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Coseismic thickness of principal slip zone from the Taiwan Chelungpu fault Drilling Project-A (TCDP-A) and correlated fracture energy

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ABSTRACT

Direct observations of the physical structures of the seismogenic zones of active faults are rare, due to the difficulty in reaching the fault zone at depth. Current geological evidences, mostly from the surface, suggest that principal slip zone (PSZ) accommodated most shear displacement and was the place where physico-chemical processes occurred during an individual coseismic event and the thickness of PSZ is a few millimeter to tens of centimeter wide. However, the actual thickness of PSZ of a large earthquake, a key parameter of seismology in understanding energy dissipation and rupture processes, remains largely unknown. The Chelungpu fault that ruptured during the 1999 Mw 7.6 Chi-Chi earthquake (Taiwan) was drilled to a depth of 2003 m providing a unique opportunity to sample an active fault that slipped in a recent large earthquake. The PSZ, corresponding to the 1999 Chi-Chi earthquake, was well characterized within cores at a borehole depth of 1111 m from the Taiwan Chelungpu fault Drilling Project-A (TCDP-A). Here we determine the interval of clay anomaly that resulted from frictional melting/thermal decomposition process by state-of-art in-situ synchrotron XRD analysis providing very high spatial resolution for mineralogy. Combined with the interval of the presence of vesicles from microstructural observation, the thickness of Chi-Chi PSZ is estimated to be 1 mm. Thus, the correlated contribution of surface fracture energy to earthquake breakdown work, at least in this locality, is quantified to be 1.9%. The huge remaining part of the breakdown work seems to be turned into heat associated with fault dynamic processes during the 1999 Chi-Chi earthquake.

1. Introduction

A brittle fault zone commonly shows three major internal components: fault core, damage zone, and host rock (Chester et al., 1993). The host rock or protolith remains basically undamaged during coseismic events. The damage zone is characterized by an increased density of subsidiary faults, fractures, veins, foliation, and folding relative to the host rock. The fault core, such as fault gouge, is typically characterized by geochemically altered and comminuted rocks produced during coseismic events and/or aseismic periods. Principal slip zone (PSZ: Sibson, 2003) within the fault core accommodated most shear displacement and/or high strain and was the place where physico-chemical processes were driven during an individual coseismic event. To aim at the fault zone geology (e.g., fault behavior such as weakening and involved mechanism, energy budget such as energy dissipation), a critical and challenging prospect, the identification of PSZ and its associated structures and reactions in an individual fault, is arising (Boullier, 2011).

Several scientific continental fault-zone drilling projects were conducted and these include the Nojima fault project following the 1995 Kobe earthquake in Japan (Boullier et al., 2001); the Taiwan Chelungpu fault Drilling Project (TCDP) following the 1999 Chi-Chi earthquake in Taiwan (Ma et al., 2006); the San Andreas Fault Observatory at Depth (SAFOD) in the U.S.A., (Zoback et al., 2010); and the Wenchuan earthquake Fault Scientific Drilling (WFSD) following the 2008 Wenchuan earthquake in China, (Li et al., 2013). The main goals of these drilling projects are to measure in-situ stress, strain, pore pressure, and other physical properties within active fault zones (e.g., porosity and permeability) (e.g., Zoback et al., 2010). Whereas, weathering (and exhumation) might erase and/or transform the signature, recorded in the fault rocks, of the physico-chemical process (e.g., melting, dehydration, etc.) occurring at depth during seismic slips (e.g., Kuo et al., 2012). To diminish the effects resulted from postseismic alteration on fault rocks, these continental fault-zone drilling projects could also provide fresh fault rocks to be directly investigated the physico-chemical processes within active fault zones (PSZ) during coseismic events. In this study, the recognition of PSZ corresponding to the 1999 Chi-Chi earthquake in Taiwan was based on the current literature from the TCDP and the details will be described later.

On 21st September 1999 the N–S-trending Chelungpu thrust fault ruptured in a Mw 7.6 earthquake near the town of Chi-Chi, producing 90-km long surface ruptures (Fig. 1a) (Lee et al., 2001). TCDP was initiated around six years after the mainshock with the intention of

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penetrating the Chelungpu fault at depth (Fig. 1b). The drill site of TCDP is 2-km east of the recently surface ruptured slip zone in the northern portion of the Chelungpu fault (Ma et al., 2006). The spatial slip distribution for the earthquake was well constrained from close strong motion and GPS data and showed a slip of 8.3 m on the fault near the drill site (Ji et al., 2003; Ma et al., 2001; Yue et al., 2005). TCDP was carried out a continuous coring for depths of 500 m to 2003 m, and 950 m to 1300 m for hole-A and hole-B, respectively. The fault core identified from the continuous core images was located at the depth of 1111 m of hole-A and 1137 m of hole-B, respectively (Fig. 1c for hole-A). The black gouge within the fault core, containing a band of highly intense grain-size reduction, was identified as the Chi-Chi PSZ (Ma et al., 2006).

The distinguishing characteristics were discovered within the PSZ: grain size distribution (Ma et al., 2006), microstructures (Boullier et al., 2009), clay–clast aggregates (CCAs) (Boutareaud et al., 2008, 2010), magnetic anomaly (Chou et al., 2012a, b; Hirono et al., 2006a; Mishima et al., 2006, 2009), inorganic carbon content (Hirono et al., 2006b), major and trace elements (Ishikawa et al., 2008), and clay anomaly (Hirono et al., 2008; Kuo et al., 2009, 2011). On the basis of current literature we presumably suggest that the formation of PSZ was due to the 1999 Chi-Chi earthquake.

The thickness of Chi-Chi PSZ from the aspect of microstructures was estimated to obtain the surface fracture energy and associated seismic efficiency (Ma et al., 2006). In this study we re-examine the thickness of PSZ from the aspect of mineralogy through characterizing the interval of clay anomaly with the in-situ synchrotron X-ray analysis. Furthermore, we also integrate our results with microstructures and the literature data from Ma et al. (2006) to obtain the correlated contribution of the fracture energy to the earthquake breakdown work.

2. Sample description and analytical methods

2.1. Petrographic thin section of Chi-Chi PSZ

The fault core of the Chelungpu fault was obtained from 1110.37 m to 1111.45 m depth in TCDP-A (Fig. 1c) and was made into sixteen

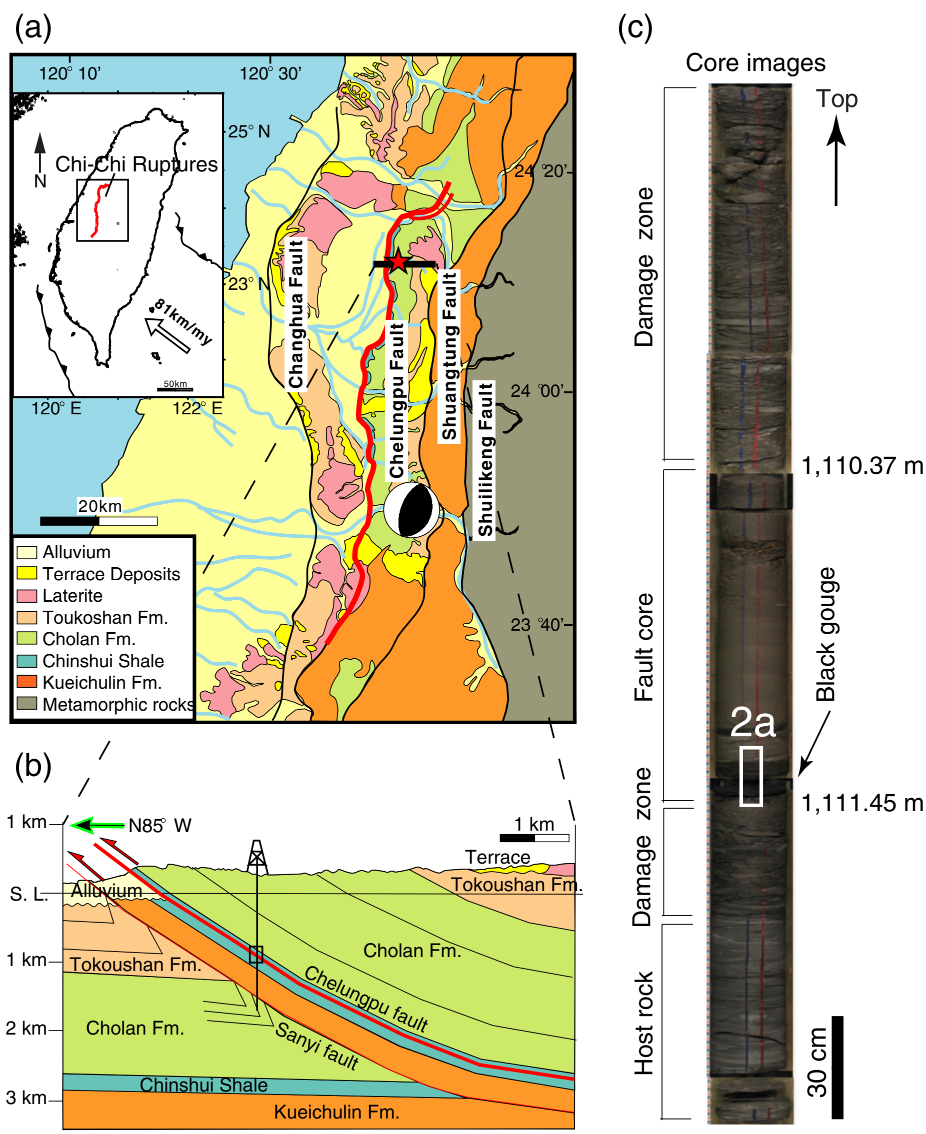

Fig. 1. Geological setting of the 1999 Mw 7.6 Chi-Chi earthquake and location of the TCDP-A drilling site. (a) Location of the TCDP-A drilling site and the 90-km-long surface ruptures associated with the Mw 7.6 earthquake at the central part of western Taiwan. The TCDP site is indicated by a red star. The focal mechanism of the Chi-Chi main shock is located at the hypocenter of the Chi-Chi earthquake. The insert box is the tectonic setting of Taiwan. (b) An E–W cross section of the TCDP-A showing the Chelungpu fault zone and surrounding formations encountered in the borehole (after Hung et al., 2007). The rectangle displaying the principal slip zone active during the 1999 mainshock was identified in the borehole at 1111.29 m depth and the images of fault core samples of the TCDP-A was enlarged in the right panel as (c). (C) The image exhibiting major portions of the Chelungpu-fault along the borehole of TCDP.