation at mud volcanoes also showed that the volcano eruptions are a direct consequence of compression during earthquakes. Systematic enquiry with local villagers and field investigation indicated that strong eruptions with water, gases and noise occurred in the Luoshan Mud Volcano. Furthermore, field study in and around mud volcanoes revealed that conjugate system of right- and left-lateral strike-slip faults developed at the surface of Leikunghuo Mud Volcano after the Chengkung earthquake. Additional observations, such as crack formation in a road near Luoshan or the response of the Leikunghuo Mud Volcano to an earthquake of magnitude $M_w = 4.5$ on 19 June 2004, confirmed that these mud volcanoes and their surroundings may react strongly to earthquakes, presumably due to increasing water and gas pressure in underground conduits (e.g., the Luoshan eruption on 10 December 2003) and possible local liquefaction (e.g., at Leikunghuo on 19 June 2004). However, any conclusion in terms of direction of compression should be considered with caution, as the stress generated seems highly influenced by fluid behavior and local sediment response, rather than being a simple expression of surrounding crustal stress.

Specifically, significant differences in mud volcano behavior exist, such as the probable absence of significant eruption of the Leikunghuo volcano during the Chengkung earthquake. This difference may be accounted for by underground water status. In the case of the Luoshan Mud Volcano the upper sedimentary section was locally saturated with water because of the presence of the neighbouring water-rich Yen-Cheng River. In contrast, the Muken River near the Leikunghuo Mud Volcano was often water-deficient and could not supply abundant groundwater for eruption. However, both the fracture development related to the 10 December 2003 Chengkung earthquake and the liquefaction phenomenon during the 19 June 2004 major aftershock concur to reveal high sensitivity of the Leikunghuo Mud Volcano to earthquakes, even though eruptions did not occur probably because of an insufficient water supply.

A problem remains regarding the mechanism of local faulting observed at Leikunghuo. The compression indicated by the fractures in the mud shield of the volcano trends surprisingly NE-SW, perpendicular to that commonly observed in the Coastal Range as a result of NW-SE convergence between the Philippine Sea plate and the Central Range of Taiwan. In other words, the stress pattern reconstructed from these local strike-slip fractures is nearly opposite to that commonly observed in the Coastal Range, through a permutation between principal stress axes, σ_1 (maximum, compressive stress) and σ_3 (minimum, extensive stress). Although local fractures are not numerous, their sense of relative displacement is certain. We infer that this compression reflects local co-seismically induced perturbation of seismotectonic stress in the mud volcano area, with permutation between maximum and minimum stress. Such faults were not observed outside of the mud shield area, thus supporting this hypothesis. In fact, large numbers of minor faults have been observed inside the Coastal Range (Barrier and Angelier 1986), and they were found clearly compatible with the WNW-ESE compression that results from the ongoing plate convergence. Stress permutations have also been documented elsewhere in the world from geological and mechanical analyses (Angelier and Bergerat 1983; Hu and Angelier 2004). Although the mechanism of stress permutation still remains unknown at the Leikunghuo site, this contrast suggests that the local fault system that we observed in this mud volcano area results from such a phenomenon and should not be interpreted as a direct expression of regional tectonism. Thus the most important conclusions of our studies deal with (1) the presence of significant active shortening inside the Coastal Range, as documented by our measurements across the Tama Fault near Tungho, and (2) the behavior of mud volcanoes while studying active co-seismic deformation. Thus earthquake can affect faulting and mud volcanoes at distances far away from the main shock; directly, as documented at Luoshan by water and gas eruption during the 10 December 2003 Chengkung earthquake and, indirectly, at Leikunghuo by the phenomena of fracturing during the Chengkung earthquake, and liquefaction during the 19 June 2004 major aftershock.

Acknowledgements This paper resulted from a continuing Franco-Taiwanese collaboration in Earth Sciences. It is funded by National Science Council of Taiwan (grants NSC95-2811-M-001-056, NSC100-2116-M-001-004) and the French Institute in Taipei, French Centre National de la Recherche Scientifique and the International Laboratory (LIA), ADEPT (Active Deformation and Environment Programme for Taiwan). The second author's research was also supported by the Institut Universitaire de France. This is a contribution of the Institute of Earth Sciences, Academia Sinica, IESAS-1549.

REFERENCES

Angelier, J., 1986: Geodynamics of the Eurasia-Philippine Sea Plate boundary: Preface. *Tectonophysics*, **125**, 9-10.

Angelier, J. and F. Bergerat, 1983: Systèmes de contrainte en extension intracontinentale. *Bull. Centr. Rech. Expl. Prod. Elf-Aquitaine*, **7**, 137-147.

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]

Angelier, J., H. T. Chu, J. C. Lee, and J. C. Hu, 2000: Active faulting and earthquake risk: The Chihshang Fault case, Taiwan. *J. Geodyn.*, **29**, 151-185.

Barrier, E. and H. T. Chu, 1984: Field trip guide to the Longitudinal Valley and the Coastal Range in eastern Taiwan. Sino-French colloquium.

Barrier, E. and J. Angelier, 1986: Active collision in eastern Taiwan: The Coastal Range. *Tectonophysics*, **125**, 39-72, doi: 10.1016/0040-1951(86)90006-5. [Link]

Barrier, E., J. Angelier, H. T. Chu, and L. S. Teng, 1982: Tectonic analysis of compressional structure in an active collision zone: The deformation of the Pinanshan Conglomerates, eastern Taiwan. *Proc. Geol. Soc. China*, **25**, 123-138.

Bonilla, M. G., 1975: A review of recently active faults in Taiwan. US Geological Survey Open-File Report, 75-41, 72.

Chang, C. P., J. Angelier, and C. Y. Huang, 2000: Origin and evolution of a mélange: The active plate boundary and suture zone of the Longitudinal Valley, Taiwan. *Tectonophysics*, **325**, 43-62, doi: 10.1016/S0040-1951(00)00130-X. [Link]

Chang, S. H., W. H. Wang, and J. C. Lee, 2009: Modelling temporal variation of surface creep on the Chihshang fault in eastern Taiwan with velocity-strengthening friction. *Geophys. J. Int.*, **176**, 601-613, doi: 10.1111/j.1365-246X.2008.03995.x. [Link]

Chao, H. C., 2003: Chemical Compositions of the Mud Volcano Gases on land in Taiwan: Possible Impact on Global Methane Sources, Master Thesis, National Chengkung University, Tainan, 81 pp. (in Chinese)

Chen, H. Y., S. B. Yu, L. C. Kuo, and C. C. Liu, 2006: Coseismic and postseismic surface displacements of the 10 December 2003 (M_w 6.5) Chengkung, eastern Taiwan, earthquake. *Earth Planets Space*, **58**, 5-21.

Cheng, L. W., J. C. Lee, J. C. Hu, and H. Y. Chen, 2009: Coseismic and postseismic slip distribution of the 2003 M_w = 6.5 Chengkung Earthquake in eastern Taiwan: elastic modeling from inversion of GPS data. *Tectonophysics*, **466**, 335-343, doi: 10.1016/j.tecto.2007.11.021. [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.

Chi, W. R., H. M. Huang, and J. C. Wu, 1983: Ages of the Milun and Pinanshan Conglomerates and their bearing on the Quaternary movement of eastern Taiwan. *Proc. Geol. Soc. China*, **26**, 67-75.

Ching, K. E., R. J. Rau, J. C. Lee, and J. C. Hu, 2007: Contemporary deformation of tectonic escape in SW Taiwan from GPS observations, 1995 - 2005. *Earth Planet. Sci. Lett.*, **262**, 601-619, doi: 10.1016/j.epsl.2007.08.017. [Link]

Chung, L. H., Y. G. Chen, Y. M. Wu, J. B. H. Shyu, Y. T. Kuo, and Y. N. N. Lin, 2008: Seismogenic faults along the major suture of the plate boundary deduced by dislocation modeling of coseismic displacements of the 1951 M7.3 Hualien - Taitung earthquake sequence in eastern Taiwan. *Earth Planet. Sci. Lett.*, **269**, 416-426, doi: 10.1016/j.epsl.2008.02.035. [Link]

Ho, C. S., 1986: A Synthesis of the geologic evolution of Taiwan. *Tectonophysics*, **125**, 1-16, doi: 10.1016/0040-1951(86)90004-1. [Link]

Ho, C. S., 1988: An Introduction to the Geology of Taiwan: Explanatory Text of the Geologic Map of Taiwan, 2nd Edition, Central Geological Survey, Ministry of Economic Affairs, Taipei, Taiwan, 192 pp.

Hsieh, J. C., H. W. Chen, G. J. Jiang, S. F. Liao, and H. T. Tung, 1993: The Investigation of Natural Resources and Landscape on Leikunghuo Mud Volcano, Taitung County, Tien-Kuang Elementary School, 70 pp. (in Chinese)

Hsieh, J. C., H. W. Chen, G. J. Jiang, S. F. Liao, H. T. Tung, and S. H. Chang, 1994: The Investigation of Natural Resources and Landscape on Luoshan Mud Volcano, Hualien County, Tien-Kuang Elementary School, 77 pp. (in Chinese)

Hsieh, P. S., 2000: The Gas Sources of Hot Springs and Mud Volcanoes in Taiwan, Master Thesis of National Taiwan University, Taipei, Taiwan, 77 pp. (in Chinese)

Hsu, T. L., 1956: Geology of the Coastal Range, eastern Taiwan. *Bull. Geol. Surv. Taiwan*, **9**, 39-64.

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

Hsu, Y. J., S. B. Yu, and H. Y. Chen, 2009: Coseismic and postseismic deformation associated with the 2003 Chengkung, Taiwan, earthquake. *Geophys. J. Int.*, **176**, 420-430, doi: 10.1111/j.1365-246X.2008.04009.x. [Link]

Hu, J. C. and J. Angelier, 2004: Stress permutations: Three-dimensional distinct element analysis accounts for a common phenomenon in brittle tectonics. *J. Geophys. Res.*, **109**, B09403, doi: 10.1029/2003JB002616. [Link]

Hu, J. C., L. W. Cheng, H. Y. Chen, Y. M. Wu, J. C. Lee, Y. G. Chen, K. C. Lin, R. J. Rau, H. Kuochen, H. H. Chen, S. B. Yu, and J. Angelier, 2007: Coseismic deformation revealed by inversion of strong motion and GPS data: The 2003 Chengkung earthquake in eastern Taiwan. *Geophys. J. Int.*, **169**, 667-674, doi: 10.1111/j.1365-246X.2007.03359.x. [Link]

Kao, H. and J. Angelier, 2001: Stress tensor inversion for the Chi-Chi earthquake sequence and its implications on regional collision. *Bull. Seismol. Soc. Am.*, **91**, 1028-1040, doi: 10.1785/0120000739. [Link]

Kuochen, H., Y. M. Wu, Y. G. Chen, and R. Y. Chen, 2007: 2003 M_w 6.8 Chengkung earthquake and its related seismogenic structures. *J. Asian Earth Sci.*, **31**, 332-339, doi: 10.1016/j.jseaes.2006.07.028. [Link]

Lee, J. C., 1994: Structure et déformation active d'un orogène: Taiwan. Ph.D. Dissertation, Université Pierre et Marie Curie, Paris, 281 pp.

Lee, J. C. and J. Angelier, 1993: Location of active deformation and geodetic data analyses: An example of the Longitudinal Valley Fault, Taiwan. *Bull. Soc. Geol. France*, **164**, 533-570.

Lee, J. C., J. Angelier, H. T. Chu, S. B. Yu, and J. C. Hu, 1998: Plate-boundary strain partitioning along the sinistral collision suture of the Philippine and Eurasian plates: Analysis of geodetic data and geological observation in southeastern Taiwan. *Tectonics*, **17**, 859-871, doi: 10.1029/98TC02205. [Link]

Lee, J. C., J. Angelier, H. T. Chu, J. C. Hu, F. S. Jeng, and R. J. Rau, 2003: Active fault creep variations at Chihshang, Taiwan, revealed by creep meter monitoring, 1998-2001. *J. Geophys. Res.*, **108**, 2528, doi: 10.1029/2003JB002394. [Link]

Lee, J. C., J. Angelier, H. T. Chu, J. C. Hu, and F. S. Jeng, 2005: Monitoring active fault creep as a tool in seismic hazard mitigation. Insights from creepmeter study at Chihshang, Taiwan. *C. R. Geosci.*, **337**, 1200-1207, doi: 10.1016/j.crte.2005.04.018. [Link]

Lee, J. C., H. T. Chu, J. Angelier, J. C. Hu, H. Y. Chen, and S. B. Yu, 2006: Quantitative analysis of surface coseismic faulting and postseismic creep accompanying the 2003, M_w = 6.5, Chengkung earthquake in eastern Taiwan. *J. Geophys. Res.*, **111**, B02405, doi: 10.1029/2005JB003612. [Link]

Lo, H. J., W. S. Chen, and S. R. Song, 1993: Explanatory text of the geological map of Taiwan, scale 1:50000, sheet: Chengkung and Tungho, Central Geological Survey.

Seno, T., 1977: The instantaneous rotation vector of the Philippine Sea plate relative to the Eurasian plate. *Tectonophysics*, **42**, 209-226, doi: 10.1016/0040-1951(77)90168-8. [Link]

Seno, T., S. Maruyama, and R. Stein, 1987: Redetermination of the Philippine Sea plate relative to the Eurasian plate motion. *Eos, Trans., AGU*, **68**, 1474.

Shih, T. T., 1967: A survey of the active mud volcanoes in Taiwan and study of their types and the character of the mud. *Petrol. Geol. Taiwan*, **5**, 259-311.

Suppe, J., 1981: Mechanics of mountain building in Taiwan. *Mem. Geol. Soc. China*, **4**, 67-89.

Suppe, J. and J. G. Liou, 1979: Tectonics of the Lichi Mélange and East Taiwan ophiolite. *Mem. Geol. Soc. China*, **3**, 147-153.

Teng, L. S. and Y. Wang, 1981: Island arc system of the Coastal Range, eastern Taiwan. *Proc. Geol. Soc. China*, **24**, 99-112.

Wu, Y. M., Y. G. Chen, T. C. Shin, H. Kuochen, C. S. Hou, J. C. Hu, C. H. Chang, C. F. Wu, and T. L. Teng., 2006: Coseismic versus interseismic ground deformations, fault rupture inversion and segmentation revealed by 2003 M_w 6.8 Chengkung earthquake in eastern Taiwan. *Geophys. Res. Lett.*, **33**, L02312, doi: 10.1029/2005GL024711. [Link]

Yeh, Y. H., E. Barrier, C. H. Lin, and J. Angelier, 1991: Stress tensor analysis in the Taiwan area from focal mechanisms of earthquakes. *Tectonophysics*, **200**, 267-280, doi: 10.1016/0040-1951(91)90019-O. [Link]

Yu, S. B. and C. C. Liu, 1989: Fault creep on the central segment of the longitudinal valley fault, eastern Taiwan. *Proc. Geol. Soc. China*, **32**, 209-231.

Yu, S. B. and L. C. Kuo, 2001: Present-day crustal motion along the Longitudinal Valley Fault, eastern Taiwan. *Tectonophysics*, **333**, 199-217, doi: 10.1016/S0040-1951(00)00275-4. [Link]

Yu, S. B., D. D. Jackson, G. K. Yu, and C. C. Liu, 1990: Dislocation model for crustal deformation in the Longitudinal Valley area, Eastern Taiwan. *Tectonophysics*, **183**, 97-109, doi: 10.1016/0040-1951(90)90190-J. [Link]

Yu, S. B., H. Y. Chen, and L. C. Kuo, 1997: Velocity field of GPS stations in the Taiwan area. *Tectonophysics*, **274**, 41-59, doi: 10.1016/S0040-1951(96)00297-1. [Link]