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Tomographic imaging of a seismic cluster in northern Taiwan and its implications for crustal fluid migration

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ABSTRACT

After the occurrence of the 1999 magnitude 7.3 Chi–Chi earthquake, a cluster of NE-SW trending earthquakes, almost distributed along the surface trace of the Lishan fault, has been detected in northern Taiwan. From the spatiotemporal distribution of hypocenters based on cluster analysis, the Lishan Fault cluster (LFC) can quantify the influence of crustal fluids on the occurrence of seismicity after the 1999 Chi–Chi earthquake. In order to investigate the possible causes of the seismicity clusters and their relationship to the movement of fluids through part of the collision/subduction system, high-resolution 3-D tomographic images of the crust are determined under the entire region of northern Taiwan by inverting a large number of arrival time data of P-waves and S-waves. The results of seismic tomographic inversion indicate that the LFC extends down to about 10 km depth and seems to be distributed in or around the low Vp, high Vp/Vs zones. This temporal expansion of the focal area during the first week may be attributed to fluid diffusion. The b-value of the LFC is about 0.98 close to the average value, 1.0 of the entire Taiwan region. Our tomographic images demonstrate a series of relatively high Vp/Vs anomalies dipping to the east which seems to form a fluid upwelling conduit beneath the Central Range. We thus suggest that the Lishan Fault might play a role of an active fluid conduit, transferring additional fluids of the Philippines Sea plate along the east-dipping fault zone into the upper crust.

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1. Introduction

Earthquakes generate stress perturbations that can promote subsequent events and trigger aftershocks. Earthquakes generally involve a variety of coseismic and post seismic responses, in which stress changes and triggered aftershocks can provide insight into Earth's internal fluid migration or aseismic slip (e.g., Lohman and McGuire, 2007; Chen et al., 2012). The increase in fluid pressure will reduce the effective normal stress, effectively weakening the fault and shear strength to a level below the prevailing shear stress (Sibson, 1991). Therefore, earthquakes may be correlated to pore pressure diffusion and stress transfer (Byerlee, 1978; Byerlee, 1990; Rice, 1992; Hainzl, 2004; Miller et al., 2004; Cappa et al., 2009; Okada et al., 2015) that may reduce crustal strength and promote earthquakes (Roeloffs, 2000; Sibson, 2013).

On 21 September 1999, a Mw = 7.6 magnitude earthquake occurred in the western foothills of central Taiwan, near the small town of Chi–Chi (120.89°E/23.82°N, depth of 8–10 km) (Ma et al., 1999) and produced a complex surface rupture extending over 80 km. The focal mechanism and fault ruptures indicate thrusting on a fault striking N-S roughly parallel to the mountain belt (Kao and Chen, 2000). Coseismic surface deformation and significant change in shallow seismic activity in the crust around the source area are also reported (Ma et al., 1999; Wang, 2000; Dominguez et al., 2003; Yu et al., 2003; Hsu et al., 2009; Rousset et al., 2012). Hsu et al. (2007) suggested that post-seismic GPS displacements inversion using cumulative displacements 15 months after the main shock concentrates afterslip close to the epicenter, with a maximum slip of 0.7 m.

Fig. 1 shows the change of seismicity of four periods: period before [(1991–1999), (1991–1998)] and after [(1999–2012), (2005–2012)] the Chi–Chi earthquake. Most of the earthquake clusters were activated after the Chi–Chi earthquake, especially the Lishan Fault cluster (Fig. 2). Those events seem to cluster in a NE-SW trend and along a horizontal interface. Most of the events with depth shallower than 15 km seems to distributed in a narrow zone. Fig. 2b shows that events of the Lishan Fault cluster clustered in only one week, with magniture smaller than $M_L < 3.0$. Time history of Lishan Fault cluster shows that it is composed of earthquake swarms rather than mainshock-aftershock sequences. Wang (2000) shows

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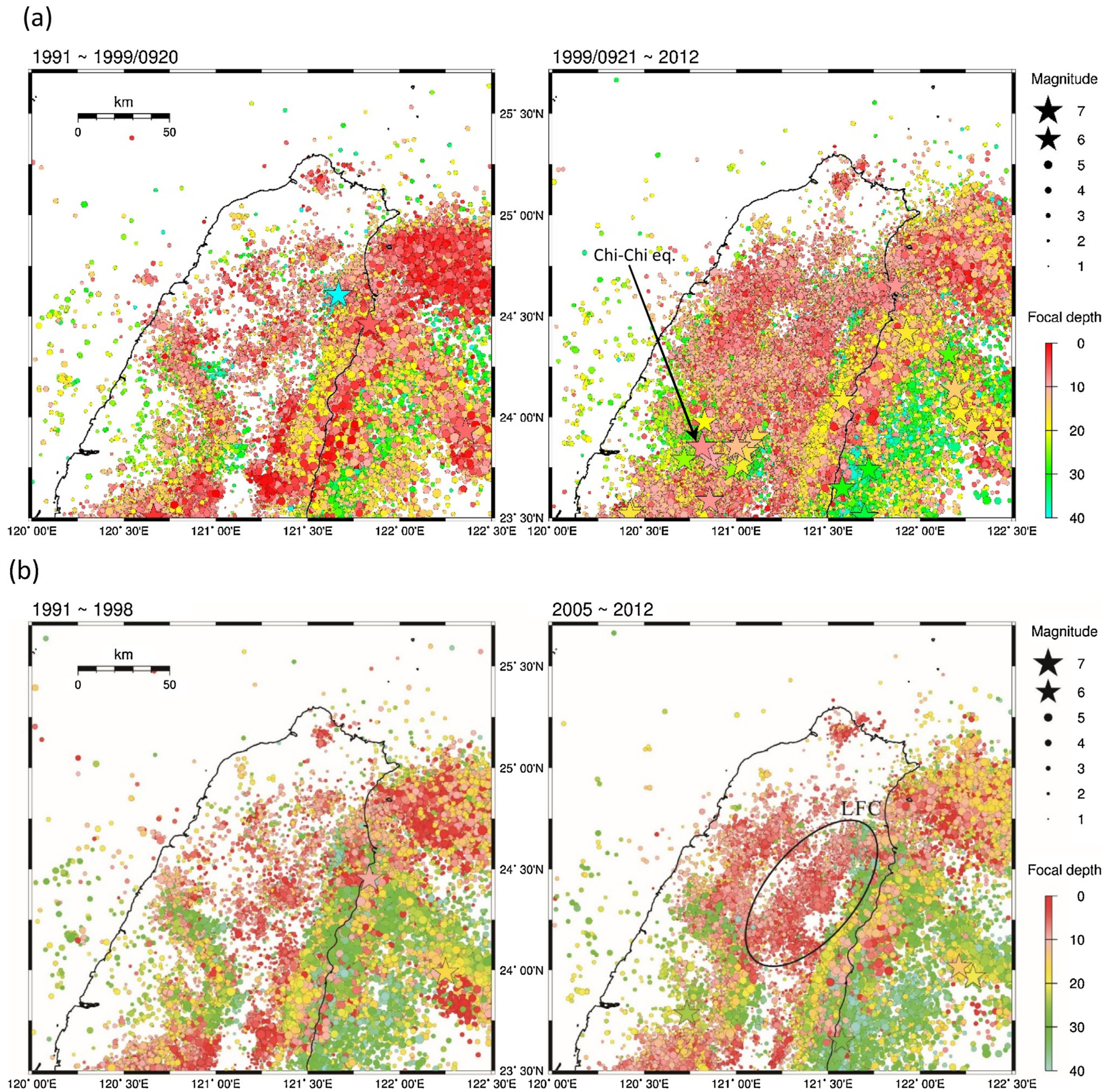

Fig. 1. Map showing seismicity of the northern Taiwan of four periods: (a) period before [(1991–1999), (1991–1998)] and (b) after [(1999–2012), (2005–2012)] the Chi–Chi earthquake based on earthquake data recorded by the Central Weather Bureau Seismic Network. Pink star represent the epicenter of Chi–Chi earthquake. Earthquake epicenters are color-coded by depth intervals shown on right. LFC: Lishan fault cluster. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that the static stress field changed because of the large slip caused by the Chi–Chi earthquake. However, some of the earthquakes in northern Taiwan have focal mechanisms that do not correspond to the stress change by the Chi–Chi earthquake. We know that pore-fluid pressure is another factor that controls the occurrence of earthquakes (Sammonds et al., 1992; Beeler et al., 2000; Miller et al., 2004; Okada et al., 2011). In particular, hypocenter migration can be attributed to the fluid diffusion process (Shapiro et al., 1997; Yukutake et al., 2011; Chen et al., 2012; Hardebeck 2012; Okada et al., 2015). Several regional seismic tomographic models have been proposed for the Taiwan area (Rau and Wu, 1995; Ma et al., 1996; Lallemand et al., 2001; Kim et al., 2005; Wu et al., 2009a,b; Kuo-Chen et al., 2012) and for northern Taiwan (Lin et al., 2004, 2015). However, most of the studies were focussed on regional plate tectonic and orogenic activities based on seismic velocity structure. In this study, we will consider some possible evidence of the influence of crustal fluid/water on the occurrence of the triggered seismicity after the Chi–Chi earthquake. We use tomographic models of Vp and Vp/Vs to examine possible causes of the seismicity clusters and their relationship to the movement of fluids through part of the collision/subduction system.

2. Tectonic setting

Taiwan is the result of active, an oblique collision between the Eurasian and the Philippine Sea plates. The Philippine Sea plate moves in the northwest direction and subducts beneath Eurasia along the Ryukyu Trench, but flips subduction polarity and over-

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