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# Is the Lishan fault of Taiwan active?

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ABSTRACT

The Lishan fault has been characterized alternately as a major discontinuity in stratigraphy, structures and metamorphism, a ductile shear zone, a tectonic suture or non-existent. In addition to being a geological boundary, it also marks transitions in subsurface structures. Thus, the seismicity to the west of the fault permeates through the upper and mid-crust while beneath the Central Range it is noticeably less and largely concentrated in the upper 12 km. A prominent west-dipping conductive zone extends upward to meet the Lishan fault. Also, the eastward increase of crust thickness from ~30 km in the Taiwan Strait quickens under the Lishan fault to form a root of over 50 km under the Central Range. In the past, the small magnitude seismicity along the Lishan fault has been noticed but is too diffuse for definitive association with the fault. Recent processing of aftershock records of the 1999 Mw 7.6 Chi-Chi earthquake using Central Weather Bureau data and, especially, data from three post-Chi-Chi deployments of seismic stations across central Taiwan yielded hypocenters that appear to link directly to the Lishan structure. The presence of a near 4-km-long vertical seismic zone directly under the surface trace of the Lishan fault indicates that it is an active structure from the surface down to about 35 km, and the variety of focal mechanisms indicates that the fault motion can be complex and depth-dependent.


## 1. Introduction

The Lishan fault of Taiwan as described in Tsan (1971) and Biq (1971) is the eastern boundary of the Hsuehshan Range and follows a topographically prominent valley that runs from the western apex of the Ilan Plain to central Taiwan for a distance of about 200 km (Fig. 1a). The fault was interpreted as an oblique left-lateral shear zone (Biq, 1971) and a major structural and stratigraphic boundary (Ho, 1975; Tsan, 1971) that separates two of the main mountain ranges in northern Taiwan, the Hsuehshan and the Backbone Ranges (Fig. 1a). Teng et al. (1991), Lee et al. (1997) and Brown et al. (2012) tied it to Paleogene normal faulting on the continental margin that subsequently was inverted after the collision of the Eurasian and Philippine Sea plates began. But Lu and Hsu (1992) and Huang et al. (1997) interpreted it to be a suture between the continental margin and the late-Miocene accretionary prism. Field evidence led Lee et al. (1997) to argue that reverse sinistral high-angle fault slips took place during late Cenozoic era, with extension at the northeastern end of the fault owing to the opening of the Okinawa Trough. Brown et al. (2012) viewed the fault as the backstop for the detachment below the fold-and-thrust belt of western Taiwan. Brown et al. (2012) emphasized the presence of ductile nature of the fault. However, lack of observable displacement in schistose strata across the presumed fault led to its deletion in the current Geologic Map of Taiwan (Chen et al., 2000).

As the subsurface information gathered, the Lishan fault zone has been noticed as a clear but rather diffuse boundary (Bertrand et al., 2009, 2012; Wu, 1978; Wu et al., 2004). For example, seismicity disseminates through the mid-crust west of a west-dipping, high conductivity zone beneath the fault (Bertrand et al., 2009, 2012) (Fig. 1b and d), where this zone is also in the vicinity where the lower crust of the seismic velocity structures (6.5–7.5 km/s) transits from gentle flexure to its west to significant thickening under the high ranges to the east (e.g., Kuo-Chen et al., 2012; Wu et al., 2014) (Fig. 1c).

The Lishan fault may or may not lead to major seismic hazards, but the ample seismicity in its vicinity can be used to assess whether the Lishan fault is active and what is the possible fault kinematics. In this paper, we combine data from CWB with data acquired during three deployments by the Earthquake Research Institute (ERI), University of Tokyo, in 1999, 2001 and 2005 across central Taiwan after the 1999 Chi-Chi earthquake (Fig. 1a). In particular, stations in the dense linear array of 2001 provided data to locate precisely a cluster of events near the Lishan fault. These new results prompted us to reexamine previously determined seismicity and focal mechanisms and sketch out a consistent vertically contiguous zone of activity. The different kinematics at different depth however depicts a relatively complex mode of deformation along the Lishan boundary.

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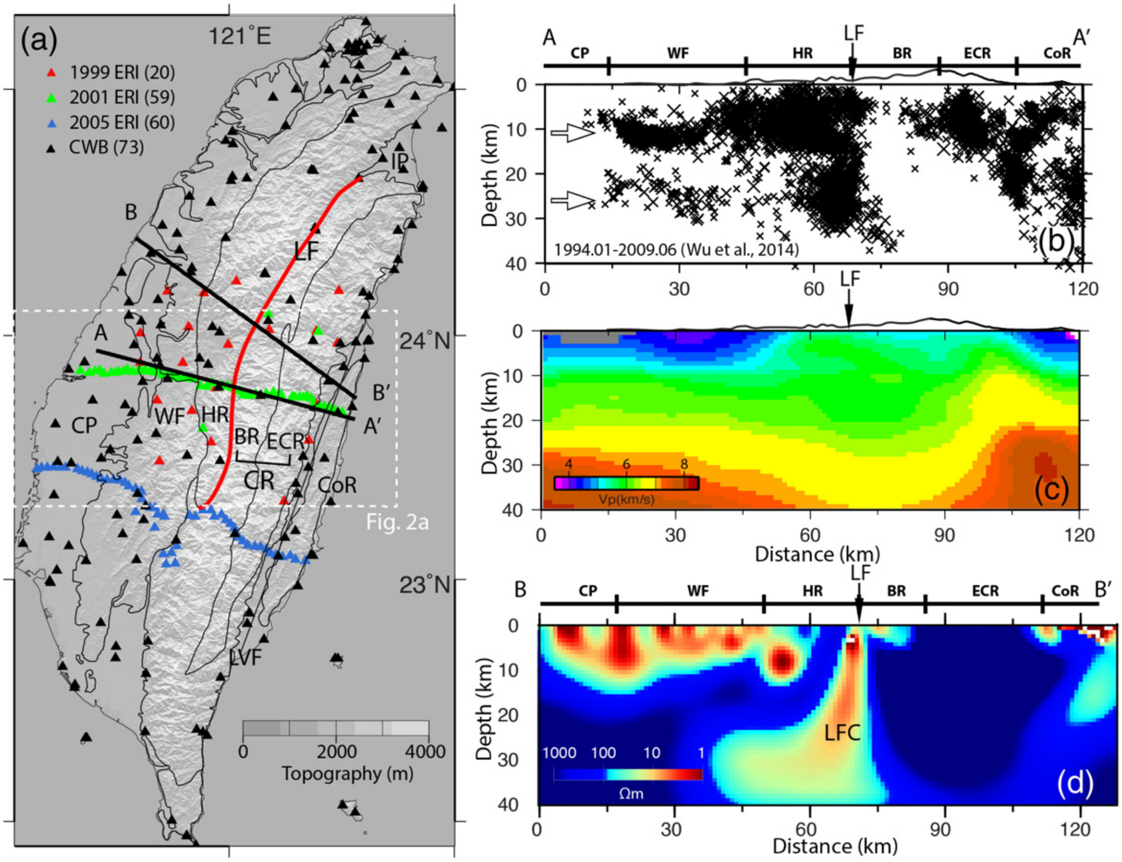


**Fig. 1.** (a) Geological provinces of Taiwan and the seismic networks of CWB (Central Weather Bureau) and ERI (Earth Research Institute of Tokyo University). IP: Ilan Plain, CP: Coastal Plain, WF: Western Foothills, HR: Hsuehshan Range, BR: Backbone Range (Western Central Range), ECR: Eastern Central Range, CoR: Costal Range. LF: Lishan fault, LVF: Longitudinal Valley Fault. White-dashed rectangular area: the study region. (b) Seismicity profile A–A′ after hypoDD relocation in central Taiwan from Wu et al. (2014). Two horizontal white arrows: double-layered seismicity. (c) Seismic Vp profile A–A′ from Kuo-Chen et al. (2012). (d) Resistivity profile B–B′ from Bertrand et al. (2009).

## 2. Tectonic framework of central Taiwan

In this section, we briefly describe the key geologic elements relevant to our ensuing discussion of the Lishan fault. The main geologic/tectonic units of Taiwan are shown in Fig. 1a and its captions. The Lishan fault is bounded on the east by the Miocene slaty rocks of the Backbone Range, the Lushan formation, and the Eocene–Oligocene rocks of higher metamorphic grade of the Hsuehshan Range on the west side. Field evidence shows that the Lushan formation is relatively thin (a few kilometers) and below it lies the Pre-Tertiary Taroko formation, with schists and other metamorphic rocks (Lee et al., 1997; Brown et al., 2012).

Near the surface, rocks in the Hsuehshan Range are recognized as composed of Eocene–Oligocene continental shelf sediments, whereas on the Backbone Range side Miocene pelitic sediments are found (Lee et al., 1997; Lin et al., 2003) and the rocks of the Taroko formation in the Eastern Central Range are pre-Mesozoic in age and likely to have been rooted in the lower crust (Jahn et al., 1976). The Lishan fault may have its origin as a normal fault when the Eurasian margin underwent extension, and had inverted subsequently (Brown et al., 2012; Lester et al., 2012) and contributed to the overall uplift of the Central Range.

## 3. Seismicity and focal mechanisms associated with the Lishan fault

### *3.1. Combined ERI and CWB data*

The 1999 Chi-Chi earthquakes produced an extensive series of aftershocks. The CWB seismic networks cover the period before and after the earthquake. In addition, one month after the mainshock, ERI deployed 20 temporary seismic stations in central Taiwan to record aftershocks for three months (October to December). Then in 2001 (March to May) and 2005 (March to April), two east–west trended linear arrays of 59 and 60 stations, respectively, were installed across central and southern Taiwan (Fig. 1a), primarily to explore crustal structures. We picked 19,172 P-wave first arrivals from the ERI data and used an additional 22,813 arrivals from the Central Weather Bureau (CWB) catalog to locate a total of 972 earthquakes. Benefited by the dense stations in the temporary seismic array, we were able to obtain as many as 27 arrivals for the smallest earthquake ($M_L$ 1.2). The initial hypocenters, based on the 1D velocity model of Chen (1995), were relocated using hypoDD (Waldhauser and Ellsworth, 2000) in order to enhance clustering.

The results of the hypoDD location show several previously recognized earthquake clusters (Fig. 2a and b) (e.g., Kao and Chen, 2000 and Wu et al., 2004). However, a new narrow, steeply dipping zone of seismicity near the Lishan fault is found amid several known clusters (Fig. 2a–c). This zone of 114 events was recorded in 2001, dipping steeply to the west within a depth range of 0–14 km (Fig. 2b). The epicenters form a narrow, ~4 km-long NW trending band intersecting with the mapped fault trace (Fig. 2c).

The combined 2001 ERI and CWB data enable us to determine the focal mechanisms of two of the largest earthquakes in 2001, with $M_L$ of 3.5 and 3.0, using P-wave polarities and the FOCMEC code (Snoke et al., 1984). Both solutions are well constrained and show similar left-lateral strike-slip motion (the average parameters are: Strike: 143°, Dip: 76°, Rake: −11°) (Fig. 2c and d).

### *3.2. Seismicity along Lishan fault based on 1994–2009 CWB catalog*

With average station spacing on the order of 20 to 30 km, the upgraded CWB network seismicity had been studied by Wu et al.